Cambridge AS & A Level · Geography 9696 · Notes

Hazardous environments A2

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Read first: **Rocks and weathering**, **Atmosphere and weather**

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What you need to know

By the end of this topic you should be able to:

1. **Describe and explain the global distribution of earthquakes and volcanoes** using **plate tectonics**.
2. **Explain earthquakes and their hazards**: **ground shaking**, **landslides**, **soil liquefaction** and **tsunamis**.
3. **Explain volcanoes and their hazards**: the **types of eruption** and their **products**: **nuées ardentes**, **lava flows**, **volcanic mudflows (lahars)**, **volcanic landslides**, **pyroclastic flows** and **ash fallout**.
4. **Describe the primary and secondary impacts** of earthquakes and volcanic eruptions **on lives and property**.
5. **Evaluate the prediction, hazard mapping, preparedness and monitoring** of earthquake and volcanic hazards, and explain the **perception of risk**.
6. **Explain the nature and causes of mass movements** and the hazards they create.
7. **Describe their impacts on lives and property**.
8. **Evaluate the prediction, hazard mapping, preparedness and monitoring** of mass movement hazards, and the **perception of risk**.
9. **Describe and explain the global distribution of the areas most at risk** from **large-scale tropical disturbances** (cyclones, hurricanes, typhoons) and **small-scale atmospheric disturbances** (tornadoes).
10. **Explain the processes that form and develop** cyclones, hurricanes, typhoons and tornadoes.
11. **Explain the hazards from large-scale disturbances**: **storm surges**, **coastal flooding**, **intense rainfall** leading to severe **river floods** and **mass movement**, and **high winds**.
12. **Explain the hazards from small-scale disturbances**: **intense precipitation** (rain and hail), **high winds** and **pressure imbalances**.
13. **Describe the primary and secondary impacts** of atmospheric disturbances **on lives and property**.
14. **Evaluate the prediction, preparedness and monitoring** of large- and small-scale disturbances, and the **perception of risk**.
15. **Know a case study** of a hazardous environment: the **problems of managing it sustainably**, and an **evaluation of attempted or possible solutions**.

It is one of the options in Paper 3 (Advanced physical geography options), where you answer two options. For this option you answer Question 7 (10 marks: a describe part and an explain part, built on a figure) and one essay, Question 8 or Question 9 (20 marks). Read the notes on rocks and weathering (slopes and mass movement) and on atmosphere and weather (instability, latent heat, the Coriolis force) first.

Understand it

Hazards, vulnerability and risk

A **natural hazard** is a natural event that threatens people and their property. It becomes a **disaster** only when it hits people who cannot cope: a magnitude 7 earthquake in an empty desert is a hazard event, not a disaster. So the size of a disaster depends on two things:

- the **hazard**: its **magnitude** (size, energy), **frequency** (how often), **speed of onset**, **duration** and **area affected**;
- the **vulnerability** of the people: how many live there, how well built their homes are, how poor they are, whether they are warned, and how well their government and emergency services work.

Geographers often summarise this as **risk = hazard × vulnerability ÷ capacity to cope**. **Capacity** is what reduces the loss: money, education, warning systems, building codes, insurance. This is why **level of development** appears in almost every mark scheme for this topic: lower-income countries usually suffer **more deaths**, while higher-income countries suffer **greater economic losses** (more valuable property) but recover faster.

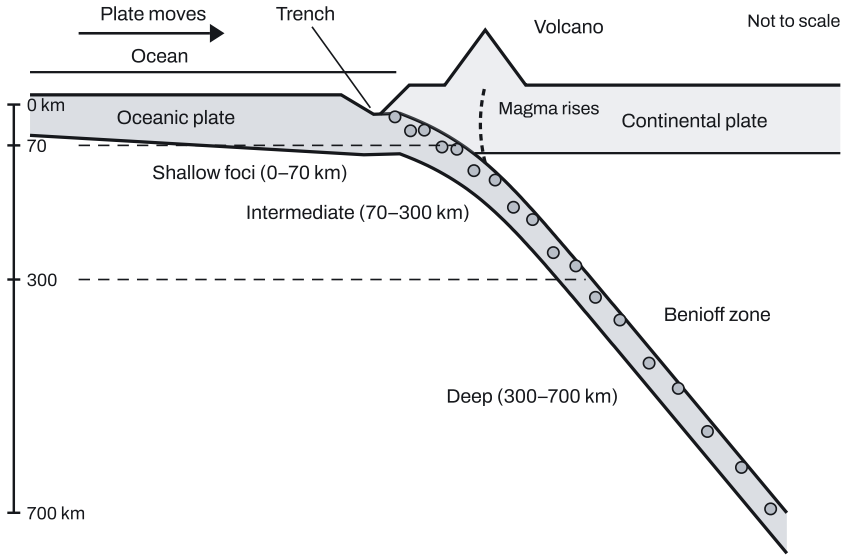
Impacts are **primary** (caused directly by the hazard: buildings collapsing from shaking, people burnt by a pyroclastic flow, roofs torn off by wind) or **secondary** (following from the primary ones: fires from broken gas pipes, disease from broken water and sewage pipes, homelessness, lost jobs and income, food shortages, migration, psychological trauma). Both affect **lives** (deaths, injuries, health, livelihoods) and **property** (homes, infrastructure, farmland, businesses).

Plate tectonics and where earthquakes and volcanoes happen

The Earth's **lithosphere** (crust plus rigid upper mantle) is broken into **plates** that move a few centimetres a year over the softer **asthenosphere**. Most earthquakes and volcanoes are in **narrow belts along plate boundaries**, above all round the Pacific (the "**Ring of Fire**").

Boundary	What happens	Earthquakes	Volcanoes	Examples
Constructive (divergent)	Plates move apart; mantle rock rises, melts as pressure falls, and makes new **basaltic** crust	Frequent, **shallow**, mostly small	**Yes**: effusive basaltic fissure and shield eruptions	Mid-Atlantic Ridge, Iceland; East African Rift

Boundary	What happens	Earthquakes	Volcanoes	Examples
Destructive (convergent): oceanic under continental or oceanic	The denser **oceanic plate subducts** into the mantle; water released from it lowers the melting point of the mantle above, making **andesitic** magma	Frequent; **shallow to very deep** (to about 700 km) along the sinking slab, the **Benioff zone**; the largest earthquakes (megathrust)	**Yes**: explosive stratovolcanoes in a line parallel to the trench, or an **island arc**	Andes; Japan; the Philippines; Montserrat (Lesser Antilles arc)
Collision	Two continental plates meet; neither sinks far, so crust is folded and thickened	Frequent, **shallow to intermediate**, spread over a **wide** zone	**Few or none**: no slab sinks deep enough to melt	Himalayas (Nepal 2015)
Conservative (transform)	Plates slide past each other; crust is neither made nor destroyed	Frequent, **shallow**, can be large	**None**: no magma is made	San Andreas Fault, California
Hotspots (not boundaries)	A plume of hot mantle rises under a plate	Some, linked to eruptions	**Yes**: basaltic shield volcanoes, in a chain as the plate moves over the plume	Hawaii



So the **depth of focus** varies: shallow wherever the crust is stretched, sheared or crumpled near the surface; deeper and deeper **away from the trench** at subduction zones, because the foci follow the slab down. **Volcanoes are absent** at conservative boundaries (no melting) and mostly at collision boundaries (thick crust, no deep slab), and are found **not at the trench** but some 100–300 km inland, where the slab reaches about 100 km depth and releases its water.

Earthquakes: how they happen and how big they are

Stress builds up where plates lock together along a **fault**. When it exceeds the strength of the rock, the rock **snaps and slips**, releasing energy as **seismic waves**. The point of rupture underground is the **focus**; the point on the surface above it is the **epicentre**. Fast **P waves** arrive first, then **S waves**, then slower **surface waves**, which do most of the damage.

- **Magnitude** measures the **energy released** (today the **moment magnitude** scale; the older Richter scale works the same way). It is **logarithmic**: each whole number up means about **10 times** the ground movement and about **32 times** the energy (see Key facts). A magnitude 9 releases about 1000 times the energy of a magnitude 7.
- **Intensity** measures the **effects at a place** on the **Modified Mercalli** scale (I to XII). One earthquake has one magnitude but many intensities. "Reported intensity" depends on who reports it, so empty areas may show little even if shaking was strong.
- **Frequency and magnitude** are inversely related: small earthquakes are far more common than large ones (see Key facts); a magnitude 8 or above happens about once a year worldwide.

Why the same magnitude can have very different impacts:

Factor	Effect
Depth of focus	A **shallow** focus loses less energy before reaching the surface, so shaking is stronger (Haiti 2010 was shallow and close to the capital)
Distance from the epicentre	Shaking weakens with distance
Geology	Soft, wet sediment and reclaimed land **amplify** shaking and can liquefy; solid rock shakes less
Building quality	Unreinforced brick and concrete collapse; reinforced and flexible buildings survive
Population density	More people exposed in cities
Time of day	At night people are at home asleep; in the day, in schools and offices
Warning and preparedness	Drills, early warning, emergency services
Level of development	Money for codes, rescue and rebuilding
Frequency	**Aftershocks** bring down already weakened buildings; but where earthquakes are frequent, people tend to be **better prepared**

Three contrasts: **Haiti, January 2010** (magnitude 7.0, shallow, close to Port-au-Prince, poorly built concrete, weak government: well over 100 000 deaths); **Christchurch, New Zealand, February 2011** (magnitude 6.2 but shallow and very close to the city: 185 deaths, and widespread **liquefaction** in the eastern suburbs); **Tōhoku, Japan, March 2011** (magnitude 9.0, in a very well-prepared country, yet about 18 000 dead or missing, most **drowned by the tsunami**).

Earthquake hazards

Ground shaking is the hazard **common to every earthquake**. Buildings collapse when shaking matches their natural sway, when floors "pancake" onto each other, or when heavy roofs fall. It causes most earthquake deaths.

Ground deformation: the ground may crack, lift, drop or be offset along a fault **scarp**, breaking anything built across it.

Soil liquefaction happens in **loose, saturated, fine sand and silt** (river alluvium, lake silts, coastal sediment, **reclaimed land**):

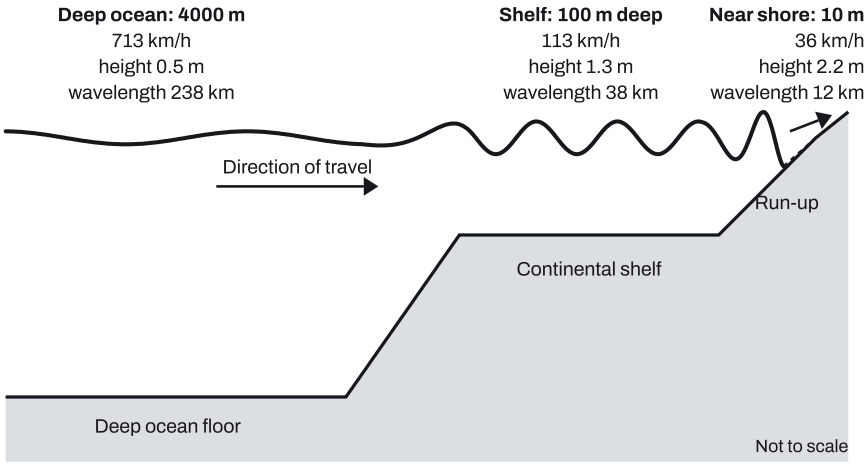
1. Before the earthquake the grains touch each other and carry the weight above; water fills the pores.
2. Shaking makes the loose grains try to **pack more tightly**, but the water in the pores cannot escape fast enough.
3. So the **pore water pressure rises** until it carries the weight instead of the grain contacts: the grains lose their grip (friction) on each other.
4. The soil **loses its strength** and flows like a liquid: buildings **tilt and sink**, buried pipes and tanks **float up**, and water and sand spurt out as **sand boils**.

Factors: **loose, fine, uniform sediment**, a **high water table**, **strong and long shaking** (larger magnitude, nearer the epicentre), and buildings on **shallow foundations**. It does not happen on solid rock or dry ground, so it is severe but **local**: Kobe (1995, the port on reclaimed land) and Christchurch (2011) are classic cases.

Landslides (and rockfalls, avalanches): shaking adds force to slopes (more **shear stress**) and loosens material (less **shear strength**), so slopes close to failing give way. They matter **only in steep areas**, but there can be thousands in one event, blocking roads and rescue (Nepal 2015).

A **tsunami** is a train of waves set off when an earthquake, landslide or eruption suddenly **pushes a huge mass of sea water out of place**. It has nothing to do with the tides.

1. Most form at **subduction zones**: the overriding plate, dragged down while locked, springs up when the fault ruptures, so the **sea bed moves vertically** and lifts the whole column of water above it. Submarine **landslides** and **volcanic eruptions** can also cause them; conservative earthquakes rarely do, because the sea bed moves sideways.
2. The water spreads out as waves in all directions. In **deep ocean** they travel at about **700 km/h**, with a **wavelength of hundreds of kilometres** and a **height often under 1 m**.
3. In **shallow water** they **slow down**, the **wavelength shortens**, and the energy is squeezed into less water, so the **height increases** greatly.
4. If a **trough arrives first**, the sea **draws back** from the shore: a natural warning. Then the wave arrives as a fast-rising flood that runs far inland (**run-up**) and drags debris back. Several waves arrive over hours; the first is often not the largest.



The numbers in the diagram come from the speed formula in Key facts and from the simple rule that height grows as the depth falls (with the fourth root of the depth ratio: $0.5 \times (4000/100)^{1/4} = 1.26$ m). In reality, bays and gently shelving shores push real tsunamis far higher: more than 10 m along much of the Tōhoku coast in 2011.

Factors in the height of a tsunami at a coast:

- **Size of the trigger**: the energy and area of sea-bed displacement (magnitude, rupture length, vertical movement).
- **Distance from the source**: energy spreads over a growing circle, so heights fall with distance; but ridges and sea-bed shape **focus** it along some paths, so some distant coasts get higher waves than nearer ones.
- **Bathymetry and coastline shape**: a **wide, gently shelving shelf** and **funnel-shaped bays** raise the wave; **steep coasts** with deep water inshore keep it lower; **islands and headlands shelter** the coasts behind them; reefs and mangroves absorb some energy.
- **Tide**: at high tide it reaches further inland.

The **Indian Ocean tsunami of December 2004** (magnitude 9.1 off Sumatra) killed about 230 000 people in 14 countries, many of them hours after the earthquake, because the Indian Ocean had **no warning system** then.

Volcanoes: types of eruption and their products

What decides the type of eruption is the **magma**: how much **silica** it has, so how **viscous** (sticky) it is, and how much **gas** it holds. Gas escapes easily from runny magma but is trapped in sticky magma until it bursts out explosively.

	Effusive eruptions	**Explosive eruptions**
Magma	**Basaltic**: low silica (about 50%), hot (about 1200 °C), **runny**, little gas	**Andesitic to rhyolitic**: high silica (60–70%+), cooler, **viscous**, gas-rich
Where	Constructive boundaries, hotspots	Destructive (subduction) boundaries
Volcano	Broad, gentle **shield volcanoes**; **fissures**	Steep, layered **stratovolcanoes** (composite cones), **lava domes**

	Effusive eruptions	Explosive eruptions
Named styles	**Hawaiian** (fire fountains, lava flows), **Icelandic** (fissure)	**Strombolian** (small bursts), **Vulcanian**, **Vesuvian/Plinian** (huge ash columns), **Pelean** (dome collapse, nuées ardentes)
Main products	**Lava flows**, lava fountains, gases	**Ash and tephra**, **pyroclastic flows**, **lahars**, volcanic bombs, **volcanic landslides**, short thick lava flows and domes
Danger	Mostly to **property**; flows are slow enough to walk away from, but eruptions can last months	Mostly to **lives**: sudden, fast, far-reaching; little warning once they start

The **products** (and so the hazards):

- **Lava flows**: streams of molten rock. Basaltic flows can travel kilometres; they burn and bury everything in their path but usually move at walking pace, so they destroy **property** more than lives (Kīlauea, Hawaii, 2018, destroyed hundreds of homes but killed no one).
- **Pyroclastic flows**: avalanches of hot gas, ash and rock fragments (often 200–700 °C) racing downhill at 100 km/h or more, hugging the ground and following valleys. They form when an **eruption column collapses** (too dense to keep rising) or a **lava dome collapses**. Nothing in their path survives: they are the deadliest volcanic hazard where they occur.
- **Nuées ardentes** ("glowing clouds"): a pyroclastic flow with a glowing, billowing ash cloud above it, typical of Pelean eruptions. In 1902 one from Mont Pelée destroyed the town of St-Pierre on Martinique, killing about 28 000 people.
- **Ash fallout (tephra)**: fragments carried by the wind and falling over a wide area. Wet ash is heavy and **collapses roofs**; it ruins crops, contaminates water, causes breathing problems and damages aircraft engines (the 2010 eruption of Eyjafjallajökull, Iceland, closed much of Europe's airspace for about a week).
- **Volcanic bombs**: lumps of lava thrown out, dangerous near the vent.
- **Lahars (volcanic mudflows)**: loose ash and debris mixed with water (heavy rain, **melting snow and ice**, a crater lake bursting) flowing down river valleys like wet concrete, fast and far beyond the volcano. They can happen **during** an eruption or for **years after** it, whenever heavy rain falls on fresh ash. In 1985 a small eruption of Nevado del Ruiz, Colombia, melted summit ice and lahars buried the town of **Armero** about 70 km away, killing about 23 000 people.
- **Volcanic landslides (flank collapse, debris avalanches)**: magma swelling inside a volcano, or weakened, altered rock on its flanks, makes part of the cone collapse. At **Mount St Helens, USA, in May 1980** the bulging north flank slid away as the largest landslide recorded, releasing a sideways blast; 57 people died, few because the area had been closed. Collapses into the sea can cause tsunamis.
- **Gases**: carbon dioxide (heavier than air; it collects in hollows and suffocates), sulfur dioxide (acid rain, breathing problems), hydrogen sulfide.
- **Jökulhlaups**: sudden floods when an eruption under a glacier melts the ice (Iceland).

So hazards **are related to the type of eruption**: effusive eruptions are dominated by lava flows; explosive ones by ash, pyroclastic flows and lahars, with little lava.

Primary and secondary impacts of earthquakes and volcanoes

	Primary	Secondary
Earthquakes	Buildings, bridges and roads collapse; deaths and injuries from falling debris; ground cracked or liquefied	Fires (broken gas pipes and power lines); tsunamis and landslides; disease from broken water and sewage pipes; homelessness; lost jobs and businesses; aid and rebuilding costs; trauma
Volcanoes	Deaths from pyroclastic flows, bombs and gases; homes buried by lava, ash or lahars; roofs collapsed by ash	Lahars for years after; crops and livestock lost, so food shortages; water contaminated; airspace closed; people evacuated and some never return (migration); tourism and investment lost; but also **benefits** later: fertile soils, geothermal energy, minerals, tourism

Lives and property are linked: losing a home or farm destroys a livelihood. Volcanoes often damage property more than lives where people are evacuated, but kill many where flows arrive without warning.

Managing earthquake and volcanic hazards

The syllabus groups management into **prediction**, **hazard mapping**, **preparedness** and **monitoring**, all shaped by the **perception of risk**.

Earthquakes

- **Prediction** of the exact time, place and size is **not possible**. Scientists **forecast probabilities** from past earthquakes, fault loading and **seismic gaps** (sections of a fault that have not slipped for a long time). Possible precursors (foreshocks, radon gas, groundwater changes, animal behaviour) are **unreliable**.
- **Monitoring**: seismometers and GPS. **Early warning systems** (Japan, Mexico) detect the fast P waves and send alerts seconds before the damaging waves arrive: enough to stop trains and close gas valves.
- **Hazard mapping**: maps of **expected shaking** (from past events, faults and geology) and of **liquefaction**, landslide and tsunami zones guide **land-use zoning** and building codes. They show **where**, not **when**.
- **Preparedness**: **building codes** (reinforced concrete, cross-bracing, **base isolation** on rubber pads, flexible frames, light roofs); retrofitting; **drills** and education (Japan holds national drills each year); emergency plans; **tsunami warnings**, evacuation routes and sea walls; insurance.

Volcanoes

Volcanoes are **easier to predict** than earthquakes, because magma rising towards the surface gives warning signs that can be measured:

- **Seismic activity**: swarms of small earthquakes and continuous **tremor** as magma breaks rock and moves (seismometers).
- **Ground deformation**: the volcano **swells** as magma fills it (tiltmeters, GPS, satellite radar).
- **Gases**: rising emissions of **sulfur dioxide** and carbon dioxide (gas sensors, spectrometers).

- **Heat**: warmer ground, springs and crater lakes (thermal infrared satellites, thermometers), and changes in **groundwater chemistry**.
- **History**: the past pattern of eruptions and their deposits.

These let observatories set **alert levels** and **evacuate**. At **Mount Pinatubo, Philippines, in June 1991**, scientists' monitoring led to the evacuation of tens of thousands of people before one of the largest eruptions of the century, saving thousands of lives; most of the roughly 800 deaths came from roofs collapsing under wet ash, because a typhoon struck at the same time. But prediction is never exact: it tells you an eruption is **likely**, not exactly when, how big or which hazards it will produce, so false alarms damage trust.

- **Hazard mapping**: maps of the areas reached by past lava flows, pyroclastic flows, lahars and ashfall, used for **exclusion zones** and land-use planning. At Nevado del Ruiz in 1985 a hazard map existed showing Armero at risk, but the warning was not acted on: a map works only if people use it.
- **Preparedness and protection**: evacuation plans and drills; **exclusion zones**; strengthening roofs and sloping them so ash slides off; lahar warning systems and **channels or dams** to guide lahars away from towns; **diverting lava**: in 1973 on **Heimaey, Iceland**, people sprayed sea water onto an advancing lava flow, cooling and slowing it, and saved the harbour. Diversion works only for slow lava flows; nothing stops a pyroclastic flow.

Perception of risk

Perception of risk is how dangerous people **believe** a hazard is, which is often different from the real risk. It decides whether they prepare, obey warnings and evacuate.

Why people live in hazardous places: **fertile volcanic soils**, **geothermal energy**, minerals, **tourism**, flat coastal land, jobs and family ties; **poverty** (they can't afford to move); lack of knowledge; the belief that it won't happen to them; long intervals between events, so people forget.

What shapes perception:

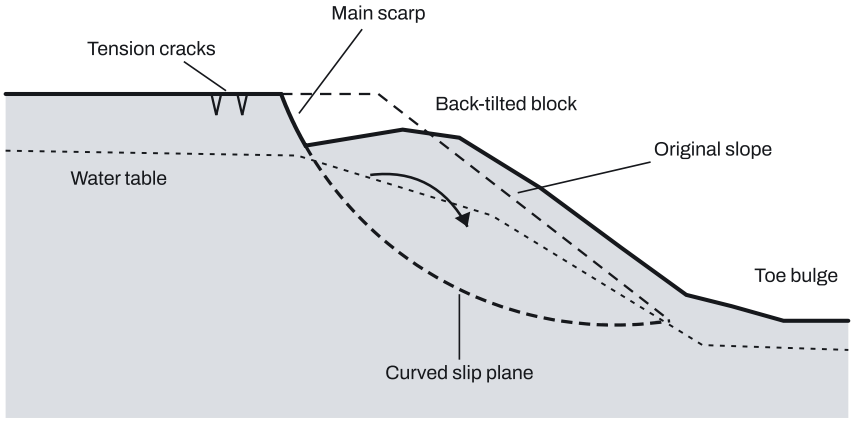
- **Experience**: people who have lived through an event take it more seriously, but a near miss or false alarm can make them complacent.
- **Education**: knowing the warning signs (the sea drawing back before a tsunami).
- **Wealth**: richer people can afford to prepare and to move; poorer people may have to accept risks.
- **Culture and religion**: some see hazards as fate (**fatalism**); others **adapt** or try to **fight** the hazard (engineering).
- **The type of hazard**: **frequent, visible, predictable** hazards (seasonal cyclones) are judged more realistically than **rare, sudden** ones (a great earthquake on a quiet fault); invisible ones (volcanic gases) are underrated.
- **Trust** in government and scientists.

Mass movements: nature, causes and hazards

Mass movement is the downslope movement of rock and soil under gravity (see the rocks and weathering note for the slope processes). For hazards, the important types are:

Type	Nature	Speed	Hazard
Falls and topples	Blocks fall freely from steep rock faces	Extremely fast	Local; roads, railways and houses at the cliff foot
Slides (translational, on a flat plane such as a bedding plane)	A mass moves as a block	Slow to very fast	Can carry away whole hillsides
Rotational slides (slumps)	A block rotates on a **curved slip plane**, its top tilting back	Slow to moderate	Repeated; damage buildings and roads on top and at the toe
Flows: mudflows, debris flows, earthflows, lahars	Saturated material moves like a fluid	Slow (earthflows) to very fast (debris flows)	**Most deadly**: fast, long run-out down valleys onto settlements
Avalanches (snow, rock)	Snow or rock rushing down mountainsides	Very fast	Ski resorts, mountain roads and villages
Creep and heave	Very slow, particle by particle	Millimetres a year	Damage only: tilted walls, poles, cracked roads

How hazardous a type is depends on its **speed** (fast ones give no time to escape), **size and run-out distance**, **water content** (flows travel far), **frequency**, **predictability** and, above all, **location** relative to people.



Causes. A slope fails when the **shear stress** pulling material downslope (mainly the part of its weight acting down the slope) becomes greater than the **shear strength** holding it (friction and cohesion). Their ratio is the **factor of safety** (see Key facts): below 1, the slope fails. Causes are either **preparatory** (making the slope weaker over years) or **triggers** (tipping it over the edge, often in hours).

- **Water**, the commonest trigger: heavy rain and snowmelt **add weight** and raise **pore water pressure**, which pushes grains apart and cuts friction; clays lose strength when wet.
- **Steepening and undercutting** by rivers and waves.
- **Earthquakes and volcanoes**: shaking, and loose ash on steep cones.
- **Geology**: weak or clay-rich rock; **bedding planes dipping parallel to the slope**; permeable over impermeable rock, so water collects at the boundary.
- **Weathering** slowly weakens the rock; **loss of vegetation** means roots no longer bind the soil.
- **Human activity**: **cutting** into slopes for roads and buildings (steepening, removing support at the toe); **loading** the top with buildings, fill or mining **spoil**; **deforestation**; leaking pipes, irrigation and poor drainage adding water; vibration from traffic, blasting and machinery. In 1966 a colliery **spoil tip** at **Aberfan, Wales**, saturated by rain and a spring beneath it, flowed onto a school, killing 144 people, 116 of them children.

How important are human causes? Human activity is now a major **preparatory** cause in hilly cities and along roads in many countries, and it puts **people in the way**. But the biggest movements are natural, and the **trigger** is usually **heavy rain or an earthquake**; human activity mostly makes slopes **more likely** to fail when the trigger comes. People can also **reduce** mass movement (drainage, retaining walls, planting).

Impacts on lives and property: burial and deaths (in February 2006 a landslide after days of heavy rain buried the village of Guinsaugon on Leyte, Philippines, killing more than 1000 people); destroyed homes, roads, pipes and power lines; rivers blocked, forming lakes that may burst; farmland lost; communities cut off. Slow movements damage property but rarely kill.

Managing mass movement hazards

Prediction. Where mass movement is likely can be predicted well from slope, geology and past events; **when** is much harder. Rainfall forecasts with **rainfall thresholds** (the amount of rain known to trigger slides in an area) allow warnings; fast falls and slides often give no warning.

Hazard mapping combines the factors that control mass movement: **slope angle**, **rock type and structure**, **soil**, **slope position and aspect** (which way it faces, so how wet and how weathered it is), **vegetation and land use**, **rainfall pattern**, closeness to faults, and the record of **past movements** (old scars and deposits). The map grades land from low to high susceptibility. It is the basis for **land-use zoning** (no building in high-risk zones), building controls, and deciding where to spend on engineering and monitoring. Its limits: it needs good data, which is expensive and lacking in many lower-income countries; it shows likelihood, not timing; land use and climate change it; and it achieves nothing unless planners **enforce** it and people can afford to live elsewhere.

Monitoring measures a slope that is known to be moving or at risk: **rain gauges**; **piezometers** (pore water pressure); **inclinometers** and **extensometers** (movement underground and across cracks); **tiltmeters**, **GPS** and satellite radar (ground movement); and simple **visual signs**: new cracks, tilting trees and poles, bulging walls, springs appearing. Monitoring allows **warnings and evacuation**, but only for slopes already identified and only where the movement speeds up before failing.

Preparedness: warning systems (Hong Kong's **Landslip Warning** is issued when heavy rain is forecast or falling), evacuation plans, **education** so people recognise warning signs, training of emergency services, insurance.

Prevention and mitigation (engineering, see rocks and weathering): **drainage** (pipes and channels to lower pore pressure: often the cheapest and most effective), **regrading** slopes to a lower angle, **retaining walls**, **pinning** with rock bolts and **soil nails**, **netting** and rockfall fences, sprayed concrete (shotcrete), **afforestation** and vegetation, catch basins for debris flows, avalanche fences and snow sheds.

Hong Kong shows how these combine. After deadly landslides in the 1970s on its steep, deeply weathered hills, the government set up a geotechnical office in 1977. It has **mapped** and registered tens of thousands of man-made slopes, **upgraded** them (soil nails, drainage), controls building on slopes, **monitors** rainfall, issues **warnings** and runs **public education**. Landslide deaths have fallen greatly, but the work is costly and never ends, and natural hillsides still fail in extreme rain.

Perception of risk for mass movement is often low: slopes look stable for decades, slow creep seems harmless, and in many cities the poorest people build on the steepest, cheapest land because they have no choice.

Where atmospheric disturbances happen

Large-scale tropical disturbances are intense low-pressure systems hundreds of kilometres across. They have one name in three regions:

- **Hurricanes**: the North Atlantic, Caribbean and Gulf of Mexico, and the eastern North Pacific.
- **Typhoons**: the western North Pacific, the most active area (the Philippines, Taiwan, southern China, Japan; about 20 tropical cyclones a year enter the area around the Philippines).
- **Cyclones**: the north Indian Ocean (Bay of Bengal, Arabian Sea), the south-west Indian Ocean (Madagascar, Mozambique) and around Australia and the south-west Pacific.

They form over **tropical oceans between about 5° and 20° from the equator**, and travel into latitudes of 30° or more. They **never form on the equator** (the Coriolis force is too weak to start rotation) and almost never in the **South Atlantic** or **south-east Pacific** (cold currents and strong upper winds). They come in a **season**, late summer and autumn, when the sea is warmest (the Atlantic season runs from June to November).

The areas most at risk are where storms **make landfall** on many **vulnerable** people: **eastern coasts and islands** on the western sides of tropical oceans, since storms move west with the trade winds (the Caribbean, the US Gulf coast, the Philippines, southern China); **low, crowded deltas** with shallow shelves and funnel-shaped bays, where surges are highest (the Bay of Bengal coasts of Bangladesh, India and Myanmar); and small islands. So latitude explains **where storms can form**, but the size of the risk depends on sea temperature, storm tracks, coastal shape and vulnerability.

Small-scale disturbances, tornadoes, are rotating columns of air from a thunderstorm to the ground, usually **tens to hundreds of metres wide**, lasting minutes. They form mainly over land in **mid-latitudes**, where warm, moist air meets cold, dry air. The **USA** has by far the most (over a thousand a year), especially on the

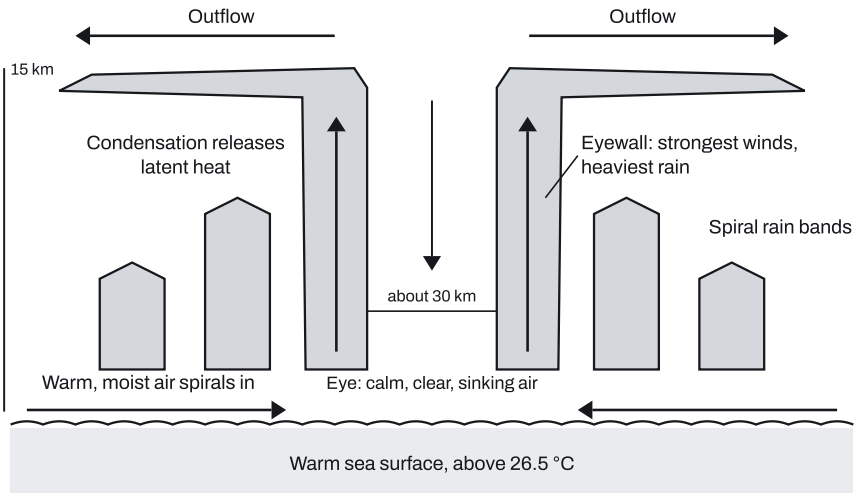
Great Plains ("Tornado Alley") in spring, where moist air from the Gulf of Mexico meets cold air from Canada and dry air from the Rockies; others occur in **Bangladesh** (the deadliest single tornado, in 1989, killed about 1300 people), Argentina, Europe and South Africa, and inside landfalling hurricanes.

How tropical cyclones form and develop

Conditions for formation:

1. **Warm sea**: surface temperature above about **26.5–27 °C** down to a depth of about **50–60 m**, so that stirring by the storm does not bring up cold water. Warm water **evaporates** fast, supplying **heat and moisture**.
2. **Distance from the equator**: at least about **5° of latitude**, where the **Coriolis force** is strong enough to make inflowing air **spin** (anticlockwise in the northern hemisphere, clockwise in the southern).
3. **An existing disturbance**: an area of low pressure, such as an **easterly wave** moving off West Africa, or a cluster of thunderstorms near the ITCZ, where air already converges and rises.
4. **Unstable, moist air** through the lower and middle atmosphere, so air keeps rising.
5. **Low vertical wind shear**: winds that change little in speed or direction with height, so the tall storm is not torn apart.
6. **High pressure in the upper atmosphere** to **pump air away** (outflow) at the top, so surface pressure keeps falling.

How it works (a heat engine): warm, moist air spirals in towards the low and **rises**; it cools and **condenses**, releasing **latent heat**, which warms the air, makes it rise faster and **lowers the surface pressure** further; more air spirals in faster, evaporating more water from the warm sea. The **warm sea is the fuel**, the **latent heat** is the energy, the **Coriolis force** organises the spin, and **low shear and upper outflow** let it grow.



Stages: **tropical depression** (winds under 63 km/h) → **tropical storm** (63–118 km/h, named) → **hurricane/typhoon/cyclone** (119 km/h or more, graded on the Saffir–Simpson scale in Key facts).

Development and movement: the storm is steered by the winds around it, westward with the **trade winds** on the equator side of the **subtropical highs**, then usually curving **poleward** and finally **eastward** into the westerlies. It **strengthens** while over warm water with low shear, and **decays** when it:

- moves **over land**: it loses its supply of heat and moisture, and **friction** slows the winds (but it can still bring huge rainfall inland);
- moves over **colder water** (poleward, or over water it has cooled itself by stirring);
- meets strong **wind shear** or dry air.

Variation from year to year comes from **ENSO** (El Niño increases wind shear over the Atlantic, so brings **fewer** Atlantic hurricanes; La Niña the opposite), shifts of the ITCZ and natural variation. **Climate change** warms the oceans, supplying more energy, so a larger share of storms may reach the **most intense categories**. Some of the apparent rise in past records comes from **better detection** by satellites.

An example: **Hurricane Katrina (2005)** strengthened from category 1 to category 5 over the very warm Gulf of Mexico, weakened to category 3 before landfall in Louisiana, then decayed quickly over land, cut off from its supply of heat and moisture.

Weighing the factors: warm sea is **necessary for both formation and development** (without it, no storm forms and an existing one dies), so it is often judged most important. But it is **not sufficient**: oceans near the equator are warm enough but have no Coriolis force, and warm water with high wind shear produces nothing. The factors work **together**; Coriolis matters for **formation**, while sea temperature, shear and landfall control **development**.

How tornadoes form

1. **Ingredients**: **warm, moist air** near the ground under **cold, dry air** aloft (a very **unstable** atmosphere); a **lifting** mechanism (a cold front, a dry line, heating of the ground); and strong **wind shear**: winds that increase in speed and **turn in direction** with height.
2. The wind shear sets the air near the ground **rolling horizontally**, like a pencil rolled between hands.
3. A powerful **updraft** in a thunderstorm **tilts** this rolling air upright, so the updraft itself rotates: a **mesocyclone**, a few kilometres wide, inside a **supercell** thunderstorm.
4. Downdrafts on the back side of the storm (the **rear-flank downdraft**) wrap around the mesocyclone and help **tighten** the rotation, which **narrows and speeds up** (like a skater pulling in their arms) into a funnel that reaches the ground: a **tornado**.

Not every supercell produces one, and scientists still do not fully understand which ones will. Tornadoes are graded on the **Enhanced Fujita (EF) scale** from the damage they cause (see Key facts).

Hazards from atmospheric disturbances

Large-scale disturbances (cyclones, hurricanes, typhoons):

- **Storm surge**: a temporary rise of sea level above the normal tide. It is caused mainly by **strong onshore winds piling water** against the coast, plus the **low pressure** letting the sea surface rise (about 1 cm for each hectopascal drop, see Key facts). It is highest where the shelf is **wide and shallow** (water has nowhere to go but up), in **funnel-shaped bays** and estuaries, on the side of the storm where winds blow **onshore** (in the northern hemisphere, to the right of the track), and when it coincides with **high tide**. It is

usually the **deadliest** hazard: **Cyclone Nargis** (Myanmar, 2008) killed about 138 000 people, mostly by a surge across the low Irrawaddy delta; **Typhoon Haiyan** (Philippines, 2013) killed more than 6000, many in the surge that rose to around 8 m at the head of San Pedro Bay, at the city of Tacloban.

- **Coastal flooding**: from surge and huge waves on top of it; salt water ruins farmland and fresh water supplies. **Hurricane Katrina** (2005) caused surge floods that broke the levees protecting New Orleans; most of the city flooded and about 1800 people died.
- **Intense rainfall**: often hundreds of millimetres in a day or two, much more if the storm **stalls** (Hurricane Harvey, Texas, 2017, brought more than 1000 mm of rain in places). It causes severe **river floods** and **mass movements** (mudflows and landslides) far inland; **Hurricane Mitch** (1998) killed about 11 000 people in Central America, mostly in floods and landslides.
- **High winds**: 119 to over 250 km/h, destroying buildings, crops and power lines, and turning debris into missiles.

Which is most significant **depends on the place**: on low, crowded coasts, the **surge**; in mountains, **rainfall**-triggered floods and landslides; where buildings are flimsy, the **winds**. A weak, slow-moving storm can do more harm with rain than a strong, fast one with wind.

Small-scale disturbances (tornadoes):

- **High winds**: the strongest on Earth, over 300 km/h in the most violent tornadoes; they destroy buildings completely and throw vehicles and debris. They are the **main** tornado hazard, but along a **narrow path**.
- **Pressure imbalances**: the pressure inside a tornado is much **lower** than outside, so air rushes in and roofs are lifted (once thought to make houses "explode"; most damage is now known to come from the wind).
- **Intense precipitation**: torrential rain causing **flash floods**, and large **hail** that damages crops, cars and roofs and injures people.
- **Lightning** from the parent thunderstorm.

Tornado impacts are **intense but local**: a strong tornado can flatten one part of a town and leave the next street untouched. **Joplin, Missouri** (2011), hit by an EF5 tornado, lost 158 lives and thousands of buildings.

Primary and secondary impacts. Primary: deaths by drowning and flying debris; buildings, infrastructure and crops destroyed. **Secondary**: disease from contaminated water, food and water shortages, power cuts, unemployment, homelessness and migration, salt-damaged soils, and years of recovery. Poorer countries suffer **more deaths**; richer ones bigger **costs**.

Prediction, monitoring and preparedness for atmospheric disturbances

Tropical cyclones are easier to predict and monitor:

- They form over oceans in **known regions and seasons**, are huge, and last days.
- **Satellites** watch them continuously; **aircraft** fly into them to measure pressure and wind; buoys, balloons and **radar** add data; computer **models** forecast tracks days ahead.
- There is still **uncertainty** about exactly where landfall will be, and **intensity** forecasts are less accurate than track forecasts.

Tornadoes are much harder:

- Forecasters can say a day ahead that conditions favour tornadoes over a **wide region** (a **watch**), but not **exactly where or when** one will form.
- **Doppler radar** detects rotation in storms and **storm spotters** report funnels; a **warning** then comes **only minutes** ahead.
- Their paths are short, narrow and erratic, and many form at night or hidden in rain.

Preparedness and management:

Method	Cyclones	Tornadoes
Warnings and evacuation	Days ahead; mass evacuation possible	Minutes: shelter in place (sirens, phone alerts, radio)
Shelters	**Cyclone shelters** on stilts (Bangladesh)	**Safe rooms** and storm cellars, interior rooms
Building codes	Hurricane straps, shutters, raised homes (Florida tightened its code after Hurricane Andrew, 1992)	Reinforced safe rooms; ordinary houses cannot survive EF4–EF5 winds
Land-use planning	No building in surge zones; mangroves and wetlands kept as buffers	Little help: tornadoes can strike anywhere in the region
Engineering	Sea walls, levees, **embankments**, flood channels, storm-surge barriers	None practical
Education and drills	Community volunteers, drills	Tornado drills in schools

Bangladesh shows what preparedness can do. A cyclone in **1970** killed an estimated 300 000 or more people; since then a **Cyclone Preparedness Programme** of trained volunteers spreading warnings, thousands of **cyclone shelters**, embankments and mangrove planting have cut deaths dramatically: **Cyclone Sidr** (2007), a severe storm, killed about 3400. Yet in wealthy New Orleans in 2005, failed levees and the slow evacuation of poorer people without cars showed that money alone is not enough.

Perception of risk varies: people who have ridden out several storms may refuse to evacuate, and the poor may stay to protect their homes or because they cannot travel.

Case study: sustainable management of Montserrat

The environment. Montserrat is a small British Overseas Territory in the Caribbean on the **Lesser Antilles island arc**, where the North American and South American plates are subducted beneath the Caribbean plate. It faces **several hazards**: the **Soufrière Hills volcano** in the south (andesitic, explosive, dome-building), **hurricanes** (Hugo badly damaged it in 1989), **earthquakes**, **lahars** when heavy rain falls on fresh ash, and landslides on steep slopes.

The hazard events. The volcano, quiet for centuries, began erupting in **July 1995** and has had long active phases since. A lava dome grew and collapsed repeatedly, sending **pyroclastic flows** down the valleys; ash fell across the island; lahars filled the valleys. In **June 1997** pyroclastic flows killed **19 people** who had stayed in or returned to the evacuated zone. The capital, **Plymouth**, was evacuated and later **buried** by pyroclastic flows and lahars, along with the port, the hospital and many government buildings, and the airport was destroyed.

Problems of sustainable management:

- **Social**: about **two-thirds of the island**, the south, became an **exclusion zone**, including the best farmland and most homes; **more than half the population left**, many to the UK or nearby islands, so families split up and the population aged. Those who stayed lived for years in shelters.
- **Economic**: the capital, port, airport and much of the tourist industry were lost; the economy shrank, and the island became **dependent on aid** from the UK. Every renewed eruption or lahar uses up recovery money.
- **Environmental**: forests and farmland were buried; ash damaged water supplies and soils; rebuilding in the north puts pressure on its limited flat land.
- **Uncertainty**: no one can say when the eruption will finally end, so long-term investment is risky; the north, the safe area for volcanic hazards, is still exposed to **hurricanes**.

Attempted solutions and evaluation:

1. **Monitoring and alerts**: the **Montserrat Volcano Observatory**, set up in 1995, monitors the volcano with seismometers, GPS and gas measurements, and runs a **hazard level system** deciding which zones may be entered. This is the key success: apart from those in the closed zone in 1997, the eruptions have caused no deaths. It lasts only as long as funding for scientists does.
2. **Hazard mapping and exclusion zones**: maps of where pyroclastic flows and lahars travel define the **exclusion zone**, moved as activity changes. It saves lives but keeps people from their land.
3. **Relocation and rebuilding in the north**: new housing, a new airport (opened 2005), and plans for a new town and port at **Little Bay**: the economy rebuilt where it is safe from the volcano, but slowly and largely with aid money.
4. **Using the hazard**: **volcano tourism**, and **sand mining** from lahar deposits for export; geothermal energy has been explored. These turn part of the problem into income, a small but sustainable step.

Judgement. Montserrat has managed the volcanic hazard **successfully for lives** through monitoring, hazard mapping and exclusion zones, but **not sustainably for the community**: the population and economy have not recovered, and the island depends on aid. Some problems, such as the loss of the capital, could only be adapted to. A comparison helps: in the **Philippines**, repeated hazards (typhoons, earthquakes, eruptions, landslides) keep using up money for recovery, so economic sustainability is hard even with good warning systems.

Key facts and formulas

There is no formula list in Paper 3, so learn all of these.

Formula	Status
Earthquake magnitude: each 1 unit higher means 10 times the ground movement and about 32 times the energy ($10^{1.5} \approx 31.6$)	Learn it
Magnitudes differing by n: ground movement $\times 10^{n}$, energy $\times 10^{1.5n}$ (2 units: 100 times the movement, 1000 times the energy)	Learn it
Frequency and magnitude: roughly 10 times as many earthquakes for each magnitude 1 unit lower	Learn it
Tsunami speed in water of depth d metres: $v = \sqrt{gd}$ m/s, with $g = 9.81$ m/s² (multiply m/s by 3.6 for km/h)	Learn it
Wavelength = speed × wave period	Learn it
Storm surge from low pressure alone: the sea rises about 1 cm for each 1 hPa fall in air pressure (the rest of the surge is from wind)	Learn it
Factor of safety of a slope $F = \dfrac{\text{shear strength}}{\text{shear stress}}$; the slope fails when $F < 1$	Learn it
On a slope of angle θ, a weight W pulls downslope with $W \sin\theta$ and presses into the slope with $W \cos\theta$	Learn it
Risk = hazard × vulnerability ÷ capacity to cope	Learn it
Saffir–Simpson scale (sustained winds): category 1, 119–153 km/h; 2, 154–177; 3, 178–208; 4, 209–251; 5, 252 km/h or more; **major** hurricanes are categories 3–5	Learn it
Enhanced Fujita scale (estimated gusts): EF0, 105–137 km/h; EF1, 138–177; EF2, 178–217; EF3, 218–266; EF4, 267–322; EF5, over 322 km/h	Learn it
Tropical cyclone formation: sea above about 26.5–27 °C to about 50–60 m depth; at least 5° from the equator; low wind shear	Learn it
Mean rate = total ÷ number of time units; range = highest – lowest; percentage change = (new – old) ÷ old × 100	Learn it

How to do it

We have tagged 87 questions for this topic (2021–2025, all Paper 3), 60 different (the variants 31, 32 and 33 often share questions). Every Question 7 (29 of them) has a describe part (a) and an explain part (b), so it counts under two types and the counts add up to 116.

Question type	Questions
Describe the pattern, distribution or features shown in a figure	24
Evaluate how well hazards can be managed, predicted or prepared for (essay)	23

Question type	Questions
Assess whether one hazard is the most significant (essay)	21
Explain the factors that control where or how severely a hazard occurs	13
Assess the relative importance of factors in forming a hazard (essay)	9
Suggest reasons for the pattern in the figure	7
Compare two series or features in a figure	5
Case study essay: sustainable management of a hazardous environment	5
Explain how a hazard event forms	4
Explain how a hazard's type, magnitude or frequency affects its impacts	4
Explain ways a hazard can be predicted	1

Marking: Question 7(a) gives **1 mark for each accurate descriptive point** (3 or 4), usually with a mark kept for **data** or a cap (often 3) without it. Question 7(b) (6 marks, sometimes 7) is marked in **three levels** (Level 3, 5–6 marks: clear explanation of two or more points, accurate and linked to the figure where it asks). The 20-mark essays are marked in **four levels** (Level 4, 16–20 marks: thorough discussion, sustained evaluation and a sound conclusion, with examples integrated), with a **maximum of 8 without examples**.

1. Describe the pattern, distribution or features shown in a figure (24 questions)

Figures: hazard **maps** (tsunami heights, liquefaction risk, landslide potential, shaking intensity, storm-surge height, global earthquakes or volcanoes, tornado trends), **time graphs** (tremor duration, earthquakes per hour), and occasionally a **photograph or diagram**.

1. **Overall pattern first**: concentrated or scattered, linear belts or clusters, increasing or decreasing with distance or time, fluctuating or steady.
2. **Highs and lows** with **places or times** and **values** (compass directions, named places, the scale or key).
3. **Gaps and anomalies**: places or times that break the pattern.
4. **Use the categories in the key**: describe the categories the question names, not "risk" in general.
5. **If two variables are named** (magnitude and frequency), describe **both**: full marks need both.
6. **Quote data** with units; manipulate it (maximum, range, how many times).
7. **Describe only**: no reasons, and **don't add what isn't shown** (examiners note answers explaining plate boundaries that the map did not show).

Variants:

- **Global maps of earthquakes or volcanoes**: narrow linear belts and clusters, the ring round the Pacific, the mid-Atlantic line, few in continental interiors, exceptions such as Hawaii.
- **Photographs and diagrams**: **describe**, don't just name: "a dense grey ash cloud hugging the lower slope" earns a mark; "pyroclastic flow" alone does not.

- **Relationships** (number of tornadoes against deaths): say whether there is a clear relationship, with data, and the anomalies.

2. Evaluate how well hazards can be managed, predicted or prepared for (essay) (23 questions)

The commonest version is **mass movement** ("hazard mapping/monitoring is the most effective", "difficult to prepare for", "most effective strategy"), then **earthquakes** ("can be prepared for"), **volcanoes** (how far their hazards can be predicted; methods of managing them), **atmospheric disturbances** (managing their hazards; large- against small-scale), comparisons (hazard-mapping earthquakes against volcanoes) and **perception of risk**.

1. **Define** the method precisely: hazard mapping shows **where**, prediction says **when**, monitoring **measures** change, preparedness gets people **ready**.
2. **Explain how the named method works**: what is mapped or measured, with which instruments, and how it reduces loss (only naming "seismographs" or "monitoring" earns little).
3. **Compare it with the other methods**: prediction, monitoring, hazard mapping, preparedness (education, drills, emergency services, warnings, evacuation), engineering, land-use zoning, building codes, perception of risk.
4. **Judge with criteria**: lives saved, damage and frequency of events reduced, cost–benefit, who can afford it.
5. **Show it depends** on the **type** of hazard (slow lava against pyroclastic flows; creep against debris flows; cyclones against tornadoes), its **scale and predictability**, the **level of development** and **governance**.
6. **Use specific examples** for each method (Hong Kong slopes, Pinatubo, Nevado del Ruiz, Heimaey, Japan, Bangladesh).
7. **Conclude**: usually that methods work best **combined** (a hazard map guides where to monitor, engineer and zone), and which matters most for this hazard.

Variants:

- **"Hazards from volcanic eruptions can be predicted"**: judge each **hazard**, not eruptions in general: lahar and lava paths follow valleys, ash fall depends on the wind, pyroclastic flows and flank collapses are sudden.
- **Hazard-mapping earthquakes against volcanoes**: earthquake maps rest on past events, faults and geology; volcanic maps mark each hazard's paths round one cone, but changing activity makes them uncertain too.
- **Large- against small-scale disturbances**: days of tracking against minutes of warning; preparation also depends on funding and technology.
- **Perception of risk and hazard type**: type matters, but experience, development, education and culture often matter more. Answer about **perception**, not the risk itself.

3. Assess whether one hazard is the most significant (essay) (21 questions)

"Tsunamis (or liquefaction) are the greatest earthquake hazard", "storm surges (high winds, high rainfall, flooding) are the most significant cyclone hazard", "high winds are the most significant tornado hazard", "pyroclastic flows are the most significant volcanic hazard", "some types of mass movement are more hazardous", "volcanic hazards affect lives more than property", "impacts vary".

1. **List the full set** of hazards from that event (see Understand it), so the named one can be compared with each of the others.
2. **Define "significant"**: deaths and injuries, homeless, economic cost, area affected, how often it happens, how long its effects last, how hard it is to manage.
3. **The case for the named hazard**, with a specific event (Tōhoku 2011 for tsunamis; Christchurch 2011 for liquefaction; Nargis 2008 for surge; Mitch 1998 for rain; Mont Pelée 1902 for pyroclastic flows).
4. **The case for the others**, explaining **where** each matters most: shaking affects every earthquake; liquefaction needs loose saturated sediment; landslides need steep slopes; tsunamis affect only coasts.
5. **"It depends"**: on magnitude, depth, location, local ground and coast shape, and level of development; primary against secondary, short against long term.
6. **Conclude**: for example, "ground shaking is the most significant overall because it is common to all earthquakes, but tsunamis are the greatest in the largest subduction earthquakes near coasts."

Variants:

- **Types of mass movement**: rank by speed, size, run-out, frequency, predictability and location; fast flows and slides are the killers, creep and slow slumps cost money.
- **Lives against property**: volcanoes often destroy more **property** than lives where people are evacuated, but kill many where flows strike without warning; property loss also wrecks lives (livelihoods, migration, psychological effects).
- **How impacts vary**: by hazard, magnitude, location, development, preparedness, time of day.

4. Explain the factors that control where or how severely a hazard occurs (13 questions)

Height of a tsunami at a coast; causes of a mass movement or of landslides; factors in liquefaction; why tornadoes occur where they do; why earthquake focus depth varies; why volcanoes are absent at some plate boundaries.

1. **Pick the factors** the question asks for (if it says "two", explain two fully, then stop).
2. **For each, a chain**: factor → process → effect on the hazard. For landslides, say how the factor **raises shear stress or lowers shear strength** (examiners note answers that say "adds weight" without saying why that causes failure).
3. **Use the figure** if one is given, but answer the general question if that is what it asks.

Variants: **tsunami height** (trigger size, distance travelled, coastline shape and water depth); **liquefaction** (sediment type and looseness, water table, shaking strength and duration); **focus depth** (shallow at constructive, conservative and collision boundaries; shallow to 700 km along the Benioff zone at subduction

zones); **volcanoes absent** (no magma at conservative boundaries; thick crust and no deep slab at collision boundaries).

5. Assess the relative importance of factors in forming a hazard (essay) (9 questions)

Sea temperature or the Coriolis force in forming and developing tropical cyclones; latitude and the areas most at risk; factors in tornado formation; human activity against physical causes of mass movement.

1. **Cover both parts** if the question says "formation and development".
2. **Explain each factor's role** (see "How tropical cyclones form and develop"): warm sea, Coriolis force, existing disturbance, instability, low shear, upper outflow; then movement, intensification and decay.
3. **Weigh them**: which are **necessary**, which are **sufficient**, which matter for formation and which for development; how they interact (warm sea gives latent heat, Coriolis organises the spin).
4. Add **ENSO**, climate change and wind shear for variation.
5. **A labelled diagram** (cyclone cross-section) is credited.
6. **Conclude**: "sea temperature is most important for both, but no single factor is sufficient."

Variants: **latitude**: explains where cyclones can form (5–20°, Coriolis, warm seas) but not where risk is highest (tracks, coast shape, exposure, vulnerability); for tornadoes it matters less than the meeting of air masses over land. **Tornado formation**: instability, moisture, lift and wind shear; shear is what makes a supercell rotate. **Mass movement causes**: separate **preparatory** causes from **triggers** (usually heavy rain); human activity counts only where it causes or increases movement.

6. Suggest reasons for the pattern in the figure (7 questions)

Storm-surge height in a bay; hurricane frequency over time; why precursors last different times for different hazards; a shaking-intensity pattern; tornado numbers against deaths.

1. **Tie every reason to something you described in (a)**.
2. **Explain the mechanism**: for surge height, wind blowing over a longer stretch of sea, shallowing water, **funnelling** as a bay narrows, falling pressure, shelter in an estuary; for hurricane frequency, rising sea temperatures, wind shear in some years, **ENSO**, shifts of the ITCZ, natural variation, **better monitoring**.
3. **Level 3 needs two or more reasons clearly explained**; one clearly explained reason is capped in Level 2.

Variants: **reported intensity** (distance from the epicentre, geology, where people live to report it); **tornadoes and deaths** (strength, warnings, population density, buildings, time of day).

7. Compare two series or features in a figure (5 questions)

Major against non-major hurricane frequency; recurrence interval against impact for different hazards; precursor against event duration; the extent of two lahars.

1. **Write comparative sentences** ("both increase, but major hurricanes more steeply").

2. Give **similarities and differences** (one kind only is capped at 3).
3. Keep **one mark for data**: quote values from both series.

8. Case study essay: sustainable management of a hazardous environment (5 questions)

"Evaluate the attempted or possible solutions", "evaluate the problems", "some problems are more difficult to manage than others".

1. **One named place at the right scale** (an island such as Montserrat, a city, a volcano and its surroundings, a delta), not a whole country or continent, and not volcanoes in general. Examiners say several scattered examples reduce depth.
2. **Describe the environment and its hazards**, with figures.
3. **Explain the problems** (social, economic, environmental, uncertainty); if the question is about **problems**, keep the focus there.
4. **Evaluate each solution** against the **three strands** of sustainability and the long term.
5. **Conclude**: which solutions worked, for whom, and whether management is sustainable.

9. Explain how a hazard event forms (4 questions)

Tsunamis, pyroclastic flows, mudflows (lahars).

1. **Cause first**, then a **step-by-step sequence** to the hazard (for a tsunami: subduction, locked plates, sudden vertical sea-bed movement, water displaced, spreads fast and low, slows and grows in shallow water, drawback, run-up).
2. For **lahars**, say what supplies the water (heavy rain, melting snow and ice, a crater lake) and the loose ash; water raises pore pressure until the ash flows. Don't confuse mudflows with lava or with slides.
3. For **pyroclastic flows**, explain the viscous, gas-rich magma and the **collapse** of the eruption column or dome.

10. Explain how a hazard's type, magnitude or frequency affects its impacts (4 questions)

1. **Magnitude**: more energy means stronger, longer, wider shaking, more liquefaction and landslides, possibly a tsunami.
2. **But impact also depends on** depth, distance, geology, building quality, time of day, population density, warning, development.
3. **Frequency**: aftershocks; frequent events bring **preparedness**, rare ones complacency.
4. **Answer about both** magnitude and frequency if both are asked (only one is capped in Level 2).
5. **Eruption type**: explain effusive against explosive and the hazards each produces (no mention of types is capped in Level 1); effusive gives time to evacuate but may last long.

Variant: **why volcanoes can have greater impacts than earthquakes**: one eruption brings several hazards (ash, pyroclastic flows, lava, gases, lahars); eruptions can last months or years; ash and lahars reach wide areas, and lahars continue for years afterwards. Against this, earthquakes give no warning, while eruptions usually give precursors and time to evacuate.

11. Explain ways a hazard can be predicted (1 question)

Two ways volcanic eruptions are predicted: choose two of **seismic activity**, **ground deformation**, **gas emissions**, **heat** and **groundwater changes**. For each: what changes as magma rises, why, and how it is measured; one clearly explained way reaches Level 2, two reach Level 3.

Worked examples

Example 1

The table shows the maximum tsunami height and arrival time recorded at six coastal places after a model earthquake of magnitude 8.8 at a subduction zone. Places B, D and E are on open coasts facing the earthquake; A is at the head of a narrowing bay with a wide shallow shelf; C is a funnel-shaped harbour on an island, in line with a submarine ridge pointing towards it; F lies behind a chain of islands.

Place	Distance from the epicentre (km)	Arrival time after the earthquake (hours)	Maximum height (m)
A	150	0.4	9.5
B	600	1.0	3.2
C	1500	2.2	3.6
D	3000	4.2	1.4
E	6000	8.3	0.6
F	6200	8.6	0.2

(a) Describe the variation in tsunami height and arrival time shown in the table. **[4]**

(b) Suggest reasons for the differences in maximum height between the six places. **[6]**

(a) One mark for each point; data are needed for full marks.

- Overall, height falls with distance from the epicentre, from 9.5 m at A, 150 km away, to 0.2 m at F, 6200 km away **(1)**.
- C is an anomaly: at 1500 km it reaches 3.6 m, higher than B at 600 km **(1)**.
- The range of heights is 9.3 m, and A's wave is nearly 16 times the height of E's **(1)**.
- Arrival time rises steadily with distance: the wave reached C, D, E and F at average speeds of 682–723 km/h, but A, across the shallow shelf, at only about 375 km/h **(1)**.

(b)

The first reason is **distance from the source**. The earthquake displaced the sea bed and a large volume of water; the energy spreads outwards in a growing circle, so the further the wave travels, the lower it is: heights fall from 3.2 m at B to 0.6 m at E. Sheltered places receive even less, as F, behind its island chain, shows (0.2 m at much the same distance as E). Across the open ocean the wave travels at about 700 km/h, which matches $\sqrt{gd}$ for an ocean about 4 km deep: $\sqrt{9.81 \times 4000} = 198$ m/s, or 713 km/h.

The second reason is the **shape of the coast and the sea bed offshore**. In shallow water the wave slows (A's arrival speed was only about 375 km/h), its wavelength shortens and its energy is squeezed into less water, so it grows in height. A **wide, shallow shelf** gives it a long distance to grow, and a **narrowing bay funnels** it into an ever smaller width, so at A it reached 9.5 m. C is higher than B although further away because the submarine ridge focuses the wave's energy towards it and the funnel-shaped harbour then narrows it, raising it to 3.6 m. Open coasts such as B, D and E have no such focusing.

Level 3 (5–6 marks): two or more reasons clearly explained with the process (energy spreading, shelter, shoaling, focusing and funnelling), and linked to the data.

Example 2

Explain two factors that influence the amount of damage caused by a tornado. **[6]**

The first factor is the **strength of the tornado**. The more unstable the air and the stronger the wind shear, the faster the mesocyclone rotates and the stronger the tornado that tightens from it. On the Enhanced Fujita scale an EF1 tornado (138–177 km/h) peels off roof tiles and breaks windows, but an EF5 (over 322 km/h) sweeps well-built houses off their foundations and turns cars and debris into missiles, helped by the very low pressure inside the vortex. Damage rises steeply with wind speed, and the width and length of the path decide how much is hit.

The second factor is **what lies in its path**, the vulnerability of the people and buildings. A tornado crossing farmland may destroy only crops, while the same tornado crossing a town destroys hundreds of homes. Mobile homes and light houses without strong fixings are destroyed by winds that brick buildings survive. Warnings matter too: in the USA, Doppler radar and sirens usually give only minutes, but that is enough to reach a cellar, while in Bangladesh, with weak warnings and light buildings, tornadoes have killed hundreds at a time. Night-time tornadoes, unseen by sleeping people, cause more deaths.

Level 3 (5–6 marks): two factors clearly explained, each with how it changes the damage, and examples.

Example 3

'Preparedness is more effective than prediction in reducing the impacts of volcanic hazards.' How far do you agree with this statement? **[20]**

Introduction. Volcanic hazards include lava flows, pyroclastic flows, ash fallout, lahars, volcanic landslides and gases. **Prediction** means forecasting when and how an eruption will happen, from monitoring; **preparedness** means everything done in advance so people can respond: hazard maps and exclusion zones,

evacuation plans, drills, building design and protective works. Effectiveness can be judged by lives saved, property protected and cost.

The case for prediction. Volcanoes give warning signs as magma rises: swarms of small earthquakes and tremor, swelling of the cone measured by tiltmeters and GPS, rising sulfur dioxide emissions and warmer ground. Monitoring these lets observatories raise alert levels and order evacuation. At Mount Pinatubo in 1991, monitoring led to the evacuation of tens of thousands of people before one of the century's largest eruptions, saving thousands of lives. Prediction is the only defence against the fastest hazards, pyroclastic flows and nuées ardentes, which no barrier can resist: people must simply not be there.

The limits of prediction. It says an eruption is likely, not exactly when, how large or with which hazards. Many volcanoes in poorer countries are not monitored, and false alarms erode trust. A prediction saves nobody unless people act on it.

The case for preparedness. Nevado del Ruiz in 1985 shows this: an eruption was expected and a hazard map showed Armero in the path of lahars, but no evacuation was ordered in time and about 23 000 people died. Prediction failed for lack of preparedness. Hazard maps guide exclusion zones (on Montserrat they have kept people out of the path of pyroclastic flows since 1997); drills make warnings work; lahar channels and sirens protect towns for years after an eruption, when predicting the eruption no longer helps; strengthened roofs resist ash, which at Pinatubo caused most of the deaths. For slow hazards it can even protect property: on Heimaey in 1973 people cooled an advancing lava flow with sea water and saved their harbour.

It depends. On the **hazard**: for pyroclastic flows prediction is essential; for lahars, ash and lava, preparedness does more. On **timescale**: prediction works in the days before an eruption, preparedness for decades. On **development**: monitoring needs scientists and equipment, but education and community plans are cheap. On **perception of risk**: people who trust warnings and have practised respond quickly.

Conclusion. Prediction tells people **when** to act; preparedness makes sure they **can and will**. Preparedness is more effective overall, because it reduces the impacts of every volcanic hazard, works for years after an eruption, and turns a prediction into lives saved, as Pinatubo and Nevado del Ruiz show. But for the fastest hazards nothing works without accurate prediction. I largely agree, provided preparedness includes the hazard mapping and evacuation plans that use predictions.

Level 4 (16–20 marks): both methods explained with how they work, judged with located examples, variation with hazard type, timescale and development, and a conclusion that answers "how far".

Common mistakes

- **Describing the figure site by site or year by year** instead of identifying the overall pattern, clusters and anomalies.
- **Not knowing what liquefaction is**, or confusing it with mudflows and lubrication on slopes. It is saturated loose sediment losing strength as pore water pressure rises during shaking.
- **Confusing mudflows with lava flows, pyroclastic flows or slides**: a lahar is ash and debris mixed with water, flowing.

- **Saying focus depth is greatest at collision boundaries**, or that all Benioff-zone earthquakes are deep: depths range from shallow near the trench to 700 km.
- **Saying volcanoes occur at all plate boundaries**: none at conservative boundaries, few at collision boundaries.
- **Listing prediction methods without explaining them** (seismographs, radon, magnetism): say what changes, why, and whether it works.
- **Treating hazard mapping as prediction**: a hazard map shows where, not when.
- **"Monitoring" with no detail**: name what is measured and how it leads to warnings.
- **Writing about mass movement in general** instead of distinguishing types (falls, slides, flows, avalanches) and matching methods to each.
- **Confusing tornadoes with large-scale disturbances**, explaining tornado formation when the essay asks about hazards, or treating high winds as the only tornado hazard.
- **Covering only formation** when the question says "formation and development", or forgetting what happens at landfall.
- **Answering about risk when the question asks about perception of risk.**
- **No real evaluation**: good knowledge of each hazard, but no judgement of their **relative** significance; weigh them against each other.
- **A case study that is a whole country or several unrelated examples**, or that lists methods when the question asks about **problems**.

How to get the marks

- **Command words. Describe** = what the figure shows, with data, no reasons. **Compare** = linked similarities and differences. **Explain** = reasons and processes, cause and effect. **Suggest** = apply what you know to the figure. **Assess**, **evaluate**, **how far**, **to what extent** = weigh both sides and reach a judgement.
- **Question 7(a)**: one point per mark; overall pattern, extremes, anomalies, data with units and places; both named variables; describe, don't name, features on photographs.
- **Question 7(b)**: Level 3 needs **clear explanation of two or more points** with process (for landslides, how shear stress rises or shear strength falls), and links to the figure where asked.
- **Essays**: define the hazard and the terms; explain the named factor or method; set it against the **full range** of alternatives; say what it **depends on** (hazard type, location, development, timescale); use **specific, located examples** accurately; finish with a judgement that answers the question. Without examples, the maximum is 8 of 20.
- **Diagrams** (a plate boundary, a tsunami, a cyclone cross-section, a rotational slide) earn credit when labelled and annotated and used in the answer.
- **Case studies**: one place at the right scale, its hazards and problems, each solution judged on social, economic and environmental sustainability.

Quick check

1. Earthquake X has magnitude 7.5 and earthquake Y magnitude 5.5. How many times greater is the ground movement in X, and roughly how many times more energy does it release?
2. A tsunami crosses an ocean 4000 m deep. Find its speed in km/h, and how long it takes to travel 2500 km. How fast does it travel when it reaches water 50 m deep?
3. A hurricane has a central pressure of 935 hPa where the surrounding pressure is 1010 hPa. Its storm surge is 4.5 m. How much of the surge is due to low pressure alone, and what percentage is due to the wind?
4. A block of soil weighing 1000 kN rests on a 30° slope. The friction holding it equals 0.7 × the force pressing it into the slope. Find the factor of safety. After heavy rain, pore water pressure cuts the force pressing it into the slope by 40%. Find the new factor of safety and say what happens.
5. Explain why tornadoes are harder to predict than tropical cyclones.

Answers

1. Ground movement: $10^{7.5-5.5} = 10^2 = 100$ times. Energy: $10^{1.5\times2} = 10^3 = 1000$ times (about 32×32).
2. $v = \sqrt{9.81 \times 4000} = 198$ m/s $= 198 \times 3.6 = 713$ km/h. Time $= 2500 \div 713 = 3.5$ hours. In 50 m of water: $\sqrt{9.81 \times 50} = 22.1$ m/s $= 80$ km/h, so it slows sharply and grows in height.
3. Pressure fall $= 1010 - 935 = 75$ hPa, so about 75 cm, or 0.75 m. The wind causes $4.5 - 0.75 = 3.75$ m, which is $3.75 \div 4.5 \times 100 = 83\%$ of the surge.
4. Downslope force $= 1000 \sin 30^\circ = 500$ kN; force into the slope $= 1000 \cos 30^\circ = 866$ kN; friction $= 0.7 \times 866 = 606$ kN; factor of safety $= 606 \div 500 = 1.21$, stable. After rain the force into the slope is $866 \times 0.6 = 520$ kN, friction $= 0.7 \times 520 = 364$ kN, and the factor of safety $= 364 \div 500 = 0.73$, below 1: the **slope fails**. The rain did not change the slope angle or the weight much; it removed strength.
5. Tropical cyclones are hundreds of kilometres across, form over oceans in known regions and seasons, and last days, so satellites and aircraft track them and models forecast their paths days ahead. Tornadoes are tens to hundreds of metres wide, form within minutes from only some thunderstorms, last minutes, and follow short, erratic paths, so forecasters can only say a region is at risk (a watch) and then warn minutes ahead when radar detects rotation.

Past questions to try

- **9696/33/M/J/25 Q7**: a map of storm-surge heights in a bay, then reasons for the variations.
- **9696/31/M/J/25 Q8**: essay on the effectiveness of methods of managing volcanic hazards.
- **9696/32/O/N/25 Q9**: case study essay on solutions to the problems of sustainable management.
- **9696/33/M/J/24 Q7**: the spread of a tsunami across an ocean, then how a tsunami forms.