Section 3.1 Activities

1 Describe the main features of an island arc system.
2 Briefly explain how island arcs are formed.

3.2 Weathering and rocks

Weathering is the decomposition and disintegration of rocks *in situ*. Decomposition refers to chemical weathering and creates altered rock substances, such as kaolinite (china clay) from granite. By contrast, disintegration or mechanical weathering produces smaller, angular fragments of the same rock, such as scree. A third type, biological weathering, has been identified, whereby plants and animals chemically alter rocks and physically break rocks through their growth and movement. Biological weathering is not a separate type of weathering, but a form of disintegration and decomposition. It is important to note that these processes are interrelated rather than operating in isolation.

Weathering is central to landscape evolution, as it breaks down rock and enables erosion and transport. A number of key features can be recognised:

- Many minerals are formed under high pressure and high temperatures in the Earth's core. As they cool, they become more stable.
- Weathering produces irreversible changes in a rock. Some rocks change from a solid state to a fragmented or clastic state, such as scree. Others are changed to a pliable or plastic state, such as clay.
- Weathering causes changes in volume, density, grain size, surface area, permeability, consolidation and strength.
- Weathering forms new minerals and solutions.
- Some minerals, such as quartz, may resist weathering.
- Minerals and salts may be removed, transported, concentrated or consolidated.
- Weathering prepares rocks for subsequent erosion and transport.
- New landforms and features are produced.

Physical/mechanical weathering

There are four main types of mechanical weathering: freeze–thaw (ice crystal growth), salt crystal growth, disintegration and pressure release. Mechanical weathering operates at or near the Earth's surface, where temperature changes are most frequent.

Freeze–thaw (also called 'ice crystal growth' or 'frost shattering') occurs when water in joints and cracks freezes at 0°C. It expands by about 10 per cent and exerts pressure up to a maximum of 2100 kg/cm² at –22°C. These pressures greatly exceed most rocks' resistance (Table 3.2). However, the average pressure reached in freeze–thaw is only 14 kg/cm².

Table 3.2 Resistance to weathering

Rock	Resistance (kg/cm²)
Marble	100
Granite	70
Limestone	35
Sandstone	7–14

Freeze–thaw is most effective in environments where moisture is plentiful and there are frequent fluctuations above and below freezing point. Hence it is most effective in periglacial and alpine regions. Freeze–thaw is most rapid when it operates in connection with other processes, notably pressure release and salt crystallisation.

Salt crystallisation causes the decomposition of rock by solutions of salt. There are two main types of salt crystal growth. First, in areas where temperatures fluctuate around 26–28°C, sodium sulphate (Na_2SO_4) and sodium carbonate (Na_2CO_3) expand by about 300 per cent. This creates pressure on joints, forcing them to crack. Second, when water evaporates, salt crystals may be left behind. As the temperature rises, the salts expand and exert pressure on rock. Both mechanisms are frequent in hot desert regions where low rainfall and high temperatures cause salts to accumulate just below the surface. It may also occur in polar areas when salts are deposited from snowflakes.

Experiments investigating the effectiveness of saturated salt solutions have shown a number of results.

- The most effective salts are sodium sulphate, magnesium sulphate and calcium chloride.
- Chalk decomposes fastest, followed by limestone, sandstone and shale.
- The rate of disintegration of rocks is closely related to porosity and permeability.
- Surface texture and grain size control the rate of rock breakdown. This diminishes with time for fine materials and increases over time for coarse materials.
- Salt crystallisation is more effective than insolation weathering, hydration or freeze–thaw. However, a combination of freeze–thaw and salt crystallisation produces the highest rates of breakdown.

Heating and cooling may cause disintegration in hot desert areas where there is a large diurnal temperature range. In many desert areas, daytime temperatures exceed 40°C, whereas night-time ones are little above freezing. Rocks heat up by day and contract by night. As rock is a poor conductor of heat, stresses occur only in the outer layers. This causes peeling or exfoliation to occur. Griggs (1936) showed that moisture is essential for this to happen. In the absence of moisture, temperature change alone did not cause the rocks to break down. The role of salt in insolation weathering has also been studied.

The expansion of many salts such as sodium, calcium, potassium and magnesium has been linked with exfoliation. However, some geographers find little evidence to support this view.

Pressure release (dilatation) is the process whereby overlying rocks are removed by erosion. This causes underlying rocks to expand and fracture parallel to the surface. The removal of a great weight, such as a glacier, has the same effect. Rocks are formed at very high pressure in confined spaces in the Earth's interior. The **unloading** of pressure by the removal of overlying rocks causes cracks or joints to form at right-angles to the unloading surface. These cracks are lines of weakness within the rock. For example, if overlying pressure is released, horizontal **pseudo-bedding planes** will be formed. By contrast, if horizontal pressure is released, as on a cliff face, vertical joints will develop. The size and spacing of cracks varies with distance from the surface: with increasing depth, the cracks become smaller and further apart. Hence the part of the rock that is broken the most is the part that is most subjected to denudation processes, namely at the surface.

Vegetation roots may also physically break down rocks. Figure 3.11 shows the impact of plants roots helping to break up rock.

Figure 3.11 Biological weathering – the physical impact of plant roots

Section 3.2 Activities

1. Define mechanical weathering.
2. Explain how freeze–thaw weathering operates.
3. Comment on the resistance to weathering (Table 3.2) compared with the pressure exerted by ice when it expands.
4. Describe the process of heating/cooling. Explain why it is common in hot, arid environments.

Chemical weathering

Water is the key medium for chemical weathering. Unlike mechanical weathering, chemical weathering is most effective sub-surface since percolating water has gained organic acids from the soil and vegetation. Acidic water helps to break down rocks such as chalk, limestone and granite. The amount of water is important as it removes weathered products by solution. Most weathering therefore takes place above the water table, since weathered material accumulates in the water and saturates it. There are three main types of chemical weathering: carbonation-solution, hydrolysis and hydration.

Carbonation-solution occurs on rocks with calcium carbonate, such as chalk and limestone. Rainfall combines with dissolved carbon dioxide or organic acid to form a weak carbonic acid.

$CO_2 + H_2O \leftrightarrow H_2CO_3$ (carbonic acid)

Calcium carbonate (calcite) reacts with an acid water and forms **calcium bicarbonate** (also termed 'calcium hydrogen carbonate'), which is soluble and removed by percolating water:

$$CaCO_3 + H_2CO_3 \rightarrow Ca(HCO_3)_2$$
calcite + carbonic acid → calcium bicarbonate

The effectiveness of solution is related to the pH of the water. For example, iron is highly soluble when the pH is 4.5 or less, and alumina (Al_2O_3) is highly soluble below 4.0 or above 9.0 but not in between.

Hydrolysis occurs on rocks with orthoclase feldspar, notably granite. Feldspar reacts with acid water and forms **kaolin** (also termed 'kaolinite' or 'china clay'), silicic acid and potassium hydroxyl:

$$2KAlSi_3O_8 + 2\,H_2O \rightarrow Al_2Si_2O_5\,(OH)_4 + K_2O + 4\,SiO_2$$
orthoclase feldspar + water → kaolinite + potassium hydroxyl + silicic acid

The acid and hydroxyl are removed in the solution, leaving kaolin behind as the end product. Other minerals in the granite, such as quartz and mica, remain in the kaolin. Hydrolysis also involves solution as the potassium hydroxyl is carbonated and removed in solution.

Hydration is the process whereby certain minerals absorb water, expand and change. For example, anhydrite is changed to gypsum. Although it is often classified as a type of chemical weathering, mechanical stresses occur as well. When anhydrite ($CaSO_4$) absorbs water to become gypsum ($CaSO_4.2H_2O$) it expands by about 0.5 per cent. More extreme is the increase in volume of up to 1600 per cent by shales and mudstones when clay minerals absorb water.

Section 3.2 Activities

1. Compare the character of rocks affected by mechanical weathering with those affected by chemical weathering.
2. Briefly explain the processes of carbonation-solution and hydrolysis.

Controls of weathering

The following factors affect the type and rate of weathering that takes place.

Climate

In the simplest terms, the type and rate of weathering vary with climate (Figure 3.12), but it is very difficult to isolate the exact relationship, at any scale, between climate type and rate of process. Peltier's diagrams (1950) show how weathering is related to moisture availability and average annual temperature (Figure 3.13; see also Table 3.3). In general, frost-shattering increases as the number of freeze–thaw cycles increases. By contrast, chemical weathering increases with moisture and heat. According to **Van't Hoff's Law**, the rate of chemical weathering increases 2–3 times for every increase in temperature of 10 °C (up to a maximum temperature of 60 °C). The efficiency of freeze–thaw, salt crystallisation and insolation weathering is influenced by:

- critical temperature changes
- frequency of cycles
- diurnal and seasonal variations in temperature.

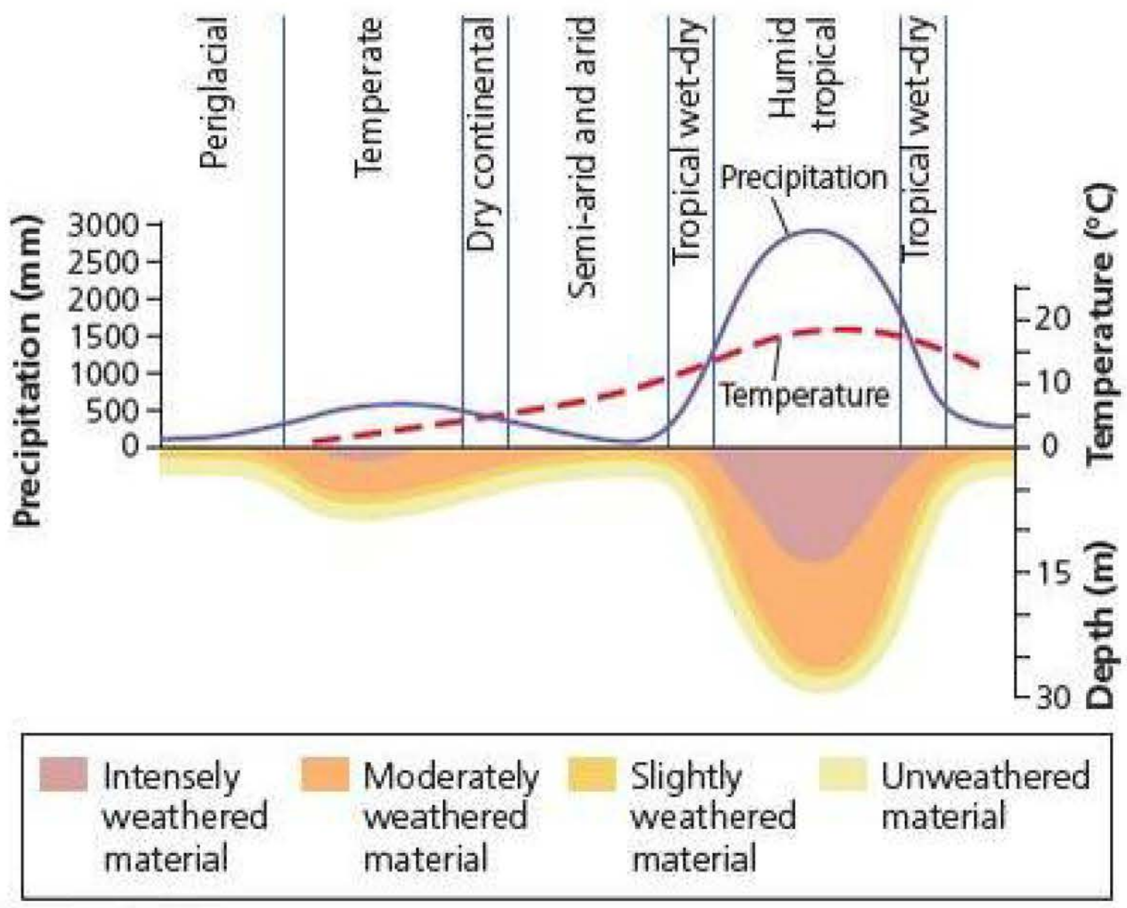

Figure 3.12 Depth of weathering profile and climate

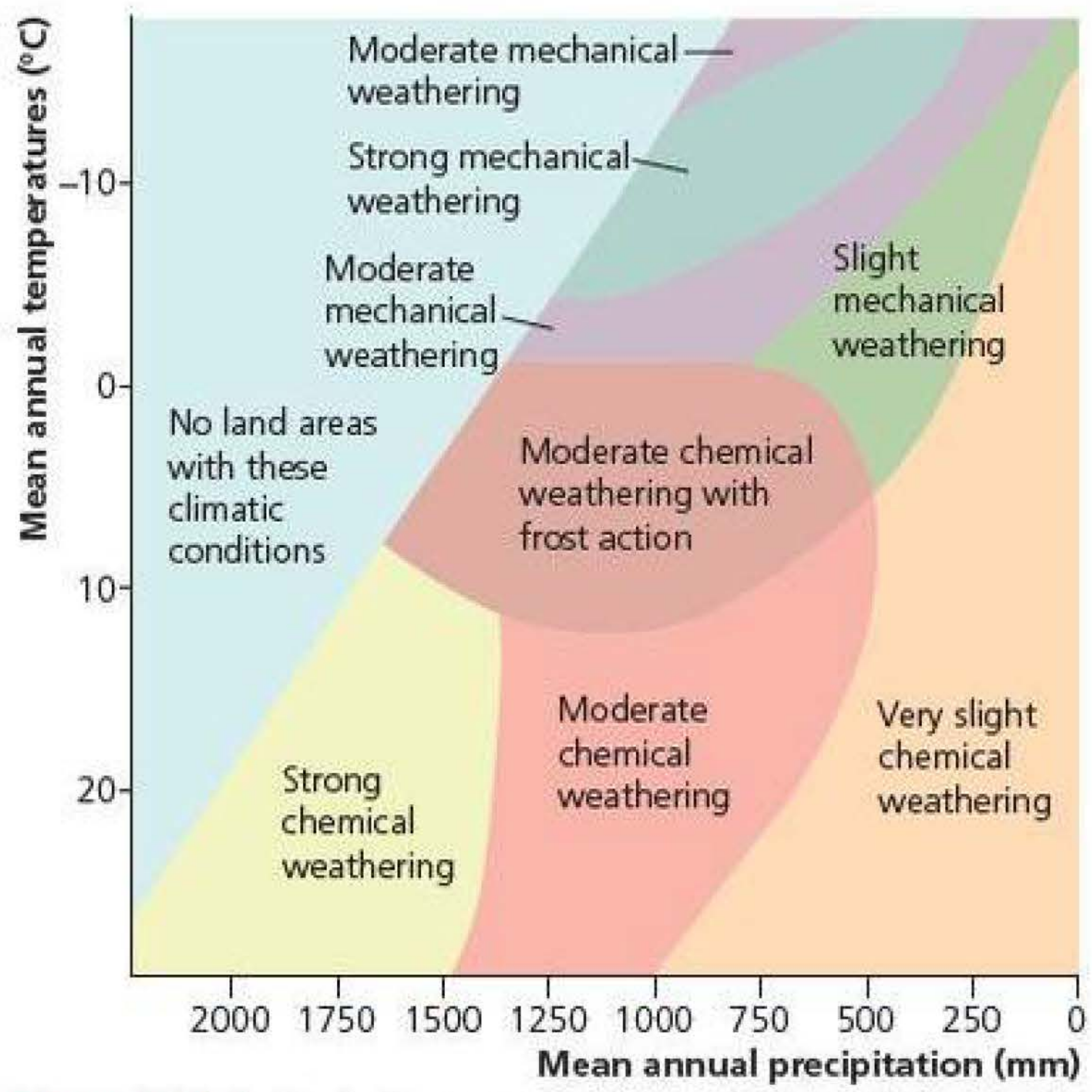

Figure 3.13 Peltier's diagram showing variations of chemical and mechanical weathering with climate

Table 3.3 Generalised weathering characteristics in four climatic regions

Climatic region	Characteristics	Examples – rates of weathering (mm yr^{-1})
Glacial/ Periglacial	Frost very important. Susceptibility to frost increases with increasing grain size. **Taiga:** fairly high soil leaching, low rates organic matter decomposition. **Tundra:** low precipitation, low temperatures, permafrost – moist conditions, slow organic production and breakdown. May have slower chemical weathering. Algal, fungal, bacterial weathering may occur. Granular disintegration occurs. Hydrolytic action reduced on sandstone, quartzite, clay, calcareous shales, phyllites, dolerites. Hydration weathering common due to high moisture. CO_2 is more soluble at low temperatures.	Narvik 0.001 Spitzbergen 0.02–0.2 Alaska 0.04
Temperate	Precipitation and evaporation generally fluctuate. Both mechanical weathering and chemical weathering occur. Iron oxides leached and redeposited. Carbonates deposited in drier areas, leached in wetter areas. Increased precipitation, lower temperatures, reduced evaporation. Organic content moderate to high, breakdown moderate. Silicate clays formed and altered. **Deciduous forest areas:** abundant bases, high nutrient status, biological activity moderate to high. **Coniferous areas:** acidic, low biological activity, leaching common.	Askrigg 0.5–1.6 Austria 0.015–0.04
Arid/semi-arid	Evaporation exceeds precipitation. Rainfall low. Temperatures high, seasonal. Organic content low. Mechanical weathering, salt weathering, granular disintegration, dominant in driest areas. Thermal effects possible. Low organic input relative to decomposition. Slight leaching produces $CaCO_3$ in soil. Sulphates and chlorides may accumulate in driest areas. Increased precipitation and decreased evaporation toward semi-arid areas and steppes yield thick organic layers, moderate leaching and $CaCO_3$ accumulation.	Egypt 0.0001–2.0 Australia 0.6–1.0
Humid tropical	High rainfall often seasonal. Long periods of high temperatures. Moisture availability high. Weathering products **a** removed or **b** accumulate to yield red and black clay soils, ferruginous and aluminous soils (lateritic), calcium-rich soils. Calcareous rocks generally heavily leached where silica content is high, soluble weathering products removed and parent silica in stable products are sandy. Where products remain, iron and aluminium are common. Usually intense deep weathering, iron and alumina oxides and hydroxides predominate. Organic content high but decomposition high.	Florida 0.005

Rock type

Rock type influences the rate and type of weathering in many ways due to:

- chemical composition
- the nature of cements in sedimentary rock
- joints and bedding planes.

For example, limestone consists of calcium carbonate and is therefore susceptible to carbonation-solution. By contrast, granite is prone to hydrolysis because of the presence of feldspar. In sedimentary rocks, the nature of the cement is crucial. Iron-oxide based cements are prone to oxidation, whereas quartz cements are very resistant.

Rock structure

The effect of rock structure varies from large-scale folding and faulting to localised patterns of joints and bedding planes. Joint patterns exert a strong control on water movement. These act as lines of weakness, thereby creating **differential resistance** within the same rock type. Similarly, grain size influences the speed with which rocks weather. Coarse-grained rocks weather quickly owing to a large void space and high permeability (Table 3.4). On the other hand, fine-grained rocks offer a greater surface area for weathering and may be highly susceptible to weathering. The importance of individual minerals was stressed by Goldich in 1938. Rocks formed of resistant minerals, such as quartz, muscovite and feldspar in granite, will resist weathering (Figure 3.14). By contrast, rocks formed of weaker minerals will weather rapidly. The interrelationship of geology and climate on the development of landforms is well illustrated by limestone and granite.

Table 3.4 Average porosity and permeability for common rock types

Rock type	Porosity (%)	Relative permeability
Granite	1	1
Basalt	1	1
Shale	18	5
Sandstone	18	500
Limestone	10	30
Clay	45	10
Silt	40	–
Sand	35	1 100
Gravel	25	10 000

Source: D. Brunsden, 'Weathering processes' in C. Embleton and J. Thornes (eds), Processes in Geomorphology, *Edward Arnold 1979*

Stability	Dark-coloured minerals	Light-coloured minerals	Susceptibility
Least stable	Olivine		Most susceptible
		Lime plagioclase	
	Augite		
		Lime soda plagioclase	
	Hornblende	Soda lime plagioclase	
		Soda plagioclase	
	Biotite		
Most stable	Orthoclase	Muscovite Quartz	Least susceptible

Figure 3.14 Goldich's weathering system

Vegetation

The influence of vegetation is linked with the type of climate and the nature of the soil. Moisture content, root depth and acidity of humus will influence the nature and rate of weathering. Vegetation weathers rocks in two main ways: through the secretion of organic acids, it helps to chemically weather the soil; and through the growth of roots, it physically weathers the soil.

Depth of soil may have an effect on the amount of weathering that occurs. Soils may protect rocks from further breakdown – or they may increase the rate of breakdown due to the vegetation it supports.

Relief

For weathering to continue, weathered material needs to be removed. If the slope is too shallow, removal might not occur. If the slope is too steep, water may flow over the surface. Hence, intermediate slope angles may produce most weathering.

Aspect is also important, as there may be important temperature differences between south- and north-facing slopes. However, this is important only if the temperature differences are around a critical temperature, for example 0°C for freeze–thaw weathering.

Section 3.2 Activities

1. a Define the terms *porosity* and *permeability*.
   b Choose a suitable method to show the relationship between porosity and permeability.
   c Describe the relationship between porosity and permeability.
   d What are the exceptions, if any, to this relationship?
2. Describe and explain how the type and intensity of mechanical weathering varies with climate.
3. Describe and explain how the type and intensity of chemical weathering varies with climate.
4. How useful are mean annual temperature and mean annual rainfall as a means of explaining variations in the type and intensity of weathering processes?
5. Describe two ways in which vegetation affects the type and rate of weathering.