CIE Geography A-level

8: Coastal Environments

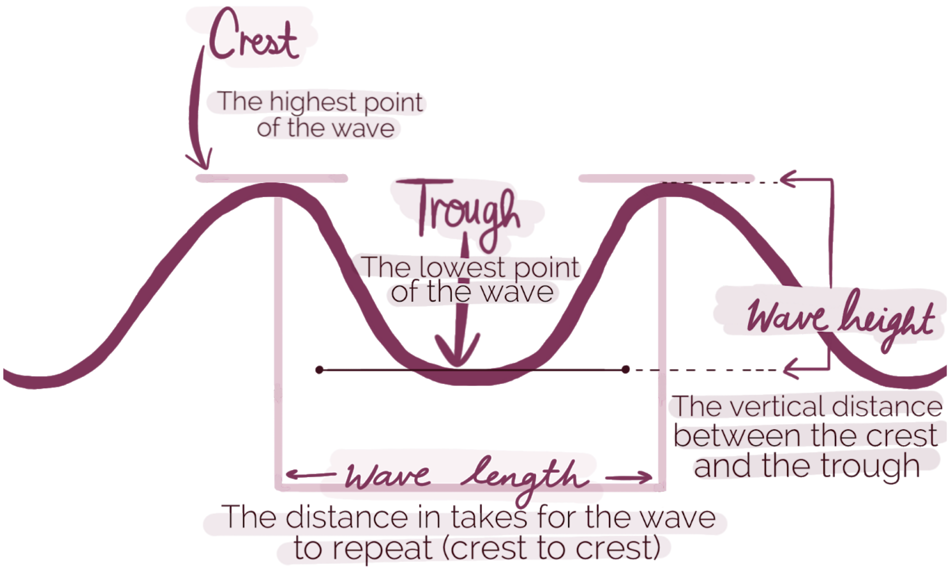
Detailed Notes

Wave Generation and Characteristics

Waves have the power to **shape a coastal environment**, creating new **landforms** and **eroding away the beach**.

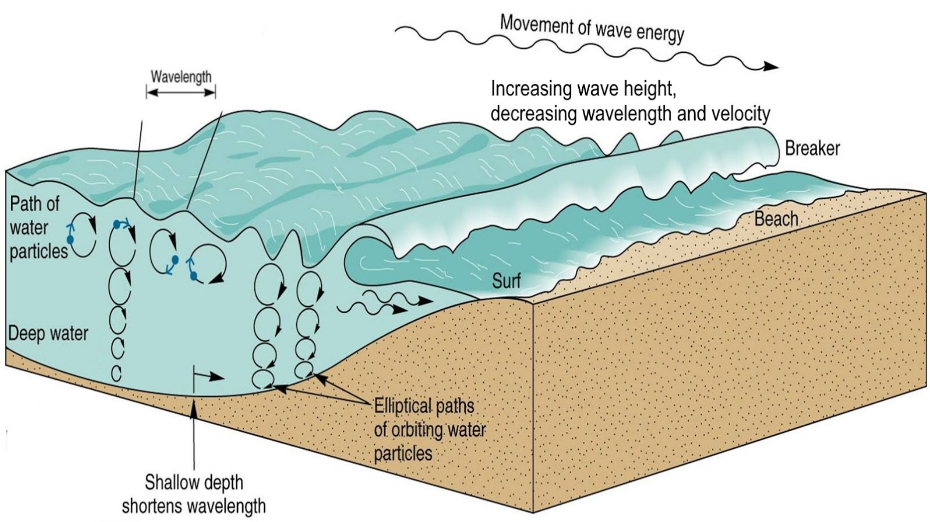
Characteristics of Waves

The crest, trough, wavelength, and wave height can be measured in a wave. These components show the **characteristics of a wave**.



Wave Formation

- Winds move **across the surface of the water**, causing **frictional drag** (resistance to the wind by the water) which creates **small ripples and waves**. This leads to a **circular orbital motion of water particles** in the ocean.
- As the **seabed becomes shallower** towards the coastline, the **orbit of the water particles becomes more elliptical**, leading to **more horizontal movement of the waves.**
- The **wave height increases, but the wavelength (distance between two waves) and wave velocity both decrease**.
- This causes **water to back up from behind the wave** until the **wave breaks (collapses) and surges up the beach**.



The size and the energy of a wave is influenced by 3 factors:

1. **Strength of the Wind:** Wind is essentially air that moves from an area of high pressure to an area of low pressure. The different pressure areas are caused by variations in surface heating by the sun. The larger the difference in pressure between two areas (pressure gradient) the stronger the winds. As waves are caused by the wind, stronger winds also mean stronger waves.

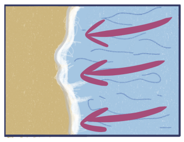
2. **Duration of the Wind:** If the wind is active for longer periods of time, then the energy of the waves will build up and increase.

3. **Size of the Fetch:** Fetch is the distance over which the wind blows. The larger it is, the more powerful the waves will be.

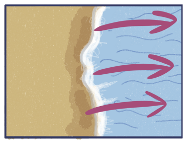
Swash and Backwash

Waves move onto and off a beach by swash and backwash.

Swash: The movement of the wave onto the beach after a wave breaks. Material being carried by waves is deposited onto the beach.



Backwash: The movement of the wave back down the beach. Backwash drags any material off a beach.



Wave Types

Constructive waves tend to deposit material, which creates depositional landforms and increase the size of beaches. In constructive waves, the swash is stronger than the backwash.

Destructive waves act to remove depositional landforms through erosion, which work to decrease the size of a beach. In destructive waves, the backwash is stronger than the swash.

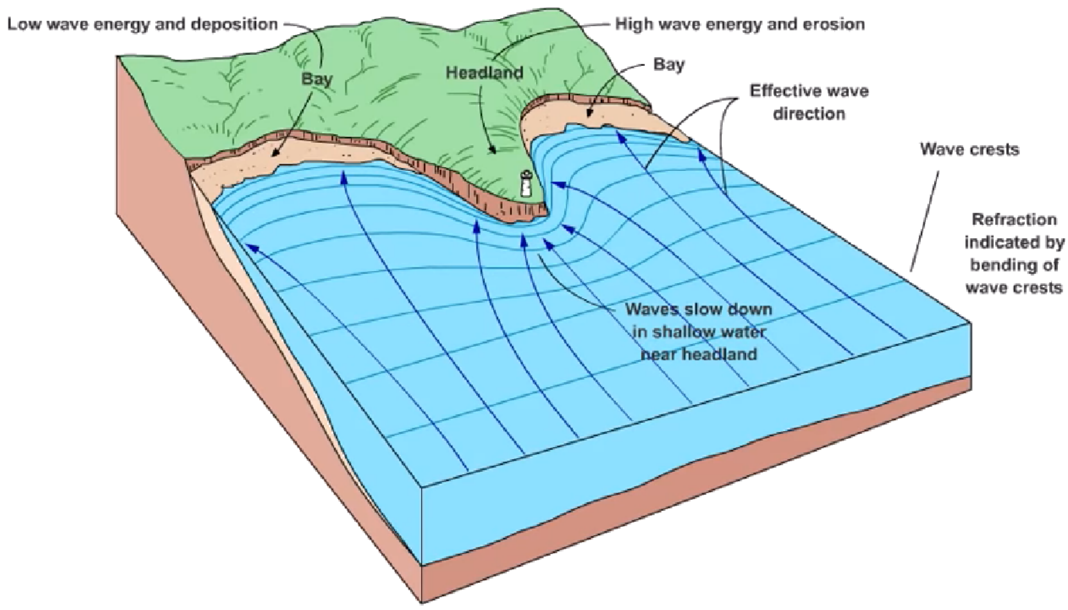
	Constructive	Destructive
Formation	Formed by weather systems that operate in the open ocean	Localised storm events with stronger winds operating closer to the coast
Wavelength	Long wavelength	Short wavelength
Frequency	6-9 Per Minute	11-16 Per Minute
Wave Characteristics	Low waves, which surge up the beach	High waves, which plunge onto the beach
Swash Characteristics	Strong swash, weak backwash	Weak swash, strong backwash
Effect on Beach	Occurs on gently sloped beaches	Occurs on steeply sloped beaches

High-energy coastlines are associated with more powerful waves, so occur in areas where there is a **large fetch.** They typically have **rocky headlands and landforms** and fairly frequent **destructive waves**. As a result these coastlines are often eroding as the **rate of erosion exceeds the rate of deposition**.

Low-energy coastlines have less powerful waves and occur in **sheltered areas** where **constructive waves** prevail and as a result these are often **fairly sandy areas**. There are **landforms of deposition** as the rates of **deposition exceed the rates of erosion**.

Wave Refraction

Wave refraction is the process by which waves turn and lose energy around a headland on uneven coastlines. The **wave energy is focussed on the headlands**, creating **erosive features** in these areas. The energy is **dissipated in bays** leading to the formation of features associated with **lower energy environments** such as beaches.



(Source: https://www.youtube.com/watch?v=G1FIBuybN78)

Why Waves Break

- Waves **interact with the sea floor** when they move into shallower waters near the shore. This causes **friction** between the wave and the floor, causing the wave to **slow down**.
- The **wavelength decreases** when the wave slows down, causing the wave to become **steeper**. This process is called **shoaling**.

- The **shoaling** process continues until the **wave height** can no longer be supported as it is too high (1:7 height:length), and at this point the wave breaks.

Marine Erosion

Erosion is the **removal of sediment from a coastline**. The main processes of erosion are outlined below:

- **Hydraulic Action** - As a wave crashes onto a rock or cliff face, **air is forced into cracks, joints and faults** within the rock. The high pressure causes the **cracks to force apart and widen** when the wave retreats and the air expands. Over time this causes the rock to fracture. Bubbles found within the water may **implode under the high pressure** creating tiny jets of water that over time erode the rock. This erosive process is **cavitation**.
- **Corrasion** - Sand and pebbles are picked up by the sea from an **offshore sediment sink** or temporal store and **hurled against the cliffs** at high tide, causing the cliffs to be eroded. The shape, size, weight and quantity of sediment picked up, as well as the wave speed, affects the erosive power of this process.
- **Abrasion** - This is the process where sediment is **moved along the shoreline**, causing it to be **worn down over time**. The stones **rubbing** against things acts like **sandpaper**, wearing down materials over time.
- **Solution** - The process of water **dissolving** rocks and material into **solutions**. The **mildly acidic seawater** can cause **alkaline rock** such as limestone to be eroded and is very similar to the process of **carbonation weathering**.
- **Attrition** - Wave action cause **rocks and pebbles to hit against each other**, wearing each other down and so becoming round and eventually smaller. Attrition is an erosive process within the coastal environment, but has little to no effect on erosion of the coastline itself.

Sub-Aerial Processes

Weathering

Weathering is the **breakdown of rocks** (mechanical, biological or chemical) over time.

Mechanical (Physical) Weathering: the breakdown of rocks due to exertion of physical forces without any chemical changes taking place. Mechanical weathering processes in coastal environments include:

- **Freeze-thaw (Frost-Shattering):** Water enters cracks in rocks and then the water **freezes** overnight during the winter. As it freezes, **water expands by around 10%** in volume which increases the pressure acting on a rock, causing cracks to develop. Over time these cracks grow, weakening the cliff making is more vulnerable to other processes of erosion.
- **Salt Crystallisation:** As seawater **evaporates**, salt is left behind. Salt crystals will grow over time, exerting pressure on the rock, which forces the cracks to widen. Salt can also **corrode ferrous (materials that contains iron) rock** due to chemical reactions.

- **Wetting and Drying:** Rocks such as clay **expand when wet** and then contract again when they are drying. The frequent **cycles of wetting and drying** at the coast can cause these rocks and cliffs to break up.

Chemical Weathering: The breakdown of rocks through chemical reactions.

- **Carbonation:** **Rainwater absorbs CO_2** from the air to create a **weak carbonic acid**. The acid then reacts with **calcium carbonate** in rocks to form **calcium bicarbonate,** which can then be easily dissolved. **Acid rain** reacts with **limestone** to form **calcium bicarbonate**, which is then easily dissolved allowing erosion.
- **Oxidation:** When **minerals** become exposed to the air through **cracks and fissures**, the mineral will become oxidised which will **increase its volume** (contributing to mechanical weathering), causing the rock to crumble. The most common oxidation within rocks is iron minerals becoming iron oxide, turning the rock rusty orange after being exposed to the air.
- **Solution:** When rock minerals such as **rock salt** are dissolved.

Biological Weathering: The breakdown of rocks by **organic activity**.

- **Root action** - Roots of plants grow into the cracks of rocks, which exerts pressure, eventually splitting the rocks. Research **Angkor Wat** for more information on this, even though it is not coastal!
- **Birds** - Some birds such as **puffins** dig burrows into cliffs weakening them and making erosion more likely.
- **Rock Boring** - Many species of **clams** secrete chemicals that dissolve rocks and **piddocks** may burrow into the rock face.
- **Seaweed Acids** - Some seaweeds contain pockets of **sulphuric acid**, which if hit against a rock or cliff face, the acid will dissolve some of the rock's minerals. (e.g. Kelp).
- **Decaying Vegetation** - Water that flows through decaying vegetation and then over coastal areas, will be acidic, thus causing chemical weathering.

Mass Movement

Mass movement is the **movement of material down a slope under the influence of gravity**. Mass movement can be categorised into four main areas: **heaves, flows, slides and falls**. The type of mass movement is dependent on:

- Cliff/slope angle
- Rock type
- Rock structure
- Vegetation
- Saturation of ground
- Presence of weathering

The different types of mass movement include:

Soil Creep: The **slowest** but most continuous form of mass movement involving the movement of soil particles downhill. Particles rise and fall due to **wetting and freezing,** and this causes the soil to move down the slope. It leads to the formation of **shallow terracettes**.

(Source: commons.wikimedia.org/w/index.php?curid=14080343)

Mudflows: An increase in the water content of soil can reduce friction, leading to earth and mud to **flow over underlying bedrock**, or slippery materials such as clay. Water can get trapped within the rock increasing **pore water pressure**, which forces rock particles apart and therefore weakens the slope. Mudflows represent a **serious threat to life** as they can be very fast flowing.

(Source:www.denverpost.com)

Rockfall: Occurs on sloped cliffs (over 40°) when **exposed to mechanical weathering**, though mostly occurs on **vertical cliff faces** and can be triggered by earthquakes. It leads to **scree** (rock fragments) building up at the base of the slope.

(Source:www.geostru.eu/rockfall-analysis/)

Landslides and Rockslides: Heavy rainfall leads to **water between joints and bedding planes** in cliffs (which are **parallel to the cliff face**) which can **reduce friction and lead to a landslide**. It occurs when a **block of intact rock** moves down the cliff face very quickly along a flat slope.

(Source:https://blogs.agu.org/landslideblog/2017/05/15/)

Marine Transportation and Deposition

Coastal transportation is responsible for transferring sediment within a sediment cell and between other sediment cells. The four main processes of **transportation** are:

- **Traction** – Large, heavy **sediment rolls along the sea bed** pushed by currents.
- **Saltation** – Smaller sediment bounces along the sea bed, being **pushed by currents**. The **sediment is too heavy** to be picked up by the flow of the water.
- **Suspension** – Small sediment is carried within the flow of the water. **Greater velocities of water are able to suspend larger and heavier pieces of sediment**.
- **Solution** – **Dissolved material is carried** within the water, potentially in a chemical form. This method of transportation is an important part of carbonation weathering.

Deposition

Deposition occurs when sediment becomes too heavy for the water to carry, or if the wave loses energy. Deposition tends to be a gradual and continuous process, so a wave won't release all its sediment at the same time. This explains why beaches are often either sandy or rocky and these areas are very distinct on the same beach.

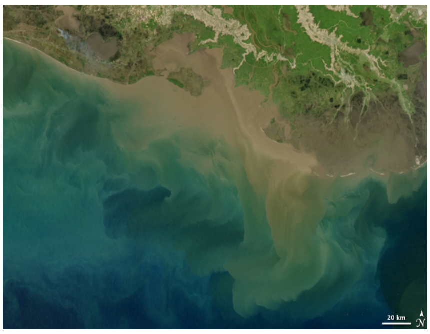
High-energy coastlines continue to transport smaller sediment, so larger rocks and shingle are deposited in these environments. Low-energy coastlines have much smaller sediment, which is only deposited in these areas where there is a much lower water velocity. As a result, specific landforms of deposition will occur. Two types of deposition are explained below:

- **Gravity Settling:** The water's velocity decreases so sediment begins to be deposited.
- **Flocculation:** This is an important process in salt and tidal marshes. Clay particles clump together due to chemical attraction and then sink due to their high density.

Sediment Sources

Rivers:

- Most of the sediment in the coastal zone is a result of an input from rivers, especially in high-rainfall environments where significant river erosion occurs. This is demonstrated by the image of the Gulf of Mexico and the sediment flowing from a river delta (Source: NASA)
- Sediment may be deposited in estuaries which are brackish (salty) areas where rivers flow into the sea. They are important wildlife habitats. The sediment is then transported throughout the coastal system by waves, tides and currents.



Cliff Erosion:

- Very important in areas with unconsolidated (uncompacted and therefore unstable) cliffs that are eroded easily. In some areas, coastlines can retreat by up to 10m per year, providing a significant sediment input. Most erosion occurs during the winter months due to more frequent storms.

Wind:

- Wind is a coastal energy source and can cause sand to be blown along or up a beach.
- Sediment transport by winds may occur where there are sand dunes or in glacial and desert environments which provide sediment inputs.

Glaciers:

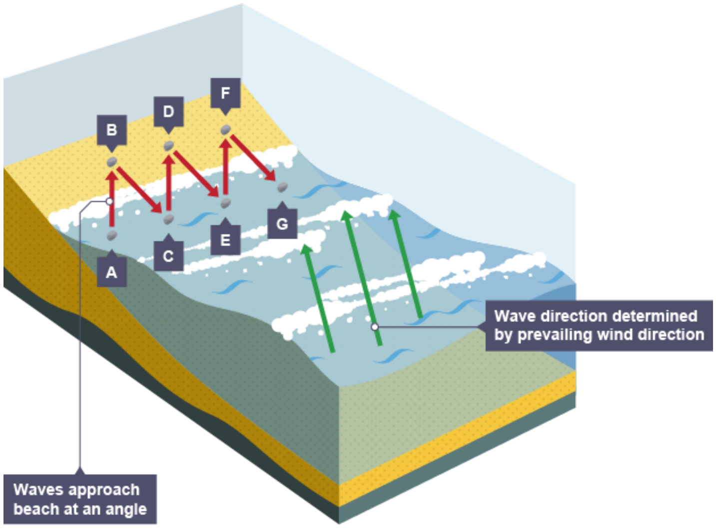
- In some coastal systems such as in Antarctica, Greenland, Alaska and Patagonia, glaciers flow directly into the ocean depositing sediment that was stored in the ice.
- This occurs when glaciers calve, a process where ice breaks off the glacier.

Offshore:

- Sediment is transferred to the coastal zone when **waves, tides and currents erode offshore sediment sinks** such as **offshore bars**. The sediment is transported onto the beach, helping to build up the beach.
- **Storm surges or tsunami waves** may also transfer sediment into the coastal zone.

Longshore Drift:

- Waves hit the beach at an **angle** determined by the direction of the **prevailing wind**
- The waves **push sediment in this direction** and up the beach in the **swash**
- Due to gravity, the wave then carries sediment back down the beach in the **backwash**
- This moves sediment **along the beach** over time
- It is one of the reasons why when swimming in the sea, you often move along the coast in a **particular direction**.



Source: BBC

The images show how the process of longshore drift occurred to block off the Pohoiki Boat Ramp in Hawaii when the Kilauea volcano erupted in 2018. Volcanic material was **transported along the coastline by longshore drift, leading to deposition and beach formation**. This formed a **spit** off the breakwater before eventually blocking the entire boat ramp. It demonstrates how quickly the process of longshore drift can have an impact on shaping the coastal environment.

Source: USGS and West Hawaii Today

Sediment Cells

Coasts can be split into sections called **sediment cells** which are often bordered by **prominent headlands**. Within these sections, the **movement of sediment is almost contained** and the flows of sediment act in **dynamic equilibrium**.

Dynamic equilibrium refers to the maintenance of a **balance** in a natural system, despite it being in a **constant state of change**. The system has a tendency to **counteract any changes** imposed on the system in order to keep this balance, which is achieved by **inputs** and **outputs** constantly changing to maintain the balance. Dynamic equilibrium in a sediment cell is where input and outputs of sediment are in a constant state of change but **remain in balance**.

Sediment cells are split up into smaller cells called **sub-cells**.

Erosional Landforms

Cliff Profile and Rate of Retreat

Cliffs are formed as a result of **weathering and erosional processes** in coastal environments.

Steep Cliffs: Most common where the **rock is strong and fairly resistant** to erosion. **Sedimentary rocks that have vertical strata** are also more resistant to erosion, creating steep cliffs. An absence of a beach, long-fetch and high energy waves also promote steep cliff development. Most commonly found in **high-energy environments**.

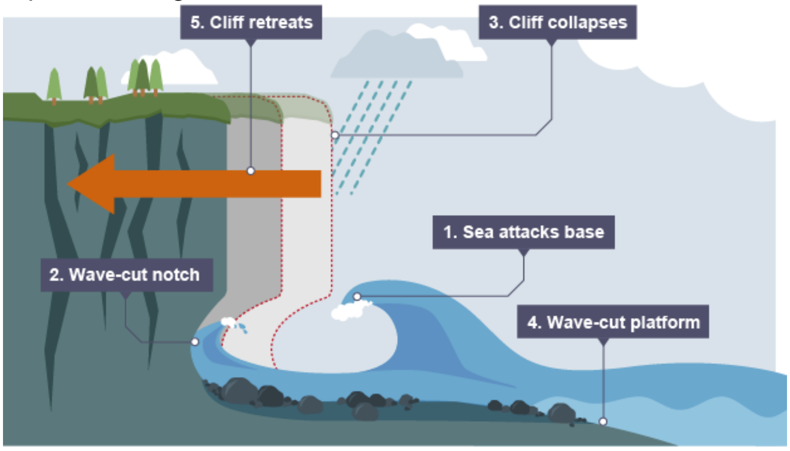
Gentle Cliffs: Most commonly found in **areas with weaker rocks** which are **less resistant to erosion** and are prone to slumping. **Low-energy waves** and a **short fetch** will lead to the formation of a scree mound at the base of the cliff, reducing the overall cliff angle. A large beach would also reduce wave energy and prevent the development of steep cliffs by reducing erosion rates. Most commonly found in **low-energy environments**.

Rate of Retreat: Dependent on the relative importance of **marine factors** (fetch, beach, wave energy) and **terrestrial factors** (subaerial processes, geology, rock strength). The cliff's most likely to retreat are those that are made of **unconsolidated rock** and sands.

The White Cliffs of Dover
(Source: By Immanuel Giel - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=25365041)

Wave-cut Notch and Platform

- When waves **erode a cliff**, the erosion is mostly **concentrated around the high-tide line**. The main processes of **hydraulic action and corrasion** create a **wave-cut notch**.
- As the notch becomes deeper (and sub-aerial weathering weakens the cliff from the top) the **cliff face becomes unstable** and falls under its own weight through **mass movement**.
- This leaves behind a **platform** of the unaffected cliff base beneath the **wave-cut notch**.
- Over time the same processes repeat leading to a **wave-cut platform** to be formed, which is normally exposed at high-tide.

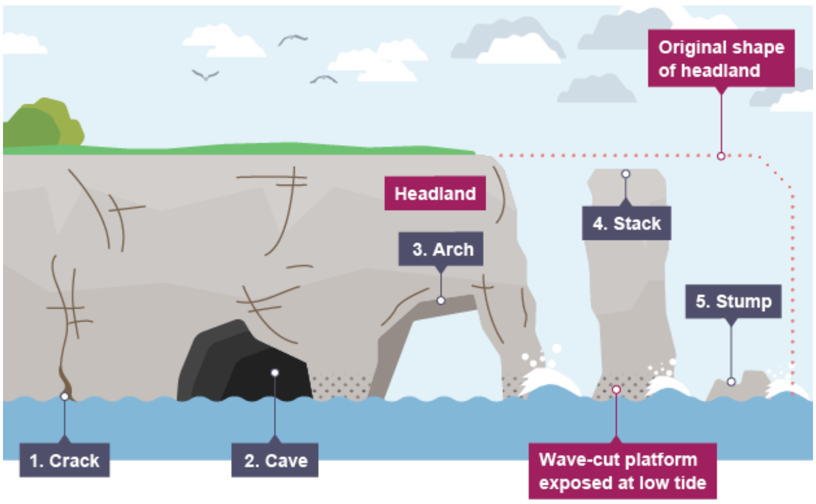


(Source: www.bbc.com/bitesize/guides/zyfd2p3/revision/1)

Caves, Arches, Stacks & Stumps

This sequence occurs on **headlands**:

- Waves enter faults and cracks in the headland, and erode the cracks through the processes of **hydraulic action and abrasion**.
- The cave will widen due to both **marine erosion and sub-aerial processes**, eroding through to the other side of the headland, creating an **arch**.
- The arch continues to widen until it is unable to support itself, **falling under its own weight** through **mass movement**, leaving a **stack** as one side of the arch becomes detached from the mainland.
- As marine erosion continues attacking the base of the stack, eventually the stack will collapse into a stump.

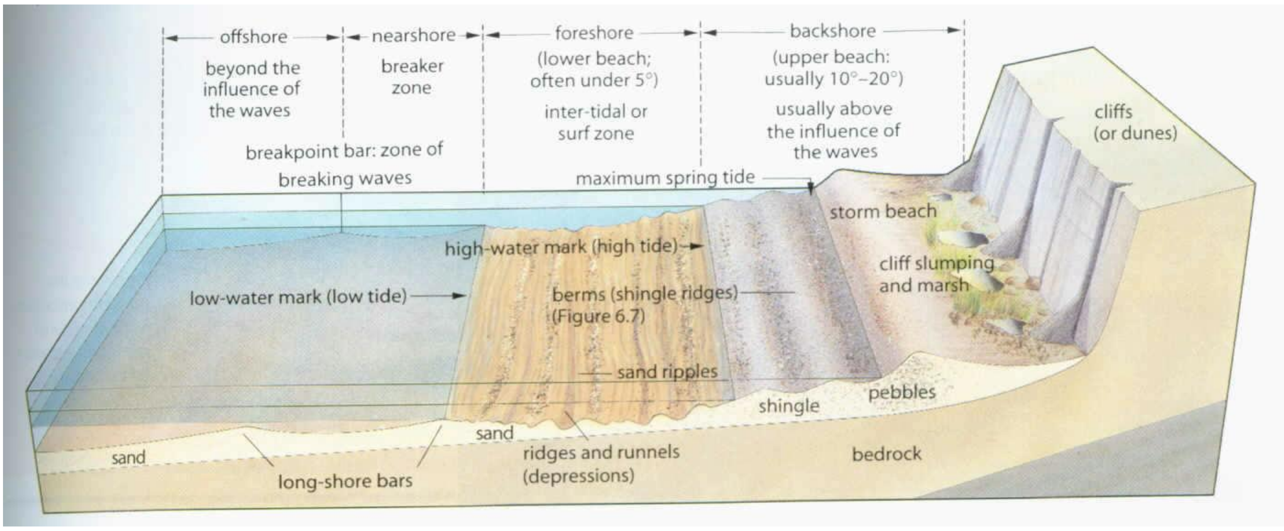


(Source: https://www.bbc.com/bitesize/guides/z8tstv4/revision/4)

Depositional Landforms

Beaches

A beach is a **depositional landform** that stretches from roughly the low tide to the high tide line. Beaches are created when sediment is deposited near the coastline when waves lose their energy.



Larger sediment is found toward the top of the beach where it has been left from winter storms. The backwash is often weaker than the swash as the water quickly percolates into the sand. As the backwash isn't as powerful the larger sediment remains at the top of the beach. Scree near the cliffs as a result of mass movement processes and weathering means that **angularity increases towards the cliff**.

Swash-aligned and Drift-aligned Beaches

The effectiveness of **transportation** is dependent on the **angle of the prevailing wind** in relation to the land and leads to the formation of different beach types:

- **Swash-aligned**: Wave crests approach **parallel to the coast**, so there is **limited longshore drift**. Sediment doesn't travel far along the beach. **Wave refraction** may reduce the speed of high energy waves, leading to the formation of a shingle beach with larger sediment.

- **Drift-aligned**: Waves approach at a significant angle, so longshore drift causes the sediment to travel far along the beach, which may lead to the **formation of a spit** at the end of a beach. Generally **larger sediment is found at the start of the beach** and weathered sediment moves further down the beach through longshore drift, becoming smaller as it does, so the **end of the beach is likely to contain smaller sediment**.

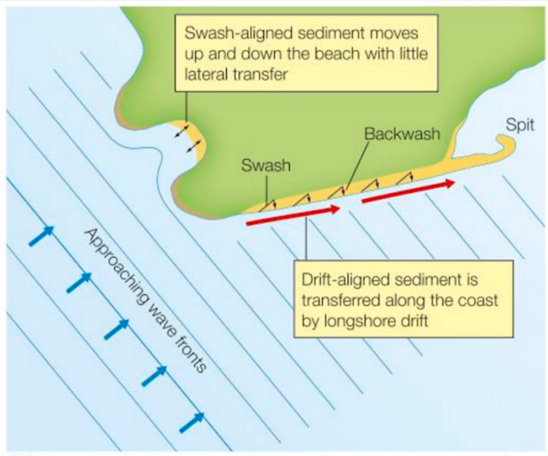
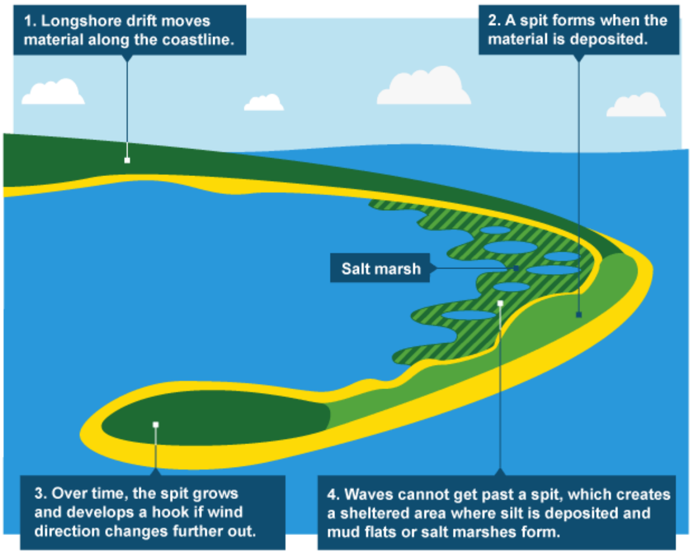


Figure 3 *The formation of swash-aligned and drift-aligned beaches*

Spits

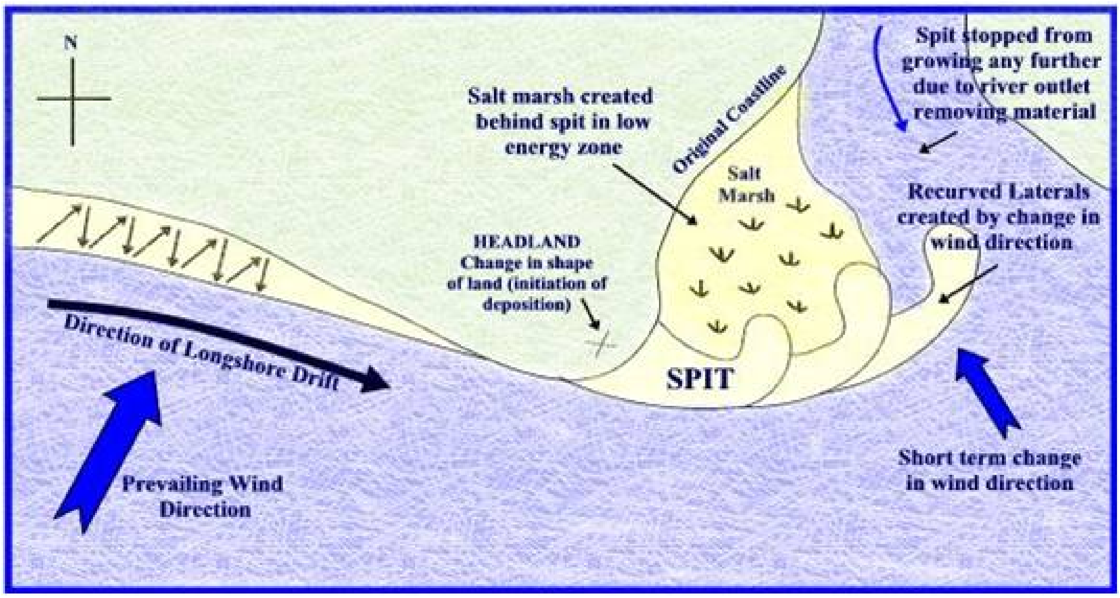
A **spit** is a **long narrow strip of land** which is formed when **longshore drift** causes the beach to extend out to sea, usually due to a **change in direction of the coastline**.



(Source: /www.bbc.com/bitesize/guides/zxj6fg8/revision/2)

This sediment projection can create a **salt marsh due to the sheltered, saline environment** where water flow speed is lower, allowing **deposition of finer sediments** to occur. The length of the spit depends on any changing currents or rivers, which will **prevent sediment from being deposited**. This means a **spit can never extend across an estuary**. A change in wind direction or wave direction can cause the end of the spit to curve (known as a **recurved end**).

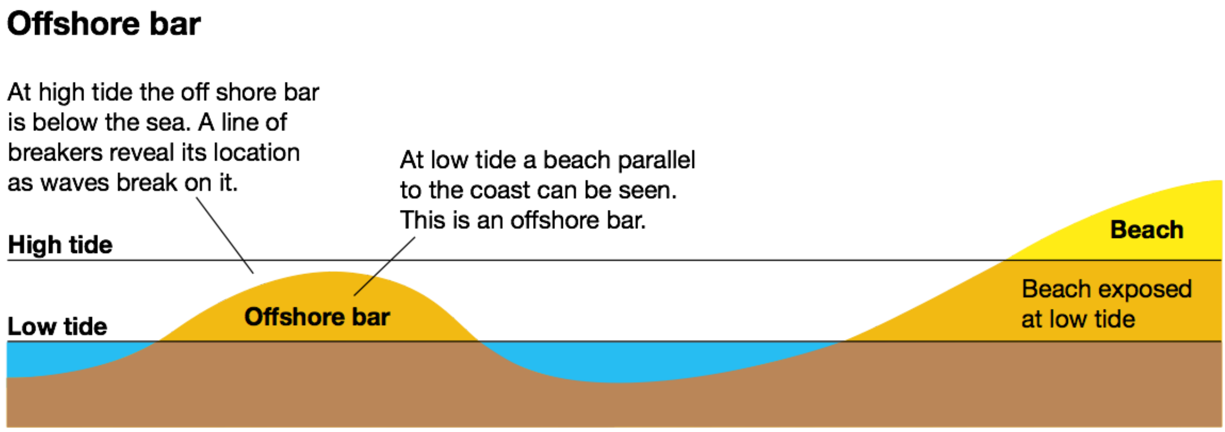
Over time, the recurved end may be abandoned, and a new spit will form on the old recurved end, and so on. This creates a spit with **multiple recurved ends**, called a **compound spit**. This is shown in the diagram below.



(Source: http://thebritishgeographer.weebly.com/coasts-of-erosion-and-coasts-of-deposition.html)

Offshore Bars

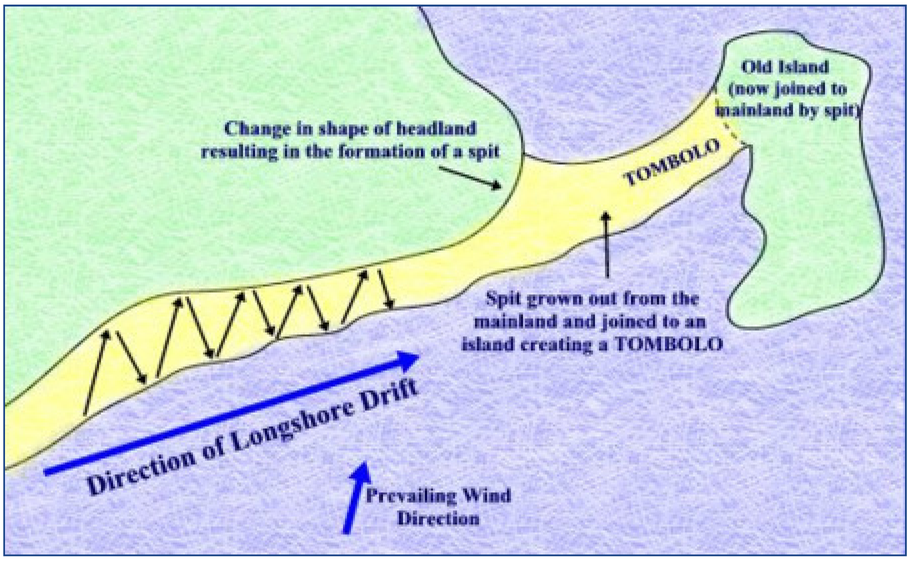
An offshore bar is an **offshore region where sand is deposited**, as the waves don't have enough energy to carry the sediment to shore. They can be formed when the wave breaks early, instantly depositing its sediment as a loose-sediment offshore bar. They may also be formed as a result of **backwash from destructive waves removing sediment from a beach**. Offshore bars may absorb wave energy, reducing erosion in some areas.



(https://www.internetgeography.net/topics/landforms-of-coastal-deposition/)

Tombolo

A tombolo is a spit that **connects the mainland to an offshore island**. Tombolos are formed due to **wave refraction off the coastal island reducing wave velocity**, leading to deposition of sediments. They may be covered at high tide if they are low lying.



(Source: www.geocaching.com)

Barrier Beach

A barrier beach occurs when a **beach or spit extends across a bay to join two headlands**. This traps water behind it leading to the formation of a brackish **lagoon** which is separated from the sea. As well as forming from present day processes, some barrier beaches may have formed due to **rising sea levels after the last glacial period**, when meltwater from glaciers deposited sediment in the coastal zone. If a **barrier beach becomes separated from the mainland, it becomes a barrier island**.

Sand Dunes

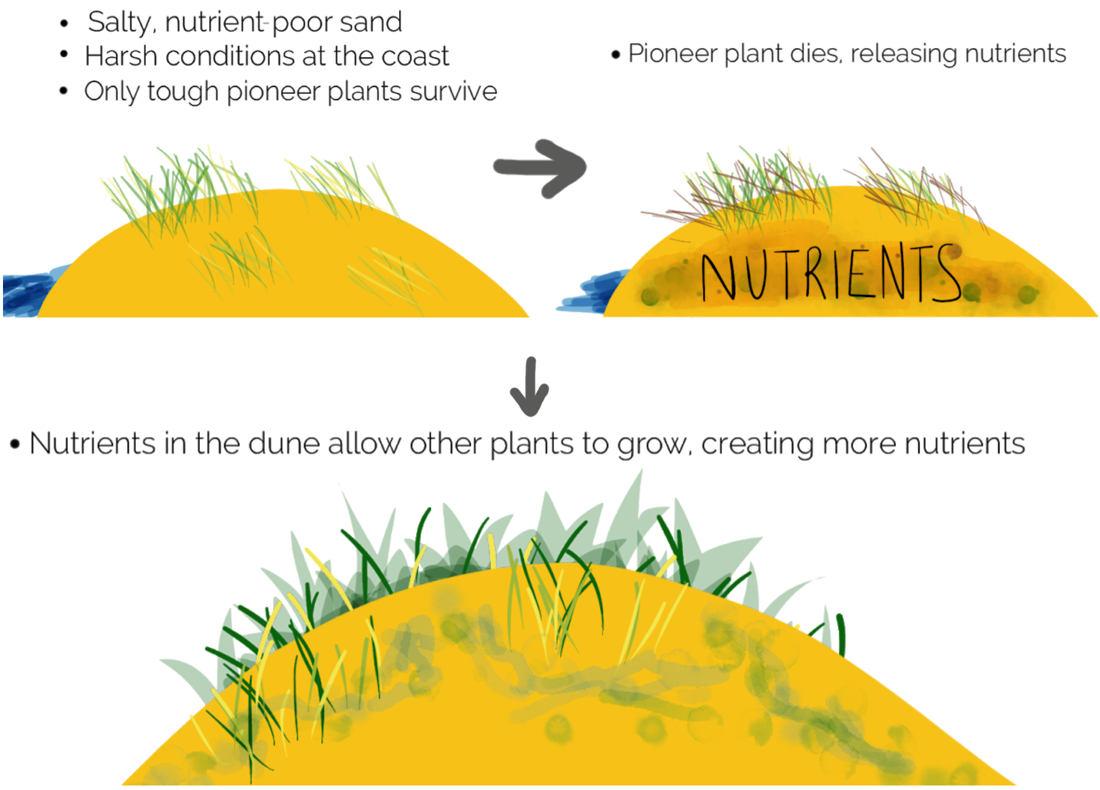
Sand dunes occur when **prevailing winds blow sediment to the back of the beach** and therefore the formation of dunes requires large quantities of sand and a large tidal range. This allows the sand to dry, so that it is light enough to be picked up and carried by the wind to the back of the beach. Frequent and strong onshore winds are also necessary. The dunes develop as a process of a vegetation succession:

Pioneer species such as **sea rocket** are resistant and able to survive in the salty sand, with its roots helping to bind the dunes together.

(Source: By Jürgen Howaldt - Self-photographed, CC BY-SA 2.0 de, commons.wikimedia)

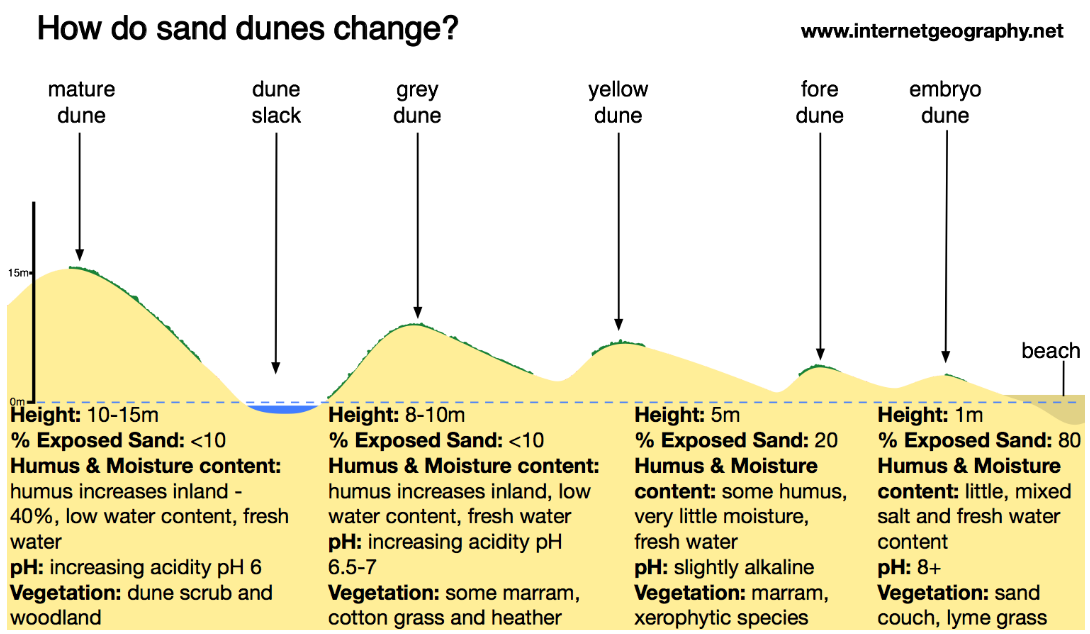
Decaying organic matter adds nutrients and humus (organic material comprised of decaying plant and animal matter) to the soil allowing **marram grass** to grow.

Larger plants are able to colonise the area and the **climatic climax** occurs when trees are able to colonise the area.



This leads to a dune structure involving different types of dunes:

- **Embryo Dunes** – Upper beach area where sand starts to accumulate around a small obstacle (driftwood, wooden peg, ridge of shingle).
- **Yellow Dunes** – As more sand accumulates and the dune grows. Vegetation may develop on the upper and back dune surfaces which stabilises the dune. This is the tallest of the dune succession.
- **Grey Dunes** – Sand develops into soil with lots of moisture and nutrients, as vegetation dies, enabling more varied plant growth.
- **Dune Slack** – The **water table** rises closer to the surface, or water is trapped between hollows between dunes during storms, allowing the development of moisture-loving plants (e.g. **willow grass**).
- **Heath and Woodland** – Sandy soils develop as there is a greater nutrient content, allowing for less brackish plants to thrive. Trees will also grow (willow, birch, oak trees) with the coastal woodland becoming a natural windbreak to the mainland behind.



(Source: https://www.internetgeography.net/topics/how-are-sand-dunes-formed/)

Salt Marshes

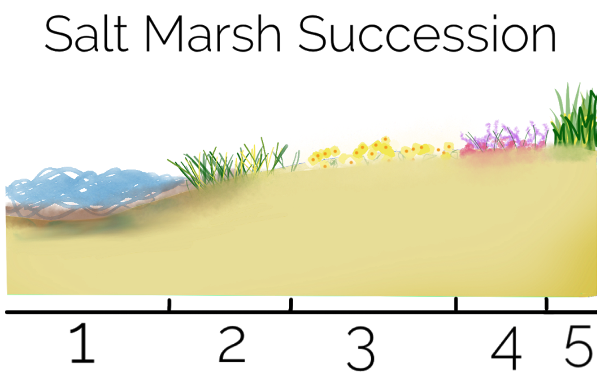
In sheltered bays or behind spits, salt and minerals will build up. Vegetation may establish, further stabilising the salt marsh. Similar to sand dunes, salt marshes can stabilise through **vegetation succession**.

A restored salt marsh on the Eden estuary

(Source: synergy.st-andrews.ac.uk)

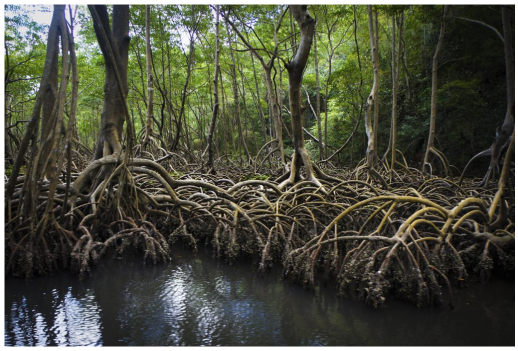
Salt Marsh Succession

1. **Algal Stage** - Gut weed and Blue green algae establish as they can grow on bare mud, which their roots help to bind together.
2. **Pioneer Stage** - Cordgrass and Glasswort grow, their roots begin to stabilise the mud allowing the estuarine to grow.
3. **Establishment Stage** - saltmarsh-grass and Sea asters grow, creating a carpet of vegetation and so the height of the salt marsh increases.
4. **Stabilisation** - Sea thrift, Scurvy grass & Sea-lavender grow, and so salt rarely ever gets submerged beneath the marsh.
5. **Climax vegetation** - Rush, Sedge & Red fescue grass grow since the salt marsh is only submerged one or twice a year.



Mangroves

Mangroves are trees that are adapted to grow in **saline, low oxygen conditions**. They develop in **coastal swamps** in tropical regions, meaning the environment around them is **constantly changing** with the tides. Mangroves can **stabilise** shorelines with roots and protect areas from erosion, as well as providing an environment for wildlife.



Mangroves in the Dominican Republic.

(Source: © Rachel Docherty/Flickr Creative Commons)

Tidal Sedimentation in Estuaries

An estuary is the **point** where a river meets the ocean. Deposition occurs in river estuaries due to the **change in water velocity** from a river to an ocean.

When the **flow of water** from the river meets with the **incoming tides and waves from the sea**, the **water flow virtually ceases** so the water can no longer carry its sediment in suspension. As most of the sediment is **small and fine** it leads to a **build up of mud** which, over time, builds up until it is above the water level. **Deposition also occurs as a result of flocculation**.

Pioneer plants colonise this area, leading to more sediment becoming trapped. This colonises the transition zone between high and low tide. **Mudflats** and **salt marshes** may develop as a result of sedimentation.

Sea Level Change

Sea levels change in short-term period such as day-to-day or minute to minute due to factors such as **high tide and low tide**, **wind strength** and **changes in wind direction** or changes in **atmospheric pressure** (the lower the pressure, the higher the sea levels). Sea level change also occurs over long-term periods, leading to the formation of various coastal landforms as a result of the following processes:

Isostatic Change

Isostatic change occurs when the **land rises or falls relative to the sea** and is a **localised change**.

Isostatic sea level change is often a result of **isostatic subsidence** (glaciers weigh down the land beneath, and so the land subsides). The melting of glaciers after the last ice age has lead to **isostatic recovery**, causing the coastline to **rebound and rise again** in the areas that were covered by ice. In the UK, this has caused a see-saw effect. Scotland and the north-west of England are **rising at around 1.5mm per year** as they were previously covered by glaciers, but this has caused the land in the south-east to **subside around 1mm a year**. In some areas of the Mediterranean, some historical ports have been submerged and other raised above the current sea level as a result of this process.

Tectonic activity (such as **earthquakes** and **volcanic eruptions**) may cause land subsidence, therefore causing **isostatic** sea level change. This was seen in the 2004 Indian Ocean earthquake, which caused the city of **Bandah Aceh to sink permanently by 0.5m**.

Eustatic Change

Eustatic change affects sea level across the **whole planet**. You can remember this using *Eustatic affects Everywhere*.

Eustatic change may be due to **thermal expansion/contraction** or changes in glacial processes. Thermal expansion is the process of **water expanding when it gets warmer**, and so the volume of water increases leading to rising sea levels.

In the last ice age, **sea levels were over 100m lower than they are currently** due as the water was stored in large ice caps as the majority of precipitation fell as snow. When the ice caps melted, this lead to rising sea levels. As a result of global warming, both processes are acting to increase sea levels with the **IPCC predicting sea level increases for 0.3m - 1.0m by 2100**. In Miami, they are currently facing significant problems, with much of the coastal strip flooding regularly during high tides as a result of rising sea levels.

Emergent Coastal Landforms

Where the land has been raised in relation to the coastline, landforms such as **arches, stacks and stumps** may be preserved. **Raised beaches** are common before cliffs which are also raised (**relic cliffs**), with wave-cut notches and similar features proof of historical marine erosion

A raised beach at Prawle Point, Devon

Submergent Coastal Landforms

Landforms of submergence occur when the **sea level rises or the coastline sinks** in relation to the sea. An easy way to imagine the effects of rising sea levels is to picture a mountainous area close to the coast and then imagine sea level rising by around 100m leading to some of the valley's being flooded. Rising sea levels leads to the following landforms:

Rias: Rias are formed when rising sea levels **flood narrow winding inlets and river valleys**. They are **deeper at the mouth of the inlet**, with the **water depth decreasing further inland**.

Sydney Harbour is a ria, seen in the image.

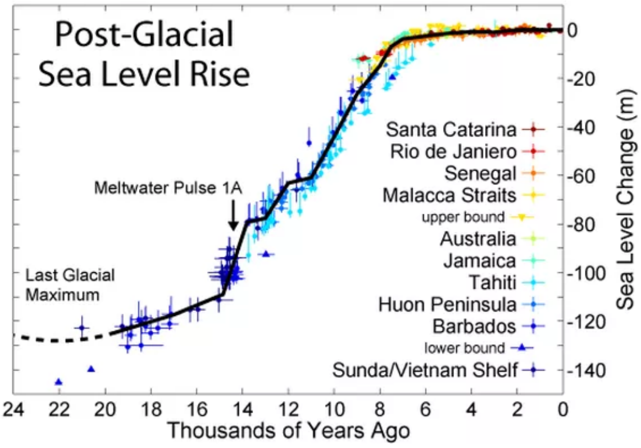
Fjords: Fjords are formed when rising sea levels **flood deep glacial valleys to create natural inlets and harbours**. Fjords can be found across the world though in some countries such as New Zealand they may be referred to as sounds. They are **deeper in the middle section than they are at the mouth**, with the shallower section identifying where the glacier left the valley.

One of the many fjords in Norway caused by rising sea levels (source: https://www.fjords.com/what-is-a-fjord/)

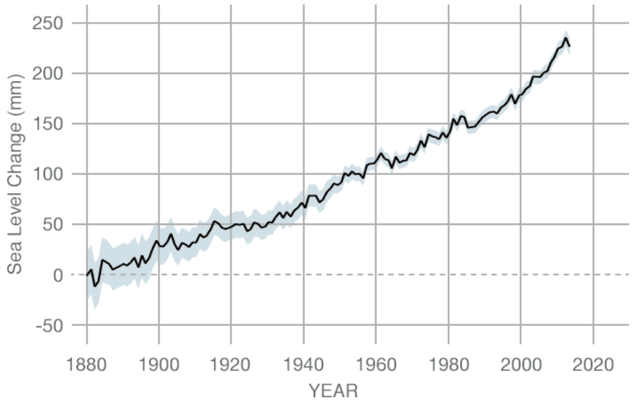
Dalmatian Coasts: This type of coastline occurs when **valleys running parallel to the coast become flooded** as a result of sea level change. This leaves a **series of narrow, long and rugged islands** and the best examples can be seen in Croatia. They may also be referred to as Pacific coasts.

Croatia has some of the most prominent Dalmatian coasts (source:https://croatia.eu/article.php?lang=2&id=11)

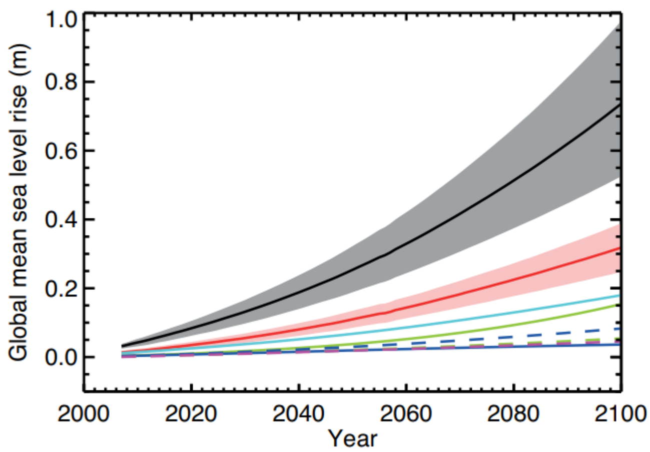
Contemporary Sea Level Change



Since records began around 20,000 years ago, sea levels have always been rising from 120m below the levels which they are now today. The graph clearly shows that sea level increase **slowed around 8,000 years ago**, and **levelled at the current height around 3000 years ago**.



Since 1880 and the industrial revolution, **sea levels have increased by around 235mm**. That may not sound significant, but it is **enough to overwhelm some sea defences**, when **combined with higher than expected storm surges**. It also affects the drainage system in coastal cities increasing the flooding risk.

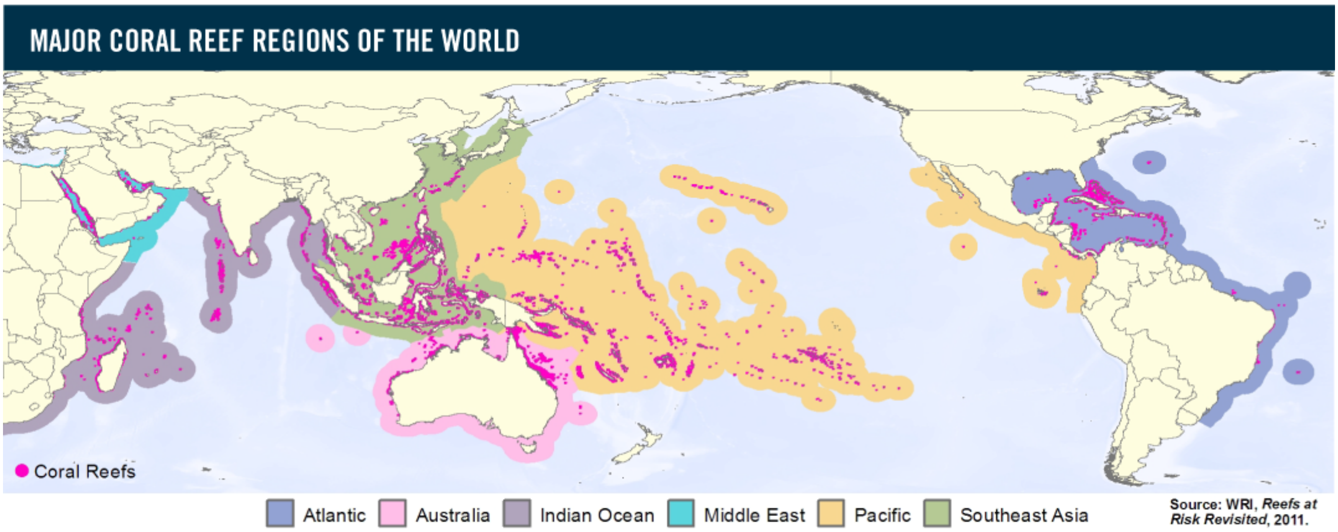


The **International Panel on Climate Change (IPCC)** predicts that sea levels may rise between **0.3 - 1.0m by 2100** and the graph shown on the left shows the **different models and climate predictions** that they have created. This could **cause aquifers to be polluted in low-lying atoll islands** (coral reefs protruding from the sea) affecting the residents who live in them. It may also **inundate many coastal cities** and significantly increase the risks from tropical storms and tsunamis. In some areas turning the coastal area into recreational land as a method of **adaptation** to climate change is proving to be a popular option.

Coral Reefs

Coral reefs are underwater ecosystems characterised by **large amounts of coral**, held together by **calcium carbonate**. These reefs create environments suitable for **abundances of wildlife** to live in.

(Source: https://www.nationalgeographic.com)



Coral reefs are majorly found in **tropical and sub-tropical regions** as coral requires certain conditions to grow and survive:

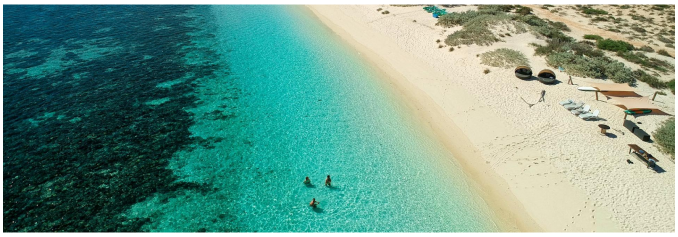
- **Salinity**: corals can only survive in **salt water**
- **Temperature**: corals thrive in warm oceans (around 23-25°C), hence why they are located within the tropics
- **Light**: **algae** lives inside corals, and this algae needs **light** in order to photosynthesise. Corals rely on this algae for oxygen among other things, meaning corals also rely on light to survive. Corals will therefore only grow in **shallower waters** where light can still reach them (around 25 metres).
- **Oxygen**: corals need a certain amount of oxygen to survive. **Localised wave movements** can encourage the growth of corals.
- **Clean water**: sediments and pollutants in water can **block sunlight**, **poison coral**, and disrupt **feeding**.

Types of Coral Reefs

Fringing Reefs

Fringing reefs are coral reefs that are attached to the **shoreline** or **run closely parallel to the shoreline**. They are the most common type of coral reef, and can be **hundreds of kilometres long**.

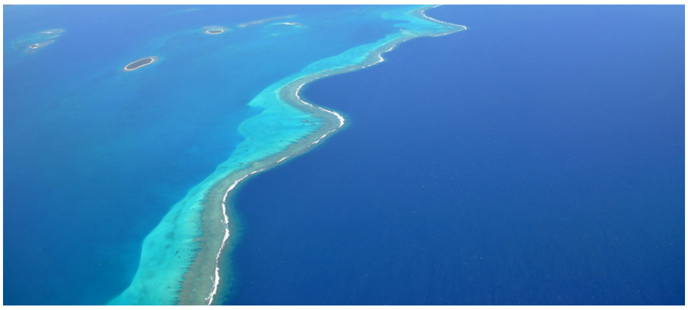
Fringing reefs do not have to grow **directly attached to the shore**, and may be separated by a **shallow backreef**. This is shown below. However, when there is a **deep, wide lagoon** between the reef and the shore it is then known as a **barrier reef**.



The Ningaloo Coral Reef in Australia (https://www.australiascoralcoast.com/region/ningaloo)

Barrier Reefs

A barrier reef is a **coral reef** that is **completely separate** from a shore by a **lagoon**. The lagoons can be 30-70 metres deep and **kilometers wide**. Like fringing reefs, barrier reefs also run parallel to the coastline, but they are separated by much **deeper and wider lagoons**.

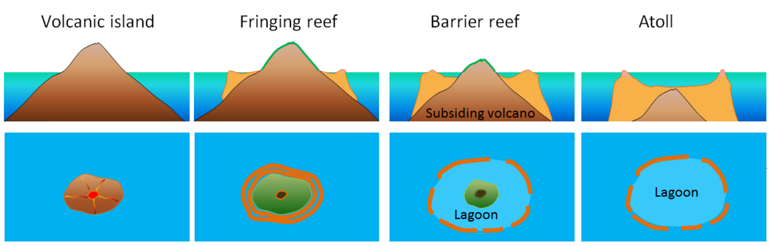


New Caledonian Barrier Reef (Source: https://www.flickr.com/photos/eustaquio/8405801692)

Atolls

Atolls are **circular** coral reefs with a **lagoon in the middle**. Atolls are thought to be the **oldest types of coral reefs**, and can take up to **30 million years** to form.

Atolls form from a **fringing reef** surrounding a **volcanic island**. As sea levels rise, or as the volcanic island sinks **back into the ocean**, the reef continues to grow. This leaves behind a **ring** of coral that once surrounded the island, with a **shallow lagoon** in the middle. (Source: earthobservatory.nasa.gov)



(Source: https://opentextbc.ca)

Threats to Coral Reefs

Pollution

Pollutants in the ocean can cause many **issues** for coral reefs:

- **Carbon dioxide** from the atmosphere is **absorbed into the ocean**, leading to **ocean acidification**. This **breaks down the calcium carbonate** and therefore comprises the **structural integrity** of coral reefs.
- Sediment and land-based pollutants can **wash into the ocean**, making the water **murky** and therefore blocking **light**, which affects the photosynthesis of algae.
- Pollutants may be **toxic** or dangerous to corals, e.g. insecticides and plastics, damaging the corals and the ecosystem that they depend on.

Global warming

A rise in **global temperatures** can cause many issues for coral reefs:

- **Coral bleaching** occurs when algae **leaves corals**, making corals more **susceptible to disease**. Coral bleaching occurs when ocean temperatures become **too high** for algae to survive in corals.
- More **diseases and invasive species** may thrive in warmer waters, potentially harming corals and the coral reef ecosystem.
- More frequent, strong storms can **disrupt and destroy coral reefs**.
- **Changing ocean currents** can disrupt **food chains** and **wave action** that coral reefs rely on.

Sea-level rise

As **global temperatures rise**, glaciers and ice sheets across the world **melt**. This has caused sea levels to rise, which leads to many problems concerning coral reefs:

- If sea levels **rise faster than the upward growth of coral**, corals may be too deep to receive **sufficient sunlight**.
- The **rise in sea levels** can cause increased **coastal erosion** in areas. Therefore, more **sediment** is transported into the oceans, which can lead to **sedimentation in coral reefs**, blocking sunlight and disrupting the ecosystem. This is a particular threat to **fringing reefs** as they are so close to the shoreline.

Physical damage

Physical damage can be done to coral reefs in a number of ways:

- **Boating** can physically **disrupt** coral reefs, especially if an **anchor** is dropped onto a reef. Large boats may **bulldoze** through areas of coral and destroy them.
- **Destructive fishing practices** can damage or destroy coral reefs. **Bottom-trawling** is a method of fishing where a large net is **dragged on the sea floor**, and this particular fishing method is **very disruptive to coral reefs**.
- **Unsustainable tourism** e.g. snorkeling can cause damage, especially if people **touch** the reefs.

Managing Coral Reefs

There are different **strategies** to manage coral reefs, for example:

Protected Areas and Exclusion Zones
Threats to coral reefs can be reduced by **reducing the activities that take place there**. Banning **fishing**, **tourist activities**, **diving etc**. outright is the most successful way of reducing the physical damage that these cause. **Temporary closures** of coral reef diving/fishing areas can be a good way of **allowing reefs to recuperate** after times of **stress** for coral reefs, e.g. bleaching.

Preventing and Controlling Invasive Species/ Predators
Invasive species can be **very harmful to coral reefs**, both affecting the coral **directly** and affecting the **ecosystem** that the coral depends on. **Management strategies** are in place to ensure these invasive species do not **enter the coral reef ecosystems**, and in the event they do they can be controlled as to **limit** the effects they have. For example, **cleaning ships** and having **disposal strategies** can help to limit the **transportation of invasive species** into **coral reef systems.**

Schemes to remove predators also help to manage coral reefs. For example, the **crown-of-thorns starfish** can be very dangerous to coral reefs when there is a severe **outbreak**, as they **eat the corals**. There are several strategies to remove these starfish, such as **injecting them** with sodium bisulfate or **manually removing them**.

Limiting Global Warming and Ocean Acidification
In the long term, **large-scale** coral reef damage is a huge threat due to the world's carbon dioxide emissions. **Reducing emissions** on a **global scale** is necessary in order to reduce the **many problems associated with CO_2** emissions (sea-levels rising, ocean acidification, global warming causing coral bleaching, diseases and invasive species caused by warmer sea temperatures etc.).

Government strategies, **greener energy sources**, and a **reduced reliance on fossil fuels** can all contribute to lower carbon dioxide emissions, therefore helping coral reefs in the **long term.**

Education and Awareness
Educating those who are **around coral reefs** on how to **interact with this environment** can be a successful way of managing coral reefs. For example, **sustainable diving practices** that limit the effect on coral reefs, such as not stirring up sediment when diving. Furthermore, the damage and destruction of **anchoring** can be reduced by the use of **buoys** and education of **unsafe places to drop anchors**.

The **Reef Resilience Network** goes into **great detail** about different coral reef management strategies. reefresilience.org/management-strategies/