Our Planet's Geophysical Hazards

E-BOOK

Stephen Codrington

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Our Planet's Geophysical Hazards

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Cover photos show a lava flow on Kilauea Volcano, Hawaii, USA.

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Preface

Our Planet's Geophysical Hazards is one of seven monographs written to support the options for the International Baccalaureate Diploma Geography (IBDP) course. These seven monographs complement three larger books that span the entire content of the IBDP Geography Program. *Our Changing Planet* covers the SL and HL Core (Paper 2), *Our Connected Planet* covers the Higher Level Core Extension (Paper 3), and *Our Dynamic Planet* includes material on all seven options in the SL and HL themes (Paper 1).

As with all the books in the *Planet Geography* series, my aspiration is that every reader of this book will acquire knowledge and wisdom to become an effective steward of our planet, committed to ensuring its healthy survival and vibrant flourishing.

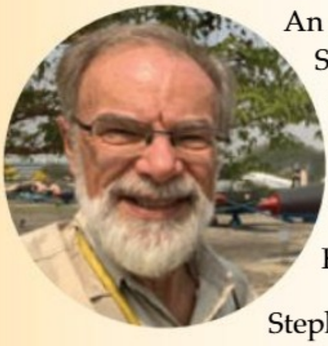
Any comments or suggestions to improve future editions of this book are always welcome. I hope you, the reader, will enjoy learning more about the geography of our fascinating planet as I have over the years.

Stephen Codrington.

The Author

Dr Stephen Codrington has a Ph.D. in Geography, and has taught the subject in several countries at both the high school and university level. He is the author or co-author of 69 books, mainly books that focus on his life-long passion for Geography.

Following his highly successful career as a teacher of Geography and Theory of Knowledge, including serving as the Head of five International Baccalaureate (IB) schools in four countries, he now works with school boards and leaders through Optimal School Governance, educates trainee teachers at Alphacrucis College, and is Chair of the Board at Djarragun College.



An Australian by birth, Stephen is a former President of both the Geographical Society of New South Wales and the Geography Teachers' Association of New South Wales (twice). He edited Geography Bulletin, the journal of the Geography Teachers' Association of New South Wales for seven years, and is now a Councillor and Treasurer of the Geographical Society of New South Wales. He has taught in schools in Australia, the United Kingdom, New Zealand, Hong Kong and the United States.

Stephen has been honoured with election as a Fellow of the Australian College of Education, the Royal Geographical Society (UK), and the Geographical Society of NSW. He was appointed to the role of IB Ambassador in 2014 and honoured with life membership of the Geographical Society of New South Wales in 2018. He is a former Chairman of HICES (Heads of Independent Co-educational Schools). Stephen's work has taken him to 161 countries, and he has been listed in Who's Who in Australia every year since 2003.

From 1996 to 2001 he served as Deputy Chief Examiner in IB Diploma Geography, setting and marking examination papers, assisting with curriculum development, and leading many teachers' workshops.

He maintains a personal website at www.stephencodrington.com that contains links to travel diaries and other items of geographical interest.

Chapter 1 Geophysical systems

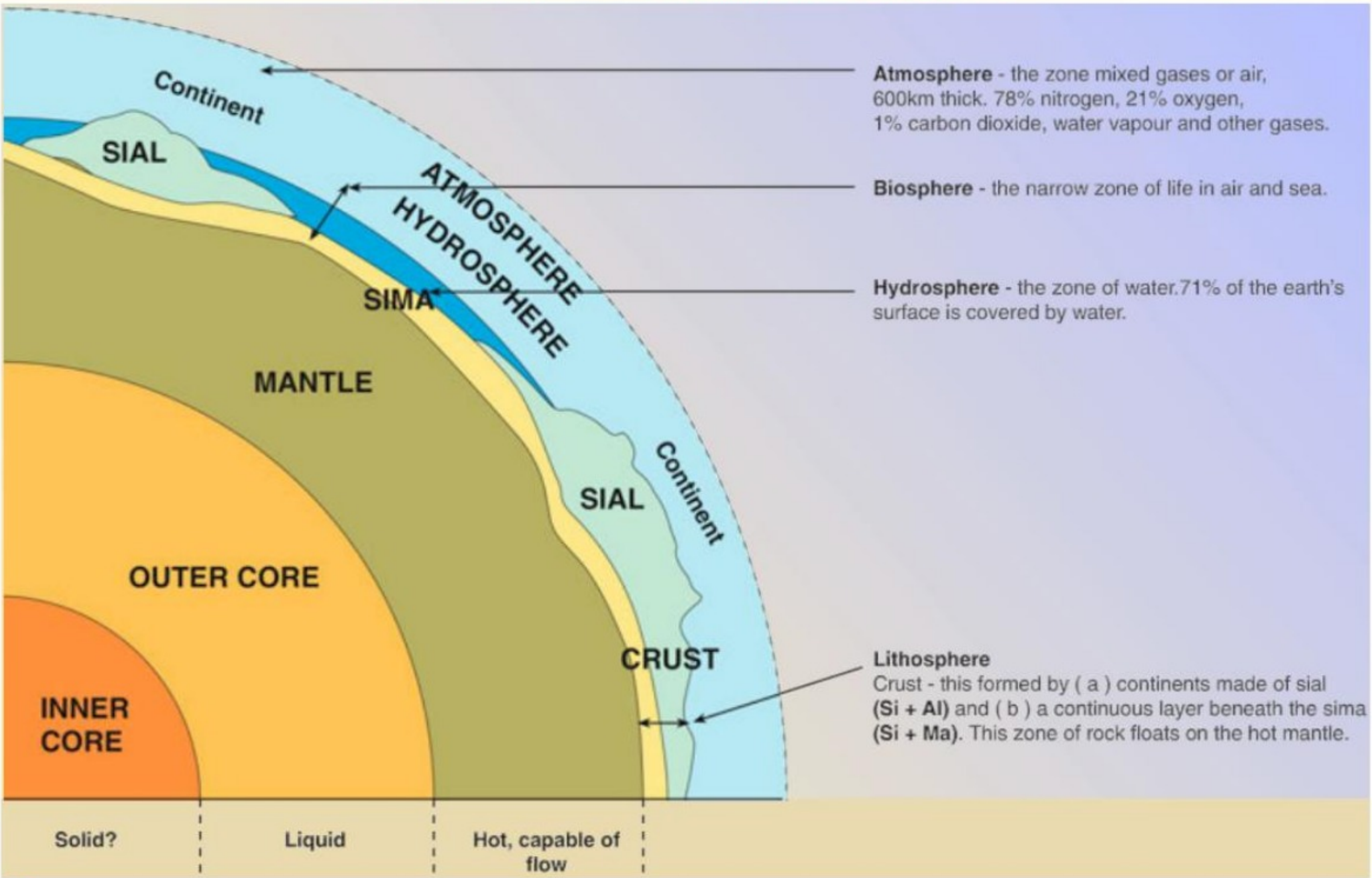
1.1 White Island, also known as Whakaari, is New Zealand's most active composite cone volcano. The volcano formed in association with the subduction zone that forms part of the Pacific 'Ring of Fire'.

Plate movement

The term **geophysical** refers to the workings of the earth. This includes movements on the earth's surface (crust) as well as beneath the surface. These movements can be hazardous for humans such as when earthquakes and volcanic eruptions occur.

Earthquakes and volcanoes occur in the earth's **lithosphere**. This is the solid zone of rock on the earth, including the crust and the upper part of the mantle, that extends downwards from the earth's surface to a depth of about 70 kilometres.

Figure 1.2 shows that the earth consists of several layers, like an onion. In the centre of the Earth is a very hot **core**. The temperature of most of the core is so high that its rock material has melted into a flowing liquid. Perhaps surprisingly, the inner core at the centre of the earth (where temperatures are highest) is solid. It is solid because of the enormous pressures pressing in on it. Surrounding the core is a **mantle** of semi-solid rocks. The closer we go to the earth's surface, the more solid the mantle becomes, although the rocks in the mantle are still able to flow like a thick honey.



1.2 The structure of the earth (not to scale).

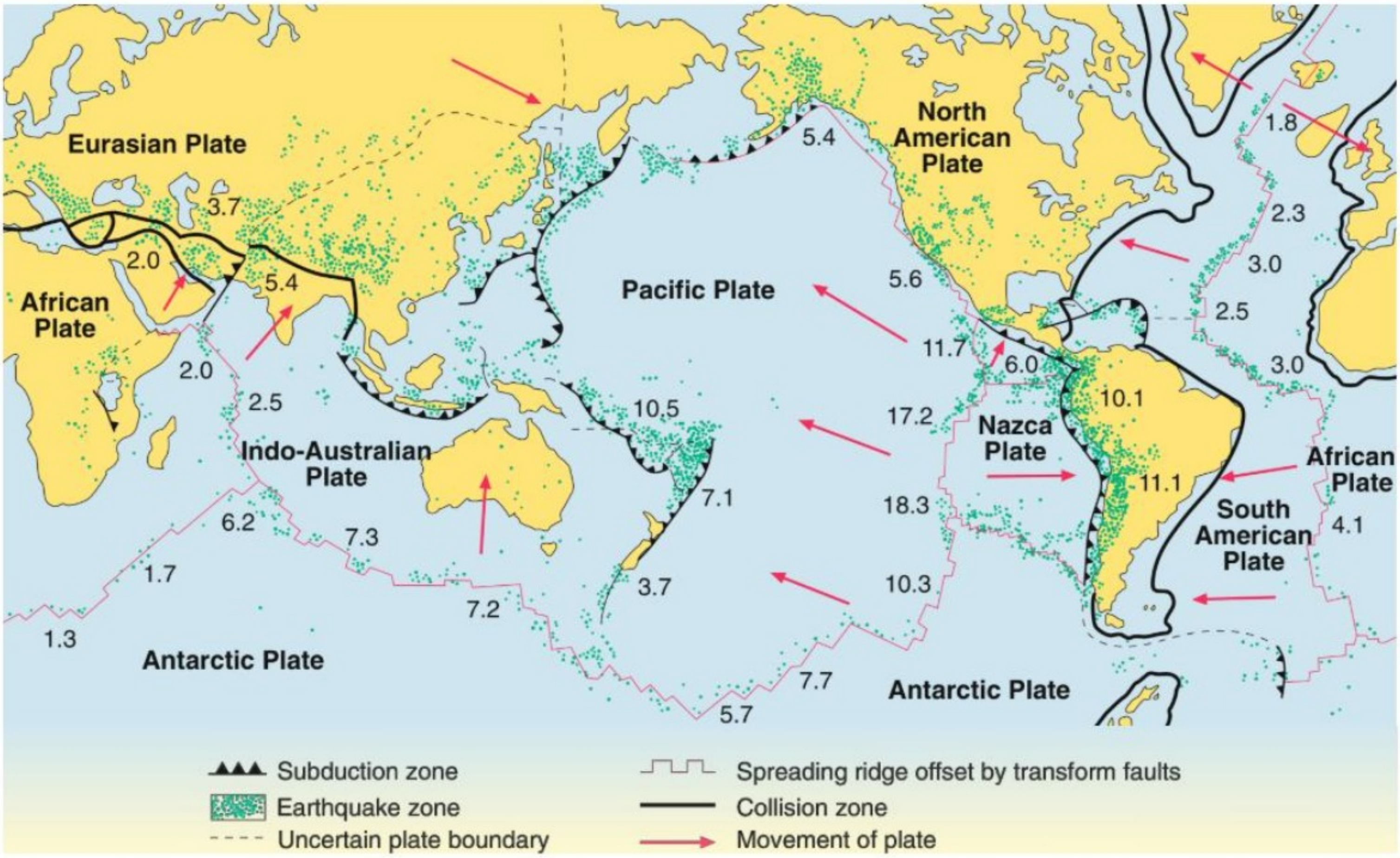
A thin **crust** forms the surface of the earth. The crust varies in thickness from about 4 kilometres under the oceans to about 40 kilometres under the mountain ranges of the continents. The continents are made up of the lightest rocks, known together as **sial**. The term 'sial' is made up of the letters 'Si' and 'Al', short for silicon and aluminium. These are two of the most common minerals in granite, which is the most common rock in the continents.

The heavier, denser layer of the crust is known as **sima**, made up of the letters Si and Ma (silica and magnesia). The world's ocean beds are made up of sima. If the earth were the size of a wet soccer ball, the crust would be as thick as the layer of water on the outside of it. We can think of the crust as being like a hard shell, 'floating' on the liquid mantle beneath it.

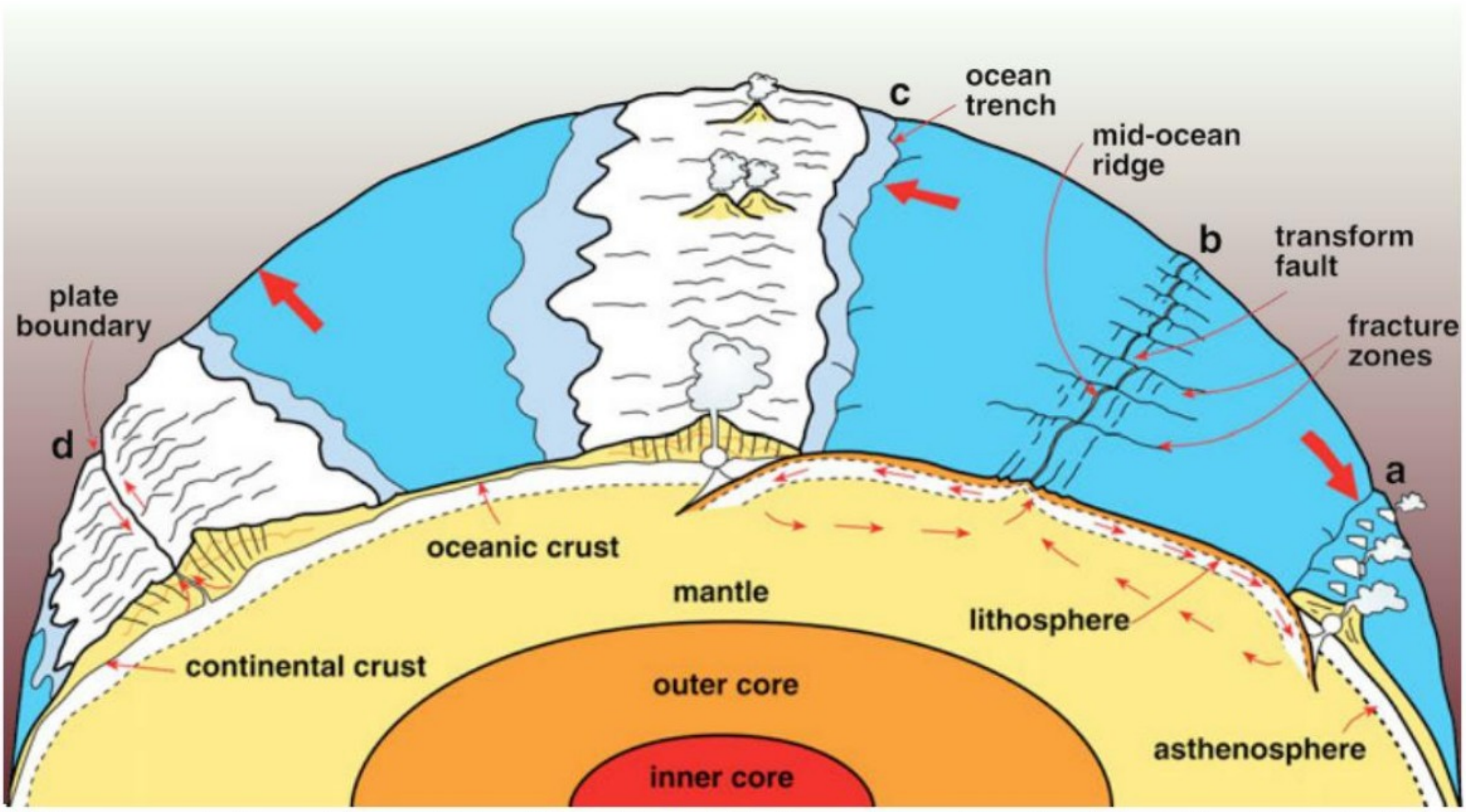
The earth's crust is not one continuous shell. The crust is made up of several **plates**, some large and some small. The plates are sometimes referred to as **crustal plates**, and also as **tectonic plates**. There are only a few main plates, and these are shown in figure 1.3. The rates at which the plates move varies greatly, from about 1 to more than 18 centimetres per year. The plates are carried 'piggy back' by the currents moving slowly in the liquid mantle, being dragged over the upper layer of the mantle which is called the **asthenosphere**. The plates are all moving in **different directions**. They come together in some parts of the world, and they move apart elsewhere.

Because the earth's tectonic plates are less dense than the mantle under them, they 'float' on the mantle, moving across the earth's surface at the rates shown in figure 1.3.

The forces driving the plates across the earth's surface require enormous energy. **Convection currents** occur in the mantle as a result of **radioactive decay**. Radioactive elements in the upper mantle constantly give off heat as they decay, and as the temperature rises, the rock expands. This causes convection currents to form as the expanded liquid rocks rise towards the surface. The radioactive decay is **unevenly distributed** through the mantle because the composition is not uniform, so upward movement occurs where the level of radioactive decay is greatest. The currents in the mantle are the means by which the earth



1.3 The world's major crustal plates. The rates of sea floor spreading and plate convergence are shown in centimetres per year.



1.4 The movement of the earth's crustal plates. Heavy plates sink into the mantle (a and c), pulling the rest of the plates behind them. This tears open the crust at the mid-oceanic ridges (b), creating ragged transform faults, where new material comes to the surface, helping to push apart the plates. Volcanic island arcs are created (a) where two sima plates collide. Where one plate is sial and one is sima (c), mountain ranges of the lighter sial buckle upwards, and volcanoes erupt. Where two sial plates collide (d) the mountains buckle upwards and are torn in different directions along a transcurrent fault.

1.5 The Mid-Atlantic Ridge can be seen at the earth's surface as it rises above sea level and passes through Iceland. This shows the Mid-Atlantic Ridge at the Lakagîgar crater row and lava flow from the eruptions in 1783.

1.6 Fissures at the explosion crater and lava flow at Krafla in Iceland mark the line of the Mid-Atlantic Ridge. The rocks in this area are still hot after the 1984 eruption.

1.7 A fumarole expelling sulphurous steam under high pressure on the Mid-Atlantic Ridge at Hverarönd, near Reykjahlid, Iceland.

dissipates heat from the hot core beneath it.

The upwellings of abnormally hot liquid rock in the mantle are known as **plumes**. Where a convection current **rises** in the mantle as a plume, **volcanic activity** occurs as the plates above are pushed upwards and outwards, thus drifting apart as new crust is formed. This creates a number of **spreading ridges**, also known as **divergent plate boundaries**. The most common form of divergent plate boundary is the **mid-ocean ridge**, such as the Mid Atlantic Ridge, where new oceanic crust is added to the earth's crust in the form of **pillow lava**. Divergent plate boundaries also occur as **rift valleys** where continents are splitting apart, such as the Rift Valley of East Africa.

At the **Mid-Atlantic Ridge**, new material is forced to the surface, forcing apart the edges of the South American and African plates. This is the force that causes Africa and South America to 'drift' apart. The Red Sea and the East African Rift also represent areas of plate margins moving apart, but in the case of East Africa, it is land rather than the sea that is pushed apart. Because new material is created at the **spreading ridges**, they are called **constructive plate margins**.

While plates move apart from each other at constructive plate boundaries, there are some places in the world where the plates **slide past** each other. These are known as **transform plate boundaries**. Transform plate boundaries may experience quite severe **earthquakes** because of the friction generated as the plates move past each other. A well known example of a transform plate boundary is the San Andreas Fault that runs near the large cities of Los Angeles and San Francisco in California, USA.

Convergent plate margins occur where plates move towards each other and collide. Because crustal material is destroyed at these margins, they are known as **destructive plate margins**.

Three alternative scenarios can occur at convergent plate boundaries.

If the two plates that collide are both of **similar density** with **light** continental (sial) material, the plates crumple into each other. Folding and faulting occurs, and the crumpled plates are forced upwards, forming a mountain range. The

1.8 Active cone volcanoes in the Andes Mountains of Chile that have formed as a result of the subduction zone collision between the Nazca Plate and the South American Plate. This is the Payachata complex of volcanoes, and the highest volcano in this view is Volcán Pomerape, which lies on the border of Chile and Bolivia.

Himalayas were formed in this way, and they are still getting higher as the Indo-Australian Plate continues to move north into the Eurasian Plate.

If the two colliding plates are of **similar density** with **heavy** oceanic (sima) material, a process known as subduction will occur. **Subduction** is the sideways and downward movement of a crustal plate into the mantle. If the two colliding plates are both sima, both plates will subduct and a deep **ocean trench** will form. The world's deepest trench, the Mariana Trench in the western Pacific Ocean, formed in this way. The deepest part of the Mariana Trench is 11,000 metres below sea level, deeper than the height to which Mount Everest rises above sea level.

If the two colliding plates have **different densities**, where one is sial and the other is sima, subduction will still occur, but only the denser plate will be subducted. The lighter sial plate will not subduct, but will fold and fault upwards against the other plate as it continues to push into it. This process leads to the formation of volcanoes, as we will see in the next section.

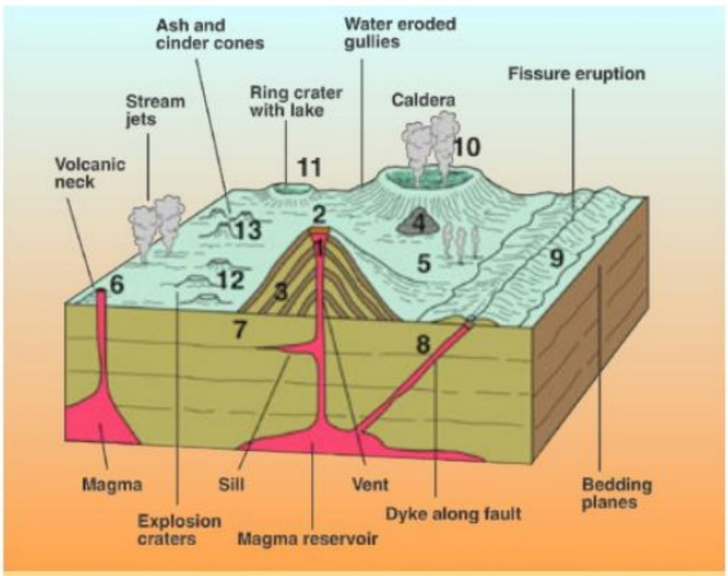
QUESTION BANK 1A

1. *Using figure 1.2, describe the relationship between the world distribution of earthquakes and the location of plate boundaries. Comment on the relationship.*
2. *Where is the earth's crust (a) created, and (b) destroyed?*
3. *What is the difference between sial and sima, and why is it significant?*
4. *What causes crustal plates to move?*
5. *Explain the differences between the three types of plate margins.*
6. *What are the three scenarios that occur at convergent plate boundaries?*
7. *Explain the formation of the following three areas: (a) the Himalayas, (b) the Mariana Trench, (c) the San Andreas Fault.*
8. *List the challenges and opportunities of building the Great Green Wall across the Sahel region.*

Volcanoes

When a sial crustal plate collides with a sima plate in a subduction zone, the oceanic (sima) plate is colder and denser than the lighter **asthenosphere** through which it is pushed downwards. The downward movement of the heavier plate exerts a drag on the asthenosphere, causing friction. This friction is the cause of **earthquakes** that are a very common feature of subduction zones.

As the plate is forced downwards, it is heated up by the surrounding mantle. Eventually, the descending plate melts, giving off steam and gases.

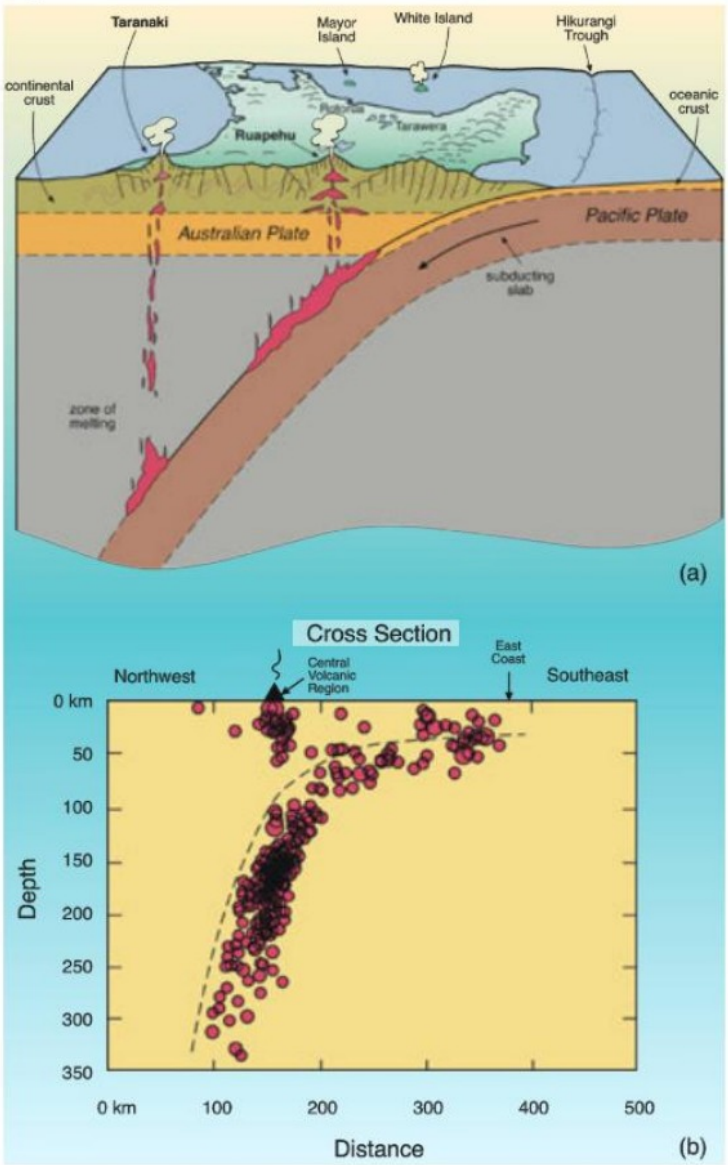


1. Side vent *or* parasitic cone *or* subsidiary cone *or* subsidiary cone
2. Crater containing lake
3. Composite volcanic cone of layers of ash and lava
4. Lava flow
5. Steam and gas jets
6. Volcanic neck (the hard rock or plug remains, much of the rest has been eroded away).
7. Sill : an intrusion of lava along the bedding planes
8. Dyke: an intrusion of lava across bedding planes
9. Lava sheet which has welled up along a fault line.
10. Caldera (often with a lake)
11. Ring crater: the raised rim is formed of ash and cinder.
12. Explosion craters
13. Ash and cinder cones

1.9 Features formed by volcanic activity.

1.10 Sunset Crater near Flagstaff, Arizona (USA), is a 305 metre high cinder cone volcano that erupted less than 1,000 years ago. The gases in the volcano threw the molten lava up into 260 metre high fountain, which blasted the lava into tiny fragments that fell downwards to form the cinder cone.

1.12 Momotombo is an active composite cone volcano in Nicaragua, near the city of Léon. Its eruption in 1610 forced the inhabitants of Léon to relocate the city 50 kilometres to the west.



1.11 The upper diagram (a) shows how the Pacific Plate is forced downwards to slide under the Indo-Australian Plate beneath the North Island of New Zealand. In the lower diagram (b), the distribution of earthquakes caused by the friction between the two plates is shown in a cross-section.

1.13 A pyroclastic flow rushes down the side of Mt St Helens in the state of Washington, USA during its eruption in August 1980. The photo was taken from a distance of 8 kilometres away, giving some idea of the size of the pyroclastic flow.

The gases rise to the earth's surface with liquid rock, known as **magma**, where it is released as a **volcanic eruption**, as shown in the example of New Zealand (figure 1.11). When liquid rock is underground, it is known as magma, but when it is released at the earth's surface, it is **lava**. In places where eruptions happen repeatedly, layers of ash and/or lava build up over time, and both cinder cone volcanoes and composite cone volcanoes are likely to form (figure 1.9).

A **cinder cone volcano** is a steep cone-shaped hill that is made up of layers of ash that have been deposited during successive **explosive eruptions**. They occur when a mix of gases and magma rises to the surface and blow violently up into the air. The violent upward explosion blasts the lava into tiny fragments that solidify as ash and cinders. The fragments then fall to the ground and form a symmetrical cone around the crater that emitted the fragments.

Cinder cone volcanoes may form very quickly. A famous cinder cone is Paricutin in Mexico. It began when a new vent opened in a farmer's corn field in 1943. The vent continued erupting for nine years, at which time the cone had built upwards to a height of 425 metres.

Composite cone volcanoes, which are also known as **stratovolcanoes**, form when a eruption spews out combinations of ash, lava, pumice or tephra at various times, which are deposited in layers to form a cone. These eruptions are **less explosive** than the eruptions that form cinder cone volcanoes. Composite cone volcanoes are the most common type of volcano, especially near subduction zones.

When they erupt, composite cone volcanoes produce lava flows and **pyroclastic** materials. They can be very hazardous for people living nearby because of the pyroclastic flows and mudflows that are often associated with their eruptions.

Pyroclastic flows are very fast moving mixtures of hot blocks of lava, pumice, ash and gases that have been extruded from a volcano during its eruption. They are usually quite dense, so they flow downhill following the valleys.

Pyroclastic flows move at **two levels**. Just above ground level, a heavy mix of ash and rocks is blown along by the high pressure gases from the eruption, while at a higher level, a tall cloud of ash rises

1.14 A lahar, or mudflow, on the slope of Tunguragua volcano in Ecuador.

1.15 A landslide in Dolina Geyzerov, a volcanic area beside the subduction zone where the Pacific Plate pushes into the Eurasian Plate at the Kamchatka Peninsula, Russia. The rocks have slid several hundred metres down the hillside.

upwards. The flow of rocks, ash and gas (known as **tephra**) moves downhill at a speed that can range from 70 to 700 kilometres per hour, with a temperature between 200°C and 800°C. Everything in the path of a pyroclastic flow is **destroyed**, either by burning, being knocked over, being shattered or buried.

Lahars are another hazard that is often associated with eruption of composite cone volcanoes, although lahars can also occur without an eruption. A **lahar** is a liquid mudflow or debris flow made up of a slurry of pyroclastic materials, rocks and water. Like pyroclastic flows, they typically flow down the sides of volcanoes through pre-existing valleys. Lahars have a density that resembles wet concrete, and they move quickly at speeds of up to 200 kilometres per hour, destroying everything in their path.

Volcanoes in cold areas with a covering of snow are especially susceptible to lahars because the heat from an eruption might melt huge quantities of snow and ice very quickly. Lahars gather extra water and materials as they move downhill, often increasing their volume by a factor of 1000%.

Volcanic eruptions sometimes cause landslides. Indeed, landslides are possible on volcanoes even when there is no eruption because the loose unconsolidated sediments on their slopes are so unstable. **Landslides** occur when large masses of rock and soil separate from the side of a mountain and slip downhill under the influence of gravity.

1.16 Part of the lava flow from Karymsky Volcano, a 1536 metre high composite cone volcano that is the most active on Russia's Kamchatka Peninsula. The shadows are caused by the plume of steam and ash that are emitted from the volcano's cone to the left of the photo.

Landslides can be initiated by earth tremors or earthquakes, or even a heavy fall of rain might be enough to reduce the friction holding the rocks in place, allowing them to slip and fall.

Landslides, which are also known as **debris avalanches**, are common in volcanic areas because many of the slopes are so steep. Moreover, the rocks on the slopes may have been weakened by the leakage of gases from beneath the ground. Like lahars and pyroclastic flows, landslides occur very quickly, and the speed of some landslides has been measured at 160 to 250 kilometres per hour.

1.17 A solidified lava flow runs parallel to the road near Sunset Crater, Arizona (USA). Known as the Kana-A flow, it resulted from an eruption some time between 1040 and 1100. The lava flowed about 10 kilometres, filling a valley to a depth of about 30 metres. Almost a millennium later, the lava flow still shows very few signs of vegetation.

Four factors can typically **trigger** a landslide in a volcanic area:

- earth tremors caused by magma intruding upwards into the neck of a volcano;
- an explosive eruption;
- a significant earthquake, usually associated with the friction of two plates colliding or rubbing past each other; and
- heavy or sustained rainfall that lubricates the rocks or saturates the ground on which they are resting.

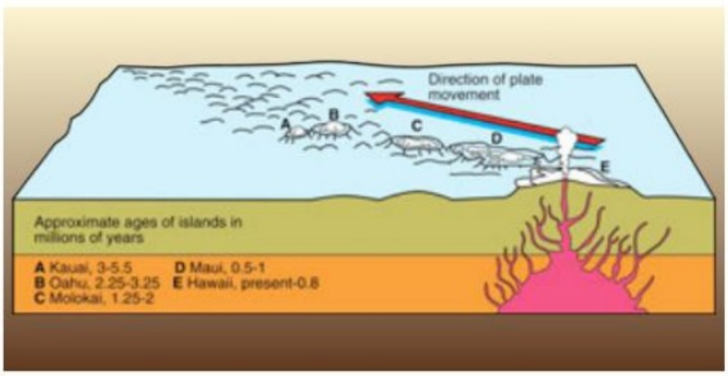
Lava flows are another hazard associated with the eruption of composite cone volcanoes. Lava flows occur when molten rock pours or oozes from an erupting volcano. As the lava flows across the ground, it cools and solidifies.

Most composite cone volcanoes emit lava flows that are not especially dangerous to people because the molten lava is so thick (viscous) that it flows quite slowly. However, the flows are difficult to stop or divert, and therefore they are a significant threat to people's property.

Volcanic activity can also be found away from plate margins, and the volcanoes that result are quite different from the cinder cone volcanoes and composite cone volcanoes near subduction zones.

There seem to be places in the mantle where radioactive decay is especially strong, resulting in enduring hot areas that are not associated with plate boundaries. In these isolated hot areas, mantle plumes form.

Mantle plumes are mushroom-shaped zones within the mantle that consist of abnormally hot material. Because they are so hot, they tend to rise towards the crust and then spread out in the asthenosphere beneath the crust as a tadpole-shaped **diapir**, or geological intrusion that forces the overlying crust upwards. The areas above plumes are known as **hot spots**.



1.18 The Pacific Plate on which Hawaii is located is moving towards the north-west over a hot spot. The older volcanoes (A and B above) have moved away from the hot spot and are now extinct. The age of the volcanoes becomes younger towards the south-east, where the hot spot is located. Hawaii's active volcanoes lie over the hot spot (E). To the south-east of the present active volcanoes, the next volcano has started to form under the ocean. Known as Lo'ihi, it is expected to rise above sea level in about 3,000 years from now.

The Hawaiian islands are situated in the mid-Pacific Ocean, well away from the margins of the Pacific Plate. However, Hawaii has several very active volcanoes. Hawaii is situated on a hot spot, where rising currents in the liquid mantle are concentrated near the earth's crust. The Hawaiian islands form a chain of volcanoes that are younger towards the south-east. The Pacific Plate, where

1.19 The caldera (collapsed crater) in the centre of this image marks the centre the huge shield volcano known as Kilauea in Hawaii, USA, that extends well beyond the limits of this photo.

Hawaii is situated, is moving towards the north-west. As the plate passes over the hot spot, new volcanoes are created that migrate towards the north–west.

The volcanoes that form over hot spots have quite a different shape from the cone volcanoes that form near plate boundaries. Eruptions over hot spots are relatively gentle as lava seeps out to the surface through fissures and vents, adding layer upon layer to previous lava flows. The result is a long, low **shield volcano**, named because its gentle slope resembles a shield resting on the ground. Most people standing on a shield volcano do not even realise they are on the mound of a volcano because the gradients are so gentle.

On Hawaii, two different **types of lava** form during eruptions, and they in turn form very different surfaces when they solidify. The first type of lava

1.20 Two types of lava are shown in this view at Mauna Loa in Hawaii. The smooth lava in the foreground is pahoehoe, while the rough dark lava behind is a'a.

1.21 A lava flow of molten rock from Kilauea volcano in Hawaii (USA) reaches the ocean, causing huge plumes of steam from the sudden heating of the water.

1.22 The Masaya Volcano near Managua in Nicaragua is an active volcano. This photo shows the lava flow from its eruption in 1772. The lava flow is now colonised by small trees and bushes that will break down the lava flow to form soil.

1.23 Yellowstone National Park in Wyoming (USA) lies above a hot spot. It has many landform features that dissipate heat from the hot mantle through the crust to the atmosphere, such as the boiling lake shown here. Some geographers speculate that the hot spot under Yellowstone will cause a massive eruption at some time in the future.

cools quickly to form **a'a**, which has a very sharp, rough surface. The second type of lava takes longer to solidify, and it forms a smooth surface that sometimes has a rope-like twisted shape; it is known as **pahoehoe**. The chemical compositions of the two types of lava flow are identical despite their very different appearances. Once cool, pahoehoe is very easy to walk on, but a'a can cut the soles of shoes and even car tyres in a matter of seconds.

Over time, lava flows become colonised by grasses and small shrubs, which begin to break down the rock to form soil. Once they have eventually formed, **volcanic soils** are very fertile because of their rich mineral content, and farmers readily use them to grow their crops. This explains why so many people choose to live on the slopes of volcanoes despite the dangers and hazards of doing so.

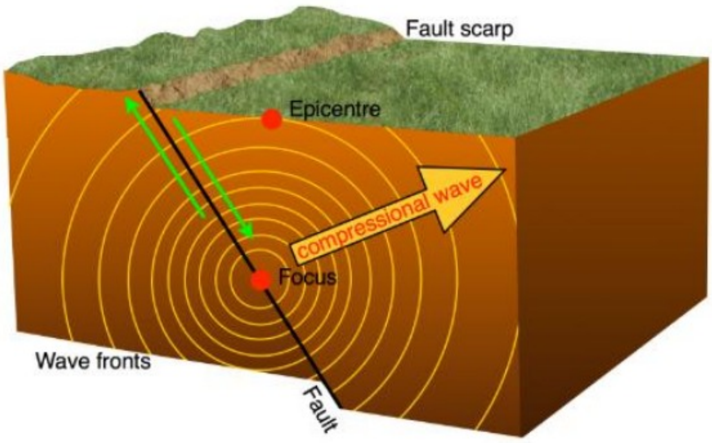
QUESTION BANK 1B

1. *There are three types of volcanoes: (i) cinder cone volcanoes, (ii) composite cone volcanoes, and (iii) shield volcanoes. Rank these three types of volcano in descending order of (a) the violence of their eruptions, and (b) the speed at which they form.*
2. *Name two examples each for (i) cinder cone volcanoes, (ii) composite cone volcanoes, and (iii) shield volcanoes.*
3. *What is the difference between the components of (a) pyroclastic flows, (b) lahars, (c) volcanic landslides, and (d) lava flows.*
4. *Briefly describe the causes of each of the following: (a) pyroclastic flows, (b) lahars, (c) volcanic landslides, and (d) lava flows.*
5. *Explain the relationship between mantle plumes and hot spots.*
6. *The volcanoes of Hawaii are younger as move from the north-west to the south-east. Explain why this is so.*

Earthquakes

An **earthquake** is a sudden movement of the ground surface. Earthquakes can range from minor shakes that are hardly felt called **earth tremors** right through to sudden, violent shifts that are so powerful that they might shake buildings apart and may last as long as several minutes. Earthquakes occur when the stresses within the earth's crust build up so much that the rocks break apart or scrape past each other. When a break occurs, **seismic energy** that has been stored up over time is released from a point of fracture known as the **focus** or **hypocentre**. The point on the earth's surface directly above the focus of an earthquake is known as the **epicentre**.

An earthquake is a form of **wave motion** through the earth's crust. When the earth's crust ruptures, usually along a fault line, **seismic waves** move outwards in all directions. The pattern of energy movement is similar to the waves of **concentric** circles that spread outwards from the point where a stone is dropped into a pond. Because the earth's crust is much denser than the water of a pond, the shock waves of an earthquake are quickly **dissipated**, and unless the earthquake is especially strong, the damage is usually confined to a few tens of kilometres from the focus.



1.24 Seismic waves radiate from the focus of an earthquake.

Three types of waves are generated during an earthquake. The first type of waves are P (primary) waves. **P waves** travel faster than the other waves, and therefore they are the first waves felt during an earthquake. Also known as compressional waves or longitudinal waves, P waves travel at speeds between 2 and 8 kilometres per second through the earth's crust. They shake the ground in the direction in which they are travelling, and they are capable to travelling through liquids such as water or the earth's mantle. When P waves travel through the mantle, they move at a faster rate than through the crust, travelling at up to 13 kilometres per second.

The second type of wave to be felt in an earthquake are S (secondary) waves. Also known as shear waves, **S waves** travel at a little more than half the speed of P waves. S waves shake the ground in

1.25 Land near a vineyard in South Napa, California (USA) has been ruptured and displaced by seismic waves during an earthquake associated with the San Andreas Fault in August 2014. The total fault slip at this location was 40 to 46 centimetres.

1.26 This surface fault rupture was caused by an earthquake in the Saudi Arabian desert in May 2009. The ground displacements in the soft sediments of the foreground are greater than in the basement rocks of the background because sediments respond differently than hard rock to the ground shaking and rupture.

two directions that are perpendicular to the direction in which the wave is travelling. In other words, whereas P waves rock the ground backwards and forwards, S waves move the ground both up and down and sideways at right angles to the seismic wave. Unlike P waves, S waves cannot travel through liquids.

P waves and S waves shake the ground at frequencies of between 1 and 30 hertz (one hertz being one cycle per second). This **high frequency** waves cause **low buildings** to vibrate, and if the waves are strong, perhaps collapse.

1.27 Tranque las Tórtolas is a large reservoir that was built to collect the toxic tailings from Los Broncos copper mine north of Santiago in Chile. The dam has been built in the fault zone of the subduction plate boundary where the Nazca plate is colliding with the South American plate to form the Andes Mountains (shown in the background). This is an active earthquake zone, and the weight of water in the reservoir may help to trigger earthquakes. If the toxic waters of the reservoir were released, it could lead to an environmental disaster.

The third type of waves are **surface waves**. These are the slowest of the three types of seismic waves, and they do not penetrate beneath the upper surface of the earth's crust. There are several types of surface waves. **Love waves** move backwards and forwards across the surface at right angles to the P waves. **Rayleigh waves** move the ground in a rolling motion, and **Scholte-Stoneley waves** form in areas where solids and liquids meet, such as on the edges of lakes or large rivers. All the surface waves are low frequency, meaning they oscillate at between 0.1 and 1 hertz. **Low frequency** waves are more efficient in causing **high buildings** to vibrate.

As we saw in figure 1.3, the **global distribution** of earthquakes is strongly related to the location of crustal plate boundaries. Earthquakes occur at all three types of plate boundaries. Transform and constructive (divergent) plate boundaries usually have **shallow focus earthquakes** that occur close to the surface. These can cause extensive damage because there is so little depth of rock to absorb the seismic energy between the focus and the surface. **Deep focus earthquakes** occur at destructive (convergent) plate boundaries as mountains are built up through folding or faulting (orogenesis) or as one plate is subducted downwards.

Human actions can trigger earthquakes, especially in areas that are prone to earthquakes anyway because the underlying rocks have fault lines. For example, **large dams** in earthquake prone areas have been shown to trigger earthquakes, as the weight of water places downward pressure on the fault lines beneath, and water that seeps downward lubricates rock movement. Similarly, other human actions that disturb the rock structure or place extra pressures, such as mining, blasting, drilling or excavating, could trigger seismic movements.

The earthquake risk associated with dams is related to the **size of the reservoir**. The risk of a human-triggered earthquake is greatest when the dam's capacity exceeds one billion cubic metres, or when the depth of the water storage exceeds 100 metres. Faults that have been stable for a million years may be displaced by the mass of such large bodies of water. Over time, the stresses in fault lines build up, and the weight of water may be enough to make the difference between stability and failure. The problem is that the most likely place for such an earthquake is where the water is deepest and exerts the most pressure, and that is right **behind the dam wall**, where the risk of major structural failure of the dam is also greatest.

1.28 The Donghekou landslide was triggered by an earthquake in nearby Wenchuan, China, in May 2008. This landslide had three source areas: the mountain slope at the top right of the photograph, a second area that resulted in a rockslide behind the geographers, and a third across the river (not shown in the photograph). The landslide dammed two confluent rivers forming a massive lake. The Chinese army created a new water course through the landslide using dynamite and heavy equipment, allowing the rivers to flow again. This also reduced the pressure of the increased water volume that had built up behind the dam. The landslide also engulfed a bus stop area, burying two large buses, a car, and 300 villagers. The volume of the landslide was so large, and it moved so rapidly, that it generated two areas of air blast that were so forceful that trees were levelled.

1.29 An earthquake in August 1959 in south-western Montana (USA) caused a major landslide that dammed the Madison River and formed a new lake, now officially named Earthquake Lake. Earthquake Lake is almost 10 kilometres long and over 50 metres deep. The landslide released 80 million tonnes of rock that slid into the river at a speed of 160 kilometres an hour, instantly killing 28 people who were camping beside the river at the time. The air blast associated with the landslide crested over a nearby dam, causing structural damage to the wall. The landslide, shown behind Earthquake Lake in this photograph, has still not stabilised.

Secondary hazards of earthquakes

When an earthquake hits, it is often just the first of the hazards that will afflict an area. Earthquakes may trigger one or more **secondary hazards**.

Landslides are one such secondary hazard. Earthquakes create stresses that can make weak slopes fail, dislodging rocks on a steep slope or even causing a new fault to fracture the hillside. If the earthquake occurs during heavy rainfall, a landslide may be even more likely because the rocks and sediments will be lubricated by the rain. Huge masses of rock may slide downhill during a landslide, destroying everything in its path. The accompanying rush of air is also highly destructive, and these can be so strong that forest trees may be knocked to the ground.

1.30 Evidence of liquefaction during the earthquake in Christchurch, New Zealand, in February 2011. Land has turned to liquid and flowed down a slope to cover part of this road near the centre of the city, partially burying some parked cars.

Another secondary hazard of earthquakes is liquefaction. **Liquefaction** occurs when an earthquake shakes an area of soil, leading to a separation of the soil's solid and liquid components. As a result, the soil loses its structural integrity, causing it to behave like a liquid and flow downhill. In areas where the soil had provided the foundations of roads and other structures, they simply collapse as the soil beneath flows away as a liquid. Even quite mild earthquakes that people hardly detect can cause landslides and liquefaction.

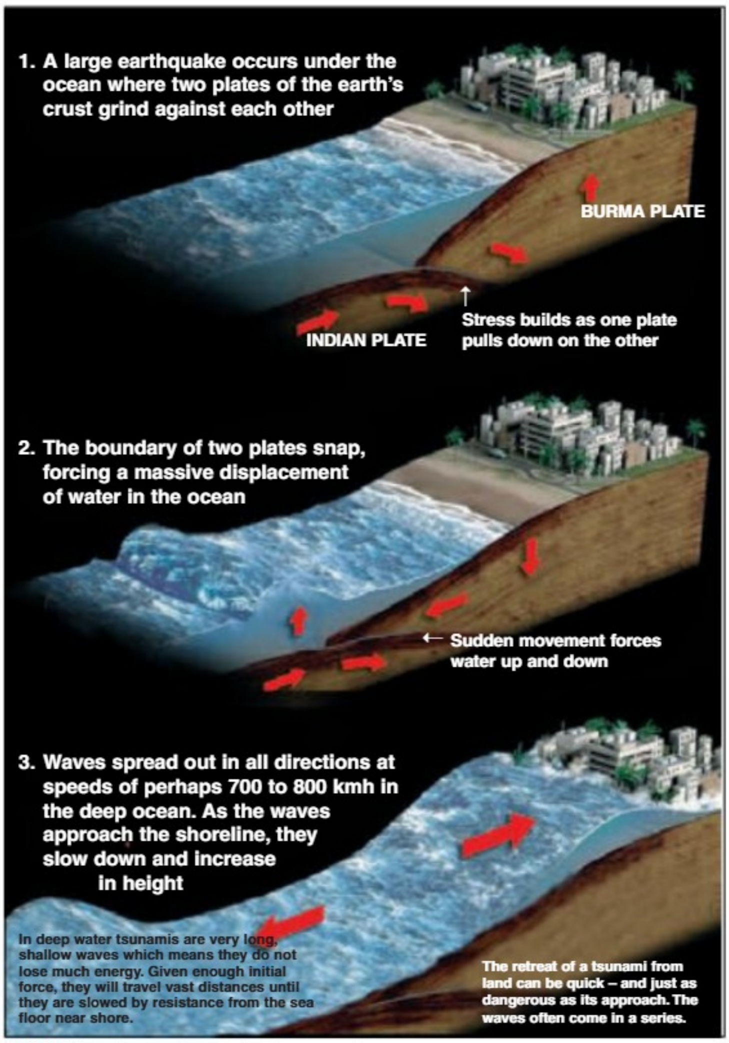
Tsunamis may also result from an earthquake. Often wrongly called tidal waves (they have nothing to do with tidal changes), tsunamis are very large sea surface waves that are caused by underwater earthquakes, underwater landslides, volcanic activity or even a meteorite strike. When they first form, they can only be detected by very sensitive measurements of changes in deep water pressure. However, when they reach the shallow waters of coastal regions, **wave height** may rise to several metres, leading to severe property damage and loss of life.

Tsunamis usually travel at **speeds** averaging 700 (and up to 1,000) kilometres per hour in the open ocean. In the open ocean, a tsunami would not be felt by ships because the wavelength would be

1.31 A tsunami warning sign in the coastal city of Iquique, Chile. Iquique is located on the plate boundary of the Nazca and South American plates, making it vulnerable to earthquakes.

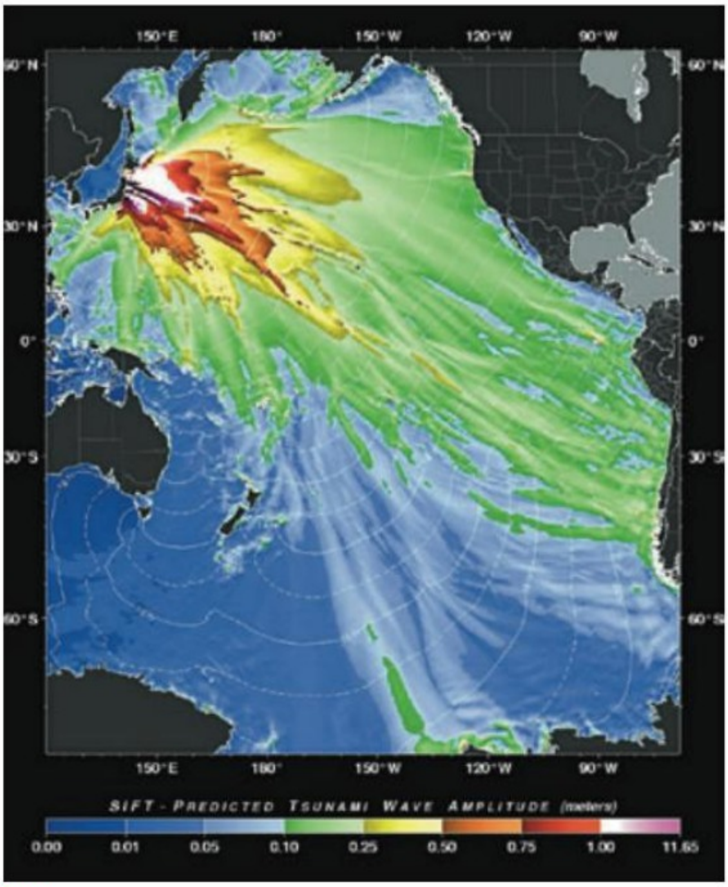
1.32 Although it is located in the central Pacific Ocean, Upolu Island in Samoa is vulnerable to tsunamis that may originate in earthquake-prone subduction zones that lie to its west and north-west. This sign near the coast in Apia points residents to head uphill if a tsunami warning is issued.

hundreds of kilometres long, with an amplitude of only one metre or so. However, as the waves approach the coast, their speed decreases and their amplitude increases because they are affected by the submarine topography approaching the shoreline. Unusual wave heights have been known to be over 30 metres high, but waves that are three to six metres high can be very destructive and cause many deaths or injuries.



1.33 The formation of a tsunami.

The areas which face the greatest risk from tsunamis are less than 8 metres above sea level and within one kilometre of the shoreline. Most deaths caused by a tsunami arise from drowning. **Secondary risks** include flooding, being hit by heavy debris carried by the moving water, contamination of drinking water, fires from ruptured tanks or gas lines, and loss of vital community infrastructure (police, fire, and medical facilities).



1.34 A map of the Pacific Ocean showing the estimated height of the tsunami that was generated by the Honshu earthquake on 11th March, 2011. Source: National Geophysical Data Center [NGDC], National Oceanic and Atmospheric Administration [NOAA]

As soon as the shock first occurs, waves travel outward in all directions like the ripples caused by throwing a rock into a pond. As these waves approach coastal areas, the time between successive wave crests varies from 5 to 90 minutes. The first wave may be preceded by a few minutes of abnormally low water, and when it hits, it is usually not the largest in the series of waves, nor is it the most significant.

Because of its large size and extent of earthquake activity, the Pacific Ocean is especially vulnerable to tsunamis. Consequently, a network of **tidal gauges** has been established through the region, centred on Hawaii, providing 26 countries with warning messages.

CASE STUDY
The Indian Ocean Tsunami, 2004

One of the most severe **tsunamis** in recent times occurred on 26th December 2004 when an **earthquake** of magnitude 9.0 on the Richter Scale occurred at a depth of 30 kilometres under the ocean off the western coast of northern Sumatra (Indonesia). The earthquake was caused by a **shift** of about 15 metres along a 1,200 kilometre long boundary section between the Indo-Australian and Eurasian crustal plates.

The shift did not happen instantaneously, but in two phases over a period of several minutes. **Aftershocks**, some as large as 6.6 and 7.1 on the Richter Scale, continued for several days after the initial earthquake. As a result, several tsunami waves were created during the period in which the plates were shifting.

During the earthquake, the surface of the ocean **shifted upwards** by several metres over the long distance of movement (1,200 kilometres). Therefore, the tsunamis created affected areas all the way **around the edge** of the Indian Ocean. There was even some impact as far away as New Zealand, Mexico and Chile. Six weeks after the earthquake, **remnants** of the wave could still be measured going back and forth across the Indian Ocean.

The tsunami caused an estimated **death toll** of about 300,000 people. The largest number of deaths occurred in Indonesia, near the **epicentre** of the earthquake, followed by the eastern coastlines of Sri Lanka and India which were openly exposed to the earthquake epicentre. Smaller numbers of deaths were reported in Thailand, Myanmar, Somalia, Maldives, Malaysia, Tanzania, Bangladesh, Kenya, South Africa and the Seychelles. About one-third of

1.35 (↑↑↑↑) 1.36 (↑↑↑) 1.37 (↑↑) 1.38 (↑) Four views of Kalutara Beach in Sri Lanka. In the top view, the beach is seen on 1st January 2004, almost one year before the tsunami. In the second view, the beach is seen on 26th December 2004 just before the tsunami hit, and the wide expanse of exposed sand is evident. In the third view, the waters of the tsunami flood the area behind the beach. In the bottom view, the waters recede back to the ocean.

the deaths were children because they did not have the strength to resist the surging waters of the tsunami. In addition to the people killed, it was estimated that about 1.5 million people were **displaced** from their homes by the tsunami. Death rates were lower in areas where **coral reefs** or **mangroves** protected the shorelines, and where people had not built dwellings too close to the beach.

Because of the time it took for the tsunami to travel through the ocean water, there was a **lag** of several hours between the earthquake and the impact of the tsunami. Despite this lag, **poor communications** meant that most victims had no warning of the danger.

The first **warning sign** of any possible tsunami is the earthquake itself. However, tsunamis can strike thousands of kilometres away, so the earthquake may be felt weakly or not at all in the tsunami hazard zone.

As shown in figure 1.37, the ocean often **recedes temporarily** away from the coast in the minutes preceding a tsunami. Many people around the Pacific Ocean recognise this as a sign to head for higher ground because they are familiar with tsunamis. However, when the water retreated on the beaches around the Indian Ocean on 26th December 2004, this rare sight apparently **attracted** people, especially children, to visit the coastline. Visitors came to the beaches to investigate the strange sight of seeing as much as 2.5 kilometres of exposed beach, and to collect stranded fish.

One of the few coastal areas around the Indian Ocean to **evacuate** before the tsunami hit was the Indonesian island of Simeulue, very close to the epicentre of the earthquake. Island folklore told of an earthquake and tsunami in 1907, and the islanders fled to inland hills after the initial shaking, well before the tsunami struck, and no lives were lost. On Maikhao beach in northern Phuket, Thailand, a vacationing 10 year old British girl named Tilly Smith had studied tsunamis in geography class at school and recognised the warning sign of the receding ocean. She and her parents warned others on the beach, which was evacuated safely with no loss of life.

The Indian Ocean had no recorded history of widespread tsunamis in the Indian Ocean before the 2004 tsunami, and so no **tsunami warning system** had been established at the time of the earthquake. In the aftermath of the 2004 tsunami, a multi-national effort began to construct a tsunami warning system. Seismometer gauges were installed to track and measure tsunami waves, both near the epicentre and distance away from the epicentre. It was agreed to include a warning system with models to **forecast** tsunamis, and an emergency **communications** system to warn Indian Ocean countries when a potentially destructive tsunami forms so that people have enough time to evacuate if necessary.

1.39 A village near the coast of Sumatra, Indonesia, lies in ruins after the tsunami in December 2004.

Beyond the heavy toll on human lives, the Indian Ocean earthquake caused a huge impact on the **environment** that will affect the region for many years. At the **local scale**, there was severe damage to **ecosystems** such as coastal wetlands, mangroves, coral reefs, forests, vegetation, sand dunes and rock formations, animal and plant biodiversity and groundwater. Furthermore, the spread of solid and liquid **waste** and industrial **chemicals**, water **pollution** and the destruction of **sewage** collectors and treatment plants caused major impacts on the environment.

One significant environmental impact was the poisoning of fresh water supplies and the soil by **salt water infiltration** and the deposition of a **salt layer** over arable farming land. In the Maldives, 16 to 17 coral reef atolls that were covered by sea waves are now without fresh water, and they will remain uninhabitable for decades. Huge numbers

1.40 Two weeks after the tsunami, hovercraft arrived to deliver materials and humanitarian supplies to Meulaboh, on the island of Sumatra, Indonesia.

of **water wells** were invaded by the ocean and filled with salt water, sand and earth. Large areas of **rice fields** in India and Thailand, together with thousands of mango and banana **plantations** in Sri Lanka were destroyed almost entirely and will take years to recover.

At a **global scale**, the earthquake and tsunami shifted the location of the North Pole about 2.5 centimetres to the east, reduced the earth's oblateness (the tendency to flatten on the top and bulge at the middle) and changed the earth's rotation. It is estimated that the earthquake shortened the length of a day by 2.68 microseconds (or about one billionth of the length of a day).

More spectacularly, some of the smaller islands south-west of Sumatra, together with the northern tip of Sumatra and parts of the Malay Peninsula, moved south-west by over 20 metres, while parts of the overlying oceanic plate moved to the north-east. Several airports shifted by distances of over a metre and needed a correction to their GPS (global positioning systems) for aircraft to use their automatic landing systems.

QUESTION BANK 1C

1. *What is the difference between an earthquake's focus and its epicentre?*
2. *Identify the differences between P waves, S waves and surface waves in terms of (a) their direction of movement, (b) their strength, (c) their frequency, (d) whether or not they move through liquids, and (e) how likely they are to cause damage to buildings.*
3. *What is the difference between shallow focus earthquakes and deep focus earthquakes.*
4. *Giving some examples, explain how human actions can be a factor in causing earthquakes.*
5. *Identify three secondary effects of earthquakes, and briefly describe how each is caused.*
6. *Why did the tsunami in the Indian Ocean on 26th December 2004 cause so much damage?*

Mass movement

Mass movement, or **mass wasting** as it is sometimes called, is the downslope movement of weathered rock materials under the influence of **gravity**. Gravity constantly affects all rock and soil. In general, rocks and soil have firm foundations and enough rigidity or stability to resist the downwards pull of gravity. However, when slopes become too steep because of undercutting, or something happens to destabilise the slope, rocks can break free and tumble downwards.

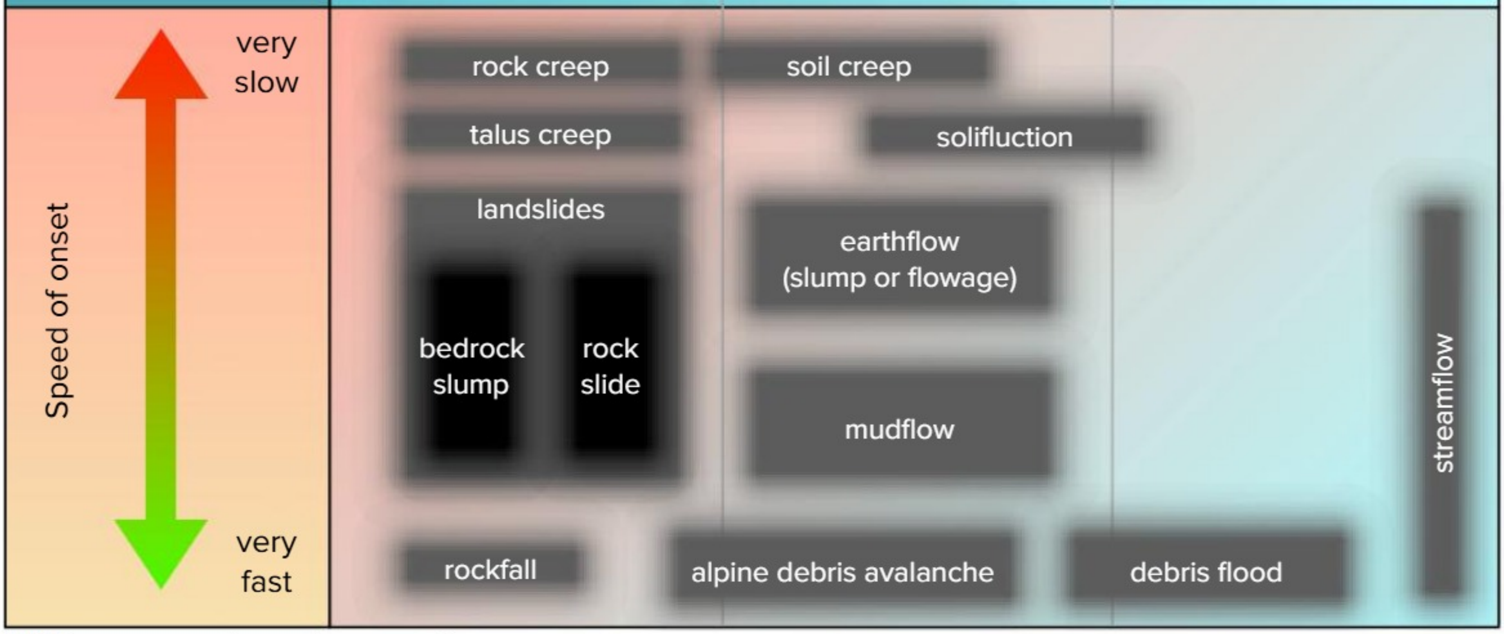
Soils and **weathered rocks** are more vulnerable to gravitational pull than bedrock because they are held together more loosely. On most slopes, there is always some downward movement, but the speed is often so slow that it is imperceptible.

Examples of mass movement include landslides, rockfalls, avalanches, debris flows, soil creep, solifluction and gelifluction. These types of mass movement are not always separate, and forms of mass movement can easily **transition** into different forms of mass movement as environmental circumstances change. Figure 1.41 shows some of the main types of mass movement as they relate to **speed of movement**, kinds of **motion** and constituent **materials**.

The four factors that promote mass movement

Mass movement occurs as a way of establishing an **equilibrium on sloping ground** between the processes of weathering and erosion. When weathered material accumulates on the upper part of a slope at a greater rate than it can be transported away by the agents of erosion, such as wind and water, or when the agents of erosion undercut the weathered materials on a slope, the equilibrium is

Types of earth materials	Dry rocks	Soil, alluvium, clay plus some water	Water and sediment
Liquidity	Hard, brittle, solid	Plasticky	Fluid
Kinds of motion	Falling, rolling, sliding	Flow within a mass	Fluid flow



1.41 Processes and forms of mass wasting (after Strahler).

disturbed and mass movement will occur. Four factors work together or separately to promote mass movement.

1. Slope

Gravity provides the energy for mass movement, so it follows that mass movement tends to be most **rapid** on **steep slopes**, and **gentler** on slopes that are **not as steep**.

Bedrock, or **regolith** as it is also known, has a natural resistance to movement. This **resistance** is greatest on gentle slopes and least on steep slopes. Downslope forces change according to the **sine** of the angle of the slope. Therefore, rocks resting on a slope of 30° experience a force that is the equivalent of 50% of the force of gravity. Rocks on a slope of 60° experience a force that is the equivalent of 87% of the force of gravity.

When agents of erosion such as rivers, coastal waves or glaciers **erode the base of a slope**, its average angle becomes steeper, the gravitational force on the slope increases, equilibrium is disrupted, and mass movement may be initiated.

1.42 The importance of slope as a factor in mass movements is shown in this photo of a large rockslide in south-eastern Montana, USA. The upper part of the slope has been over-steepened, causing it to collapse. The fallen rock material accumulates at a gentler and more stable angle at the foot of the slope.

2. Water

Water can help trigger mass movement in three ways. First, rainfall adds **weight** to the weathered material on a slope, disrupting the slope's equilibrium. Second, water destroys the **cohesion** between rocks and soil particles by providing

1.43 Erosion by a small stream has undercut this slope, causing over-steepening and subsequent earthflow. On the upper slope, another form of mass movement known as terracettes (a form of soil creep) can be seen. This slope is west of Kirkjubæjarklaustur in Iceland.

lubrication, making them more slippery. Third, water pushes particles apart by exerting **pressure** on the spaces between them.

3. Texture of the weathered material

Different types of **particles** such as sand, clay, soil and rock particles behave differently under the influence of gravity because of their various sizes, smoothness and angularity. Particles that are coarser and rougher resist mass movement more effectively than smooth particles, which usually have fewer opposing frictional forces.

4. Initial impetus

Many slopes are able to maintain an equilibrium that resists mass movement for long periods of time. Then, a **triggering event** upsets the equilibrium and causes mass movement to occur.

Triggering events may be **physical**, such as an earthquake or a heavy fall of rain, or **human**, such as blasting for roadworks or mining. Even lightning, trains and gun shots have been known to trigger sudden mass movements. Other triggering events include burrowing animals, the removal of vegetation, alternate freezing and thawing, and heavy falls of snow.

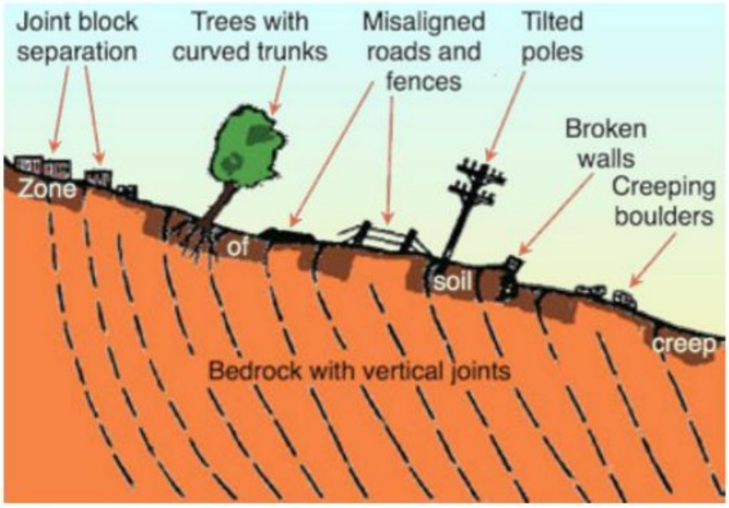
Mass movement types

Each form of mass movement involves one or more of four **types** that depend on the four **processes**: creep, flow, slides and falls, and subsidence.

Slow creep

Creep is the slow movement of surface material, such as soil, downhill under the influence of gravity.

It is a **continuous** movement, but often so **slow** that it cannot be seen with the naked eye. Speeds of soil creep vary depending on the moisture content of the soil, but typical speeds are 1.5 to 3 metres per 50 years. Although slow, the effects of soil creep are quite obvious. Fence posts, telegraph poles and walls develop a marked lean downhill, and trees develop bent trunks as the try to grow upwards while their roots are shifting downhill.



1.44 Features associated with soil creep.

Terracettes are a form of creep, although their formation is slightly different from 'smooth' soil creep. Terracettes form when saturated soil particles on **steep** slopes **expand** during rain, and then **contract** when the soil dries again. This repeated process causes small steps to form that

1.45 The non-vertical angles of the tree trunks on this slope in the Galičica Mountains near Koritski Rid in North Macedonia, indicate soil creep, probably exacerbated by the road cutting.

dislodge from the underlying soil and move downhill under gravity. They are sometimes called 'cattle tracks', but although cattle will use the terracettes once they have formed, they are not responsible for their initial formation.

Rock creep and **talus creep** are other types of slow mass movements. **Talus**, or **scree**, means the weathered rock fragments that have become dislodged from a slope. Under the influence of gravity, talus and scree forms talus slopes at the foot of steep slopes that have shed weathered rock material. Typically talus slopes come to rest at an angle of 35°, which is sometimes known as the **critical angle**. If the talus slope becomes steeper than its critical angle, equilibrium will be lost and mass movement will occur to restore the 35° angle.

1.47 Terracettes can be seen on the slope in the right foreground, indicating slow downward movement of the surface soil. This view is near Kingston, Norfolk Island.

1.46 Talus slopes rest at their uniform critical angles at the bottom of the slope that provided the rock material at Logan Pass, Montana, USA.

1.48 A talus slope in an arid terrain, Muley Point, Utah, USA.

1.49 A rotational slump in an arid environment. This example is in Karijini National Park in the north-west of Western Australia. In rotational slumps, the shear plane along which the slope fails resembles the arc of a circle. Rotational slumps may occur on natural hillslopes as seen here, but they are even more common in excavations or on fills made by people.

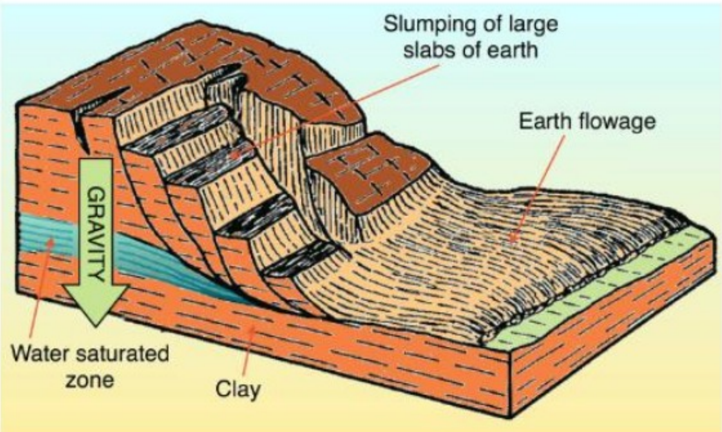
Rapid flowage

The **three major types** of rapid flow mass movements are earthflows, mudflows and debris avalanches.

Earthflows are like slow moving landslides. They occur on slopes when the earth is saturated with water and becomes capable of treacle-like slow-moving flowage. Earthflows cannot usually be seen with the naked eye as they move because they move so slowly, but they can be observed over a period of hours of days.

An even slower form of earthflow is **solifluction**, which is most common in periglacial environments. In areas with permafrost, the upper layer of the ground is permanently saturated because water cannot soak away. The slushy material that results moves down even the gentlest of slopes under the influence of gravity.

Earthflows leave scars on the hillside, usually marking a point at the top of the scar where the earthflow began, and broadening out to a wider, bulging slump of earth at the foot of the slope. The way in which earthflows move is shown in figure 1.50.



1.50 Earthflow and earth slump.

Mudflows are a faster form of rapid flowage. Unlike earthflows, mudflows move quickly enough to be observed by the naked eye. They occur when heavy rains destabilise a slope and cause a mix of soil, rocks and boulders to slide downhill. In **deserts**, mudflows lead to the development of **alluvial fans** at the foot of the slope. In **mountain** areas, mudflows occur on steep slopes when a sudden **thaw** melts the accumulated snow. When they occur in **volcanic** areas, they are known as **lahars**, and they occur most commonly on the loose slopes of **cinder cones**.

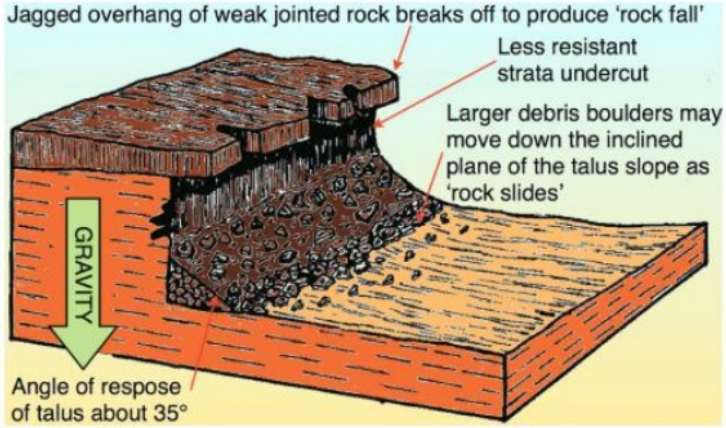
Debris avalanches are another type of rapid flowage. They occur in alpine areas, and less commonly in humid areas at lower altitudes. Like earthflows and mudflows, debris avalanches leave significant scars on the slopes of mountain where they occur.

Rockfalls and landslides

The term landslide is often mistakenly applied to all sudden movements of rock and soil material, but the term has a narrower meaning. Strictly speaking, **landslides** are the rapid sliding and slipping movements of large masses of bedrock, usually down a steep hillslope or along a fracture plane.

1.51 The aftermath of a recent mudflow can be seen in the foreground of this view near Hetagima in the Highlands of West Papua, Indonesia.

1.52 A landslide on the side of Bunsen Peak in Golden Gate Gorge, Wyoming, USA.



1.53 Rockfalls and landslides

1.54 Rock fragments have come to rest beneath a shear plane after several landslides on this cliff at Jebel Fihrayn on the Tuwaiq Escarpment, Saudi Arabia.

1.55 Rockfalls after weathering and exfoliation developed a shear plane on this high cliff in Monument Valley, USA.

Landslides occur when a '**slip surface**' develops and there is a lack of support for a large section of the land. The slide surfaces may be of two types. **Curved** shear surfaces produce slumps, whereas **planar** shear surfaces, such as rock joints, bedding planes and fault planes, produce rock slides.

When sudden mass movements occur as landslides, the large rocks tumbling downhill break into many smaller **fragments**. These fragments (talus, or scree) come to rest at a constant angle, typically about 35°, although this may vary slightly according to rock type.

Rockfalls are similar to landslides, but they happen even more quickly. In rockfalls, one or a few large rocks separate from the slope and drop down, rolling rapidly downhill after their vertical fall. As with landslides, the rocks accumulate at the foot of the slope as talus.

Subsidence

Subsidence is the downward settling of material with very little horizontal movement. It occurs when material is removed from beneath the earth's surface, such as erosion by an underground stream, dissolving of rocks such as limestone, or mining. Subsidence can also occur when groundwater is pumped out for human use, reducing the hydraulic pressure of the aquifer containing the water.

Localised subsidence forms **sinkholes**, and they can either form slowly or almost instantaneously. **Cover-subsidence sinkholes** form slowly over a period of **decades** or even **centuries** as soil is transported by underground drainage channels into an underground reserve, such as a cave. Cover-subsidence sinkholes cause gradual downward sinking of land. Although this can damage buildings by shifting their foundations, there is generally enough warning of movement for the building to be repaired or renovated.

Cover-collapse sinkholes are far more dangerous because they appear seemingly **without warning**. Cover-collapse sinkholes form in two main ways. One way they form is during heavy rain when **clay** or **sandstone** particles beneath the surface become saturated. **Saturation** of clay and sandstone causes their glue-like **cohesion** to disintegrate suddenly, causing a sinkhole to open. One minute, everything on the surface seems intact, and the next minute, the ground loses its solidity and collapses.

1.56 More than 110 sinkholes formed in the Dover area of Florida (USA) during a freeze event in January 2010. Ground water levels dropped to record-setting lows as farmers pumped water to irrigate their plants for protection from the cold temperatures. The sinkholes destroyed homes, roads and sections of cultivated areas.

The second way that a cover-collapse sinkhole develops is when the roof of an underlying **cave** collapses. Caves are very common in limestone, because limestone dissolves in water. Over time, seepage dissolves underground limestone, and if this reaches a critical point where the strength of the limestone can no longer support the weight of the ground overhead, it will collapse suddenly as a sinkhole.

Cover-collapse sinkholes can be the result of **human actions**. Mine collapses, pipeline breaks, over-extraction of groundwater, and altering the flow of sub-surface drainage channels can all lead to ground collapse and the formation of a sinkhole.

CASE STUDY
The Darvaza sinkholes

Darvaza is a remote location in the Karakum Desert of central Turkmenistan, about 250 kilometres north of the country's capital city of Ashgabat. The Darvaza area has several features that are known locally as **gas craters** but which are **cover-collapse sinkholes** formed by **human actions**.

Turkmenistan has one of the world's largest underground **natural gas fields** in the world, the proven reserves amounting to 2.86 trillion m^3.

Before the disintegration of the USSR in 1991, Turkmenistan was part of the Soviet Union. In 1971 and 1972, Soviet government geologists began drilling for gas in the Karakum Desert. They found a large **underground cavern** filled with natural gas, but unfortunately the ground on which the drilling rig was placed **collapsed**. This triggered a succession of further collapses in the **crumbly sedimentary rocks** of the area, eventually creating several open **craters**, the largest of which has a diameter of about 70 metres and a depth of 30 metres. The size of the crater is increasing as the extreme heat causes the rim to crumble inwards.

1.57 The largest gas crater at Darvaza, Turkmenistan, is a cover-collapse sinkhole formed by human actions.

1.58 Gas still burns in this cover-collapse sinkhole at Darvaza, Turkmenistan, almost 50 years after the land collapsed.

The leaking gas soon began to cause environmental problems as **animals** roaming in the area began to die from the gas that was escaping into the atmosphere. In order to protect the wildlife, a **flaming tyre** was rolled into the sinkhole, which set the gas alight and started a large fire which has been burning with intense heat in a spectacular fashion ever since.

Unfortunately, animals find the fire mesmerising, and are still **attracted** to the sinkhole, especially at night. From time to time, swarms of thousands of local **spiders** gather at the edge of the flaming crater and then run en masse into the sinkhole to their deaths. The authorities in Turkmenistan today believe that the country has so much gas that it is easier simply to let the gas burn than to try and stop the gas escaping.

It is now several decades since the fire in the large Darvaza sinkhole began, and the flames are still burning very fiercely. At night, **insects** are attracted in huge numbers to the light and warmth. However, because of the intense heat and lack of trees, there is nowhere to rest and after flying above the warm, bright sinkhole they **collapse** from exhaustion and plummet downwards into the flames. **Birds** are also attracted by the large numbers of insects at night, and like the moths, many of them become so exhausted that they collapse and fall into the sinkhole's flames. Larger birds such as hawks come to prey on the smaller birds, and many of them also die each night,

1.60 Broken pipes on the side of the Darvaza gas crater show where the land collapsed when the sinkhole formed. The pipes continue to support part of the rim from crumbling.

1.59 The searing heat from the Darvaza gas crater has been heating the atmosphere 24 hours per day, seven days per week for almost 50 years since human actions caused the sinkhole to form.

overcome either by the intense heat of the flames or by escaping gas fumes. It is small wonder that locals refer to the sinkhole as the '**Gateway to Hell**'.

Only two of the estimated twenty or so sinkholes at Darvaza contain **fire**. The other sinkholes, which were all formed by human actions when the capping rock collapsed into caverns containing gas beneath the surface, are still **emitting gas** into the atmosphere, albeit at a slower rate than the large, burning crater. **Evidence** of the escaping gas is the strong smell of sulphur near the sinkholes, caused by pollutants in the natural gas (which itself is odourless). Further evidence are bubbles formed by the escaping gas which can be seen in the bottoms of those craters that contain water.

1.62 Gas bubbles up through water in another sinkhole at Darvaza, Turkmenistan.

QUESTION BANK 1D

1. *What is mass movement?*
2. *Briefly describe the role played by each of the four factors that promote mass movement.*
3. *With reference to figure 1.41, rank the types of mass movement in terms of (a) their speed of onset, and (b) their liquidity.*
4. *Choose three contrasting types of mass movement, and describe how they can be triggered naturally and by humans.*
5. *Identify at least two types of mass wasting in figure 1.63, and describe the processes underway.*
6. *Explain how and when the Darvaza sinkholes formed.*

1.61 In this sinkhole at Darvaza, Turkmenistan, gas bubbles up through a small lake of water that has drained into the cavity from nearby aquifers. The gas is burning in several small fires.

1.63 Mass movement at Skógafoss, Iceland.

Chapter 2 Geophysical hazard risks

2.1 A man stands in front of his ruined house in Maocao village, in the mountains of Guizhou province, China. During a simultaneous snowstorm and earthquake, a tree fell on his house, killing the man's mother and injuring his niece who were in the house at the time.

Hazards

At its simplest level, a **hazard** is anything that poses a risk to humans.

In our study of geography, we take a slightly more sophisticated view, which is to regard a hazard as any **threat** (whether natural or human) that has the potential to cause loss of life, injury, property damage, socio-economic disruption, or environmental degradation.

It is important to distinguish between a hazard and a **hazard event**. A hazard event is the occurrence (or realisation) of a hazard, together with the changes in demographic, economic and / or environmental conditions which result. **Hazards** have the **potential** to affect people, but it is the **hazard event** that actually has an **impact** on people. An 'event' only becomes a 'hazard event' if it has a negative impact on people or their property.

A **geophysical hazard** is a hazard that is associated with **earth processes**, either on the earth's crust or in its sub-structure. Examples of natural geophysical hazards include the phenomena we examined in the previous chapter — earthquakes, volcanoes, tsunamis, and mass movement hazards

2.2 The world distribution of 500 significant volcanic eruptions. To be 'significant', an eruption meets at least one of the following criteria: it caused fatalities, it caused moderate damage (approximately $1 million or more), it had a Volcanic Explosivity Index (VEI) of 6 or larger, it caused a tsunami, or it was associated with a major earthquake. Source: Map developed from data at the National Geophysical Data Center / World Data Service (NGDC/WDS): Significant Volcanic Eruptions Database. National Geophysical Data Center, NOAA. doi:10.7289/V5JW8BSH

such as landslides, mud flows, rockfalls and sinkholes.

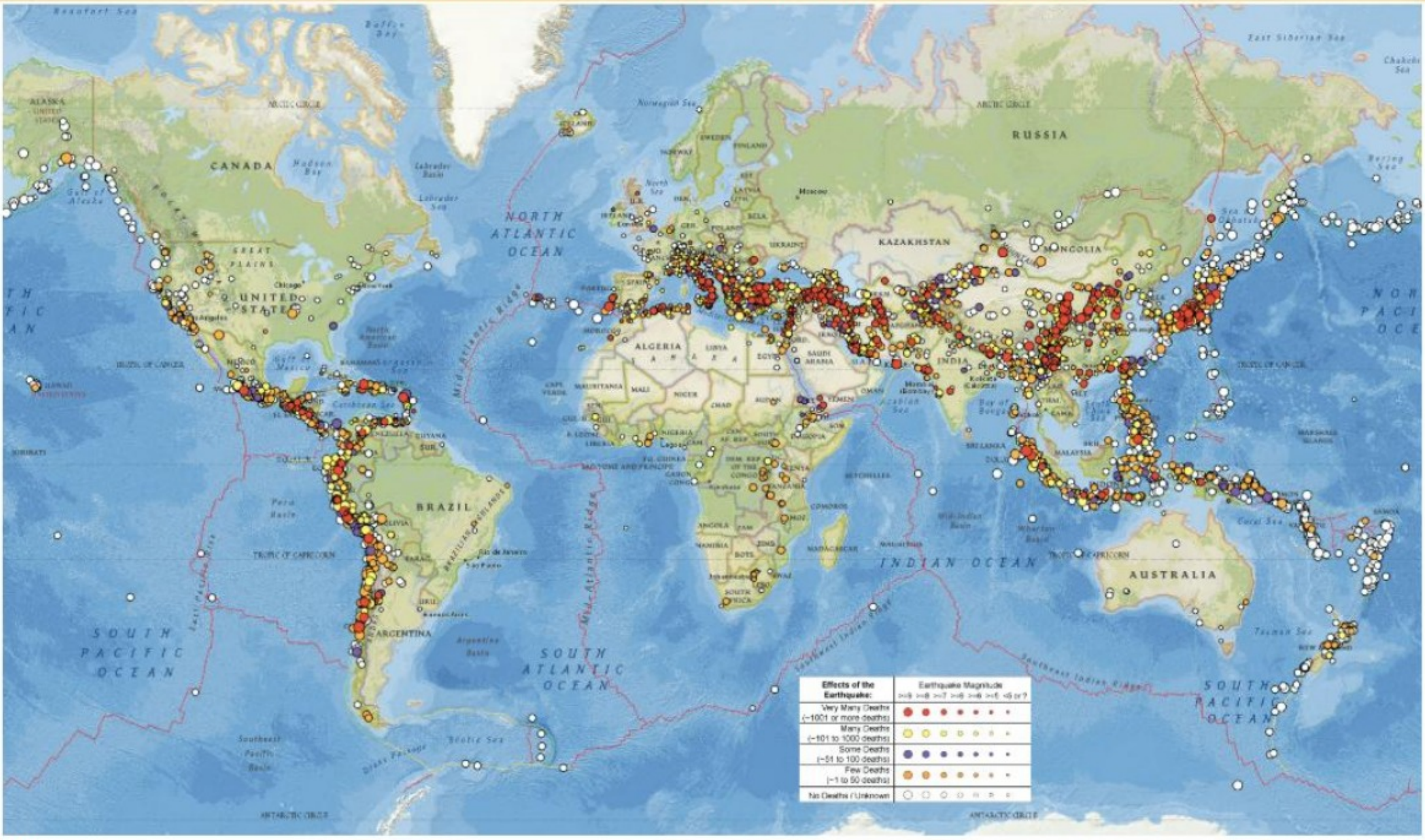
The **specific distribution** of the various geophysical hazards was described in the previous chapter. In summary, as shown in figure 2.2, **volcanoes** and their associated hazards (such as pyroclastic flows, lahars, lava flows, and so on) are concentrated along convergent plate boundaries where subduction occurs. A smaller number of volcanoes are found at divergent plate boundaries. Some volcanoes are not found at plate boundaries at all; these are located above a mantle plume or hot spot.

As shown in figure 2.3, **earthquakes** and their associated hazards (such as landslides and liquefaction) are also concentrated on plate boundaries. Although earthquakes can occur on all three types of plate boundary — divergent, convergent and transform — the earthquakes that are most hazardous to people are mainly found on convergent plate boundaries. Tsunamis, a secondary hazard of earthquakes, begin at or near the epicentre of an earthquake, and then radiate outwards long distances across ocean waters.

Because they are the result of gravity, **mass movement** hazards are most likely to occur on steep hills. The risks of mass movement are especially great on steep hills in areas of heavy rainfall, in places where freeze-thaw actions occur frequently, where snow falls, in an earthquake zone or in areas of limestone rocks.

QUESTION BANK 2A

1. *What is meant by the word 'hazard'?*
2. *What is the difference between a hazard and a hazard event?*
3. *With reference to figure 2.2, describe the distribution of (a) the areas with the greatest density of volcanoes, and (b) the areas with volcanic eruptions that have caused the largest numbers of deaths.*
4. *Referring to figure 2.3, relate the distribution of earthquakes that have caused more than 1,000 deaths to (a) the types of plate boundaries where they are located, and (b) the level of economic development of the countries where the earthquakes occurred.*
5. *Identify exceptions to the general trends you have identified in your answer to question 4.*



2.3 The world distribution of significant earthquakes from 2150BC to the present day. To be 'significant', an earthquake meets at least one of the following criteria: moderate damage (approximately $1 million or more), 10 or more deaths, magnitude 7.5 or greater, Modified Mercalli Intensity X or greater, or the earthquake generated a tsunami. Source: Map developed from data at the National Geophysical Data Center / World Data Service (NGDC/WDS): Significant Earthquake Database. National Geophysical Data Center, NOAA. doi:10.7289/V5TD9V7K

Hazard magnitude and frequency

In order to save lives, reduce injuries, and preserve infrastructure, huge efforts are made to manage the risks presented by geophysical hazards. **Risk management** involves identifying, assessing and prioritising risks, and then allocating resources in an economical, co-ordinated and effective manner to reduce the potential hazards for people and property. In order to implement effective risk management, it is important to have tools available that can measure the **magnitude**, **frequency** and likely **recurrence** of hazards.

Earthquakes

Earthquakes are a major **hazard** to people living on plate margins. **Measuring** earthquakes presents a challenge to geographers. **Two methods** of measuring **earthquake magnitude** are used, one devised by Mercali and the other by Richter. Although the **Mercali** scale is not used as widely as the Richter scale, it is useful because its descriptions can be related to observations. The Mercali system is outlined in table 2.1. The more common way to measure the intensity, or magnitude, of an earthquake is to use the Richter Scale, a scheme developed in 1935 by an American geographer, Charles Richter.

On the **Richter Scale**, figure of 2 or less can hardly be felt. The Richter Scale is **logarithmic**, so a figure of 3 is ten times stronger than a figure of 2. A figure of 4 is ten times stronger than a figure of 3, and one hundred times stronger than a figure of 2. An earthquake measuring 5 or over may cause destruction. An earthquake of 7 or more will cause major damage if it is centred near a settled area. Table 2.2 gives details of the measures used in the Richter Scale. The earthquake that caused the **Indian Ocean tsunami** in December 2004 had a force of 9.1 on the Richter Scale, while the earthquake in **Tangshan, China**, in July 1976 that killed almost 250,000 people had a force of 7.8. The strongest known earthquake ever measured was a shock in **Valdivia, Chile**, in 1960 that measured 9.5.

Table 2.1
The Mercali Scale of Earthquake Intensity

Scale	Description
I	Not felt except by a very few people under especially favourable circumstances.
II	Felt by only a few people who are sitting or lying down, especially on upper floors of buildings. Delicately suspended objects may swing.
III	Felt noticeably indoors, especially on upper floors, but many people do not recognise it as an earthquake. Standing cars may rock slightly. The vibration is like a passing truck.
IV	During the day, felt indoors by many, outdoors by a few. At night, some people are woken up. Dishes, windows and doors are disturbed. Walls make a creaking sound. Sensation is like a heavy truck striking a building. Cars rock noticeably.
V	Felt by nearly everyone. Many are awakened. Some dishes and windows are broken. Some plaster on walls may crack, unstable objects fall. Disturbances of trees, poles and other tall objects may be noticed. Pendulum clocks may stop.
VI	Felt by all, many are frightened and run outdoors. Some heavy furniture is moved, a few instances of fallen plaster or damaged chimneys. Damage slight.
VII	Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly designed or badly built structures; some chimneys broken. Noticed by people driving cars.
VIII	Damage slight in specially built structures; considerable in ordinary substantial buildings, with partial collapse; large damage in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, columns, factory stacks, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water levels.
IX	Damage considerable in specially designed buildings, well-designed frame structures thrown out of plumb; great damage in substantial buildings with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.
X	Some well-built wooden structures destroyed; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Water splashed over banks.
XI	Few, if any, masonry buildings left standing. Bridges destroyed. Broad fissures in the ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.
XII	Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upwards into the air.

Table 2.2
The Richter Scale

Scale	Intensity	Description
1	***Instrumental***	Detected only by seismographs.
2	***Feeble***	Noticed only by sensitive people.
3	***Slight***	Like the vibrations due to a passing truck, felt by people at rest, especially on upper floors.
4	***Moderate***	Felt by people while walking, loose objects and stationary cars are shaken.
5	***Strong***	Trees sway and suspended objects swing; some damage from loose and falling objects.
6	***Destructive***	General alarm, walls crack, plaster falls, car drivers seriously disturbed, chimneys fall, poorly constructed buildings are damaged.
7	***Disastrous***	Ground cracks badly, many buildings destroyed and railways bent, landslides on steep slopes.
8	***Very disastrous***	Few buildings remain standing, bridges destroyed, all services (railways, pipes, cables) out of action, great landslides and floods.
9	***Catastrophic***	Total destruction, objects thrown into the air, ground rises and falls in waves.

2.4 The ruined library of the Tangshan Mining and Metallurgical Institute in Tangshan, a city in north-east China, destroyed in an earthquake on 28th July, 1976. One part of the building was totally destroyed (foreground), then the intact section in the background was moved sideways 1.5 metres during the 23 seconds that the earthquake lasted. The Tangshan earthquake measured almost 8 on the Richter Scale, and its focus, or epicentre, was right below the city, only 12 kilometres beneath the surface.

Earthquake **frequency** is another important statistic for risk management. Frequency refers to how often an event occurs. Table 2.3 shows the number of earthquakes of varying strengths over recent years, together with the number of deaths that resulted.

QUESTION BANK 2B

1. *With reference to the Mercali Scale of earthquake intensity, suggest which of two earthquakes in an urban area — one in a less economically developed country, and one in a more economically developed country — would be likely to cause more damage.*
2. *Use data in table 2.3 to calculate the average frequency of earthquakes of magnitude (a) 8.0 to 8.9, (b) 7.0 to 7.9, (c) 6.0 to 6.9, (d) 5.0 to 5.9, and (e) 4.0 to 4.9.*
3. *Describe the relationship between earthquake magnitude and earthquake frequency.*
4. *It is sometimes suggested in the media that the frequency of earthquakes is increasing. Does table 2.3 provide any evidence (either for or against) this suggestion?*
5. *The data in table 2.3 suggests that there is no clear relationship between the number of earthquakes and the number of deaths in a year. This seems counter-intuitive. Suggest reasons why there is no clear relationship.*

The data in table 2.3 shows that some years suffer abnormally **high death tolls** due to earthquake activity. These are usually explained by individual earthquakes that were extremely hazardous. For example, the high death toll in 2004 is mostly explained by the effects of the Indian Ocean tsunami, while the high number of deaths in 2010 mainly resulted from one earthquake in Haiti.

Table 2.3

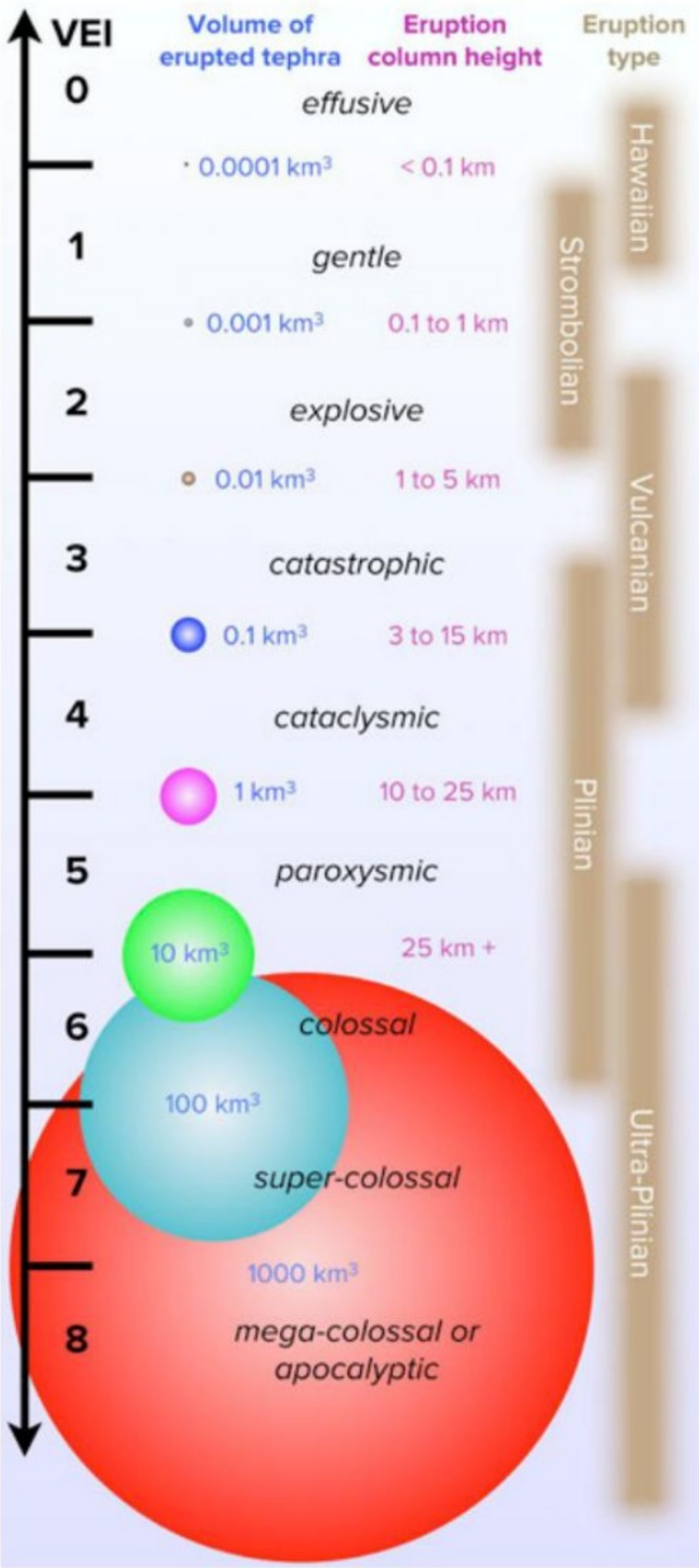
Number of earthquakes worldwide with magnitude 4.0 or greater, 1990-2019

Year	Earthquake magnitude (Richter Scale)					Deaths
	8.0 to 8.9	7.0 to 7.9	6.0 to 6.9	5.0 to 5.9	4.0 to 4.9	
1990	0	18	109	1,617	4,437	52,056
1991	0	16	96	1,457	4,335	3,210
1992	0	13	166	1,498	5,128	3,920
1993	0	12	137	1,426	4,999	10,096
1994	2	11	146	1,542	4,518	1,634
1995	2	18	183	1,318	8,003	7,980
1996	1	14	149	1,222	8,756	589
1997	0	16	120	1,113	7,903	3,069
1998	1	11	117	979	7,303	9,430
1999	0	18	116	1,104	6,972	22,662
2000	4	16	146	1,344	8,008	231
2001	1	15	121	1,224	7,991	21,357
2002	0	13	127	1,201	8,541	1,685
2003	1	14	140	1,203	8,462	33,819
2004	2	14	141	1,515	10,888	228,802
2005	1	10	140	1,693	13,917	88,003
2006	2	9	142	1,712	12,838	6,605
2007	4	14	178	2,074	12,078	712
2008	0	12	168	1,768	12,291	88,011
2009	1	16	144	1,896	6,805	1,790
2010	1	23	150	2,209	10,164	320,120
2011	1	19	185	2,276	13,315	21,953
2012	2	11	96	1,295	8,710	629
2013	2	17	123	1,454	11,878	1,463
2014	1	11	143	1,574	15,813	664
2015	1	18	127	1,420	13,790	9,635
2016	0	16	130	1,549	13,699	1,274
2017	1	6	104	1,455	11,544	1,157
2018	1	16	117	1,674	12,774	5,173
2019	1	9	133	1,489	11,364	215

Source: USGS National Earthquake Information Center

Volcanoes

The intensity of volcanic eruptions is measured using the **VEI (Volcanic Explosivity Index)**. The VEI ranges on a scale of 0 to 8, with 0 being a non-explosive eruption and 8 being mega-colossal or



2.5 The VEI (Volcanic Explosivity Index) is based on the volume of tephra that is produced during an eruption. The spheres in this diagram show the relative differences in volume for each stage of the VEI. The words in black italics represent the generally accepted descriptions of eruptions at each stage. The eruption types shown at the right of the diagram overlap and merge into each other.

apocalyptic. The VEI is quantified by the **volume of tephra** (rock fragments and particles emitted during the eruption), and this is defined using a logarithmic scale as shown in figure 2.5. Each increase by one point in the VEI represents a ten-fold increase in the volume of tephra.

An eruption with a VEI of 0 is typical of shield volcanoes in Hawaii where lava pours or spurts from a fissure but does not explode. **Hawaiian-type** eruptions may occur as frequently as every day on some volcanoes, releasing pressure so that an explosive eruption is very unlikely.

2.6 A fissure erupting west of Pu'u 'O 'o Crater on Kilauea Volcano in Hawaii, USA. The lava spatter reached heights of 40 metres, so the eruption had a VEI of 0.

Strombolian eruptions are stronger than Hawaiian-type eruptions, and they have a VEI of 1 or 2. Named after Stromboli Volcano in Italy, which has been erupting continuously since Roman times, Stromboli eruptions are mildly explosive, sending tephra to heights up to one kilometre.

Vulcanian eruptions, which are named after the Italian volcanic island of Vulcano, have a VEI of 2 to

2.7 Viti explosion crater is part of the Askja caldera near Reykjahlíð, Iceland. The 300 metre wide crater is a remnant of several Vulcanian eruptions between 1724 and 1961.

4 depending on the size of the individual eruption. Vulcanian eruptions produce dense clouds of ash that rise to great heights, perhaps as high as 20 kilometres or so. Pyroclastic flows are fairly common in vulcanian eruptions, adding to the immediate danger of rocks as large as a metre diameter and volcanic bombs (molten blobs of lava) being thrust explosively out of the crater.

Stronger eruptions with a VEI of 3 to 6 may be Plinian eruptions. **Plinian eruptions**, which are also known as Vesuvian eruptions, are known for their high columns of volcanic ash and gas that extend 25 kilometres or more up into the stratosphere. Huge quantities of lava are released, so much so that the magma chamber beneath the volcano may become depleted, and the loss of pressure causes the volcano to **collapse**, forming a **caldera**. Famous examples of Plinian eruptions include Mount Vesuvius, Italy (79AD), Krakatoa, Indonesia (1883), Mount St Helens, USA (1980), Mount Pinatubo, Philippines (1991) and Eyjafjallajökull, Iceland (2010).

2.8 Part of the ash cloud rising about Mount Pinatubo, Philippines, during its eruption in June 1991.

Fortunately, **Ultra-Plinian eruptions** which have a VEI of 6 or more are very rare. The most recent Ultra-Plinian eruption was in 1815 when the Indonesian volcano Mount Tambora erupted with a VEI of 7. The explosion was reportedly heard 2,600 kilometres away, and ash from the eruption fell at least 1,300 kilometres from the volcano. Pyroclastic flows spread up to 20 kilometres from the volcano's cone, and tsunamis of about 4 metres in height were formed. The ash cloud reached almost 45 kilometres up into the stratosphere, causing a change in average global temperatures of up to -0.5C° for three years after the eruption.

There have been some even more catastrophic eruptions in the past, notably the eruption of **Yellowstone Supervolcano** in Wyoming, USA, 630,000 years ago. The Yellowstone eruption had a VEI of 8, the only eruption of such a large size that we know about. The eruption created a caldera (collapsed crater) measuring 72 kilometres by 55 kilometres. The hot spot under Yellowstone is still active, and the area remains very active geothermally. Some commentators suggest that Yellowstone may erupt again with an impact so great that it could threaten life on the planet.

QUESTION BANK 2C

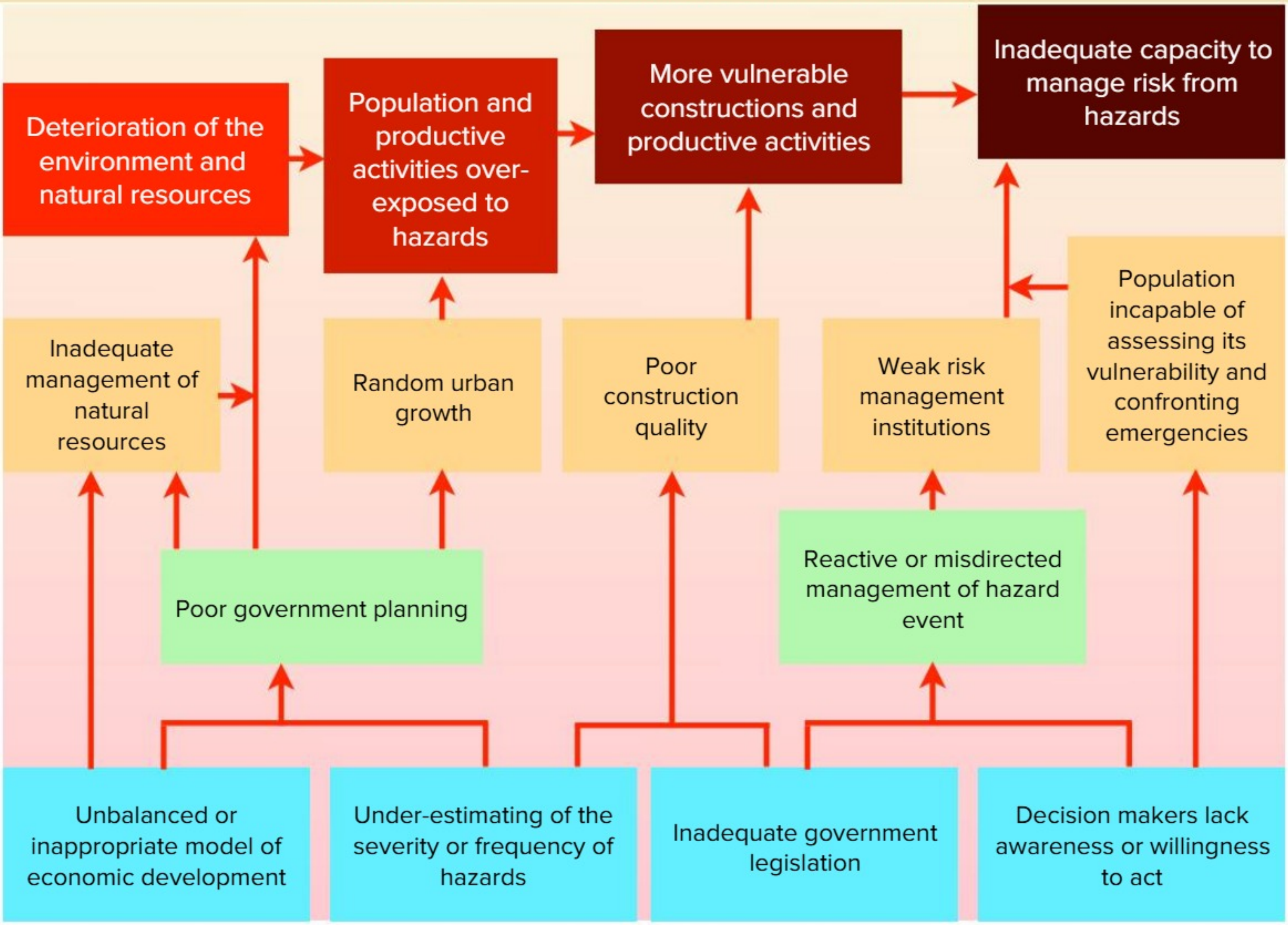
1. *What does it mean when we say the VEI is a 'logarithmic' scale? Explain how this applies to the VEI.*
2. *Describe the key differences in (a) magnitude as measured by volume of tephra and eruption column height, (b) frequency, and (c) typical VEI figures for each of the following types of eruptions: (i) Hawaiian, (ii) Strombolian, (iii) Vulcanian, (iv) Plinian, and (v) Ultra-Plinian.*

Risk and risk assessment

Analysis of risk

Analysing the risk from **potential hazards**, and trying to predict their likelihood, are very specialised activities. Insurance companies try to analyse and predict hazards in a very detailed manner, but even when sophisticated computer models are used, errors occur much more frequently than anyone would wish.

One of the **challenges** in analysing risk is that there are many **variables** as well as different **time scales** to be considered. For example, if we were considering the risk of mortality (death) from an earthquake in a particular area, we need to consider both **direct effects** (deaths caused during the earthquake, such as when a tree or a building falls on a person), as well as **indirect effects**, which are consequences that occur after the event. Indirect effects can be **short-term** or **medium-term**, periods that are difficult to define precisely. **Short-term effects** might include deaths resulting from respiratory, infectious or parasitic diseases that start to spread as a result of the earthquake. **Medium-term effects** might include deaths resulting from



2.9 Factors that aggravate vulnerability in the risk assessment of hazards.

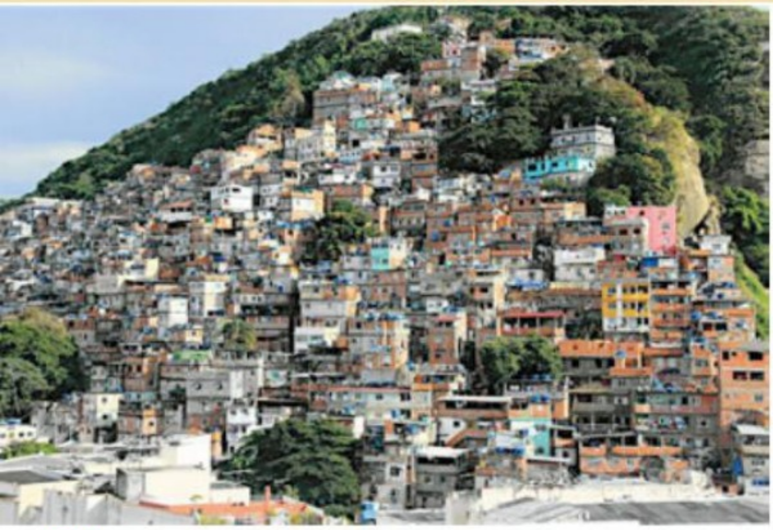
the deterioration of living conditions, a deterioration of basic services that affect health standards, or factors that increase people's vulnerability, such as poverty and malnutrition.

In analysing the risks presented by different hazards, it is important to take into account the factors that **aggravate** the **vulnerability** of individuals and groups of people. Figure 2.9 identifies some of the most important such factors.

One of the key reasons that risks are often misjudged is that planners and individuals **under-estimate** the **severity** or the **frequency** of hazards. This indicated by the second box from the left on the bottom line of figure 2.9.

Underestimating hazards can occur for many reasons. In the case of some governments in economically poor countries, the seriousness of hazards may be **deliberately minimised** so that certain individuals or companies are spared the expense or effort of dealing with the remedies required. More commonly, hazards are underestimated because people do not have the necessary long-term **data** and **information** to access the risk accurately. In the case of many people living in hazard-prone areas, the risk may be known and understood, but it is **psychologically suppressed** so that the benefits of living in an area (such as access to employment or to good soils for cultivation) are not challenged. This is known as **psychological denial** of the risk.

Once the risk of a hazard has been **assessed** for a particular area, taking **effective measures** to **prepare** for a hazard event or to **minimise** its impact can be initiated. For example, the shanty settlement shown in figure 2.10 would be assessed as a high-risk area for several reasons. Located in Rio de Janeiro, Brazil, this area shows a very steep, unstable slope, with poorly constructed buildings that house large numbers of people from very poor backgrounds in an area that experiences periodic heavy rainfall.



2.10 A vulnerable shanty settlement (favela) in Rio de Janeiro, Brazil.

In a situation such as this, where there is a significant risk of landslides, the hazard risk can be **reduced** or **minimised** through measures such as land use planning, relocating people to safer areas, ensuring that construction standards are met, and trying to reduce the level of poverty of the people in the area. Many researchers agree that the best way to protect people from the risk of hazards is to reduce **poverty**, as this is the most effective way of reducing vulnerability.

QUESTION BANK 2D

1. *Why do people live in hazardous areas?*
2. *Explain the reasons why some sectors of a population might be more vulnerable to hazards than others.*
3. *With reference to figure 2.9, explain why under-estimating the importance of hazards can cause major problems.*
4. *Why do individuals and communities often underestimate the probability of hazard events occurring?*
5. *Discuss the factors that influence a person's perception of the risk posed by hazards.*

Hazard event prediction

As we have seen, **estimating** the risk of hazard events, or **predicting** their probability, is very difficult to do with precision. The best hazard predictions are usually based on examining **historical records** of past events, because these provide some evidence to predict likely **recurrences**. The information in historical records is meshed with understandings of the **physical geography** of an area, such as its slope stability, whether it experiences freeze-thaw action, and so on.

There are several methods used to estimate the probability of hazards, some of which are extremely complex and use sophisticated computer algorithms. One of the simpler approaches is the **DRI** (**Disaster Recovery Index**), developed by the UNDP (United Nations Development Program).

The **DRI** estimates the risk of **loss of life** that might occur from a hazard event, **ignoring** the possible damage to livelihoods and the economy. The advantage of this measure is that it highlights the hazard risk in a **clear and simple** way which also avoids the common problem that arises when comparing different countries with fluctuating currency exchange rates.

Risk is calculated using the formula **R = H x P x V**, where R is the risk (expressed as the number of deaths), H is the hazard (measured by its frequency and expected strength), P is the population size of the exposed area, and V is the vulnerability of the population, a factor that depends on the socio-economic and political context of the location being assessed.

The DRI does suffer from **shortcomings**. Trying to estimate the number of deaths from an event is difficult, and it has been criticised for failing to include any measure of the capacity of the **government** to improve the state of development in a way that reduce the risk. It is seen as being particularly imprecise in urban environments because of their greater complexity and diversity compared with rural areas.

In an attempt to overcome these shortcomings, the IADB (Inter-American Development Bank) in Latin America worked with the United Nations Foundation (UNF) and IDEA (the International Debate Education Association) to develop four alternative indices of risk assessment and hazard prediction.

The first of the IADB measures is the **DDI** (**Disaster Deficit Index**). This index models the consequences of a hazard event in **macro-economic** and **financial** terms, representing the maximum probable loss over a determined period of time and the capacity of the country to deal with it. The DDI is designed to allow planners to know in advance what the gap will be between need for funds resulting from a hazard event and the capacity of the government in terms of its access to local or foreign money to restore the goods that have been lost or affected. The DDI is **calculated** by **dividing** the **cost of the impact** of the hazard event (as measured by its financial cost) by the **economic resilience** of the government (as measured by the funds the government can raise to deal with the event). If the DDI is greater than 1.0, then the government cannot raise sufficient funds to cope with extreme hazards. The greater the **gap** between the probable losses and the capacity to cope with them, the greater the country's indebtedness.

The second IADB measure is the **LDI** (**Local Disasters Index**), which measures the risk of **social and environmental problems** resulting from regular hazard events at the local scale, especially those which have the greatest impact on the poorest groups. To do this, the LDI **adds** the number of **expected deaths**, the number of **people** affected and the **losses** of the people affected for different local areas.

A third measure of hazard risk is the **PVI** (**Prevalent Vulnerability Index**), which is a **composite indicator** of vulnerability to the risk of hazards based on three other indicators — the **PVIes** (Indicator of Exposure and Susceptibility), the **PVIsf** (Indicator of Socio-economic Fragility), and the PVIlr (Indicator of [Lack of] Resilience). The PVI is a more complex measure requiring considerably more **data** — which is a problem when used in many poorer countries that may lack the resources to gather detailed data. Nonetheless, if the data is available, the PVI has the advantage of providing a **comprehensive** picture of vulnerability.

The fourth measure used to assess the risk of hazards is the **RMI** (**Risk Management Index**). The RMI is another **composite** measure that estimates the **effectiveness** of risk management in terms of institutional organisation, capacity and development to reduce losses. It does this by combining **four factors**, each of which is also a complex composite indicator: risk identification, risk reduction, hazard reduction and effectiveness of governance.

Unfortunately, there is currently **no consensus** on which of these measures is the most useful. Any system of predicting hazards must consider the **probability** that a certain type of hazard event will occur, as well as the potential **impact** of that event on lives and property. Obviously, the probabilities of different types of hazard vary from place to place and from environment to environment.

QUESTION BANK 2E

1. *What are the priorities when trying to predict hazards and minimise their impact?*
2. *Five different measures of risk analysis are explored in this section. What are the different emphases of each? Giving reasons, explain which approach you prefer.*

Factors affecting geophysical hazard risks

The **United Nations International Strategy for Disaster Reduction** (ISDR) maintains a database of hazard events and disasters dating from 1900 to the present day. ISDR categorises hazards into three groups:

- **Hydro-meteorological disasters**, which includes floods and wave surges, storms, droughts and related disasters (extreme temperatures and forest/scrub fires), landslides and avalanches;
- **Geophysical disasters**, which includes earthquakes, tsunamis and volcanic eruptions; and
- **Biological disasters**, covering epidemics and insect infestations.

2.11 Although the ISDR classifies mass movements as hydro-meteorological disasters, most geographers see them as geophysical hazards. This sudden earthslump was triggered when heavy rains near Koror (Palau) destabilised the slope supporting this road, which collapsed with the nearby grass verge as a result.

According to the ISDR, the number of disasters has been growing markedly since 1900, both in terms of the **number** of disasters and the **value** of the damage they cause. It is quite possible, however, that many of the earlier disasters were **not reported** and the actual increase in the number of disasters may be less than the ISDR suggests.

Vulnerability

Some groups of people are more vulnerable to geophysical hazards than others. In exploring **vulnerability,** we need to examine the factors that reduce a person's or group's ability to withstand or endure a hazard or a hazard event.

Many people wonder why anyone would choose to live in an area where hazards might threaten their lives. Why would anyone choose to live near an active volcano, or on an active fault line, or in an area that frequently experiences disasters of any kind?

Of course, for many people, there is **no choice**. Most of the world's people have no option but to live in the place where they were born, perhaps because of extended family ties, perhaps they are in debt to a landlord or money lender, or perhaps because they lack the finances to move. Many farmers lack the skills required to gain employment if they were to move to an urban area.

Many people living in hazardous areas simply **do not realise** that there might be a hazard in that location. For example, earthquakes do not always strike in places where there have been earthquakes in the past. Even if hazards have affected an area, many people believe the old (erroneous) superstition that "lightning never strikes the same place twice".

For other people, there is a **conscious decision** to live in an area where there is a hazard. In many parts of the world, such as the Highlands of Papua New Guinea and the islands of the Philippines, the most densely populated areas are on the sides of **active volcanoes**. The reason for this is that when volcanoes erupt, they distribute ash that aids the fertility of the soil. In other words, the most fertile areas for cultivation are near active volcanoes, and as cultivation occurs annually but volcanoes erupt only infrequently, it seems to be a good rational decision to live there.

2.12 Despite its hazardous location, where people are vulnerable to volcanic eruptions, earthquakes and mudflows, people still build their homes on the side of Taal Volcano in the Philippines.

Economic factors

There is another reason that many poor people live in areas that expose them to geophysical hazards — hazardous areas often **cost less**, and they may be the only places that can be afforded.

Many of the world's poorer people live in **shanty settlements** (slums) in rapidly expanding cities. People who live in shanty settlements are especially vulnerable to hazards because their housing usually lacks even the most basic facilities, such as clean water, drainage, telecommunications, and fire services. Furthermore, shanty settlements are often built in the most high-risk locations, such as on the steep sides of valleys, near flood-prone rivers, or on the fault lines of tectonic plates.

2.13 This large shanty settlement in Caracas, Venezuela, poses several geophysical hazards for its impoverished residents. The steep land is susceptible to landslips in heavy rain, and the area experiences earthquakes from time to time.

Poorer countries face more challenges than wealthier societies in paying for **early warning systems** that notify residents when there is an impending risk from a hazard event such as a tsunami or earthquake. Not only are the early warning systems likely to be absent, but where they are present, the **technology** and **communication systems** to warn people are likely to be inadequate.

2.15 Damage to buildings in central Kathmandu, Nepal, following an earthquake. Many of the buildings were vulnerable to damage because their construction was not done to earthquake-resistant standards.

Building standards in many poorer countries are often low or non-existent, so when a hazard event such as an earthquake or landslide occurs, many structures are damaged or destroyed, perhaps trapping anyone inside. Sometimes the low building standards arise because it is simply cheaper to 'cut corners', but **corruption** can also be a factor in some countries when building developers pay bribes to corrupt government officials to get approval for the construction of cheap, sub-standard buildings.

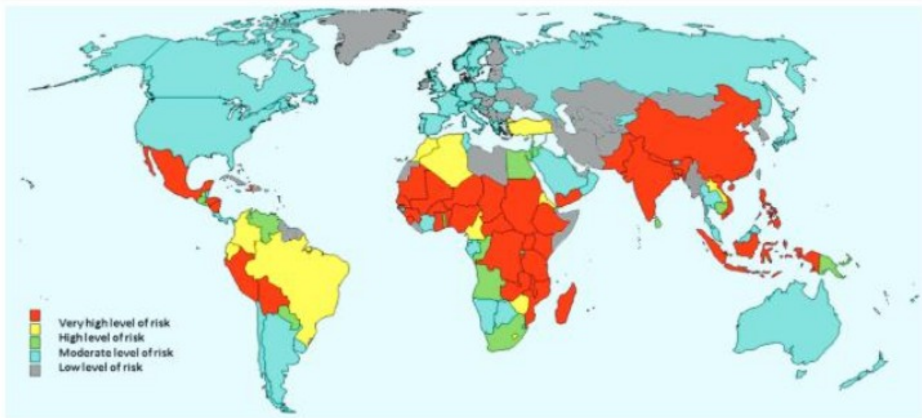
2.14 Reinforced buildings with masonry infill walls have totally collapsed during an earthquake in Lushan, China. The rubble that spilled over into the street has been cleared away.

Compared with rich countries, poorer societies tend to have less well equipped **emergency services** with fewer **personnel** and more basic levels of **technology**. Whereas a wealthy country may have expensive ultrasound search devices, fleets of ambulances, well-equipped hospitals with emergency facilities and excavation equipment to aid in rescue operations, relief workers in poorer countries may have to work with little more than shovels and human effort. This hampers the relief effort in the aftermath of a hazard event, resulting in larger numbers of deaths and injuries.

2.16 San Francisco (USA) is located on the San Andreas Fault, and thus experiences frequent earthquakes. As a wealthy country, the US insists that buildings are constructed to high standards to resist earthquakes. This example is the Transamerica Pyramid Building, the tallest skyscraper in the city.

Poorer people are less likely to have **insurance coverage** against disasters than people in wealthier societies. Therefore, when a disaster hits, it may take much longer for repairs to be made in poorer countries, if indeed repairs are made at all. On the other hand, buildings and infrastructure in wealthier countries are likely to have a greater **financial value** than those in poorer countries because of their higher costs of construction and greater level of services provided. Countries with higher levels of economic development tend to have assets and resources with higher cash values, and therefore when damage occurs they will cost more to repair, especially when the higher wages in those countries are considered.

2.17 Risk from hazards when vulnerability is assessed by economic factors (after André).



2.18 Risk from hazards when vulnerability is assessed by social factors (after André).

Therefore, hazard events in wealthier countries are likely to have a greater **financial cost** than equivalent hazard events in poorer countries, even though the **human cost** (death toll plus injuries) may be greater in the poorer country. However, to place this in perspective, hazard events that cause less economic damage (by value) may cause significantly **greater hardship** if they happen in a poorer country because the damage is likely to represent a **greater proportion** of that country's **total wealth** (as measured by Gross Domestic Product or similar indicators).

Social factors

There are two ways used to measure the cost of hazard events, the economic method (or financial cost that was emphasised in the previous section), and the social method. The researcher **Gilles André** has investigated the relationship between vulnerability to hazards using both the economic and social methods, and discovered that hazard risks look very different.

André found that when we focus on the **economic cost** of hazard events (as we did in the previous section), then 'rich' countries are much more vulnerable to the impact of hazard events than the 'poor' countries (to use his terminology). On the other hand, if we focus on the **social cost** of hazard events, then it is the 'poor' countries that have the highest levels of exposure to risk.

It is not difficult to understand why **socially deprived** people are more vulnerable to geophysical hazards. Those people who have received **less education** will be less likely to recognise the dangers associated with living in hazardous areas, and less able to take preventative action. In Japan and California (USA), which are wealthy countries that experience frequent earthquakes, school students routinely practice earthquake drills as a way to reduce fatalities and casualties.

Gender is another social factor that affects people's vulnerability to hazards. According to the ILO (International Labour Organisation), **women** are more vulnerable to hazards because they tend to have less access to **resources**, and because they tend to be the main **caregivers** to children, the disabled and the elderly. Consequently, they are less likely to be in a position to respond to a disaster with the resources needed to make a large-scale difference.

2.19 Students participate in earthquake drill at a US school using the ‘drop, cover and hold on’ safety procedure that is based on the Japanese Earthquake Early Warning System.

The ILO has also noted that women are especially vulnerable to **sexual violence** and **exploitation**, including human trafficking for prostitution or slave-labour, in the period following a hazard event.

Demographic factors

Demographic structure is a variable that affects people’s vulnerability during a hazard event. Although **the elderly** cannot move as quickly or with as much agility as younger people, they are often **neglected** in the aftermath of a disaster. In a major earthquake in Kobe (Japan) in 1995, about half the deaths were elderly people, even though only 14% of Kobe’s population were elderly at the time.

At the other end of the age scale, **children** are another vulnerable group. Children often experience long-term **psychological problems** when hazard events occur because they cannot fully understand what is happening. Furthermore, like women, children are sometimes vulnerable to **trafficking** and **abuse** after a disaster, especially if they have been orphaned and are hungry. If the child has also experienced poverty, inadequate **diet** could make the child especially vulnerable to disease and even death if infections break out in the aftermath of a disaster.

In a major earthquake in China’s Sichuan province in 2008, over 69,000 people were killed in spite of the valiant efforts of government officials and the army. Of this number, more than 19,000 were schoolchildren. This was because many of the schools in the area had been built using inadequate **construction materials**, making the children more vulnerable to the earthquake than the general population. During the earthquake, at least 7,000 school buildings in Sichuan collapsed, more than any other type of building.

2.20 Buildings destroyed in the Sichuan earthquake. Children were particularly vulnerable in this earthquake because schools were especially prone to being destroyed by the shock waves.

2.21 Tbilisi, capital city of Georgia, is in a hazardous zone in the Caucasus Mountains. As a result of its location on a faultline that marks the boundary of the Arabian and Eurasian plates, the city experiences frequent earthquakes. The risk for its one million residents is great due to its high population density and narrow laneways in the old parts of the city. An earthquake in 2002 left almost 70,000 people homeless.

The risk of death or injury to people from geophysical hazards is amplified in areas with a **high population density**. Many of the world’s fastest growing cities are located in areas that are vulnerable to earthquakes, volcanic eruptions or mass movement. Areas with a high population density poses greater risk of injury during hazard events because it is more difficult to evacuate large numbers of people from a small area, and because it is more difficult to get rescue crews into areas with lots of people, especially people who are dazed, confused or injured.

If large numbers of people living in an area are **recent arrivals**, such as rural-urban migrants from the countryside, the risks of death or injury during a hazard event may be even greater, This is because recent arrivals are less likely to know their way around, making evacuation after a disaster slower and less efficient. Furthermore, recent arrivals are less likely to understand, or even know about, the potential geophysical hazards existing in their new area of residence.

Political factors

Political conflict can make people more vulnerable to hazards. For example, Afghanistan experiences frequent earthquakes and mass movement events such as landslides and mudflows. Rescue efforts in that country are impeded by the civil unrest and conflict that continues to occur throughout the country.

The **political structures** of governance in some countries may also be a barrier to mounting effective rescue efforts after a hazard event. In 1976, during the era when China's government was centrally controlled, an earthquake hit the north-eastern city of Tangshan, resulting in the deaths of over 240,000 people from a total population of about one million people. Because of the secrecy that was routinely practised in China at that time, it took several days before the government (which controlled all the news and media outlets) even announced the earthquake, delaying initial efforts during the critically important initial rescue and recovery period.

QUESTION BANK 2F

1. *Define vulnerability.*
2. *Why do many choose knowingly to increase their exposure and vulnerability to geophysical hazards?*
3. *Explain why a hazard event is likely to cause more economic damage in a wealthy country but more human suffering in a poorer country.*
4. *Identify and rank the most important factors that make people vulnerable to geophysical hazards in the country where you live. Justify your ranking.*

Geographical factors affecting geophysical hazard event impacts

We have seen that **physical location** plays an important role in determining vulnerability to geophysical risks. A place that is located on a plate boundary has a higher risk of experiencing an earthquake or volcanic eruption than a place that is not on a plate boundary. Similarly, locations on the sides of steep mountains are more likely to experience mass movement events than places that are on open, flat land.

Other geographical factors can either amplify or reduce the risks of physical location. **Time of day** can play a significant role affecting the impact of a hazard event. For example, earthquakes that strike at busy times of the day, such as rush hour when many people are travelling, are likely to cause more deaths and injuries than earthquakes when most people are at home asleep in bed. This is because more people will be out in the streets and away from their familiar areas during the day, and because congested streets make it difficult for rescue vehicles to fight fires, get to damaged buildings and free victims who are trapped under rubble and debris.

2.22 Evening rush hour in Lima, capital city of Peru. Lima is located at the foot of the Andes mountains near the boundary of the Nazca and South American Plates, a subduction zone that causes frequent earthquakes in the city (mostly minor). If a major earthquake struck Lima, it would lead to many more deaths and injuries at rush hour than pre-dawn on a weekend morning.

The type of location, such as whether a place is in a **rural** or an **urban** location, can also affect death and injury rates in a hazard event. In general, urban locations carry greater dangers from falling walls and collapsing buildings than rural areas, although the risks of being killed or injured by a landslide are probably greater in rural areas where unstable slopes are less likely to have been strengthened or stabilised. Furthermore, rural areas generally have fewer rescue services to respond to a hazard event.

2.23 Villagers from Kerauja in the Gorkha district, Nepal, gather below a rockslide that resulted from a magnitude 7.8 earthquake. A rockslide such as this more likely to affect a rural area than an urban area.

Rural/urban location is related to another factor that influences vulnerability to geophysical hazards, which is **remoteness** and **isolation**. In general, people who live in isolated communities are more vulnerable because rescue services will take longer to reach the site of the hazard event, and communications regarding the disaster may be less reliable because telephone and internet links may be less developed. Furthermore, isolated communities often have less well equipped hospitals and emergency centres, requiring injured people to be transported over long distances for treatment.

2.24 A rural medical clinic in Hetigima, a remote village in the earthquake-prone Highlands of West Papua, Indonesia. Clinics such as this in isolated rural areas of poor nations can cope only with limited numbers of routine cases, and would be completely overwhelmed if a major earthquake or landslide struck the area.

QUESTION BANK 2G

1. *Explain how 'time of day' can affect the impact of geophysical hazard events.*
2. *Are people more vulnerable to death or injury in rural locations or urban locations? Give reasons.*
3. *In what ways do remoteness and isolation affect the impact of geophysical hazard events?*

Chapter 3 Hazard risk and vulnerability

3.1 Volcanic activity is a daily occurrence in Yellowstone calderas. This lake of boiling water, known as Grand Prismatic Spring, is hazardous to humans, but it is also a welcoming environment for thermophiles (heat loving micro-organisms) that give its overflow streams a vibrant orange colour.

Case studies

In this chapter, we will be looking at **six case studies** that illustrate the concepts and principles we have been developing in previous chapters. The case studies will be in **pairs**: one pair of case studies to illustrate **volcanic hazards**, one pair for **earthquake hazards**, and one pair for **mass movement hazards**.

In each case study we will focus on the primary and secondary hazards, the impacts of these hazards, variations in vulnerability within and between communities, and responses to the hazards.

Volcanic hazards

Two case studies of volcanic hazards will be studied from **contrasting plate boundary locations**.

The first case study examines volcanic hazards in **Yellowstone**, USA, looking at an array of current and ongoing volcanic hazards in a **hotspot** location that is well away from any plate boundary.

The second case study, which explores volcanic hazards in **Iceland**, focuses on a **divergent** (constructive) **plate boundary**, looking at several recent volcanic eruptions and associated hazards.

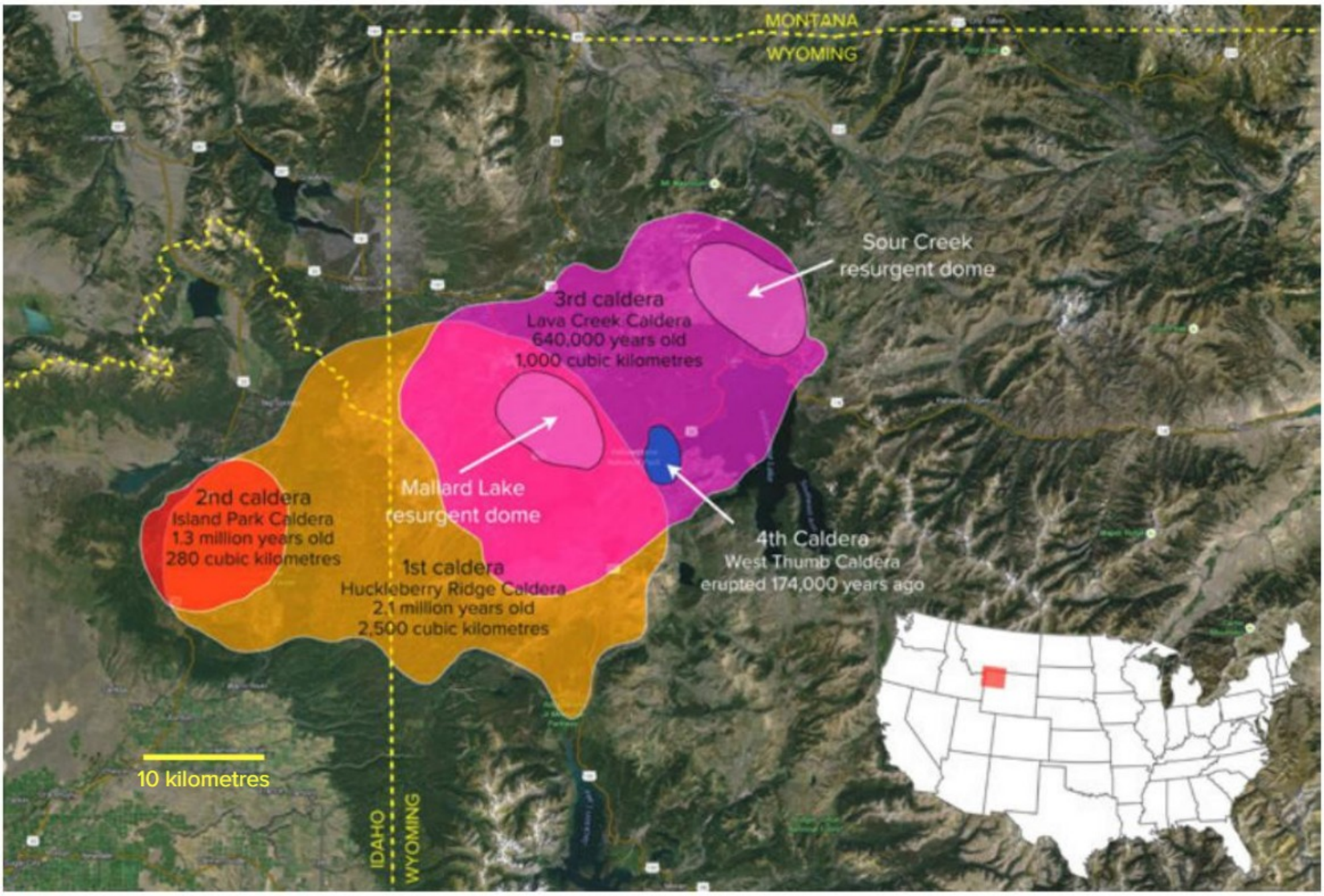
CASE STUDY
Volcanic hazards in Yellowstone

Yellowstone is a volcanic zone that measures 70 kilometres by 55 kilometres in north-west Wyoming, USA. Yellowstone comprises **four calderas** (collapsed volcanic cones). It is sometimes referred to as the **Yellowstone Supervolcano** because of the explosive nature of the huge eruptions that formed the calderas.

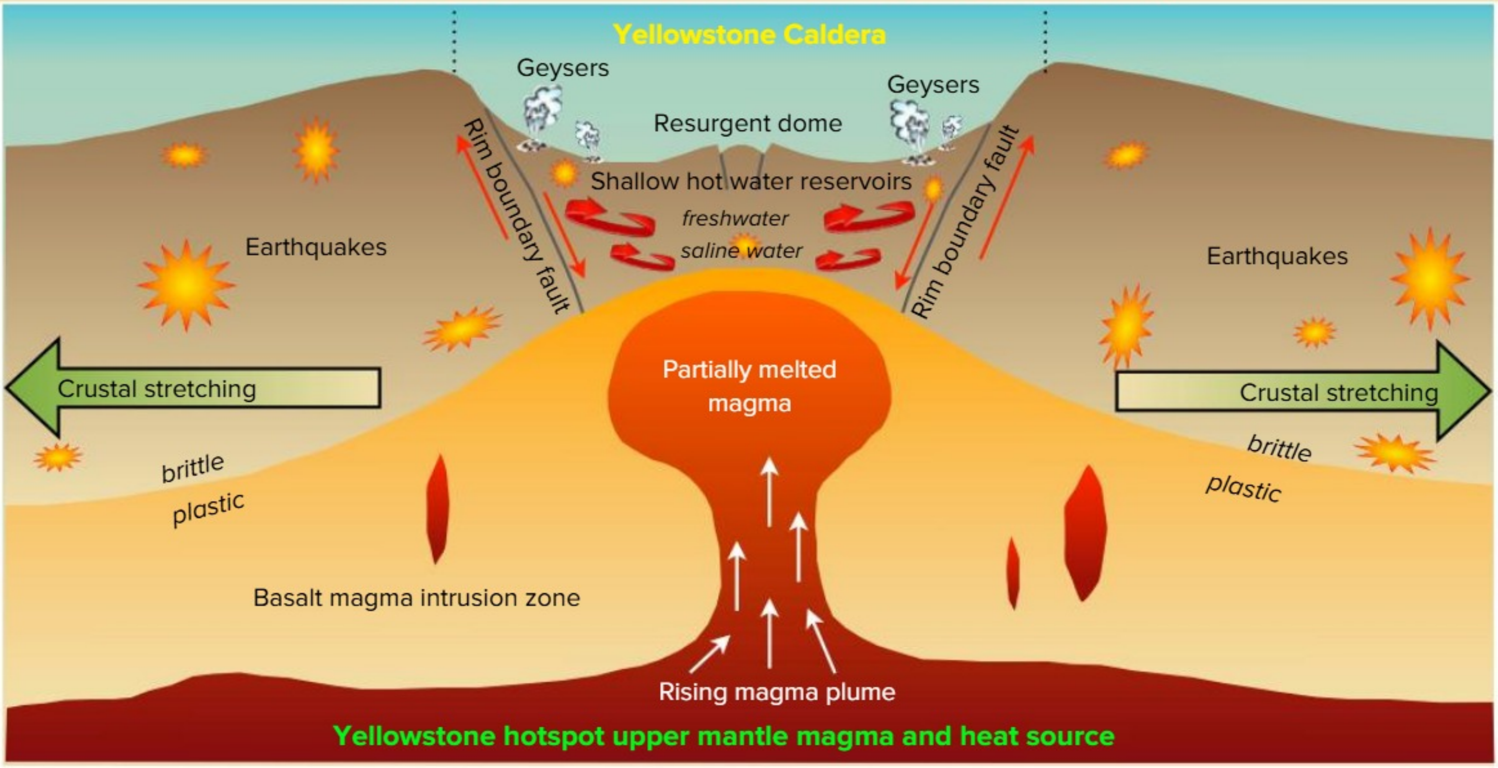
The sites of the **four eruptions** that formed the calderas over the past two million years are shown in figure 3.2. Yellowstone is not located near a plate boundary, but it remains volcanically active as it sits over a **hotspot** with a large **magma plume** that causes a range of geophysical events on a daily basis. There are signs that **volcanic pressures** are building up, and some experts warn that Yellowstone may have another super-eruption in the near future, with catastrophic effects for the US and perhaps the entire northern hemisphere.

Volcanic eruptions began in Yellowstone just over two million years ago when the North American Plate moved to the north-west (as it is still doing), bringing it over the shallow magma body that is known today as the Yellowstone Hotspot. Heat

3.3 A lake has flooded and filled West Thumb Caldera, the most recent of Yellowstone's large volcanoes to erupt. The eruption occurred 174,000 years ago, after which the crater collapsed to form a caldera. The lake is fed by almost 12,000 litres of hot water every day from nearby geysers and hot springs such as the one in the foreground of this photo. The cone around the spring formed when minerals were deposited as the hot water flowed from the spring into the cold waters of the lake.



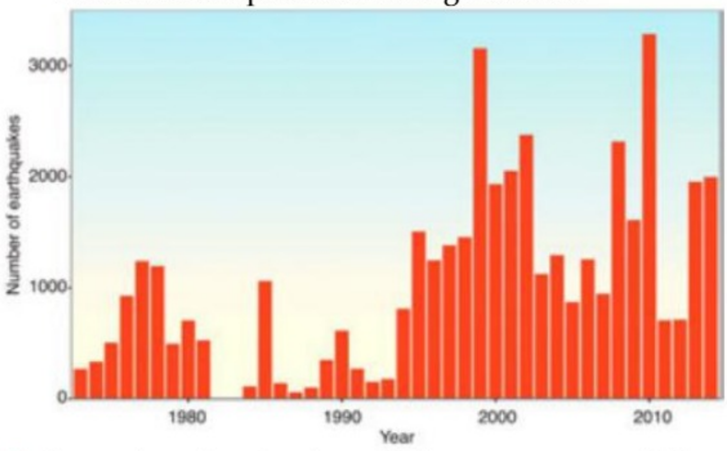
3.2 Yellowstone sits on four calderas, several of which overlap Adapted from Smith and Siegel, drawn on base from Google Maps.



3.4 Cross-section through the Yellowstone Caldera. A magma plume rising from a hotspot beneath Yellowstone drives the geysers and other geophysical hazards. Rainwater infiltrates into the ground and enters a groundwater circulation system. Some of this water circulates deeply, is superheated and is then blasted out of a geyser.

from the hotspot continues to rise to the surface, causing the **crust** to expand, rise and stretch apart.

This movement causes 1,000 to 2,000 small **earthquakes** each year as the crust stretches and moves away from the zone above the mantle plume. Yellowstone thus experiences an average of three to six earthquakes every day, most of which have a magnitude of 3.0 or less. The largest earthquake to affect Yellowstone in recent years occurred in March 2014 when a magnitude 4.8 earthquake struck the area. Although no damage was reported, the earthquake marked the beginning of a period of abnormally rapid uplift of the land within the calderas. Prior to that earthquake, Yellowstone experienced a magnitude 6.9



3.5 The number of earthquakes in Yellowstone per year, 1973 to 2014. Based on data from the University of Utah.

earthquake in 1983, and one with 7.3 magnitude in 1959.

From time to time, the frequency of earthquakes increases. When many earthquakes are detected over a short time frame, an **earthquake swarm** is said to occur. Almost 100 earthquake swarms have affected Yellowstone since 1983. Although earthquake swarms can indicate threatening movement in the magma chamber or magma plume, they may also occur less threateningly as rocks slip by each other along fault lines, relieving pressures that have been building up over time.

Yellowstone's earthquakes are a **secondary hazard** that arises from the **primary hazard**, which is **volcanic activity** caused by the hotspot and magma plume. Volcanic hazard events occur on a **daily basis** in Yellowstone.

The upward force from the mantle plume has resulted in two **resurgent domes** within the Yellowstone caldera area that are still rising. Resurgent domes form when the floor of a caldera swells and rises due to the pressure of movement in a magma chamber beneath (figure 3.4). The Sour Creek resurgent dome rises about 300 metres above the caldera floor and measures about 10 kilometres wide and 16 kilometres long. It began forming

630,000 years ago, and been rising ever since. The Mallard Lake dome, which began forming 150,000 years ago, is about 12 kilometres long and 8 kilometres wide. Overall, the **magma chamber** beneath Yellowstone is about 70 kilometres long, 30 kilometres wide, up to 20 kilometres deep, and it has a capacity of about 4,000 cubic kilometres. The resurgent domes in Yellowstone are monitored very carefully because **rising land elevation** in a resurgent dome is evidence that the magma beneath is rising towards the surface, a warning sign of a possible impending eruption.

Land elevation within the Yellowstone calderas, including the resurgent domes, varies by about 1.5 centimetres every year as a result of changes in the pressure of the magma chamber. From time to time, the land elevation shows **consistent rises**, such as happened between 2004 and 2008 when the land rose about 7.5 centimetres per year. This caused some concern, but the rise began to slow down in 2009, and it has returned to the more normal rate of 1.5 centimetres per year since.

The **driving force** of Yellowstone's geothermal processes is heat. Indeed, the **heat** flowing from the ground that provides the energy for Yellowstone's volcanic activity is thirty to forty times greater than the heat emitted from average ground anywhere else in the world. Heat from the hotspot beneath Yellowstone **powers** the volcanic activity by melting rock in the mantle and crust, and this molten rock in turn heats groundwater to produce geysers, hot springs, and other geothermal formations.

Heat is released from the ground in Yellowstone in two ways. Most of the ground heat (75%) is released by **convection** currents in fluids such as magma and hot water. Near the surface, convection drives geysers, hot springs, fumaroles, steam vents and other features.

The remaining 25% of ground heat is released by **conduction** as heat flows from hot rocks into adjacent cooler rocks. Conduction helps to transfer the heat that builds up in the magma chamber, thus reducing the probability of an imminent catastrophic earthquake.

Yellowstone's ongoing **volcanic activity** has resulted in the formation of several distinctive **geothermal landforms**. These landforms present both **geophysical hazards** to people, and **attractions to tourists**. Indeed, the spectacular nature of Yellowstone's geothermal formations led the area to be proclaimed a **national park** in 1872, becoming the first official national park in the world.

Geothermal activity occurs where rocks have been raised to higher temperatures than surrounding regions by natural activity. Because hotspots and magma plumes give off quite a lot of heat, geothermal activity is often found in areas where there are hotspots.

When heat is transferred in rocks beneath the earth's surface, it can either be conducted by the rock itself or by convection as water that has been heated by the hot rocks moves elsewhere. Water that originally fell as rain seeps downward through cracks in the rocks, absorbing heat from the hot rocks, thus becoming hotter and hotter. Hot water is less dense than cold water, so if it can get access to the surface, it discharges as geysers or hot springs, or in modified ways such as fumaroles or boiling mud.

3.6 Jet Geyser erupting in Yellowstone.

Geysers are intermittent discharges of boiling hot water with steam. Most geysers have a narrow neck draining a larger underground reservoir. As pressure builds up under the ground, the water reaches boiling point, and then a violent ejection of water and steam occurs as the water is forced up through the narrow neck. When the pressure has been released, the geyser stops shooting water, and the process begins again as the reservoir recharges itself. The water in geysers usually contains dissolved sodium and chloride, and the runoff from geysers usually precipitates these chemicals as the water cools. Geysers are relatively rare, and apart from Yellowstone they are only found in Rotorua (New Zealand), Dolina Geyzerov (Russia) and in Iceland.

3.7 Black Pool, a hot spring near West Thumb Caldera. The water is 73°C, and this view shows the deep cavity down into the crust that feeds the hot spring.

3.8 Silex Spring, another hot spring in Yellowstone, shows the bright orange colours of heat-tolerant thermophiles that cannot survive in the hot water of the spring, but thrive in the cooler runoff water around the spring.

Hot springs are a continuous natural discharge of water onto the earth's surface at temperatures that are higher than the air temperature. Like geysers, they form when water comes into contact with hot rocks. Unlike geysers, however, the water does not build up under pressure because it is trapped before flowing out of the ground. This is because the reservoir of water is at the earth's surface, although they may also have an additional underground reservoir with chlorine and silica dissolved in the water.

Hot springs carry minerals to the surface that have dissolved in the hot water while underground. Some of the hot springs bubble from limestone, a white rock composed of calcium carbonate, which is highly soluble in water. When the water in calcium carbonate saturated hot springs emerges at the surface, it cools and deposits the calcium carbonate, forming large deposits known as **travertine terraces**.

3.9 Hot water from Palette Spring is depositing white calcium carbonate to form these travertine terraces near Mammoth Springs.

3.10 A fumarole blows a constant jet of hot steam in the Fountain Paint Pot area of Yellowstone.

Fumaroles are like hot springs, but instead of discharging water, they mainly release steam. Fumaroles are therefore gas vents which release steam and other gases, but hardly any liquid water. They occur near volcanoes and in geothermal fields where temperatures beneath the surface are about boiling point. Fumaroles form when water boils in underground reservoirs, and the gases and steam that result are released through a vent to the surface. The most common gas released in fumaroles is sulphur, a foul-smelling, poisonous gas that can make walking through a geothermal field quite unpleasant.

Boiling mud forms when steam and gas from boiling water are trapped beneath a pond. The escaping steam reacts with the overlying mud base of the pond, and produces turbulent eruptions of mud. The thickness (viscosity) of the mud varies according to the amount of rainfall; during droughts the mud becomes thicker (more viscous).

3.11 A pool of boiling mud in the Hayden Valley area of Yellowstone. The yellow colouring around the edge of the pool forms from sulphur deposits.

3.12 Tourism is a major income earner for the Yellowstone area, with millions of people attracted each year by the geothermal formations.

The daily hazard events in Yellowstone have both **positive and negative impacts** on human well-being. There are two significant **economic benefits**, one actual and one potential. The **actual benefit** brought by Yellowstone's geothermal activity is **tourism**. Each year, more than three million visitors come to Yellowstone to see the geothermal activity, spot rare animals and plants, spend time camping, go fishing, and hike trails of varying difficulty. In 2015, visitors to Yellowstone spent $US493.6 million, and the Yellowstone economy supported 7,700 jobs.

The **potential economic benefit** of Yellowstone's geothermal fields is the possibility to produce an abundant quantity of **pollution-free energy**. Heat from underground geothermal areas can generate electricity by using the underground steam to turn turbines that generate electricity. **Geothermal power** is used in suitable areas elsewhere in the world such as Wairakei in New Zealand, Krafla in Iceland, and the Kamchatka Peninsula of Russia.

3.13 Old Faithful geyser is Yellowstone's most famous feature. It erupts every 90 minutes or so. During each eruption of 1½ to 5 minutes, it expels 14,000 to 32,000 litres of hot water in a plume that is typically 30 to 55 metres high. Fear of weakening this and other geothermal features has stopped the development of geothermal power generation in Yellowstone area.

So far, no geothermal power stations have been approved in the Yellowstone area because of concerns that tapping into the heat energy might deplete the flow of energy into nearby hot springs and geysers.

Because the Yellowstone calderas are located in a national park that receives millions of visitors every year, the everyday dangers of the ongoing geophysical hazards are **managed** very carefully. Nonetheless, the hazards have the potential to **adversely affect human well-being** in several ways, including:

- Geyser and hot spring areas have fragile and **unstable ground**, and the land can easily collapse if weight (such as a person walking) is applied to it. Some visitors have fallen through the surface crust to find themselves in a pool of near-boiling water, suffering severe burns as a consequence. To make access more secure, elevated boardwalks have been constructed so visitors can walk across unstable areas safely.
- Geysers, hot springs, boiling mud and fumaroles eject water, steam and gases that are so hot they cause **injury** if a person gets too close. To address this issue, fences and barriers are erected to keep people at a safe distance.
- Fumaroles, and to a lesser extent, hot springs emit **toxic gases** such as sulphur dioxide, carbon dioxide, hydrogen sulphide and hydrogen chloride that are unsafe for humans and animals to breathe.

3.14 A sign in Yellowstone gives visitors detailed warnings of the dangers of geothermal hazards and the precautions that are required.

3.15 A boardwalk in Lower Geyser Basin allows visitors to walk safely across hot, fragile and unstable land to observe the geothermal features.

3.16 The trees beside this hot spring have been killed by the rising hot waters that have affected the roots of the trees.

- Toxic gases and hot water are not only dangerous for humans and animals, they are killing many of the area's **trees** and other **vegetation**. Many trees cannot tolerate suffocation by sulphurous gases. In areas where hot water rises to the surface, the root zone of vegetation will be drowned and burnt, thus killing the trees.

The main potential hazard in Yellowstone is, of course, the threat of another **eruption** of the supervolcano. Yellowstone is classified as volcanically active, and as we have seen, the area experiences multiple geophysical hazard events on a daily basis.

The consensus of vulcanologists is that Yellowstone will almost certainly erupt again within the next 100,000 years. Although there are signs of rising land elevations in the resurgent domes and elsewhere that indicate growing pressures in the magma chamber beneath the surface, an imminent catastrophic super-eruption is not generally expected. Nonetheless, some **sensationalist television** programs have created a different **perception** among many in the general public. Following some newspaper articles and alarmist internet sites, it is reported that many people believe a supervolcanic eruption at Yellowstone is not only imminent, but may wipe out much of life as we know it across the northern hemisphere.

Being a national park, Yellowstone is able to manage and **minimise people's vulnerability** to its geophysical hazards by **controlling entry** into the caldera zone. If a major hazard event were imminent, the National Parks Service could easily evacuate the area and prevent the entry of new arrivals. There are no permanent residents living within Yellowstone National Park.

Monitoring of geophysical activity is being undertaken by YVO (Yellowstone Volcano Observatory) staff of the USGS (United States Geological Service). **Seismographs** and GPS (**Global Positioning System**) sensors are constantly taking readings to measure ground motion to check for imminent hazards. YVO confirms the findings of scientists elsewhere, that there are signs of activity suggesting an imminent super-eruption at Yellowstone.

QUESTION BANK 3A

1. *A **Hazard Profile** is defined as 'a description of a geophysical hazard event, including its magnitude, duration, frequency, probability, and extent'. Briefly describe the hazard profile of each of the following hazards in Yellowstone: (a) supervolcanic eruptions, (b) earthquakes, (c) geyser eruptions, (d) hot spring eruptions, (e) fumarole gas releases, (f) boiling mud activity.*

2. *For each of the hazard events in question 1, write a few lines to describe the impact each has on human well-being.*

3. *How accurate are people's perceptions of the various geophysical hazards in Yellowstone?*

4. *What management measures are being undertaken to reduce the impact of hazard events in Yellowstone?*

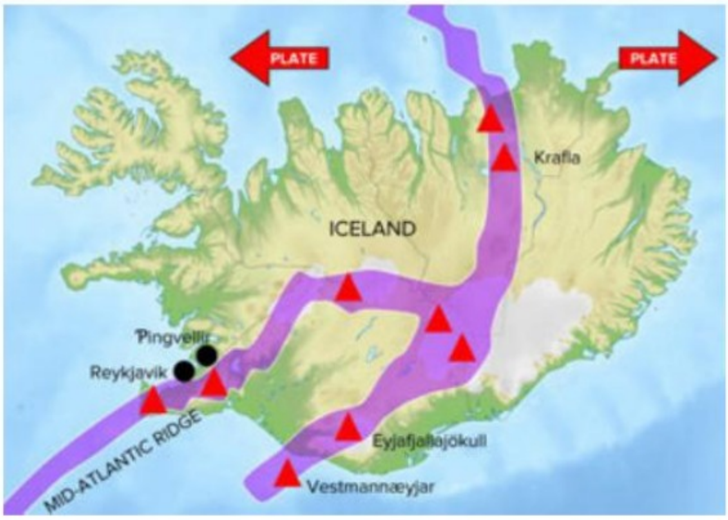
5. *With reference to the photos, maps and diagrams in this section, and especially figure 5.4, describe the processes that cause the daily geophysical hazard events in Yellowstone.*

6. *How significant is Yellowstone's location over a hotspot in determining the types of volcanic hazards it experiences?*

CASE STUDY
Volcanic hazards in Iceland

Iceland is a volcanic island situated on the **constructive plate margins** of North American and Eurasian Plates that form the Mid-Atlantic Ridge. Also known as a **spreading ridge**, Iceland is the only place in the world where the Mid-Atlantic Ridge rises above sea level to allow easy observation. New crust forms as magma rises from below and pushes the two tectonic plates apart at a rate of about 1.8 centimetres per year.

Energy for Iceland's constructive plate margin comes from a **hotspot** that lies directly beneath Iceland. The crust beneath Iceland is just a few kilometres thick, much thinner than the crust in the central parts of crustal plates. The movement of the crust causes many cracks, faults and fissures to develop, and when magma enters these fissures and rises to the surface, a volcanic eruption occurs.

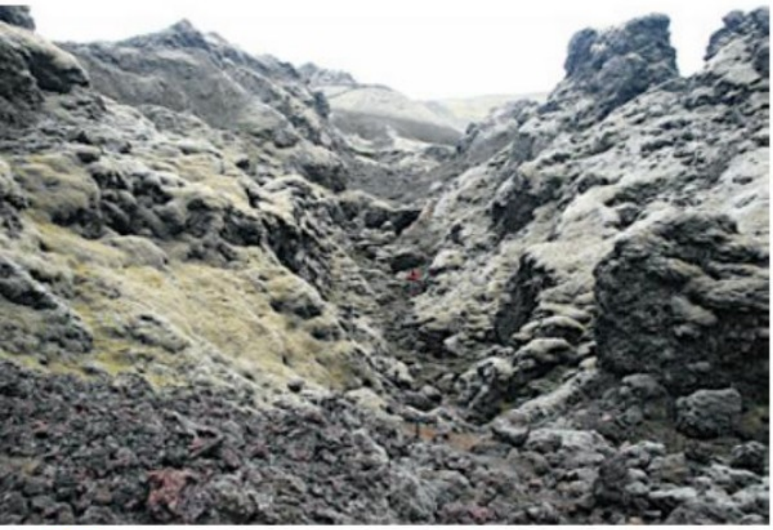


3.17 Map of Iceland showing the constructive plate margins at the Mid-Atlantic Ridge. Active volcanoes are shown as red triangles. Krafla and Þingvellir are areas with especially active volcanic activity. The island of Vestmannæyjar has two active volcanoes, Surtsey, which erupted from 1963 to 1967, and Eldfell, which erupted in 1973. Eyjafjallajökull, whose precise location in southern Iceland is latitude 63°38′N, longitude 19°36′W, erupted in 2010. The off-white areas on the map show the several ice caps that cover much of the surface area of Iceland.

Volcanic activity in Iceland is focussed along the spreading fissure of the Mid-Atlantic Ridge. There are around 30 volcanic zones in Iceland, and on average an eruption occurs about every five years.

One of the largest volcanic eruptions in Iceland's history, and certainly the most hazardous as it caused the most fatalities, was the Skaftáreldar (fires of Skaftá) in 1783-84 along the row of craters known as Lakagígar. About 25% of Iceland's population were killed as a result of the eruption. The deaths were not so much due to the **primary impacts** of lava flow and ash cloud, but by **secondary impacts**. These included **cooling of the climate** due to shade from the ash cloud, and famine that resulted from the deaths of half the island's livestock from poisonous gases released during the eruption. The 1783 eruption in Lakagígar released about 14 cubic kilometres of lava, thought to be the largest quantity of lava from a single eruption in recorded history.

3.18 Part of the line of craters at Lakagígar that erupted from 1783 to 1784, producing the extensive lava field that spreads across the view in most of this photo.



3.19 The centre of the fissure at Lakagígar. The man with the red jacket gives a good idea of the scale of the fissure.

Most volcanic eruptions in Iceland are a mix of lava, explosive pyroclastic material that includes pumice and tephra, and clouds of ash. Some eruptions occur in volcanoes that are located beneath the island's icecaps, and these are especially explosive, producing ash and tephra together with large quantities of steam and meltwater.

The **fissures** of the Mid-Atlantic Ridge can be seen very clearly at several locations in Iceland, notably at Þingvellir and Krafla. As a result of the spreading movement of the plates, Iceland experiences several minor **earthquakes** every day. Iceland occasionally experiences larger earthquakes, usually in association with a volcanic eruption, but most are minor because they occur so frequently that large pressures do not build within the crust.

3.20 The land is ripped apart at the Mid-Atlantic Ridge in Þingvellir, north-east of Reykjavik. A small stream flows through the gap that has been created by the spreading ridge.

3.21 Steam escapes from an active fissure that forms part of the Mid-Atlantic Ridge at Krafla.

Because Iceland is located over a hotspot as well as being situated on a constructive plate boundary, many of the **geothermal landforms** found in Yellowstone are also present in Iceland. The average temperature of the ground under Iceland's surface rises from 30°C at a depth of 500 metres up to 300°C at 2,000 metres. These are **hotter subterranean temperatures** than in most places around the world, and they reflect the underground hotspot and the thin crust near the constructive plate boundary. These high temperatures, combined with **high moisture content** in the ground that result from heavy rainfall and widespread infiltration from snow cover, provide excellent conditions for hot water driven **geothermal features** to form. Examples of geothermal landforms that are found in Iceland include geysers, hot springs, boiling mud pools and fumaroles.

3.23 A pool of boiling mud at Hverarond, near Reykjahlíð on the Mid-Atlantic Ridge in north-eastern Iceland.

Like Yellowstone, Iceland's geothermal features have positive and negative effects on **human well-being**. One significant benefit brought by geothermal activity is the revenue earned from **tourism**. Almost one million visitors come to Iceland each year, the vast majority of whom come to see and experience Iceland's geothermal features. In 2015, tourism comprised almost 30% of Iceland's export income and supported 22,000 jobs.

3.22 The Strokkur geyser at Geysir. Geysers were named after Geysir, because Geysir was the first place that these periodically erupting hot springs were studied.

Unlike Yellowstone, Iceland makes great use of its geothermal potential to generate electricity. The accessible heat content in the upper three kilometres of Iceland's shallow crust is the equivalent of 28 billion gigawatt-hours, of which 900,000 gigawatt-hours is available for generating **geothermal electricity**. Five major geothermal power plants operate in Iceland, and they produce approximately 26% of the country's electricity. In addition to this amount, **geothermal heating** supplies the heating and hot water needs of most of Iceland's buildings. In spite of these figures, less than 1% of the technically accessible geothermal heat is currently being exploited.

3.24 A section of the large geothermal power station at Krafla, Iceland.

Geothermal power brings a wide range of benefits to Iceland's residents to enhance their **well-being**. Geothermal energy is used for:

- **heating buildings** — 87% of Iceland's buildings are connected to geothermal heating services;
- providing **hot tap water** — although not normally used for human consumption;
- **heating greenhouses** where vegetables and flowers are cultivated;
- **heating the soil** to speed up the growth of traditional crops such as potatoes, carrots and turnips, as well as trees for replanting;
- **generating electricity**, mainly by using steam to turn turbines;
- producing **industrial steam** for manufacturing processes such as producing salt from underground saline water, drying fish and seaweed, and producing a range of products such as concrete blocks, car tyres and bread baking;
- **aquaculture**, where hot water is used to hasten the growth of fish on fish farms;
- **health facilities**, where geothermally heated water is used in heated pools and mud baths; and
- **snow melting systems**, such as de-icing car parking spaces and removing snow from roads.

Like Yellowstone, measures have been implemented to **protect visitors** from the hazards of visiting geothermal areas. Unlike Yellowstone, however, visitors are **less restricted** in their movements, and although boardwalks are provided in some areas, tourists in Iceland are relatively free to walk across hot lava flows, get quite close to geysers and hot mud pools, and walk right up to fumaroles that are blowing hot steam.

3.25 An elevated boardwalk and viewing platform encourages visitors not to walk too close to fumaroles and hot mud pools at Hverarond, which lies on the Mid-Atlantic Ridge.

3.26 Visitors walk across the Leirhnúkur lava flow, which is still hot and steaming after its last refresh.

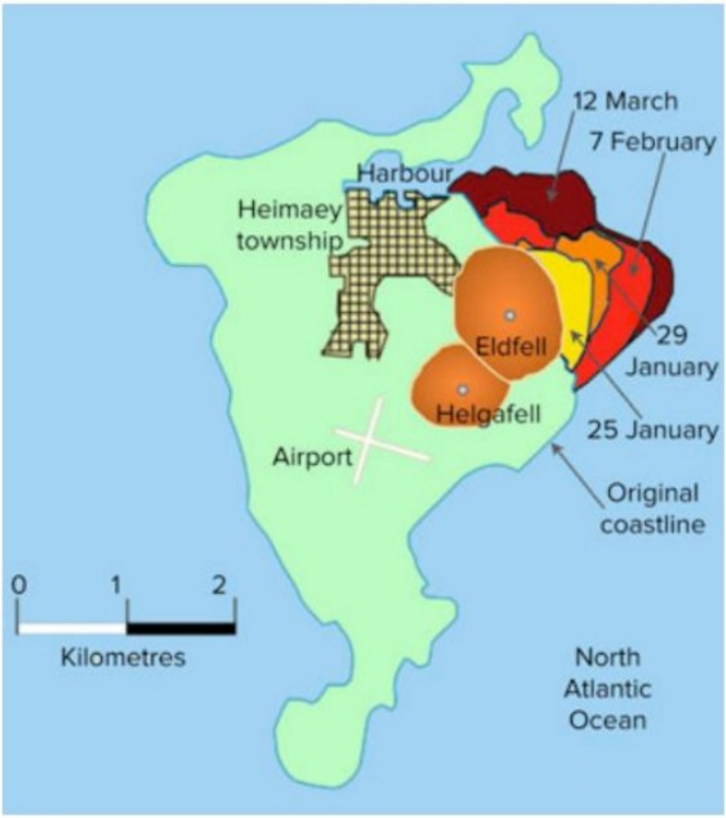
The most significant volcanic hazards faced by people in Iceland are **volcanic eruptions**, together with associated hazards such as lava flows and ash clouds. Iceland experiences frequent eruptions, and in the rest of this section, we will examine two recent significant volcanic eruptions and their associated hazard events.

The eruption of Eldfell, 1973

The small island of Vestmannæyjar lies just to the south of the main island of Iceland. The island lies on the eastern branch of the Mid-Atlantic Ridge. The zone around Vestmannæyjar has a long history of volcanic eruptions. The **most recent eruption** occurred in 1973 when a new volcanic cone formed that had not previously existed. The new volcano was named **Eldfell**, which means 'Mountain of Fire'.

The **eruption began** just after midnight on 23rd January, 1973. A 1.6 kilometre long fissure suddenly opened on the north-eastern side of the island, and worryingly for the residents, it was only 200 metres away from the eastern edge of the township of Heimaey. Some 40 **lava fountains** shot lava up into the air, but fortunately the land sloped away from Heimaey and the lava flow did not threaten the settlement.

Nonetheless, most of the town's population **evacuated** to mainland for safety reasons, travelling in a fleet of boats from the Harbour. This was a fortunate move, as the intensity of the eruption continued to grow, and on the second day, a new fissure began discharging molten lava right beside



3.27 Map of Vestmannæyjar island, showing the close proximity of Eldfell Volcano to the township of Heimaey. The precise location of Eldfell is latitude 63° N, longitude 20° W. The coloured zones to the north-east of the island were ocean before the 1973 eruption. The coloured zones show the growth of the island as the lava flow expanded between January and March 1973.

3.28 Lava fountains during the early phase of Eldfell's eruption in late January 1973. The cone of the volcano has not yet built upwards, and the fissure is still very close to the coastline.

the houses on the eastern edge of the town. The rate of lava discharge reached 100 cubic metres per second at that time. Within a month of the start of the eruption, 100 houses had been destroyed by the lava flow, which had buried, partially buried or burnt everything in its path.

As February progressed, a **cone** began to build above the new fissure. By 15th February, the cone was 220 metres high, and was sending flaming balls of molten rock and huge quantities of ash over Heimaey. On the eastern side of the town, the thickness of the ash and tephra was about two metres, causing many houses and buildings to **collapse** under the weight.

Efforts were made to **protect** as many of the remaining buildings as possible. Tephra was **removed** from the roofs of intact buildings by a team of 250 volunteers that remained on the island. The windows of houses facing the volcano were **covered** with sheets of corrugated iron to protect the glass from flying lava bombs. Protective **walls** were erected to try and stop the flow of lava into the town.

3.29 Fires on the lava flow approach the entrance to the fishing port in Heimaey, threatening to close the port's entry to the sea.

3.30 The trees beside this hot spring have been killed by the rising hot waters that have affected the roots of the trees.

On 19th February, the western rim of the new crater collapsed, releasing more lava which flowed downwards into the town, **burying** more houses. The lava flow continued to flow in all directions, expanding the area of the island by **reclaiming** more and more ocean to the north-east of the island (figure 3.27). By late February, the lava flow was threatening to **block the entrance** to the Harbour, something that would destroy the island's fishing industry. A round-the-clock campaign had began earlier in February to **pump cold sea water** onto the lava flow to cool it down, reduce its viscosity, and thus slow it down and stop the relentless movement. This program was intensified as the lava flow continued to approach the harbour's entrance. The ambitious and difficult campaign was **successful**, and the entrance to the Harbour remained open.

3.31 Eldfell erupted in 1973, creating the ash cone in the foreground and the extensive lava flow in the background. Before the eruption, the cone was flat land and the area occupied by the lava flow was ocean water. The narrow channel of water between the lava flow and the cliff in the background shows where the molten lava threatened to close the Harbour during the eruption.

3.32 The Eldfell eruption produced a lava flow that buried many homes in the town of Heimaey. The remains of one of the destroyed buildings can be seen at the foot of the lava flow in the left foreground.

The eruption slowed down by April, although **toxic gases** such as carbon dioxide were still emitted in large quantities. Indeed, the only **fatality** from the Eldfell eruption was a person who died from carbon dioxide asphyxiation in mid-April 1973.

By May, some of the town's fish factories that had survived **resumed production**, and the eruption was declared finished on 25th June. Although 400 of Heimaey's buildings had been destroyed, the **population** began to return, and by the end of 1973, more than 2,000 of the island's 5,300 residents had returned to Heimaey.

3.33 A building crushed by the weight of the Eldfell lava flow on the eastern edge of Heimaey. Many more buildings remain completely buried beneath the lava flow.

Eruption of Eyjafjallajökull, 2010

Eyjafjallajökull is a small ice cap in southern Iceland that covers the caldera of a gently sloping shield volcano, also called Eyjafjallajökull, which has a summit elevation of 1,666 metres (figure 3.17). As it located right on the Mid-Atlantic Ridge, the volcano is **very active**, having erupted many times since the last Ice Age. The most recent major eruptions were in 920, 1612, 1782 and from 1821 to 1823.

In late December 2009, many **small earthquakes** were recorded in the area around Eyjafjallajökull, suggesting that magma was accumulating in the magma chamber under the volcano. In February 2010, GPS devices recorded a displacement in the local crust of three centimetres towards the south. Of these movements, some shifts totalling one centimetre occurred during a single four day period. These events were seen as further evidence that magma was flowing into the **magma chamber** beneath the volcano, increasing the pressure for an imminent eruption. The main eruption of Eyjafjallajökull began on 14th April, 2010.

3.34 Eyjafjallajökull during a dormant phase in 2007, prior to its recent eruption.

3.35 Eyjafjallajökull on 17th April 2010, three days after its eruption began.

The eruption of Eyjafjallajökull was marked by a huge **cloud of ash**, known as tephra, that rose up to nine kilometres (9,000 metres) into the atmosphere. During the four weeks in which the eruption continued, it was estimated that about **250 million cubic metres of ash** were sent into the atmosphere.

The cause of the huge ash cloud was the millions of tonnes of **ice** that had built up since the previous eruption in 1823. When the eruption began, this ice melted and **collapsed** into the volcano. As it did so,

3.36 A huge plume of ash erupts from Eyjafjallajökull during its 2010 eruption, causing major headaches for airlines and air travellers.

superheated steam began generating large-scale explosions that shot the ash up into the atmosphere.

Volcanic ash represents a major **hazard to aircraft** because ash clouds can travel thousands of kilometres and affect areas that are far away from the volcano. The ash plume from Eyjafjallajökull in April 2010 **shut down most flights** over Europe for the first six days of the eruption, causing significant **disruptions** and **economic losses**.

Several factors combine to make volcanic eruptions with large ash plumes a **danger to aircraft**. First, the particles in volcanic ash are made up of **hard** and extremely **sharp materials** such as rock, glass and sand. When these particles are ejected into the upper atmosphere, they may be carried by the high winds over long distances that may disperse them over **large areas**. Another factor is that ash plumes are usually not dense enough to be seen easily by airline pilots, although they are dense enough to cause **severe damage** to the engines, which may cut out and fail. Failure happens when the fine dust particles block up the air vents or melt in the hot engines to form a solid mass of glass-like substance.

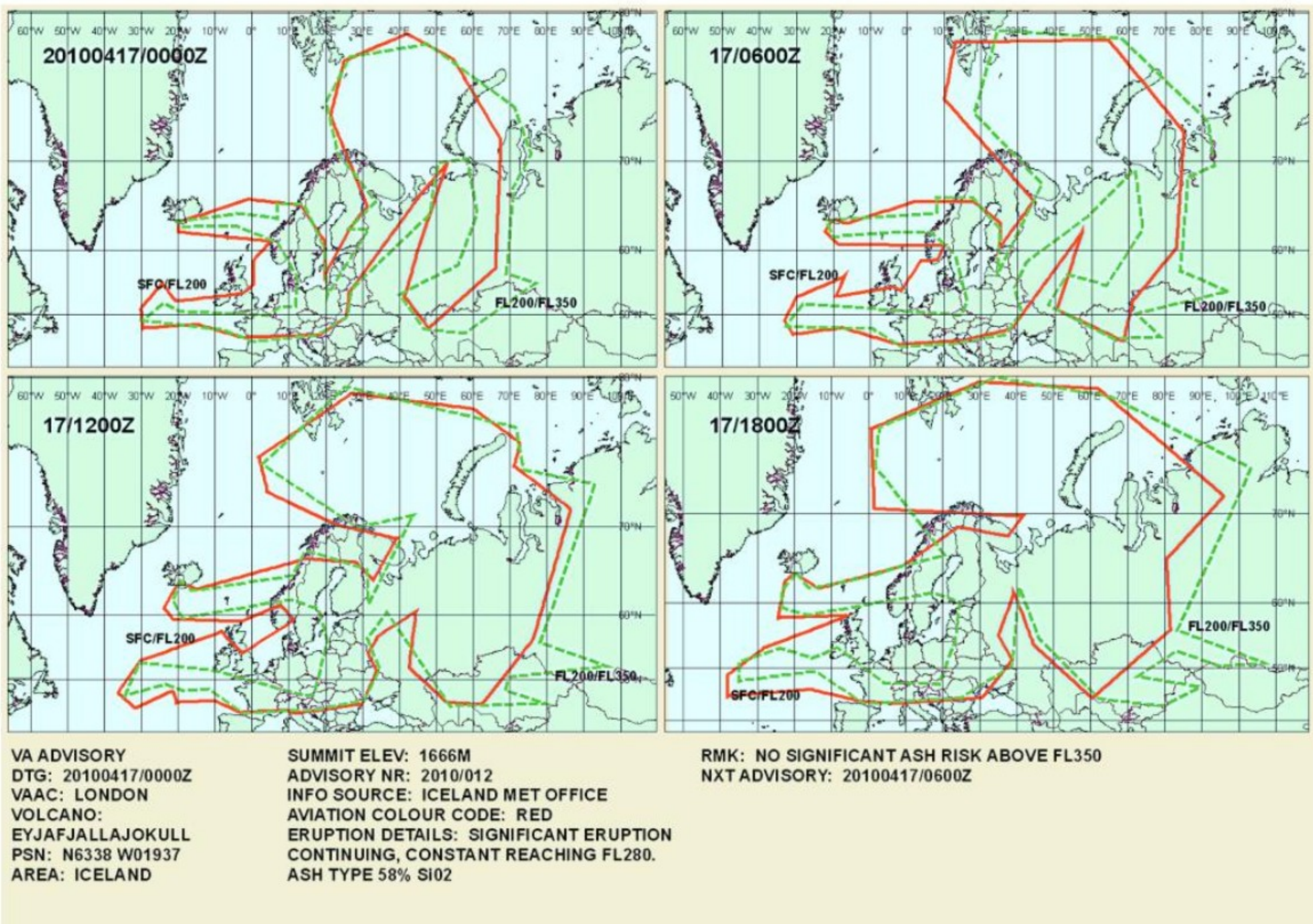
The nervousness about flying through an ash cloud can be partly explained by an incident that occurred in 1982. On 24th June of that year, a British Airways Boeing 747 airplane flew unexpectedly into the ash cloud of Mount Galunggung, an erupting volcano over Indonesia. The pilots were not aware of the ash plume because it was night time, and aircraft radar does not detect volcanic ash. As soon as the plane entered the ash cloud, all **four engines failed**, the plane lost power and the pilot famously announced to the passengers "Ladies and gentlemen, this is your captain speaking. We have a small problem. All four engines have stopped. We are doing our damnedest to get them under control. I trust you are not in too much distress".

The pilot was eventually able to glide the plane down to a lower altitude, where the force of the air blowing through the engines cleared the ash, enabling the engines to be re-started in flight one-by-one. Nonetheless, **damage to the aircraft** amounted to $80 million, including the replacement of all four engines.

Smoke and ash from eruptions causes other hazards for aviation by reducing visibility for visual navigation, and microscopic particles in the ash can sandblast aircraft windscreens.

The **ash cloud** from the eruption of Eyjafjallajökull spread quickly across Europe, forcing the cancellation of almost all flights within, to and from Europe. Most airliners in Europe were kept on the ground, often with plastic wrapping around the engines to protect them from any stray ash that might blow into them.

It was estimated that the closure of European airspace left five million **travellers stranded** around the world. Although most travellers were stranded in Europe, several thousand passengers were also stranded in Asia, the United States and Australia. The disruption had a particularly significant effect on **schools** in the United Kingdom because the eruption began at the end of the annual Easter holidays and many students and teachers were thus stranded abroad. In some cases, travellers took very long and arduous journeys by bus, train and



3.37 Aviation warning maps for Europe on 17th April 2010, the third day of the eruption of Eyjafjallajökull. The top left map shows the situation at midnight at the start of 17th April. The top right map shows the situation six hours later, at 6:00 am. The lower left map shows the situation after another six hours (at midday), while the map in the lower right shows the situation after a further six hours (at 6:00 pm). On all four maps, the green dotted lines show the extent of the ash cloud as a result of wind movements between 20,000 feet and 35,000 feet (6,100 metres to 10,700 metres). The red fixed line shows the flying exclusion zone that was being enforced at the time between sea level and 20,000 feet (0 to 6,100 metres) as a result of the hazard caused by the ash plume. Maps: Met Office

3.38 The ash plume from the eruption of Eyjafjallajökull on 17th April 2010. In this view, north is at the top of the satellite image. The ash in this image is at two different altitudes. A concentrated brownish plume from an explosive phase blows to the south, throwing a shadow on a wider plume that is also moving south, but at a lower altitude. At the time the photo was taken, the volcano had been emitting ash in puffs that reached between 5,000 and 7,500 metres.

3.39 During the period they were grounded by the eruption of Eyjafjallajökull, many airliners had their engines wrapped in plastic to protect them from possible damage by wind-blown volcanic ash. This Boeing 737 aircraft was grounded at Cologne, Germany.

ferry to complete their journeys. Meanwhile, the International Air Transport Association (IATA) estimated that **airlines** were losing about **$200 million per day** during the period of the disruptions to flights.

Within the first few days of disrupted flights, **shortages** of imported flowers, fruit and electronic hardware were being reported across Europe. At the other end of the supply chain, Kenya's flower growers, who depend on the European markets for their livelihood, were unable to air freight their fresh flowers to the markets. On each day the

3.40 The eruption continues on 10th May 2010. The ash cloud is still rising from the crater, and the heavier ash particles can be settling beneath the main plume.

flights were disrupted, 400 tonnes of fresh flowers were destroyed in Kenya, causing the **loss** of vast sums of money. **Exports** of hi-tech equipment from Europe were especially affected as companies were unable to transport their products to overseas buyers.

Pharmaceuticals companies in Europe also lost large sums of money because many of their products were time-sensitive, meaning that a delay of even a few days meant the medicines became unusable. Imports of **medications** into Europe were also affected for the same reason, and organs for **transplants** could not be moved for surgery. Some shortages of **fresh foods** were also reported in many parts of Europe because of the disruptions to air freight. Perhaps most significantly for business, air freight of **documents** ceased, disrupting many business transactions.

Within Europe, many sporting, entertainment and other **events** were cancelled, delayed or disrupted as either individuals or teams found themselves unable to travel to their destinations.

The disruptions to air transport did not only affect people in Europe. As far away as Hong Kong, the press reported that air freighted fresh Norwegian salmon was in short supply, and some people began buying tickets on the Trans-Siberian Railway to get home to Hong Kong from London.

After about six days, Eyjafjallajökull's eruption stopped producing the large **ash plume** that had caused the widespread disruption to transport. This change in the volcano's behaviour came about because the **supply of ice** that had built up on top of the volcano following the previous eruption in 1823 was exhausted, and the explosive force created by tonnes of ice falling into the hot chamber of molten magma was thus removed.

Paradoxically, during the period of the eruption, prevailing winds kept Iceland's own major international airport at Keflavík free from Eyjafjallajökull's ash cloud. Although air transport was shut down across most of Europe, Iceland's air links with non-European destinations continued without impact.

The Eyjafjallajökull eruption had a **VEI** of 4, making it 'cataclysmic'. The eruption went through both **Strombolian** and **Vulcanian** phases, and at its peak, the ash cloud rose to a height of nine kilometres. It is estimated that **250 cubic metres** of ash, lava and tephra were ejected.

Despite its size, there were **no fatalities** during the Eyjafjallajökull eruption. The immediate area around the volcano was uninhabited, but some people who lived under the ash cloud reported respiratory symptoms about six months afterwards.

QUESTION BANK 3B

1. *Why is Iceland so volcanically active?*
2. *Compare the plate boundary locations of Yellowstone and Iceland.*
3. *Compare and contrast the geothermal and volcanic landforms found in Iceland and Yellowstone.*
4. *How has Iceland used its geothermal potential to improve human well-being?*
5. *Remembering the definition of a **Hazard Profile** (a description of a geophysical hazard event, including its magnitude, duration, frequency, probability, and extent), compare the hazard profiles of the Eldfell and Eyjafjallajökull eruptions.*
6. *What is significant about Eyjafjallajökull's location that suggests it will be a very active volcano?*
7. *Why are airliners vulnerable to damage by volcanic ash?*
8. *Describe the pattern of spread of the ash cloud over Europe on 17th April 2010 as shown in figure 3.37.*
9. *Describe the economic and other consequences of the eruption of Eyjafjallajökull in 2010.*
10. *Explain why the size of the ash plume diminished after a week even though Eyjafjallajökull's eruption continued.*

Earthquake hazards

Two case studies of earthquake hazard events will be studied with **similar magnitudes** but with **contrasting human impacts**.

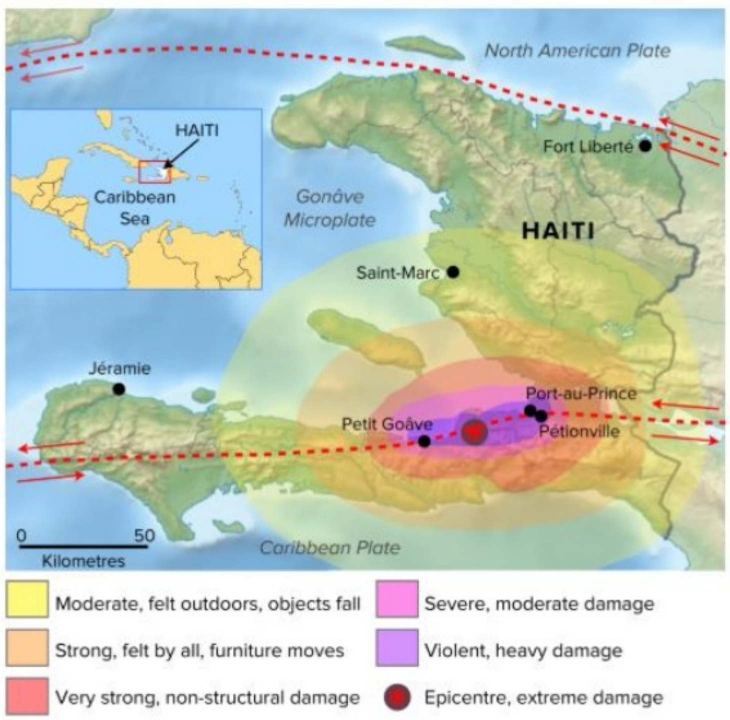
The first case study examines the earthquake in **Haiti** in January 2010, which had a **magnitude of 7.0**, resulting in about **160,000 deaths** (although estimates of the death toll very widely).

The second case study, which explores the **Kumamoto** earthquake in **Japan** in April 2016, also had a **magnitude of 7.0**, but the death toll was much lower — **49 deaths**.

CASE STUDY
Haiti earthquake, 2010

Haiti is a small country that occupies the western half of Hispaniola, an island in the Caribbean Sea. The eastern half of the island is occupied by the Dominican Republic. The population of Haiti is 10.7 million, of whom 2.6 million live in the capital city, Port-au-Prince, and its surrounding metropolitan area.

At 4:53pm on the afternoon of **12th January, 2010**, a **magnitude 7.0 earthquake** struck near the town of



3.41 Map of Haiti showing the extent of the January 2010 earthquake. Plate boundaries are shown as red dashed lines, with arrows indicating the direction of plate movement. Haiti's capital city is Port-au-Prince. The location of the epicentre was latitude 18°27'N, longitude 72°32'W.

3.42 The Haitian Presidential Palace shows heavy damage after the earthquake shook the capital city, Port-au-Prince on 12th January 2010.

3.43 A poor neighbourhood in Port-au-Prince shows extensive damage after the earthquake on 12th January 2010.

Léogâne, 25 kilometres west of Port-au-Prince. This was soon followed by eight **aftershocks** during the two hours following the initial shock with magnitudes ranging from 4.3 to 5.9. More aftershocks came in the following days, including one of 20th January that measured 5.9, centred on the town of Petit Goâve about 55 kilometres west of Port-au-Prince. Altogether, 52 aftershocks had hit Haiti following the initial shock by 24th January.

Haiti is situated near the junction of two sets of **plate boundaries**. To the north of Haiti, the North American Plate is moving towards the west, while to the south of Haiti, the Caribbean Plate (which is part of the Nazca Plate) is moving towards the east by 20mm per year in relation to the North American Plate. Haiti is located on a tiny plate in between these two large plates, known as the Gonâve Microplate, which is moving towards the west at a different rate to the North American Plate, which it joins on a transform fault.

The 2010 earthquake occurred on the **transform fault** that separates the Gonâve Microplate from the Caribbean Plate in the south of Haiti. A rupture that caused the earthquake opened suddenly along a 65 kilometre long crack that slipped an average of 1.8 metres. In some places, the movement was as great as 4 metres. The **focus** of the earthquake was 13 kilometres below the surface, which is regarded as a fairly **shallow depth**. Consequently, the shock was felt over a large area, including parts of Cuba, Jamaica, Puerto Rico, and of course, in the neighbouring Dominican Republic.

The town of Léogâne was essentially levelled by the earthquake, and there was **extensive damage** in the densely populated metropolis of Port-au-Prince. In Port-au-Prince, noteworthy **historical building**s that had stood for many years were badly damaged, including the Presidential Palace, the National Assembly Building, the Cathedral, the United Nations headquarters, and the National Penitentiary. Museums and art galleries were destroyed, damaging or destroying countless works of **art** and **historical artefacts**. Half the **schools** in Port-au-Prince were damaged, as were all three of the city's universities, effectively bringing the **education** to a halt.

However, it was in the **poorly built residential areas** of Port-au-Prince that widespread damage was caused and many casualties occurred. It was estimated that 250,000 homes and 30,000 commercial buildings were either destroyed by the earthquake or were so badly damaged that they needed to be demolished. As a poor country, Haiti had **no building codes**, and therefore many of the country's buildings had been constructed without regard to any established standards.

Haiti is the **poorest country** in the Caribbean. Its average annual income is (and was in 2010) about $US350 per capita. Haiti was therefore ill equipped to cope with such a disastrous hazard event as this earthquake. Furthermore, Haiti had been hit by two hurricanes and two severe tropical storms just 18 months earlier, and medium-term recovery operations from those events were still underway.

Appeals were issued for **international assistance** and humanitarian aid. Haiti's neighbour, the

Dominican Republic, was the first to respond, sending food, water, doctors and medical supplies, together with heavy lifting machinery almost as soon as the government received the request for help. The Dominican Republic also made its hospitals available to treat the injured, and it allowed its airports to be used for bringing in emergency supplies.

3.44 Haitians pull out a body from the rubble of a school that collapsed during the earthquake. Rescues such as this were the first priority after the earthquake struck Port-au-Prince on 12th January 2010.

Within a few days, assistance came from **elsewhere**, notably the governments of Iceland, China, Qatar, Israel, South Korea, Cuba, Canada, Argentina and the United States. Shipments from overseas emphasised medical supplies, temporary field hospital facilities, and tents for emergency accommodation.

In order to support the relief efforts, many **NGOs** and **aid organisations** established relief funds to solicit donations, and during one 24 hour period, the American Red Cross raised $US7 million for the Haitian relief fund. MSF (Médecins Sans Frontières — Doctors Without Borders) was especially involved in the field, and within six days of the earthquake, that organisation alone had treated more than 3,000 injured people. This was in spite of frustrations experienced by MSF as US air traffic controllers who had taken over the airport's operations repeatedly turned away MSF aircraft carrying medical supplies and equipment, giving priority instead to the transport of security troops and evacuation flights for citizens of certain preferred countries. **Airport operations** were chaotic after the earthquake as the demand for take-offs and landings far exceeded the capacity of the facilities to cope, and there were so many aircraft on the ground that there was too little space for loading and unloading operations to function effectively.

The efforts of aid organisations were supported internationally by **social media** sites such as Facebook and Twitter that distributed messages and pleas for help. Some medical assistance, rescue personnel, engineers and support teams arrived from international aid organisations, but the scale of the challenge was overwhelming.

3.45 Local people and MINUSTAH (United Nations Stabilization Mission in Haiti) peacekeepers load an injured woman into a helicopter after the earthquake.

The immediate focus of **rescue efforts** was trying to find and rescue survivors in the mass of rubble, and provide **emergency supplies** of food and water. A week after the earthquake, aid had only reached Port-au-Prince, and a fortnight after the earthquake, only a few sporadic packages of supplies were reaching a few outer urban centres. Rescue efforts were **hampered** by the shortages of clean water, the failure of the electrical power grid, and overcrowding in hospitals. Several hospitals collapsed in the earthquake, and even the morgues were overloaded with a backlog of tens of thousands of bodies, and these had to be buried in mass graves.

Damage to air and road transport **infrastructure** also hampered the recovery operation. The control tower at Port-au-Prince's **airport** was seriously damaged, and damage to the runway meant only robust cargo aircraft could land. The **seaport** in Port-au-Prince was so damaged that normal cargo operations were impossible, as the container crane had partially collapsed. All goods brought in by sea had to come through the northern port of Gonaïves and then be transported overland. Unfortunately, many of the **roads** in Haiti were blocked by fallen rocks and building materials, and many of the road surfaces had broken up or fallen away. To overcome the road blockages, US **helicopters** began dropping food supplies to inaccessible areas about four days after the earthquake.

3.46 Massive rock slides were caused by strong ground shaking during the main shock of the Haiti earthquake and several of the stronger aftershocks. This mountain road leads to the city of Dufort, located near the larger city of Léogâne near the earthquake's epicentre.

3.47 This young girl stands in front of a massive crack in the road on highway Nationale 2 near Petit Goâve, Haiti. The highway collapse was caused by lateral spreading of the underlying soil during the earthquake that struck Haiti on 12th January, 2010.

The **communications** infrastructure was also badly damaged, with landlines unusable and mobile phone networks badly damaged. Many people relied on radio broadcasts for news, but this too was inoperable for a week after the earthquake.

During the rescue operation, about 100 people had been found and rescued in the ruined buildings, but as time went on, the likelihood of finding more survivors faded. By 22nd January, agencies under the leadership of the United Nations declared that the rescue phase of the operation had ceased because it was so unlikely that any more survivors would be found.

3.48 A collapsed multi-storey building occupied by 'Centre D'Edudes La Concorde' in Port-au-Prince, a result of the earthquake that struck Haiti on 12th January 2010. An examination of the adjacent buildings indicates that this structure was either two or three stories tall. Interviews with eye-witnesses confirm that most structures collapsed within about ten seconds, giving building occupants little time to escape.

Three million people were **affected** by the Haiti earthquake. Of this number, one million were **homeless**, and had to find emergency accommodation of donated tents or in shanty settlements built with scrounged materials. Many people simply slept in the streets, partly from fear that further aftershocks might make being inside a building unsafe.

Estimates of the **death toll** varied widely, something that is quite common in poorer countries where reliable statistics are difficult to obtain even in normal conditions. The Haitian Government stated that 316,000 deaths resulted from the earthquake. USAID (The United States Agency for International Aid) estimated a much lower figure of between 46,000 and 85,000 deaths. USGS (the United States Geological Service) estimated 100,000 deaths, and a study by the University of Michigan

3.49 Residents of Port-au-Prince wait in line for water distributed by Haitian Firefighters near the Haitian National Palace after the earthquake.

3.50 Local residents who have lost their homes wash themselves in a public fountain near the ruined Presidential Palace.

put the figure at 160,000 deaths. It is impossible to think that a precise number will ever be known as so many bodies had to be disposed of quickly in bulk.

Although most of the deaths occurred **during** the earthquake, many also occurred **after** the earthquake because there were so few doctors, nurses and paramedic staff to treat the injuries. **Children** whose parents were killed in the earthquake were especially vulnerable to hunger with no-one to look after them, and many were reported to have been abused and taken away for human trafficking. Furthermore, several of Haiti's orphanages were destroyed in the earthquake. In order to address these issues, arrangements were made to make it easier for American and Dutch families to adopt Haitian orphans, although bureaucratic obstacles meant the number of adopted children was quite small.

It is also difficult to know the number of injured people and displaced persons. One estimate by USAID suggested that 1.5 million people had been **displaced** (left homeless), of whom 550,000 still had no shelter two years after the earthquake. Two years after the earthquake (2012), only about half the rubble in Port-au-Prince had been cleared away. Although many damaged residences had been repaired and were being used again, over half a million people were still living in tents. Three years after the earthquake (2013), the number of people living in tents had fallen to 360,000, still too high a figure as many of the tents had deteriorated markedly by that time. By 2014, 100,000 people still had no permanent housing, and by 2016 the figure remained high at 62,000 people. Those living in temporary camps experienced very **difficult conditions**, with no electricity, no running water, no sewage disposal systems and widespread crime, especially against women and girls.

Many of the people who have moved into permanent housing have returned to **shanty settlements** that are not only of poor quality, they would have little chance of standing if another earthquake Haiti. Haiti's **infrastructure** continues to recover from the earthquake, and by 2016 (six years after the earthquake) Port-au-Prince was still experiencing frequent blackouts because the electricity infrastructure had not been re-built.

Nine months after the earthquake (October 2010), there was an outbreak of **cholera** in the area of the Artibonite River, a few kilometres north of Saint-Marc. It seems that the outbreak occurred as a result of **faecal pollution** of the river by UN peacekeeping forces from Nepal who had brought the infection from their home country. By November, the cholera outbreak had spread southwards into the tent housing camps of Port-au-Prince where it spread widely. The outbreak was still continuing six years later, and by mid-2016, 770,000 Haitians had been affected by cholera. Of this number, 9,200 had died from the disease.

In an effort to help Haiti **recover** from the scale of the earthquake, the G7 countries agreed to waive Haiti's **foreign debt** of just over $US 1 billion in early 2010. Other institutions followed this example, and in march the IADB (Inter-American Development Bank) forgave $US447 million, followed by the World Bank in May when it waived Haiti's debt of $US36 million. It is fair to say that Haiti had no realistic way to repay any of these debts in the aftermath of the earthquake anyway.

In the **aftermath** of the earthquake, almost $US 4.5 billion was pledged internationally to help Haiti recover from the earthquake. Of this amount, only about half was ever received and distributed. The main ways that the relief funds have been used for recovery has been for **infrastructure** such as ports, industrial parks, roads and housing projects (many of which had begun before the earthquake) and **HIV/AIDS mitigation**.

3.51 Following the devastating 2010 Haiti earthquake, extensive external assistance is being used during the ongoing recovery phase. The USGS (United States Geological Service) has been helping with earthquake awareness and monitoring in the country, with continued support from USAID (the United States Agency for International Development). This assistance has helped Haiti's BME (Bureau des Mines et de l'Énergie) in Port-au-Prince establish a Seismology Technical Unit and develop the first-ever national seismic network in Haiti. The Seismology Technical Unit also has an active outreach program aimed at education for local schools as well as Haitian officials, and has established itself as the authoritative local agency for matters related to earthquake hazard. A total of 15 seismic stations are now operating in Haiti with six NetQuakes instruments owned and operated by the BME, seven USGS instruments that remain in Haiti on long-term loan, and two instruments installed by National Resources Canada. For any earthquake large enough to be felt, the NetQuakes instruments transmit triggered data via the Internet to the BME as well as several international data centers, providing a rapid-assessment capability that was lacking at the time of the 2010 earthquake. In this photo, a BME engineer is setting up a booth and preparing for an outreach exposition later that day in Cap Haitien, the largest city in northern Haiti.

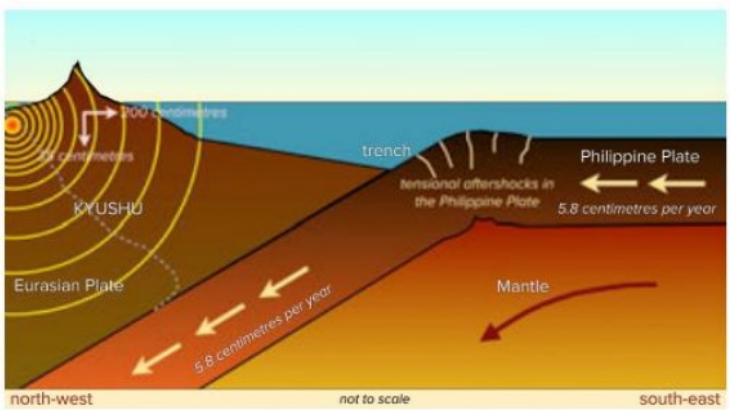
QUESTION BANK 3C

1. *What are the physical reasons that Haiti is vulnerable to the impact of earthquakes?*
2. *What were the primary hazards, and the secondary hazards, of the Haiti earthquake?*
3. *How did the location of the focus of Haiti's earthquake contribute to the extent of the damage?*
4. *How did the state of Haiti's economy contribute to the extent of the damage?*
5. *What were the main priorities in the immediate rescue phase, and how did these differ from the later rehabilitation and recovery phases?*
6. *What aspects of the post-earthquake operation in Haiti could have been improved to advance human well-being?*

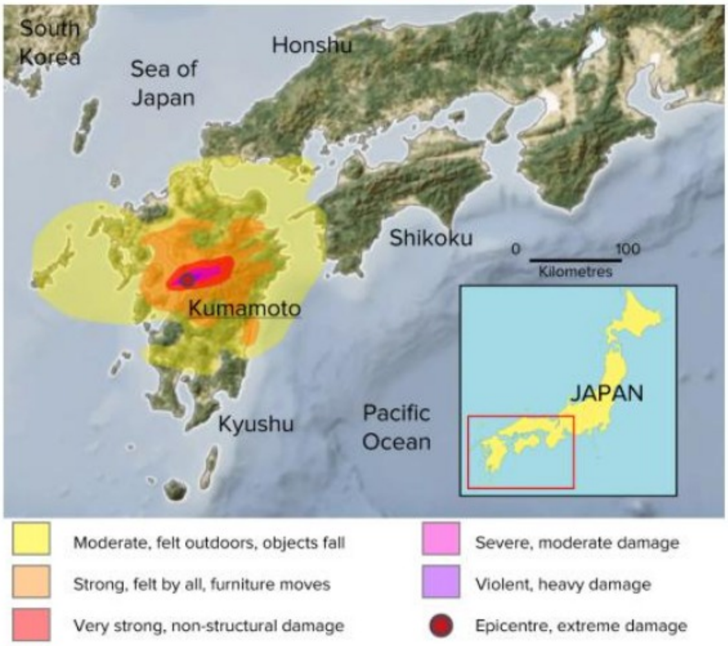
CASE STUDY
Kumamoto earthquake, 2016

Japan is one of the most **tectonically active** places in the world. It lies to the immediate west of the upper corner of the **Philippines Plate**, which is moving towards the west at a rate of 5.8 centimetres per year. The Philippines Plate in turn lies to the west of the much larger **Pacific Plate**, which is moving west at a faster rate than the Philippine Plate, 9 centimetres per year. Just to the east of southern Japan, the Philippines Plate collides with the **Eurasian Plate**, which is moving towards the south-east. The result of the collision is a **subduction zone** where the heavier Philippines Plate is forced under the lighter Eurasian Plate. The boundary of the two plates is a deep ocean trench.

Figure 3.52 shows a north-west to south-east cross section of the island of Kyushu, which lies towards



3.52 A diagrammatic cross-section of Kyushu showing the location of the earthquake on 15th April 2016. The shifts in the earth's crust as a result of the earthquake are also shown.



3.53 Map of south-western Japan showing the extent of the April 2016 earthquake. The epicentre of the earthquake was the city of Kumamoto, located at latitude 32°48'N, longitude 130°42'E. When comparing the extent of damage in this map to figure 3.41, be sure to note the different scales in the two maps.

the south-western end of Japan. As shown in the diagram, as the Philippines Plate is forced downwards, stress builds up as a result of friction. Some of this stress is released fairly frequently as minor tremors and earthquakes. However, if the stress builds up over a long period of time without being released, a major earthquake can occur.

Another effect of the Philippines Plate's subduction is that it heats up as it is driven down into the mantle. As the plate melts, it releases gases that rise to the surface, emerging in the form of volcanic eruptions. The build-up of volcanic deposits is one reason that Japan exists as land above sea level, the other reason being that the Eurasian Plate crumples upwards as it collides with the Philippines Plate.

As a result of the **crumpling** of the Eurasian Plate, many cracks, **faults** and **fissures** form in the rocks that constitute Japan. Constant pressures and movement in these faults results in earthquakes, and Japan experiences multiple earthquakes on a daily basis. Fortunately, most of these earthquakes are minor, but Japan does suffer from large earthquakes more often than anywhere else in the world.

One of these larger earthquakes associated with fault lines occurred at 1:25am on **16th April, 2016** when a **magnitude 7.0 earthquake** struck. The **focus** of the earthquake was directly beneath

3.54 An oblique aerial view of Kumamoto city about one year before the earthquake, showing the extent of the city and its topography.

Kumamoto, a city with a population of 735,000 people that served as capital city of Kumamoto Prefecture. The earthquake struck at a fairly **shallow depth**, 10 kilometres beneath the surface.

The earthquake on 16th April had been preceded by several smaller, but still substantial, earthquakes in the previous few days. Of these **foreshocks**, one on 14th April 2016 had a magnitude of 6.2, being centred just a few kilometres north of Kumamoto with a depth of 11 kilometres. This quake was followed by 11 strong **aftershocks** with magnitudes from 4.5 to 6.0. During this series of shocks, **nine people were killed**, 800 were **injured** and **damage** was sustained on many buildings, notably the historic Kumamoto Castle. More than 44,000 people were **evacuated** as a result of the foreshocks, and search and rescue operations were still underway a couple of days later.

Residents thought that the earthquakes had finished when the main earthquake struck with a magnitude of 7.0 on 16th April. The focus of the main quake was directly below Kumamoto in a **fault** within the upper Eurasian Plate. The cause was a **fault failure** (technically known as a strike-slip fault) that resulted from the pressures applied to it by the foreshocks over the previous few days. The rupture surface was about 30 kilometres long, and the displacement was up to 200 centimetres horizontally and 35 centimetres vertically.

The effects of the earthquake were **widely felt** (figure 3.53). Unlike the Haiti earthquake of 2010 that had a similar magnitude, the earthquake

3.55 This annotated photo shows the displacement of farmland that occurred in a field near Mashiki during the Kumamoto earthquake of April 2016. The right lateral offset of the footpath in the field is about 200 centimetres, or two metres.

waves from Kumamoto travelled less equidistantly, as Japan's rugged topography **absorbed** the waves in some directions more effectively than in others. In general, the earthquake waves travelled further and more strongly through areas where there were no dense masses of high mountains to absorb the wave energy. Especially bad damage to buildings was found on **flat ground** near the foot of hills and up into the hills for a few hundred metres. This pattern of damage occurred because this was the zone where soft flat ground adjoined steep rocky ground, and was therefore the zone where earthquake waves were **reflected**, bouncing back across the flat ground to hit buildings and infrastructure a second time. Therefore, some reasonably well-built houses near the base of hills were sometimes quite severely damaged.

3.56 Timber frame houses in Kumamoto destroyed by the earthquake on 16th April 2016.

The **most severe damage** was concentrated in a belt that measured about 3 kilometres by 1 kilometre along the northern side of a valley that contained the residential town of Mashiki. This zone of severe damage was directly above the fault plane that ruptured to cause the earthquake. The areas suffering the worst damage had buildings constructed on shallow alluvial soil that overlay volcanic rock at the base of the low hills on the northern side of the valley. This zone included a combination of one and two-storey new and older structures that were fairly typical of any Japanese suburban area.

A **tsunami warning** was issued immediately after the earthquake as it was feared that a wave somewhere between 200 centimetres and one metre in height might form. No tsunami formed, however, and the warning was lifted about one hour after the earthquake.

3.57 A car park in the Minamiaso district of Kumamoto after the earthquake on 16th April 2016.

Given the magnitude of the earthquake, it is perhaps surprising that damage was fairly limited. The **water supply** and **electricity** in the city of Kumamoto stopped working for several days, and it took over a week before all the broken water pipes had been repaired. **Gas** supplies were turned off until the underground pipes had been checked for damage and leaks to avoid accidental fires, but services resumed within a week of the earthquake.

Disruptions to **transport** caused some delays in getting rescue workers to Kumamoto. Japan's famous 'bullet train', the **Shinkansen**, suspended services for several days pending a check of the condition of the track. **Kumamoto Airport** was closed because of some damage in the terminal building, but flights resumed after four days. Some **expressways** and bridges were damaged, and one **bridge** collapsed into a river valley. Furthermore, some roads were damaged by cracking during the earthquake and a few were covered by **landslides**.

3.58 A landslide, triggered by the earthquake on 16th April 2016, has closed this major road in the mountainous area to the east of Kumamoto.

Telecommunications were disrupted at first, but within a day, temporary **wi-fi hot spots** had been installed in various places that had suffered damage. These hot spots allowed free mobile phone access for texting, voice calls or internet to anyone within range. Within two days of the earthquake, mobile phone and internet communications had been fully restored.

The **industrial area** north-east of Kumamoto included almost 50 large firms engaged in the manufacture of vehicles, electronic components and pharmaceuticals. The island of Kyushu is sometimes referred to as Japan's 'Silicon Island' because of its hi-tech industry. Larger firms such as Sony, Mitsubishi, Honda, Toyota and Renesas Electronics **suspended production** in their factories for a week to check for damage, and also to allow employees to tend to their own damaged property.

A **historic temple**, the 400 year old Aso Shrine, was damaged quite severely, and some houses were badly damaged. Most of the damaged houses were **wood-frame houses** and small commercial buildings. Overall, about 15% of the wood-frame buildings needed to be demolished and re-built, while another 30% required extensive repairs. For a magnitude 7.0 earthquake, relatively few buildings

3.59 Japanese Self Defence Force personnel assist with the rescue and recovery response to the Kumamoto Earthquake.

were damaged or destroyed, and this was because Japan has quite **strict building codes** that require structures to be earthquake-resistant.

A total of **24 people were killed**, and a further 1,000 were **injured**. Several hundred people were **rescued** after bring trapped under rubble, and about 92,000 people had to be **evacuated** from houses that had been structurally damaged. Much of the relief effort was undertaken by Japan's well-prepared and experienced Self-Defence Force personnel, and **no calls** were made for overseas assistance. **Emergency facilities** were set up quickly by local authorities, including a sports complex for use as an emergency distribution centre for food and bottled water. Fortunately, the area's hospitals were well-built and suffered no serious damage, and no schools suffered any structural damage in the earthquake.

QUESTION BANK 3D

1. *What are the physical reasons that Japan is vulnerable to the impact of frequent earthquakes?*
2. *What were the primary hazards, and the secondary hazards, of the Kumamoto earthquake?*
3. *Remembering the definition of a* ***Hazard Profile*** *(a description of a geophysical hazard event, including its magnitude, duration, frequency, probability, and extent), compare the hazard profiles of the Haiti and Kumamoto earthquakes.*
4. *Explain why the extent of damage, death tolls and impacts on human well-being are different in the Haiti and Kumamoto earthquakes, even though they both had a magnitude of 7.0.*

Mass movement hazards

Two case studies of mass movement hazard events will be studied with **contrasting physical characteristics**.

The first case study examines the **landslide** in **Dolina Geyzerov** (Russia) in June 2007. The landslide was caused when a **combination of processes** weakened the slope, causing 20 million cubic metres of material to collapse in **three components**; two solid and one loose. No-one was killed in the landslide, but it filled a large valley, obliterating many geothermal landforms and altering the flow of some rivers.

The second case study, which explores the **Oso mudslide** in **Washington** (USA) in March 2014, occurred when an **earthquake** during **heavy rainfall** caused part of an unstable hill to collapse, sending mud and debris down the hill and across a river. The mudslide engulfed a rural settlement, covering an area of two and half square kilometres. Forty-three people were killed in the mudslide.

CASE STUDY
Dolina Geyzerov landslide, 2007

Dolina Geyzerov, also known as Valley of Geysers, or Долина гейзеров in Russian, is a **geothermal area** on the eastern side of the Kamchatka Peninsula in the Far East of Russia. Its precise location is latitude 54°26′N, longitude 160°08′E. This six kilometre long valley contains the world's second largest concentration of geothermal features, with approximately ninety geysers, plus many hot springs, boiling mud pools and fumaroles.

Geysers are a rare feature, being found only in Kamchatka (Russia), Geysir (Iceland), Rotorua (New Zealand), El Tatio (Chile) and Yellowstone (USA). Because of its special geography, Dolina Geyzerov was made part of the Kronotsky Nature Reserve, which in turn is part of the World Heritage Site known as 'Volcanoes of Kamchatka'.

The area had very **limited tourism** during the Soviet era in the 1960s and 1970s. It was closed to visitors from 1977 until 1993 when it re-opened for visitors, subject to a strict limit of fewer than 3,000 people per year.

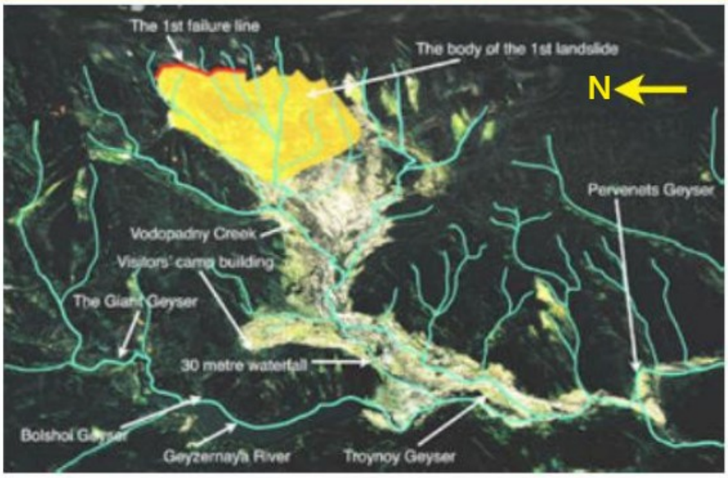
The geysers are mainly situated on the left bank of the Geyzernaya River, which flows through an eroding valley into which hot (95°C), geothermal waters flow. The waters enter the valley from a nearby active composite cone volcano called Kikhpinych, at the foot of which is a depression known as the 'Valley of Death' where toxic volcanic gases accumulate and kill birds and mammals. The whole area is geothermally active, and temperatures of 250°C have been measured at a depth of 500 metres below the ground.

3.60 A general view of Dolina Geyzerov, looking north along the Geyzernaya River Valley. The area where the steam is rising is the 40 metre high Vitrazh (Stained Glass Wall), which contains the Giant Geyser.

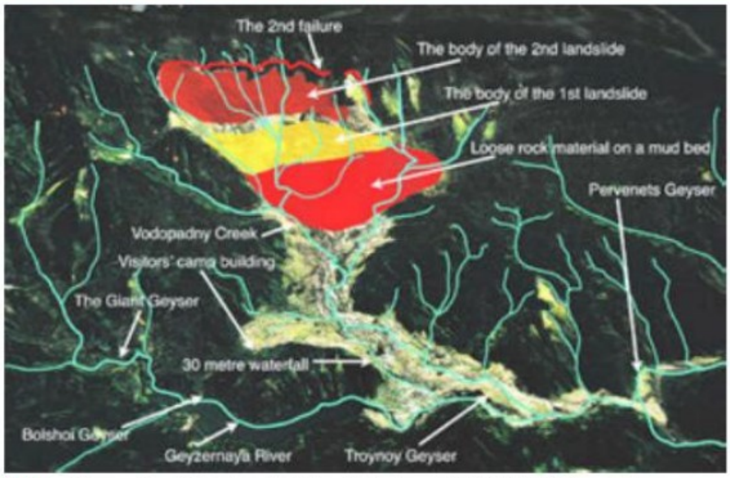
On **3rd June 2007**, at 2:30pm in the afternoon, a landslide was triggered that buried about half the geysers in the valley and created a new lake by damming the Geyzernaya River. As shown in figures 3.61 to 3.66, the landslide occurred in **several stages**. By the time the landslide finished, it had torn a scar across the land, sweeping aside all the trees in its path, burying a number of geysers, waterfalls, hot springs and mud pools in the valley. It also blocked the Geyzernaya River, causing a new thermal lake to pool upstream.

The landslide and avalanche extended over a distance of 1.7 kilometres with a width of 200 to 400 metres. The volume of the rock material in the flow amounted to about 20 million cubic metres, making it by far the largest landslide ever recorded in Kamchatka, and one of the largest recorded in historical time in Russia.

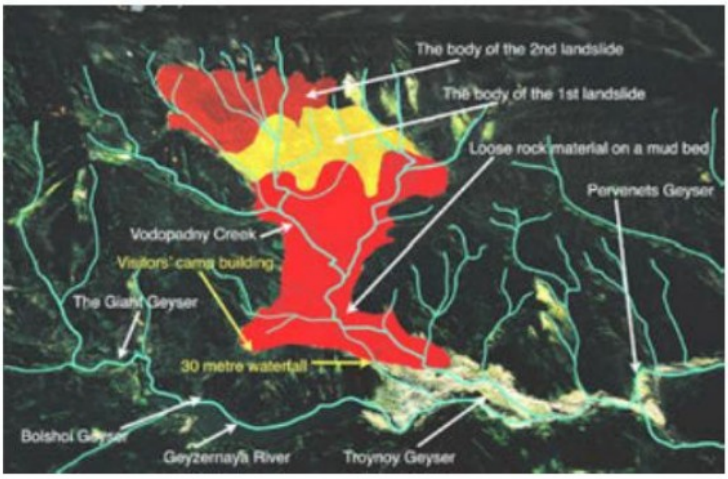
The **cause** of the landslide was the cumulative impact of several factors. Even though it was early



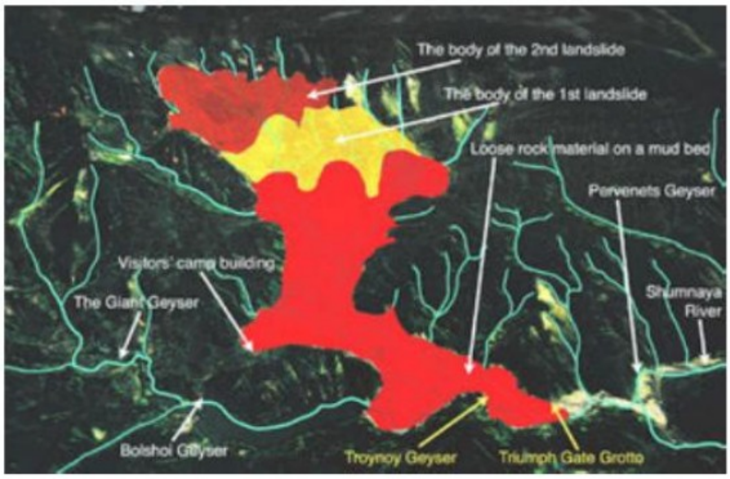
3.61 Stage 1 of the landslide: 3rd June 2007, 2:30pm. The slope failed from a sheer wall on the eastern edge of Vodopadny Creek valley. The first landslide rotated down the hill largely as a single block of earth and rock.



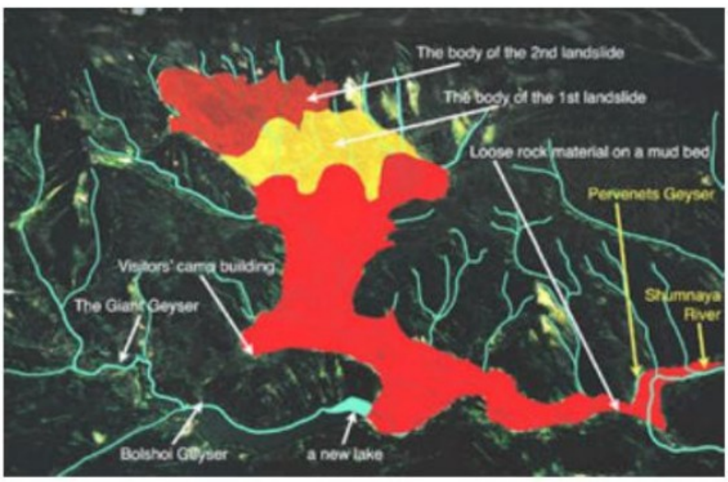
3.62 Stage 2 of the landslide: 3rd June 2007, 2:32pm. A second, larger failure occurred on the slope, uphill from the first failure. This caused a second landslide to fall, pushing the first landslide downhill ahead of it, breaking off loose rocks from the first landslide which continued downhill at a faster rate on a bed of mud.



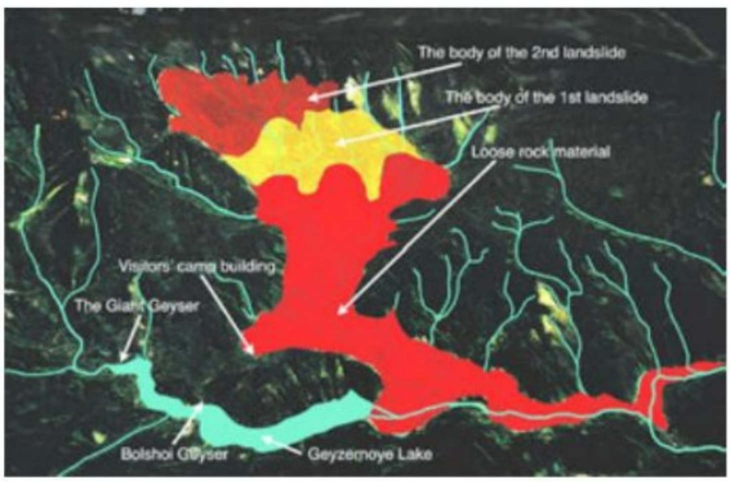
3.63 Stage 3 of the landslide: 3rd June 2007, 2:35pm. The rock fragments stopped just one metre short of rolling into the visitors' camp building. The rock fragments buried a 30 metre high waterfall on Vodopadny Creek. The second landslide moved downhill as a single, unfragmented body.



3.64 Stage 4 of the landslide: 3rd June 2007, 2:37pm. The loose rock materials continued moving downhill into the Geyzernaya River valley, blocking the flow of the river, burying Troynoy Geyser, and destroying a rock formation known as Triumph Gate.



3.65 Stage 5 of the landslide: 3rd June 2007, 2:40pm. Rock debris formed a dam that blocked the flow of the Geyzernaya River, creating a new lake. The rock debris moved further down the Geyzernaya River valley, burying Pervenets Geyser.



3.66 Stage 6 of the landslide: 7th June 2007, 2:30pm. The maximum depth of Geyzernoye Lake was 30 metres. After four days, the landslide dam was breached and the Geyzernaya River formed a new river bed as it began flowing again, lowering the water level in the lake by 9 metres.

June — the early phase of summer — the upper slopes around the valley were still covered with snow. The lower areas of the valley were snow-free because of the warmth rising from the geothermal activity below the ground surface.

At the time, Dolina Geyzerov was experiencing abnormally **warm weather**, so rapid melting of snow allowed water to seep into the soils and rocks of the slope, **lubricating** the joints within the rocks. There had been two significant **earthquakes** just off the south-eastern coast of Kamchatka a few days earlier, and this had shaken the rocks in Dolina Geyzerov and shifted their balance.

The **geothermal** nature of Dolina Geyzerov was another factor in making the slope unstable. One consequence of the presence of hot water beneath the surface is that water vapour is produced that rises through the rocks and soil above it. The rising water vapour can transform hard rock into softer **clay** over time, reducing its capacity to hold a heavy, overlying mass of rock.

3.67 The separation wall of the landslide, upper Vodopany Creek valley, 7th June 2007.

The landslide began when a **sheer rock wall failed** at the upper end of the Vodopadny Creek valley. Almost immediately, the landslide separated into **three separate slides**. At the upper end of the valley, the rocks that failed began sliding down the steep hillside, lubricated by the melting snow, remaining as a huge **single block**. Shortly afterwards, a second rock wall failed immediately above the first failure. This released a **second block** of unfragmented rock mass that slide downwards, pushing the first rock mass ahead of it.

Beneath the two unfragmented blocks, a lower slide developed as a **mix** of loose stones, melting snow, trees, and boulders that moved quickly down the valley on a slippery bed of mud formed from the melting snow. As the diverse mass moved downhill, it mixed with more soil and water, making the bed of the rocks more and more slippery and able to fall at **faster speeds**. The rocks slid down the valley of Vodopadny Creek, reaching the larger valley of the Geyzernaya River within just a few minutes.

3.68 An aerial view of the middle part of the landslide on 7th June 2007, looking to the south-west. The loose rocks have slid downwards along Vodopadny Creek (to the left of the photo), and have reached the larger valley of the Geyzernaya River (to the right of the photo), and then moved further along the Geyzernaya River valley to its junction with the Shumnaya river (through the hills in the background). By this time, the landslide reached almost 2 kilometres in length. A landslide dam has formed on the Geyzernaya River with a height of up to 60 metres, and this has already caused a rapid rise in water level and the formation of a landslide-dammed lake (in the right of the photo). The lake flooded several geysers and came close to the main geyser field, known as Vitrazh, or Stained Glass, that contains the Giant Geyser. The landslide almost reached the Visitors' Camp Building, seen in the right foreground.

Once the landslide reached the main valley of the Geyzernaya River, it moved downstream along that valley to its junction with the Shumnaya River, forming a 60 metre high wall of rock debris that dammed the river, causing the water to bank up behind it. Before the landslide, the Geyzernaya River valley had been a deep gorge with steep sides and numerous geysers; all this was buried by the landslide and the new lake.

There were fears that the build-up of water would cause the dam to breach suddenly, causing a

3.69 Dolina Geyzerov today, showing the landslide beside the Visitors' Camp Building. Vegetation has started to colonise the surface of the landslide.

3.71 The Geyzernaya River flows along its new, raised bed of gravel through the valley where the lake formed by the landslide dam flooded the area for several years. In the mid-foreground, the Bolshoi Geyser is beginning an eruption.

3.70 The Dolina Geyzerov landslide today, showing the debris filling Vodopadny Creek valley.

catastrophic flood downstream. Fortunately, four days after the landslide on 7th June, the water reached its maximum height of 30 metres and then began to seep through the dam wall, allowing the **water level** to begin to decline slowly. The lake remained for a few years, drawing visitors because of its beauty as it had a bright turquoise colour due to the large quantity of thermophilic algae contained in it. The lake was also remarkable because it changed temperature quite dramatically due to the level of activity of nearby hot springs and geysers. After a few years, the waters of the lake began to seep more quickly through the landslide dam wall, and seven years after the landslide, the lake had **drained completely**, leaving behind a rubble-strewn river bed.

When the fragmented rock component of the landslide raced downhill, it destroyed the house of the park's caretaker, a diesel power plant, and two helipads, stopping within a few metres of destroying another helipad, the visitors' camp buildings and a hostel.

The material of the landslide filled the valley with rocks and mud to a maximum **depth** of about 60 metres, burying tens of geysers. Because of the depth of the material deposited by the landslide, experts believe it is unlikely that the geysers will be able to force a new opening through the thick layer overhead, at least for many decades or perhaps centuries.

The landslide not only destroyed geysers and other geothermal landforms, but it has damaged the **natural ecosystem** within Dolina Geyzerov. In its natural (pre-landslide) state, the warm waters of the geysers and hot springs, together with the heated steam jets from fumaroles, made the valley warmer than the surrounding landscape, and this warmth supported a unique ecosystem. When the landslide buried the valley, plants and animals were **killed**, and the **heat source** just below the ground surface was lost. As a result, the surface of the landslide became a **desert-like wasteland**. The few scrubby plants that have tried to establish themselves on the surface of the landslide have been **different species** of plants, more suited to colder, alpine areas than the pre-landslide conditions of the geothermal valley. In the river environment, salmon that spawn within the Geyzernaya River have been confined to the lower reaches of the river since the landslide. Bears, which depend on eating the salmon, have had to shift their feeding grounds as a consequence.

Given the large scale of the landslide, it was remarkable that **no-one was killed**, although this was partly because the area had no permanent inhabitants. The few people in the area at the time of the landslide — 19 tourists plus six local guides — were **evacuated** from the area by helicopter; fortunately the mudflow stopped just a few metres short of the helicopter landing pad they needed to use.

3.72 The Dolina Geyzerov landslide today, showing debris at the junction of Vodopadny Creek (coming in from the left) and the Geyzernaya River (main valley). The Geyzernaya River has cut a new course through the landslide debris.

3.73 Helicopters are the sole means of transport for getting in and out of Dolina Geyzerov. This heliport pad was the one that just survived the 2007 landslide, the tongue of which can be seen in the right of this photo. Since the landslide, several more helipads have been built in an effort to develop the area and help it recover from the effects of the landslide.

In the aftermath of the landslide, **management strategies** were established to plan for the future of Dolina Geyzerov. An **aerial photography** program was put in place to survey the area's new topography so that a **sustainable tourist industry** could be established. New tourist **boardwalks** were designed and constructed to allow visitors to see geysers and boiling mud pools safely, and new **helipads** were constructed on stable land to allow more visitors to come to the area by helicopter, the only form of transport giving access into Dolina Geyzerov. Although more than half the geysers and geothermal features were wiped out by the landslide, the area still has an abundance of geothermal features that make the area attractive to tourists and visitors.

QUESTION BANK 3E

1. *In what ways is Dolina Geyzerov a distinctive area?*
2. *What caused the 2007 Dolina Geyzerov landslide?*
3. *Outline the key events in each stage (1 to 6) of the Dolina Geyzerov landslide. Which of these events would you classify as 'secondary hazards'?*
4. *Outline the impact of the Dolina Geyzerov landslide on (a) geothermal features in the area, (b) the rivers of the affected area, (c) local ecosystems, (d) tourism, and (e) human well-being.*
5. *What future plans have been put in place for the Dolina Geyzerov area in the aftermath of the landslide?*
6. *Do you think Dolina Geyzerov is less vulnerable, or perhaps better prepared, for future landslide hazard events? Give evidence to support your viewpoint.*

CASE STUDY
The Oso mudslide, 2014

Oso is a **rural area** in Washington State, in the north-west of the United States. It is located about 90 kilometres north-north-east of Seattle, or 185 kilometres south-south-east from Vancouver (Canada), in the western foothills of the Rocky Mountains.

The mudslide occurred on the outskirts of Oso at Skaglund Hill, six and a half kilometres east of Oso town centre on **22nd March, 2014**. The precise location of Skaglund Hill is latitude 48°17'N, longitude 121°51'W. The hill is on the edge of a plateau that is a little under 200 metres high, and the mudslide slid down the southern side of the hill, blocking a large meander of the Stillaguamish River. Overall, the mudslide covered an **area** of 2.6 square kilometres, **destroyed** 49 buildings and **killed** 43 people, mostly residents. The mudslide was 700 metres long, 600 metres wide and had a depth up to 21 metres, giving it an estimated **volume** of two million cubic metres.

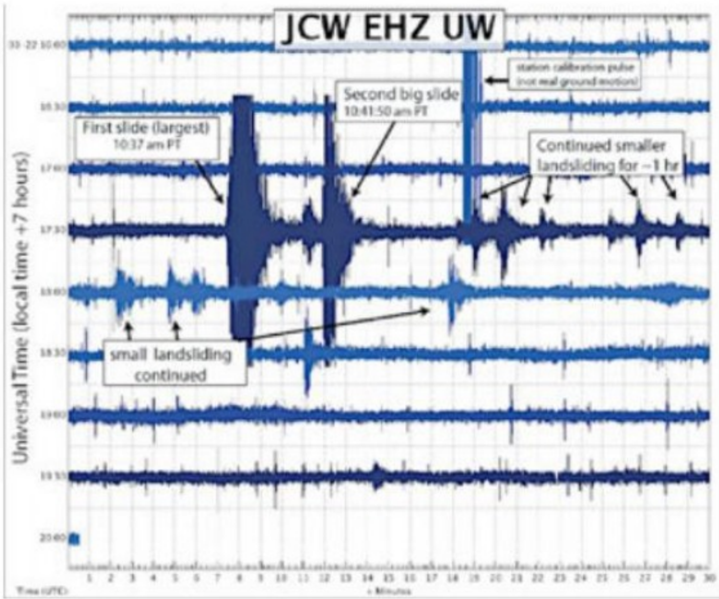
3.74 An overview of the Oso mudslide, a week after the event on 29th March 2014. At the right of the photo, the curved rotational failure can be seen. Beneath it is a solid mass of rock and soil that slid downhill largely intact. Beneath that, to the left of the photo, the debris flow can be seen extending down to the river valley.

The main **cause** of the Oso mudslide was high **rainfall** that saturated the hillslope, making it unstable. In the six weeks before the mudslide, Oso received double its average rainfall for the period. An additional factor was **forestry** operations that had been conducted near the upper edge of the slope. The forestry operations had ceased several years earlier (in 2005), but the clear-cut felling operation had destabilised the soil and allowed additional water to seep into the groundwater over the years, lubricating the sub-soil beneath the surface of Skaglund Hill.

Yet another factor was vibration of the land due to a minor **earthquake** (with a magnitude of 1.1) twelve days earlier on 10th March. This small earthquake shook land that had already been destabilised by logging and was saturated after prolonged rainfall. Some earth tremors were recorded at Oso on the day of the mudslide, but these were the result of the mudslide, not its cause.

The **initial collapse** occurred at 10:37am when liquefied soil and debris started flowing down the

3.75 The rotational failure at the top of Skaglund Hill.



3.76 Seismograph readings for 22nd March 2014 show no earthquake activity to trigger the Oso mudslide. The earth tremors caused by the first and second slide, as well as the effects of several smaller slides, can be seen.

hillslope for about two and a half minutes. The slope failure had a curved shape, indicating that the initial slippage was a **rotational failure**. The mudslide caused further shaking of the ground in the form of earth tremors, destabilising the slope further until a **second mudslide** began at 10:42am, almost five minutes after the first slide. Some minor slips continued for three and a half hours, finally coming to an end at 2:10pm.

The mudslide had two major components. Most of the slide was a **debris flow**, which is liquefied slurry of water and mud. These can travel great distances at very fast speed, engulfing everything that is in their path. This is the section of the mudslide that covered the road, dammed the river, and destroyed several buildings. At the upper end of the mudslide, close to the top of the slope of Skaglund Hill, the material that separated from the slope stayed more solid and intact, resembling a normal **rotational slump**.

Skaglund Hill is a fairly 'young' hill, comprising sand and gravel that was deposited during the last Ice Age, the Pleistocene that ended about 12,000 years ago. Its composition meant that it had a fairly **loose structure** that was very **porous**, making it vulnerable to infiltration and destabilisation by rainwater. The hill had a history of instability, and earlier landslides and mudflows had been recorded in 1937, 1951, 1952, 1967, 1988 and 2006. However, all of the earlier slides were far smaller in scale than the mudslide of 2014.

Because of its history of instability, some **protective measures** had been implemented. The lower end of the slope had some **protective walls** built around it so that the river would not erode and over-steepen the slope. There had been discussions about diverting the river away from the slope, but this had not been done because it would have increased the risk of flooding elsewhere in the valley.

When the mudslide reached the Stillaguamish River, it completely over-ran the protective walls that had been built and filled the lower valley, **blocking** the flow of the river and **damming** it. Water filled in a new lake that was 10 metres deep behind the mudflow dam for about 30 hours, at which time the river found a way through the dam and it began to erode a new course. A flash flood warning was issued because it was feared that the river might burst the dam suddenly, but this proved to be unnecessary.

Although Skaglund Hill had experienced landslides in the past, the large scale of the mudslide on 22nd March 2014 was unexpected. A **slope failure model** had been developed by district officials, based on a range of variables such as slope angle, friction and gravity. According to their model, a major slope failure on Skaglund Hill would have been expected to block the river and perhaps destroy a few buildings, but the 2014 mudslide travelled considerably further than the model had predicted. This is why a larger than expected number of deaths occurred. Mudflows tend to behave **erratically** when they reach a certain size, thought to be about one million cubic metres. The

3.77 A close view of the surface of the debris flow zone of the Oso mudslide.

3.78 The Oso mudslide, looking down hill from Skaglund Hill towards the Stillaguamish River.

errors that make prediction difficult include specific local factors such as minor variations in slope angle, the impact of fine rock dust, the extent of lubrication of the base layer by water, and cushions of air that form when a mudslide moves downhill at high speed.

As soon as news broke of the mudslide, **first responder personnel** from local counties and the US Navy's search and rescue unit raced to the scene. A total of 600 people, including 160 local volunteers, worked on the immediate rescue and recovery operation. A State of Emergency was declared, and the Governor toured the site by air before holding a news conference.

The **search for victims** of the mudslide continued into April, with eight people being rescued and taken to hospital. It was later confirmed that the final **death toll** from the mudslide was 43 people.

In early April, the Oso mudslide was declared a 'major disaster' by President Obama. This declaration released **federal funds** to help with the recovery effort. It was estimated at the time that 30 families needed assistance with housing, and the financial losses from the mudslide were estimated to be $US10 million.

After the mudslide, researchers and planners used the data gathered to refine their **predictive models** in the hope of making them more accurate. Three '**spiders**' were installed in Oso, these being portable instrumentation units with high-precision GPS units for detecting landslide movement, together

3.79 About a week after the Oso mudslide, the Stillaguamish River had breached the blockage and was flowing once again.

with geophones for detecting small vibrations, linked remotely to centralized computers. The hope was that by learning lessons from Oso, future deaths and injuries might be avoided or reduced through a clearer understanding of the dynamics of large-scale mudflows.

One question that arises is why people **choose** to live in a known mudslide hazard area such as Oso when they know the hillslopes are unstable and dangerous. Part of the answer is that most people are prepared to accept what they believe to be acceptable risks, knowing that almost every place to live has hazards of some kind — fires, flooding, storms, typhoons, earthquakes, tsunamis, asteroid impact, solar storms, nuclear meltdowns, terrorism, murders, out of control motor vehicles — no location is guaranteed to be completely hazard-free.

There is a broad international agreement that a one-in-a-million per annum **risk** of death by landslide is **acceptable** when zoning land. Some places have

3.80 A 'spider' unit, which is being used to study the Oso mudslide that occurred on 22nd March 2014.

different ratios, such as Hong Kong, where tighter standards apply and the acceptable risk is somewhat higher at 1-in-ten-million annually. On the other hand, for economic reasons, the Philippines has a lower acceptable risk ratio, which is 1:100,000 deaths from landslides per annum.

QUESTION BANK 3F

1. *Remembering the definition of a **Hazard Profile** (a description of a geophysical hazard event, including its magnitude, duration, frequency, probability, and extent), compare the hazard profiles of the Dolina Geyzerov and Oso mass movement events.*
2. *What caused the 2014 Oso mudslide?*
3. *Outline the key events of the Oso mudslide in each of these stages: (a) rescue, (b) rehabilitation, and (c) reconstruction.*
4. *Outline the impact of the Oso mudslide on (a) the landforms of the area, and (b) human well-being.*
5. *Do you think Dolina Geyzerov or Oso was better prepared for its mass movement event? How well did the level of preparedness prevent deaths in the two events?*
6. *Do you think Dolina Geyzerov or Oso has done the better job of changing hazard perceptions and planning for the future? Explain your answer.*

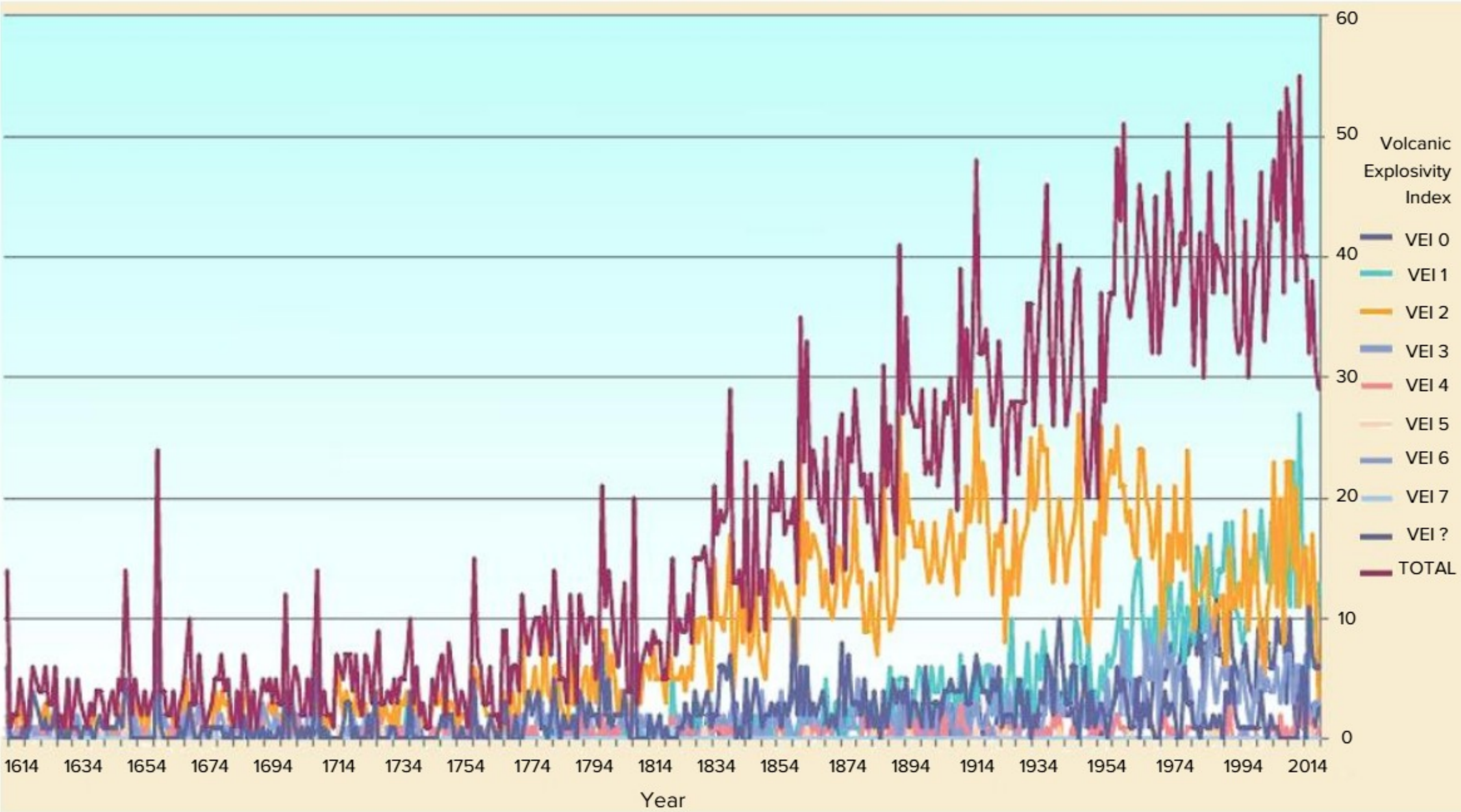
Chapter 4 Future resilience and adaptation

4.1 Evidence suggests that the level of global volcanic activity is increasing, but of course recovery also occurs. This view shows Mount St Helens in Washington state, USA, which erupted explosively in 1980, blasting away the northern side of the cone (shown here) in a large pyroclastic flow. In the decades since the eruption, the natural environment has begun the long process of recovery.

Trends and projections

In chapter 2, we saw in table 2.3 that there seems to be a **trend** at the **global scale** for the number of **earthquakes** per year to be increasing. A similar trend seems to be underway with **volcanic eruptions**. Figure 4.2 shows the number of volcanic eruptions per annum over the past 400 years. Although there are year-by-year fluctuations, the average number of volcanic eruptions per year is trending upwards in the long term. The **danger** posed to humans by earthquakes and volcanic eruptions is also growing, especially when we remember that some of the world's most earthquake-prone regions have also become some of the most **densely populated**.

Extrapolating past trends is the most accurate basis we have to make **future projections**. Today, there is a global network of seismographs that detects about one million small earthquakes each year. Of this number, the USGS (United States Geological Service) predicts that each year the world will experience about 18 major earthquakes (with a magnitude of 7.0 to 7.9) plus one very large earthquake (with a magnitude of 8.0 or higher).



4.2 The number of volcanic eruptions with VEI 1 to 7, and total eruptions (shown in purple) from 1600 to the present day. The number of eruptions per year is shown on the right hand axis. Source: Smithsonian Institute.

Projecting the frequency of future geophysical hazard events would be more accurate if we had a clear understanding of **why** the frequency seems to change over time. Unfortunately there is **no consensus** on this question.

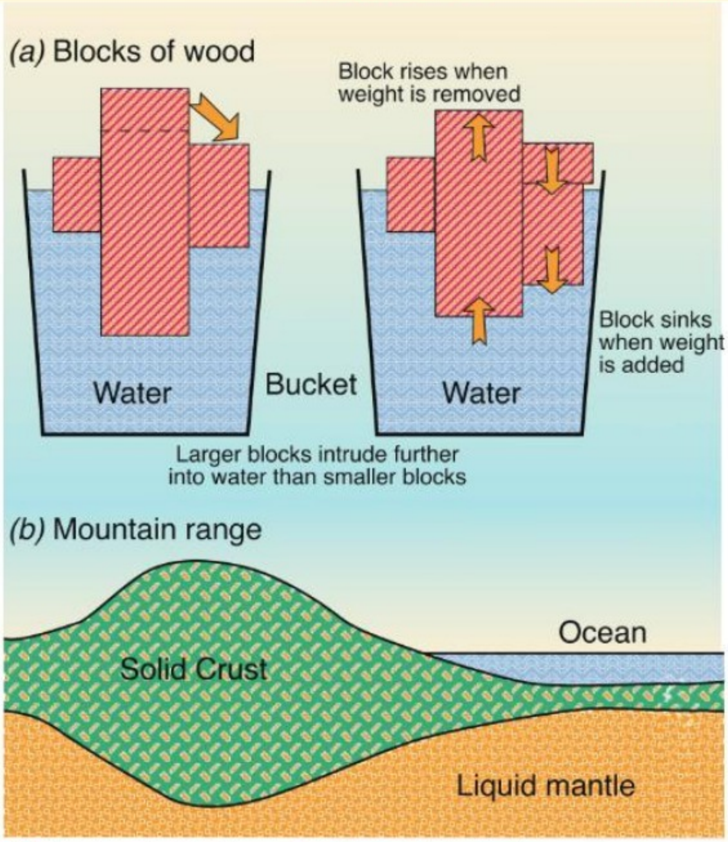
One hypothesis suggests that volcanic eruptions and earthquake activity are related to stresses within the earth that result from **instability** in the earth's **orbit**. We know that the earth's orbit around the sun fluctuates a little from year to year, and that the earth's **rotation** wobbles slightly as the precise location of the earth's magnetic poles migrate. This hypothesis suggests that these small changes may affect the strength of **magnetic** attraction between the earth and the sun, and between the earth and the moon. The combination of all these changes could in turn alter the **circulation** of liquid rock within the mantle, changing the points of upwards and sideways pressure in ways that cause an increase in the frequency of earthquakes and volcanic eruptions.

Another hypothesis relates the frequency of volcanic eruptions and earthquakes to long-term **climate change**. After the last ice age ended about 11,500 years ago, global temperatures rose markedly for about 5,500 years. During this period, the vast ice sheets that covered much of northern Europe and other areas to a depth of two kilometres melted, raising sea levels around the world and removing a massive weight of ice from the land.

The retreat of the ice cap led to the raising of the land due to **isostatic readjustment**. When the ice sheets covered the land during the **Ice Age** (also known as the Pleistocene period), their immense weight forced the land downwards into the liquid mantle upon which the solid crust of the earth 'floats'. When the ice melted, the land rose, although there is a lag effect which means that even now, the **crust is still rising**.

The effect of isostatic readjustment in Britain, for example, is that the island as a whole is slowly tilting. The north-west (which was covered in ice) is slowly rising, while the south-east (which was not covered with ice) has been slowly sinking. The sinking in the south-east has been responsible for problems such as increased flooding in London and for the flooding of the Norfolk Broads.

It is suggested that as isostatic readjustment is still occurring, this could place stress on the earth's crust and thus might be one of the triggers for long-term changes in volcanic and earthquake activity.



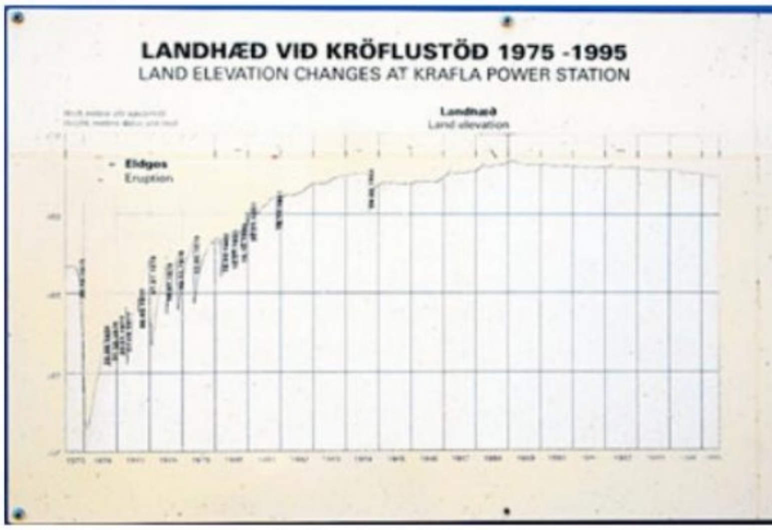
4.3 Isostasy is the theory that the world's land masses are 'floating' on the liquid mantle beneath, and that like blocks of wood floating in a bucket of water, they will rise and fall as mass is added or removed (shown in 'a' above). This is why the crust under the oceans is shallower than the crust under mountain ranges, which have 'roots' of crust protruding downwards in to the mantle.

The 'isostasy' hypothesis has been related by some scientists to **contemporary global warming**. As the earth warms, the Arctic and Antarctic ice caps shed ice mass, and it has been estimated that Antarctica is currently losing about 40 billion tonnes of ice each year. The release of this weight allows the

4.4 The ice cap over Greenland, shown here, is between two and three kilometres thick. As this mass of ice continues to shed, the land beneath will rise according to the principles of isostasy, perhaps triggering more earthquake and volcanic activity.

crust to bend and rise upwards, allowing changes in the currents within the mantle to occur and, according to some scientists, making it easier for magma to rise to the earth's surface.

One of the disturbing aspects of the global trends of earthquake and volcanic activity is that activity levels seem to be rising at many of the **supervolcanoes** — volcanoes where an eruption is likely to have a VEI of 7 or 8. Volcanoes such as the Yellowstone Caldera (USA), Santorini (Greece), Laguna del Maule (Chile), Uturuncu (Bolivia) and several large volcanoes in Iceland are showing signs of inflation. **Inflation** means that the ground level is rising, and this is usually an indicator of pressure from an upwelling of magma or a plume beneath the surface building upwards as a prelude to an eruption.



4.5 A sign near the Krafla Geothermal Power Station in Iceland shows the rise in land elevation over time as the magma chamber beneath rises and causes upwards pressure. The geothermal power station is built in the caldera of a supervolcano. The caldera has a diameter of 10 kilometres and has erupted 29 times in recorded history.

Although it is difficult to reduce the risk to people from geophysical hazards by making projections of future trends on a **global scale**, more meaningful work can be done at the **local scale**. Geographers can study the **deposits** of ash and cinders on the slopes of volcanoes to get a clear idea of the frequency of eruptions for that individual volcano and to predict the likelihood of an imminent eruption. A greater challenge is trying to predict when a **dormant volcano** might awaken and erupt, and how large the eruption is likely to be. Composite cone volcanoes are **more difficult** to predict than cinder cone volcanoes because of the complexity of their eruptions.

Once a volcano shows initial signs of activity, such as earth tremors or inflation, geographers can set up an array of sensitive **instruments** on the volcano to monitor the activity. With precise data, accurate predictions can be made about the **timing** and **magnitude** of an imminent eruption. **Seismometers** measure earth movements and tremors, **tiltmeters** measure ground deformation and swelling of the earth, while **laser beams** can provide accurate data on tiny earth movements along fault lines due to underground pressures.

4.6 A geologist looks across to the northeastern slope of Mount Hood, a potentially active composite cone volcano in Oregon (USA) from the Shellrock monitoring station.

These instruments assist the task of **predicting** an imminent eruption or earthquake. Predictions are more reliable in places where earthquake activity and volcanic eruptions occur **frequently** or **regularly**. Regardless of frequency, however, signs of an imminent hazard event typically include a **combination** of indicators including ground **inflation**, **tilting** of the land, and clusters of **microearthquakes** or tremors.

Other indicators of an imminent earthquake include significant changes in the level of **groundwater**, because groundwater can flow into newly opened up underground cracks, and increases in the **electrical conductivity of rocks** because their moisture content has increased. The release of inert **radon gas** from the ground into the atmosphere is another indicator, as radon seems to escape from faults as rocks under pressure begin to crack.

Other less direct ways are also used to try and predict earthquakes. It has been found that some **animal species behave** in strange ways before an earthquake hits or a volcano erupts. Ancient writings tell of rats, snakes, weasels and centipedes leaving their homes for safety immediately before an earthquake might strike an area. In the days leading up to the large 1976 earthquake in Tangshan, China, zookeepers reported examples of unusual animal behaviour such as snakes refusing to go into their holes, swans refusing to go near water, pandas screaming, and so on. Animal behaviour is the focus of several major studies in China today to ascertain how reliably animal behaviour can be used to predict earthquakes.

Research on all indirect indicators remains at an **early stage** and more work needs to be done before they can be considered useful ways to reduce the impact of geophysical hazards for people and property.

A frequent comment about earthquakes and volcanoes is "the longer the period of calm, the larger the event is likely to be". In other words, the **longer** the period between hazard events, the **larger** the next hazard event is likely to be. The thinking behind this comment is that when forces build up within a rock mass, the rocks can only resist breaking up to a certain amount of pressure. The longer the **resistance** lasts, the more the **stress** builds up, and because the stresses are not being released periodically, then eventually the rocks will need to **snap violently** into a new position.

The historical evidence supports this thinking, and this helps geographers to **predict** the likely force of an impending eruption or earthquake.

QUESTION BANK 4A

1. *Using the data in table 2.3 in chapter 2, describe the trend (changes over time) in the number of earthquakes world-wide.*
2. *Using the data in figure 4.2, describe the trend in the number of volcanic eruptions world-wide.*
3. *Briefly describe the hypotheses that attempt to explain the reasons for the trends you identified in your answers to questions 1 and 2.*
4. *What evidence is used when trying to predict whether an earthquake or volcanic eruption is imminent?*
5. *How does the frequency of past hazard events help us forecast the magnitude of future events?*

Adaptation to hazards

The question of how to live with geophysical hazards has been with people since the beginning of human history. Indigenous peoples in Indonesia and the Philippines used to offer human sacrifices to appease the volcanoes. In Hawaii, villagers used to make offerings to the goddess of volcanoes, Pele, by throwing live pigs into the lava. In Portugal, people were ceremonially burnt alive over a slow fire after the 1755 earthquake in an attempt to prevent future disasters, while other people bought pills sold with the claim 'very good against an earthquake'.

These methods proved to be unsuccessful, and attempts continue today to find effective ways of **controlling** hazard events and **adapting** to them.

In 1669, a lava flow from Mount Etna threatened the city of Catania in Italy. Residents of the city, who protected themselves from the heat with animal hides, tried to break down a layer of scoria (lava crust) to divert the lava flow. If they had succeeded, the lava flow would have engulfed another city, Paterno, and when they realised this, the citizens of Paterno chased the Catanians away and the lava continued to flow. As a consequence, Italy passed a **law** that **prohibited** anyone interfering with the passage of a lava flow or **diverting a lava flow**. Despite this, a lava flow from Mount Etna in 1983 was diverted into a safe area using **explosives** to break the wall of the flow.

Many **effective adaptations** to geophysical hazards occur at the **local scale**. In Japan, **earthquake detectors** send signals automatically to the braking systems on the bullet trains to slow them to a safer speed whenever shaking starts — perhaps several times per day. Similar systems are used in Japan for factories, power stations and strategic facilities.

4.7 Lava flows on Mount Etna, Italy.

Electronic warning systems have also been installed at points along the San Andreas Fault in California USA) and the Cascadia subduction zone to its north. These **motion detectors** give residents a minute or two warning before an earthquake hits. This may not seem like much notice, but it is enough to evacuate people from significant danger points.

Many individual residents in countries such as the USA and Japan have installed earthquake detecting devices, and this is an example of **personal resilience** as an adaptation to hazard events. Other ways that people show personal resilience include taking out **insurance policies** against hazard events and **preparing their homes** and workplaces for hazard events. Making sure that homes are **built** to withstand hazard events that are likely in the area, maintaining **emergency supplies** of food, batteries, and perhaps having an electrical generator on hand are all ways that personal resilience can offer protection against disasters.

At a larger scale, governments can assist adaptation through their planning mechanisms, such as **land-use zoning**. In places where it is known that the risk of a hazard event is high, land-use zoning can impose restrictions such as prohibiting residences, schools and hospitals on vulnerable land. Similarly, specific restrictions can be placed on construction in such areas, such as requiring additional structural strengthening, additional fire-fighting services, or requiring certain access or exit designs.

QUESTION BANK 4B

1. *List some of the ways that people adapt to hazard events at the local and personal scale.*
2. *How might land-use zoning reduce the risk of hazard events in areas threatened by (a) earthquakes, (b) volcanic eruptions, (c) landslides, and (d) sinkholes?*
3. *Are there any ways in which traditional methods of attempting to adapt to earthquakes and volcanic eruptions could have been made more effective?*
4. *Is adaptation to geophysical hazard events more effective at the local scale or at a wider scale? Explain your answer.*

Pre-event management strategies

There are ways to manage hazards so that the impacts on people and property are **mitigated**, or made less severe. This applies to all types of geophysical hazard events.

There are several ways in which potentially hazardous slopes that are vulnerable to **mass movements** such as **landslides** can be stabilised. The strategies include:

- **Artificial structures**, such as terraces or walls, can be built to prevent major landslides, or rocks can be bolted together to make rockfalls less likely;
- **Vegetation** can be planted to bind the soil;
- **Surface streams** that flow across a slope, lubricating and eroding the surface, can be diverted to flow across more stable lands;

4.8 Low rock walls and been built across this slope to prevent downslope soil movement near Tiquina, Bolivia.

4.9 Trees have been planted and irrigated to stablilise this slope near Ashgabat, Turkmenistan.

4.10 Slope stabilisation is possible even in very traditional societies with little money for capital investment. This sweet potato garden near Wadangku in the Highlands of West Papua, Indonesia, has been stabilised by placing logs across the slope, each log being supported by several vertical posts.

- Pipes can be installed to **drain saturated soil** and ease the pressure from groundwater; and
- **Excavations** can be used to change the shape of a slope, making it less steep and thus less vulnerable to sliding or slumping.

An important took in managing unstable slopes is the **landslide hazard map**. These maps identify the areas that are more likely to suffer a slope failure by using data that has examined the historical records of the area. The variables considered include several **physical factors**, such as slope stability, whether or not there are any landslide-triggering factors, and the scale of a likely slide, considering the depth and volume of material, the area of a possible slide and its potential rate of movement. **Human factors** are also considered, such as the potential economic losses, the population of the affected area, and the potential damage to property and infrastructure.

Landslide hazard maps typically categorise slopes according to their hazard risk. For example, a map may group areas into:

- **Permanent avoidance:** very unstable areas where settlement and development is forbidden;
- **Temporary avoidance:** unstable areas where seasonal use might be permitted or where very good warning systems are in place to allow rapid evacuation if required;

- **Qualified use:** areas where there is some risk, so land-uses are restricted to low value activities or functions that do not make the slope even more unstable. Special building standards may be required, and special measures might be needed to prevent or control slope movement; and
- **Unrestricted use**: stable areas where there is little or no risk of slope instability.

Areas that are susceptible to **subsidence** benefit from a different set of management strategies, such as:

- Regulating and **restricting mining activities** in areas prone to subsidence;
- Making sure that underground mines are **properly constructed** with reinforced structures;
- Tracking the flow of **underground streams** and seepage, especially in areas of limestone, so that cavity areas are known and monitored; and
- Constructing buildings that have **flexible structures** that can withstand ground movements.

The management strategies that can be implemented in **earthquake-prone areas** before an earthquake strikes are quite different from areas affected by mass movement hazards. In earthquake-prone areas, possible strategies include:

- **Building on suitable ground**, such as areas with hard rock foundations. There is a popular saying "earthquakes don't kill; buildings do". It is best to avoid constructions on sand and silt because buildings tend to sink downwards in these areas when the ground is shaken, as the soils become jelly-like in their structural integrity.
- Choosing the **right building materials**. There are two approaches with respect to building materials. On one hand, **rigid** materials that will not disintegrate under pressure can be used. Alternatively, the use of **flexible** materials allows a building to bend but not break in an earthquake. In general, the most suitable building materials in earthquake-prone areas are reinforced concrete and steel (for rigidity), or timber (for flexibility). Bricks are less capable of withstanding shocks, and if used in an earthquake-prone area, they need additional support with vertical beams.

4.11 This house in Lahic, Azerbaijan, has been built in an earthquake-resistant manner. Note the side wall has been built with alternating layers of stones interspersed with long, flat wooden slabs that have stopped the wall collapsing from earthquake damage.

4.12 Damage to this building in Lushan, China, shows the difference in earthquake resistance of building materials. The wall built with bricks has fallen away at the lower level, whereas reinforced concrete has remained intact at the upper level.

4.13 This house in Lushan, China, has withstood the same earthquake that destroyed the building shown in figure 4.12. Built of timber using a traditional design, the 'soft connections' in the construction have endured little damage during the earthquake because of their flexibility.

- Constructing buildings to be **solid**. In earthquake-prone areas, a 'solid' building has strong foundations, load-bearing walls and roof that is strongly attached to the walls. Walls are best when reinforced, such as using horizontal and vertical steel rods in concrete walls or wire mesh cemented onto brick walls to act as a laminate.

In general, residents in **poorer countries** have less ability to cope with natural disasters, such as earthquakes, than residents of more affluent countries. **Tokyo**, capital of one of the world's most affluent countries, Japan, experiences about 50 significant earthquakes each year. A major earthquake in Tokyo in 1923, that measured 8.2 on the Richter Scale, killed 143,000 people. Japan experiences a large number of earthquakes because it is situated above the subduction zone that marks the boundary between three plates, the Pacific Plate moving in from the south-east, the Eurasian Plate to the north-west, and the Philippine plate moving in from the south. Indeed, about 10% of the world's earthquakes each year occur in Japan.

4.14 Earthquake-resistant high-rise buildings in the Tokyo suburb of Shinjuku, Japan.

4.15 Overhead electrical wires in Tokyo, Japan. The wires have not been placed underground to avoid damage during earthquakes.

Because Tokyo is so prone to earthquakes, most of the city has very **few high-rise buildings** and **services** such as electricity and telephone lines are built **above ground level**. In recent years, the high price of real estate in Tokyo has encouraged the construction of some 'skyscrapers' in order to earn more revenue from each square metre of ground space. Japanese engineers have used several techniques to make these **tall buildings** resistant to damage from earthquakes. In addition to using additional **reinforced steel**, some buildings are constructed with **widened bases** to encourage stability, while others have **foundations** of fluid, rubber or springs to enable movement during earthquakes without becoming brittle. Another technique used in Japan is to employ electronically controlled **counter-weights** that offset the shocks from an earthquake. Measures such as these are quite expensive, and well beyond the capacity of most poorer countries.

Pre-hazard management strategies can also be implemented for the secondary effects of earthquakes, such as **tsunamis**. These include:

- **Building tsunami walls**, either to reflect the wave energy back to sea or to absorb the wave energy.
- Establishing a network of **buoys** in the ocean that can track the movement of a tsunami in the ocean

4.16 A tsunami wall on the coastline of Kamakura, which is situated on the south coast of Japan's largest island, Honshu. This wall is designed to absorb as much energy of the tsunami as possible.

4.17 A tsunami warning siren on the beach in front of a hotel in Bolinao on the west coast of Luzon Island, the Philippines. The sign on the fence informs hotel guests who may not be familiar with tsunamis about the dangers and the actions that must be taken in the event of a tsunami.

to give advance warning of the approach of a tsunami;

- Setting up **local warning stations** on land with sirens to give residents notice of the need to evacuate; and
- Establishing **evacuation areas** on high ground where people can assemble safely if a tsunami is approaching, with clearly marked access routes.

The range of pre-hazard management strategies is more limited for **volcanic hazard**s because the strength of an eruption is so great. Nonetheless, there are strategies that can be implemented to reduce the risk, such as:

- **Hazard maps** and **disaster plans** can be developed and distributed to residents in threatened areas. These should include instructions about potential hazards and the actions that can be taken in the event of an eruption.
- Buildings in areas threatened by ash deposits should have strong, steeply **sloping roofs** that can withstand the weight of volcanic ash while also minimising the quantities that can accumulate.

4.18 The weather station in Uzon Caldera, an active volcanic area on Russia's Kamchatka Peninsula, has steep roof angles to minimise the accumulation of ash during volcanic eruptions.

- Some attempts have been made to **build walls and troughs** across the anticipated paths of lava flows to **divert** the flows away from homes and property. This is a difficult management strategy to implement effectively because the paths of future lava flows are almost impossible to predict with any real accuracy.

4.19 A warning sign at the still active Leirhnjúkur crater offers advice to visitors about the safety of walking through the area.

- Some areas of active volcanic activity become attractions for tourists. In such areas, an important management strategy is **warning visitors** of the dangers and encouraging them to remain in areas that are considered safe.

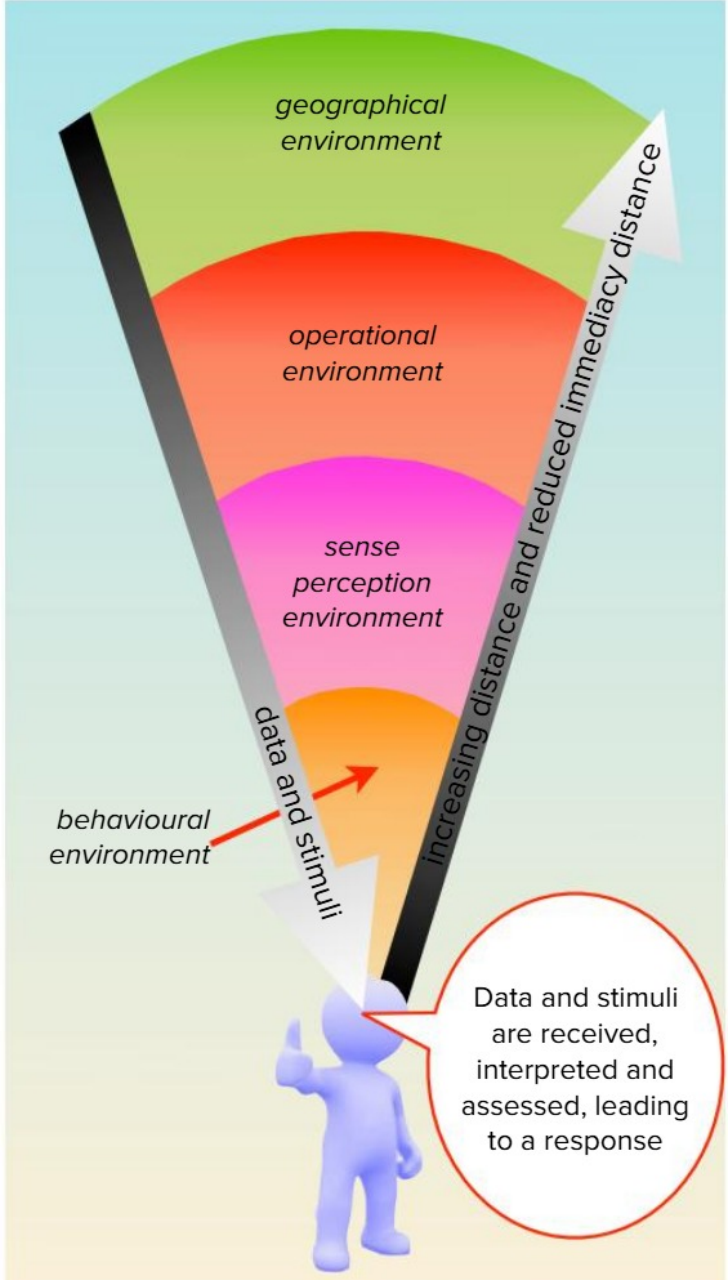
QUESTION BANK 4C

1. *Make a point form list of the pre-event management strategies that can effectively reduce the risk of: (a) landslides, (b) subsidence, (c) earthquakes, and (d) volcanic eruptions.*
2. *How do you think the perspectives of people in poorer countries might differ from the perspectives of people in richer countries regarding preparing against hazard events?*

Post-event management strategies

People's **responses** to hazards are affected by their **perspectives**. Everyone's understanding of truth and reality is **limited** by the knowledge and understandings they form from the data and information they receive.

Figure 4.20 shows why humans form different **perceptions** about hazard events, including recent events they have witnessed. People spend most time functioning in their **behavioural environment**, which is the realm of immediate, everyday, familiar behaviour, emotions and responses. Beyond the behavioural environment, individuals access information through the senses — sight, sound, touch, smell, taste — and interpret this information to form new understandings. This is the **sense perception environment**.



4.20 The process of receiving and processing information about geophysical hazards that leads to partial understandings and different perspectives.

More remotely, people function regularly in their **operational environment**, which is the wider zone where individuals interact with others, work and travel. Beyond that is the **geographical environment**, which can be thought of as 'the wider world' from which people gain knowledge through reading, language and the media.

People's understandings are never complete or perfect. This is partly because the information available is always incomplete and imperfect, and also because everyone filters information according to their prior understandings, preconceived ideas, cultural and other biases, and so on. Consequently, people's responses to hazards are usually based on partial, selective knowledge and understandings.

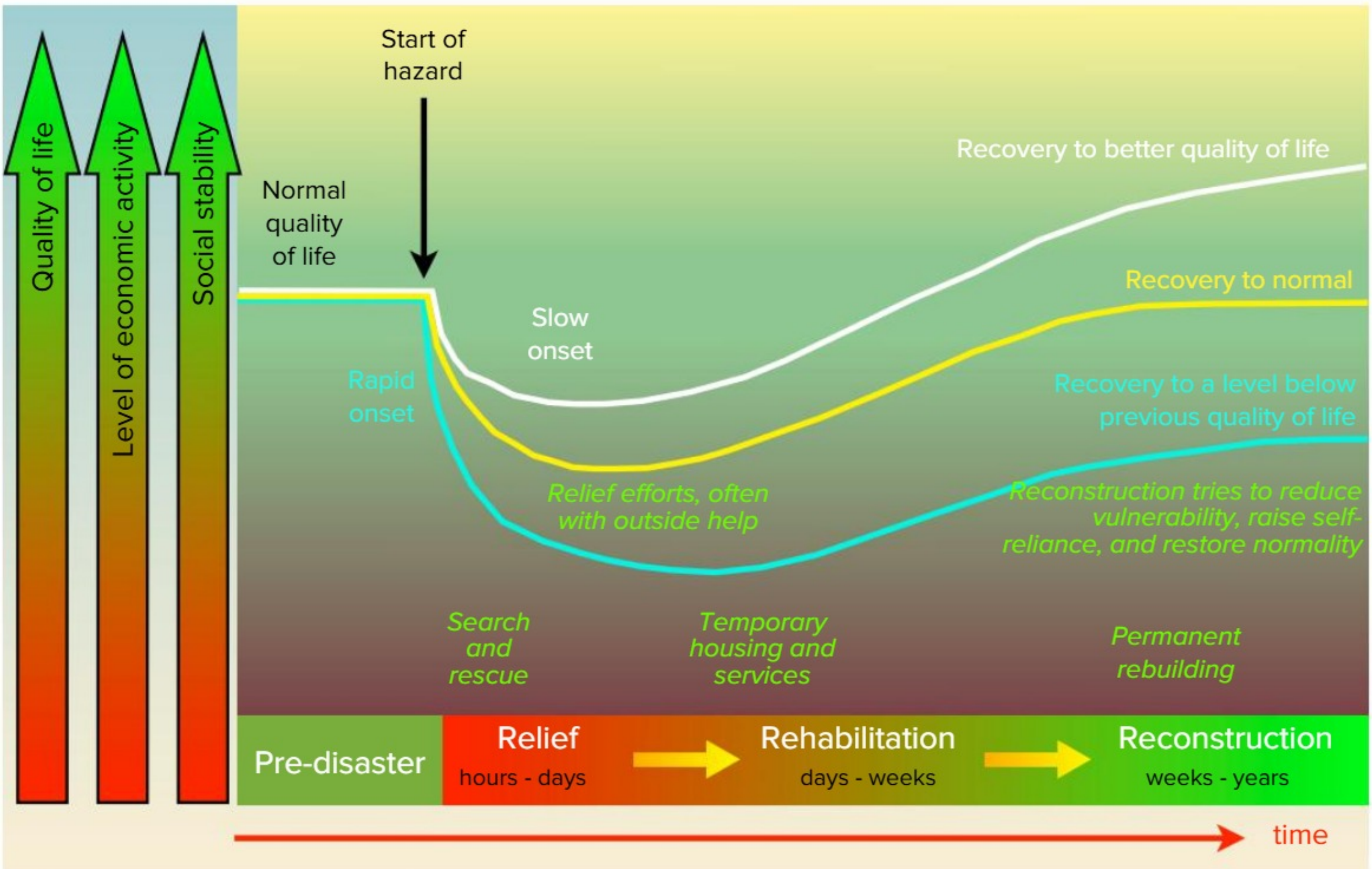
People's **responses** to hazards fall into **three phases**. **The first phase** takes place **before** the hazard event, and as we saw in the previous section, it involves preparation, prevention and education. **Pre-hazard responses** include **identifying** the hazard, **analysing** the potential of the hazards that have been identified, providing **warning** of the developing threat and ascertaining the **vulnerability** of the community. Prevention and mitigation involves either **preventing** the threat eventuating or **minimising** the impact of the threat, such as by land-use zoning that attempts to separate people from known hazards. Preparation also includes **alerting** people to the threat, raising **awareness** of the need to prepare, allocating **responsibilities** and **stockpiling** essential food and equipment.

The second phase is the response **during** the hazard event and immediately after a hazard event has occurred, shown as '**Relief → Rehabilitation**' in figure 4.21. The responses **during the hazard event** usually range from **panic** and **psychological paralysis**, through to the implementation of co-ordinated **emergency measures** by organisations such as the police, army, fire brigades, ambulances and emergency service teams.

The **initial response** immediately following the hazard event may be **migration** or **evacuation** to other areas, outbreaks of **disease** and medical problems. The immediate response also involves **addressing the cause** and impact of the hazard, **assisting** people affected and minimising the impact of repeated events.

The third phase comprises the **medium** and **long-term** actions taken to **repair** major damage and **minimise the suffering** from any repeats of the event if possible. This is indicated by the period '**Rehabilitation → Reconstruction**' in figure 4.21. **Recovery** includes cleaning up and repairing damage, ongoing medical treatment, counselling victims, financial and legal support, revision of the hazard analysis, and evaluation of prevention and mitigation measures.

In all three phases, people in **richer nations** are better placed than those in **poorer countries** to cope. Buildings in economically developed countries tend to be more substantial, education is



4.21 Phases in the responses to a hazard event. After Chris Park.

usually more widespread, government agencies are better funded and more adequately trained, lines of communication have more back-ups, and there is more money to pay for repairs.

In the **immediate aftermath** of a hazard event ('**Relief → Rehabilitation**' in figure 4.21), responses fall into two categories: biomedical and psychosocial. **Biomedical** responses include death and injuries, both direct (resulting from the hazard itself) and indirect (resulting from the consequences of the hazard event).

Psychosocial responses are the ways that people react, consciously or unconsciously, to the hazard event — responses such as worry, anxiety, grieving, blaming, losing community cohesion, and rushing in to offer aid and assistance to those in need. At the broader scale of **governments** and **aid agencies**, psychosocial management strategies include providing emergency food supplies, erecting temporary shelter and accommodation, locating survivors (increasingly using modern technology), and working to re-establish basic services such as water and electricity.

4.22 Emergency shelter camp for thirty families erected at the site of Longmen, a village that was destroyed in the Lushan (China) earthquake in 2013.

In the **longer term aftermath** of a hazard event ('**Rehabilitation → Reconstruction**' in figure 4.21), responses can still be classified as biomedical and psychosocial. In the **biomedical** sphere, deaths and injuries may continue for some time after the initial hazard event because poor hygiene allows disease to spread, and crude medical facilities struggle to cope with the scale of the injuries sustained.

Post-event **psychosocial** management strategies are designed to restore or improve the quality of life

4.23 Damage to a road in China caused by the Sichuan earthquake in 2008. Diverting traffic around the damaged infrastructure and stabilising the slope are urgent priorities after an earthquake.

4.24 Tufts of grass have been planted on the loose slopes of the active Masaya Volcano, near Managua in Nicaragua, in an attempt to stabilise the ash and cinders.

4.25 Wind-break fences have been built on the side of the Eldfell Volcano in Iceland to stabilise the slope. Grasses have been planted between the fences in a further effort to bind the loose surface.

4.26 An elevated pathway has been built for visitors to climb down into the crater of Mount Paektu, a volcano in North Korea. The pathway enables people to descend and ascend the loose talus slopes without over-steepening and destabilising them.

that existed before the hazard event, and stabilise the environment to mitigate the impact of a similar future hazard event. During this phase, permanent structures are built, infrastructure facilities such as piped water and reliable electricity are restored, and measures are taken to stabilise unstable slopes and surfaces that were disrupted during the hazard event.

The location of geophysical hazard events often coincides with places that are popular with **tourists**, such as mountain areas and geothermal zones. In such areas, an important post-event management strategy is securing the area so that it is safe for visitors who are not necessarily familiar with the hazards associated with volcanic eruptions, earthquakes or mass movement events.

4.27 A wall erected on the road between Zeravshan II and Iskander Kul in Tajikistan to protect the road from mass movement hazards has been partly destroyed by repeated avalanches, providing valuable lessons for future planning.

4.28 Wire netting has been built over this roadside slope and attached with steel posts to prevent loose rocks falling or rolling onto the roadway at Dochula, Bhutan.

QUESTION BANK 4D

1. *Explain why most people have incomplete understanding or misunderstandings of hazards. Why is this dangerous?*
2. *Phase 1 of hazard responses is pre-event management strategies. Briefly explain what this involves.*
3. *Phase 2 of hazard responses is Relief → Rehabilitation. What is the time frame of this phase, and what are its key characteristics?*
4. *Phase 3 of hazard responses is Rehabilitation → Reconstruction. What are key ways in which it differs from phase 2?*
5. *What is the difference between biomedical and psychosocial responses to a hazard event? In your opinion, which is more important?*
6. *What are some of the post-event management strategies that help to minimise the impact of future volcanic eruptions?*

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