



Coastal landforms of sea level change

Coasts are dynamic systems which are constantly being altered, with landforms being created and destroyed. Sea level change plays an important role in shaping coastlines and fluctuations in sea levels both on a global and local scale act to create a variety of coastal landforms.

Changes in sea level

The cause or causes of a change in mean sea level are often complex. Sea level changes can result from a change in the level of the actual **sea**, or a downward or upward movement of the **land** which means that the sea level **relative** to the land has changed. Sometimes, the change in sea level can result from a combination of **both** land *and* sea movements, and it is the fastest or most significant movement which determines whether there is an overall rise or fall in sea level relative to the land that the sea meets (**Box 1**).

Box 1. There are three possible scenarios that can lead to a fall in relative sea level and three which may lead to a rise in relative sea level.

For a *fall* in sea level:

- A. The sea level falls and land either rises, stays still or subsides at a slower pace;
- B. The sea level remains fixed whilst the land rises;
- C. The sea rises but the land rises at a greater pace.

For a *rise* in sea level:

- A. The sea level rises and land either subsides, stays still or rises at a slower pace;
- B. The sea level remains fixed whilst the land subsides;
- C. The sea level falls and the land subsides at a greater pace.

An overall **rise** in sea level can be referred to as a **positive** change in sea level. An overall **fall** in sea level can be referred to as a **negative** change in sea level. Relative sea level (the level of the sea in relation to the land with which it meets) has fluctuated over geological time with several rises and falls in evidence.

When there is a rise in the relative sea level and the sea flows over the land to cover areas which would have formerly been exposed, this is known as a **marine transgression** and during this time the *coastline* is said to **retreat**. The opposite may occur when sea level falls and land, once inundated by sea, is revealed. This is called a **marine regression** and during this time *coastlines* will **advance**.

Why does sea level change?

Changes in sea levels, both on a global and local scale occur due to a number of reasons. Changes in the level of the actual sea are called **eustatic** changes. Eustatic changes in sea level are **global** due to the interconnected nature of the world's ocean basins. Vertical movements of the land can be due to either isostatic or tectonic forces. These changes in sea level are localised. **Isostatic** movements are associated with depression or uprising of the **land** owing to addition or reduction of weight which may be put on to the land due to the accumulation of sediments, ice or large quantities of lava flows. See **Figure 1**.

Figure 1. Factors controlling sea level

Controlling factor	Influence on sea level	Vertical influence on the land (and therefore on relative sea level)
The amount of ice on the land is greater during colder glacial periods and less during warmer interglacials.	Changes in sea level owing to accumulation and melting of ice that covers continental land masses are known as glacio-eustatic . Sea levels change when ice forms and melts as continental ice caps and sheets are formed from water which has been taken from, and is released back into, the oceans. The growth or decline in the size and amount of floating sea ice , including icebergs ice shelves and pack ice has no influence on the sea level when it melts. This is because sea ice will displace the equivalent of its own mass of water. (See Fig 2 and Fig 3 for further information on the influence of ice).	The accumulation of significant amounts of ice on the land as ice caps and ice sheets during periods of glacial advance can depress the Earth's crust. Melting of ice during interglacials will result in an isostatic rebound as the land uplifts to restore a state of equilibrium. As the ice melts and results in eustatic sea level rise, the resulting marine transgression and weight of the water can depress the continental shelf; this is called hydro-isostatic subsidence (hydro-isostasy) and leads to a further increase in the sea level which has already risen. The reverse can also happen, with continental margins rebounding as sea levels fall and the weight of the water lessens.
Steric changes are related to changes in how atoms in a molecule are arranged (determined by temperatures and salinities) and therefore the space that a molecule may occupy.	As oceans cool they reduce in size and when they warm they expand: thermal contraction and expansion . Similarly, a decrease in salinity will result in a rise in sea level and vice versa. Changes in temperature are only believed to be able to make a difference of around 10 metres to global sea levels and so are much less significant than other factors driving eustatic change.	

Figure 1. Factors controlling sea level *continued*

TECTONIC 1: Epeirogenic movements are large-scale vertical tectonic motions of the crust involving depression or uplift of ocean floors and continents.	If the shape of ocean basins is altered, their water-holding capacity will change. If the basin is reduced in size this will result in a global rise in sea level and if it increases; a fall in global sea level. Such changes are termed tectono-eustatic .	Epeirogenic movements can also change the level of the land, so that sea level is altered relative to the land when continents rise periodically, causing a fall in relative sea level.
TECTONIC 2: Orogenic movements are associated with mountain building episodes in places where tectonic plates converge.		In the mountain building regions, any displacement in the height of the land which takes place can be gradual, as a result of the mountain building process, or sometimes sudden as a result of an earthquake . Where this displacement leads to uplift of the land it results in a lowering of the sea level relative to the land; if the land is lowering, relative sea level will rise.
TECTONIC 3: Volcanic activity	The creation of volcanic ocean islands could displace water and increase sea levels. The weight of volcanic islands such as those in the Pacific Ocean may also act to depress the crust supporting them, thus leading to epeirogenic changes (<i>see above</i>) involving a lowering of sea level.	Volcanic activity may also result in relative sea level change as magma chambers below the Earth's surface fill and empty resulting in uplift and subsidence of the land and therefore relative falls and rises in sea level respectively, this is known as bradyseismic change .
Sediment accumulation	Sedimento-eustatic global changes in sea level can occur if there is a large accumulation of sediments carried from land to offshore locations by erosive agents such as rivers, winds and glaciers. This can reduce the ocean basin's holding capacity, leading to a rise in sea level. This increase is slow and small compared to other factors. The sediment mass could also depress the ocean floor, which would <i>increase</i> the ocean's volume leading to a fall in sea level.	Where vast amounts of sediments build up in coastal regions at a delta, the land will subside under the weight of this sediment, resulting in a rise in relative sea level, unless the rate of the sediment build-up can equal the rate of subsidence.
Human actions	Humans are believed to influence global sea levels through greenhouse gas emissions which enhance the greenhouse effect, leading to global warming and associated rises in sea levels.	Humans can influence sea level via removal of oil, natural gas or water from within the ground, resulting in subsidence and therefore a rise in relative sea level.

Figure 2. A brief history of 'recent' glacial advance and retreat

<p>Around 2.6 million years ago the Quaternary Period began with the Ice Ages of the Pleistocene Epoch. Since the beginning of this phase, a number of major changes in global temperatures have occurred leading to a series of colder glacial periods and warmer interglacials. A series of corresponding falls and rises in global sea levels coincided with these temperature fluctuations as continental ice accumulated and melted accordingly.</p> <p>The last Ice Age, the Devensian, began around 70,000 years BP and ended around 10,000 years ago. 18,000 years BP, temperatures were around 5°C lower than present and the continental ice was at its maximum extent, meaning that the world's sea level was at its lowest point, with estimates suggesting that sea levels were 100-150 metres lower than present. When the ice melted in the ensuing interglacial, the glacio-eustatic rise in sea level led to an inundation of coastlines. This increase in global temperatures and corresponding rise in sea level occurred in a period of time known as the Holocene, when the oceans advanced and inundated the land. This was the Flandrian transgression. The oceans reached their current level around 6,000 years ago. (BP – before present)</p>

Figure 3. The sequence of sea level change resulting from glacial advance and retreat

<ol style="list-style-type: none"> 1. During a glacial period, temperatures fall and ice sheets, ice caps and glaciers form on land leading to a global eustatic fall in sea level; there is a negative change in base level. 2. The continental ice increases in size causing localised isostatic depression of the land; sea level rises locally; this gives a positive change in base level (a rise in relative sea level). 3. Temperatures rise during an interglacial, the ice begins to melt. This leads to a global eustatic rise in sea level and positive change in base level. 4. The continental ice continues to melt. As the weight of the ice on the land decreases isostatic uplift takes place which results in a localised negative change in base level (a fall in relative sea level).

Emergent and submergent coastlines

Emerged or **emergent** coastlines and their associated features are created when there has been a relative fall in sea level. **Submerged** or **submergent** coastlines and their associated landforms are created when there has been a rise in the relative sea level.

Landforms on emergent coastlines

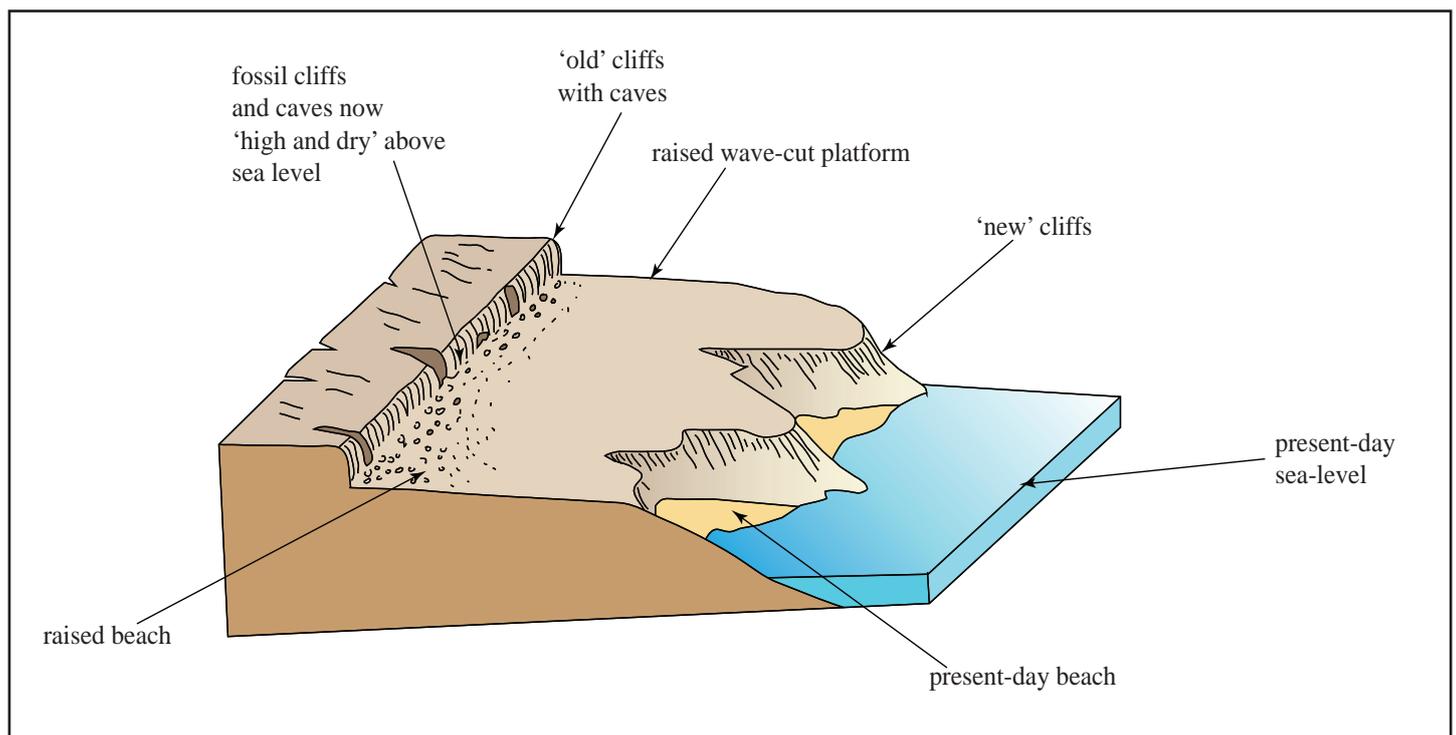
The landforms created on emergent coastlines are created either by a fall in sea level; uplift of the land, or both, resulting in the sea level being at a lower level relative to the land than it has been previously. Emerged coastlines are evident when beach deposits and marine shell beds are found stranded above the present-day high tide level, creating a **raised** or **emerged beach** sometimes called a **fossil beach**, often backed by **relict cliffs**. These beach deposits and shell beds would have been formed when the sea was previously at a higher level and has subsequently fallen. The raised shore platform, often with beach deposits creates a **terrace**, an area of flat land, which is backed by the relict cliffs. The presence of the raised platform indicates that before sea level fell, the sea must have been at a relatively fixed level for a considerable period of time to have allowed that platform to develop. Relict cliffs can often be identified due to their steep slope angle, but may not be as steep as they were at the time of their formation due to break down via sub-aerial processes. Sometimes there will be a *series* of terraces and relict cliffs at various heights above sea level. For example, in western Scotland, platforms are found at approximately 8m, 15m and 30 metres above present sea level. The emerged beach material can consist of cobbles and pebbles that have been rounded by wave action as well as fossilised remains of sea creatures. Coastal sand dune deposits which would have backed the beaches may also be found high above current sea levels. Associated with the raised marine platforms and cliffs, can be other coastal features, such as relict caves, wave-cut notches and, in theory, arches and stacks (**Figure 4**).

In Great Britain, as a result of the diminished ice that once covered the northern part of the island, the north is isostatically rebounding, resulting in the southern parts of Britain being tilted downwards and slowly submerging. The Isles of the west coast of Scotland where isostatic rebound is ongoing provide examples of numerous raised beaches, but also raised caves. The well-cited example of King's Caves in Arran, an island situated off the west coast of Scotland, provide a good example of raised sandstone cliffs and a sequence of caves, carved out by wave action when the sea level was higher and could reach the cliff face. On Mull, another west-coast Scottish isle, a spectacular cave carved out of the cliff-face composed of basalt columns has been raised above the present high tide mark.

In western Crete, a Greek island situated in the Mediterranean Sea, coastal landforms have been raised above the current sea level due to tectonic activity. The west of Crete is moving upwards, whilst the eastern side of the island is subsiding. In the west, this uplift is evidenced by dark water marks which show the sea level of the past and what appears to be a raised shore-platform on the tiny, uninhabited island of Gramvousa which lies just off the north-west coast of Crete. This platform is backed by cliffs and covered on its most inland portion by scrub vegetation, showing that the waves can no longer reach the base of the cliff and the beach has been elevated. Raised coastal features, once emerged are left 'high and dry' above the influence of waves and tides. The extent to which they will remain often depends on their geology and their subsequent level of resistance to denudation over time.

Depositional features can also be altered owing to coastal emergence. **Mangrove swamps** and **salt marshes** increase their extent as coastlines emerge and may be incised by the creeks that run across them. Beaches and dunes may widen as sediments are washed ashore and provide depositional material to feed their extension; spits will become more exposed as they emerge and increase in size.

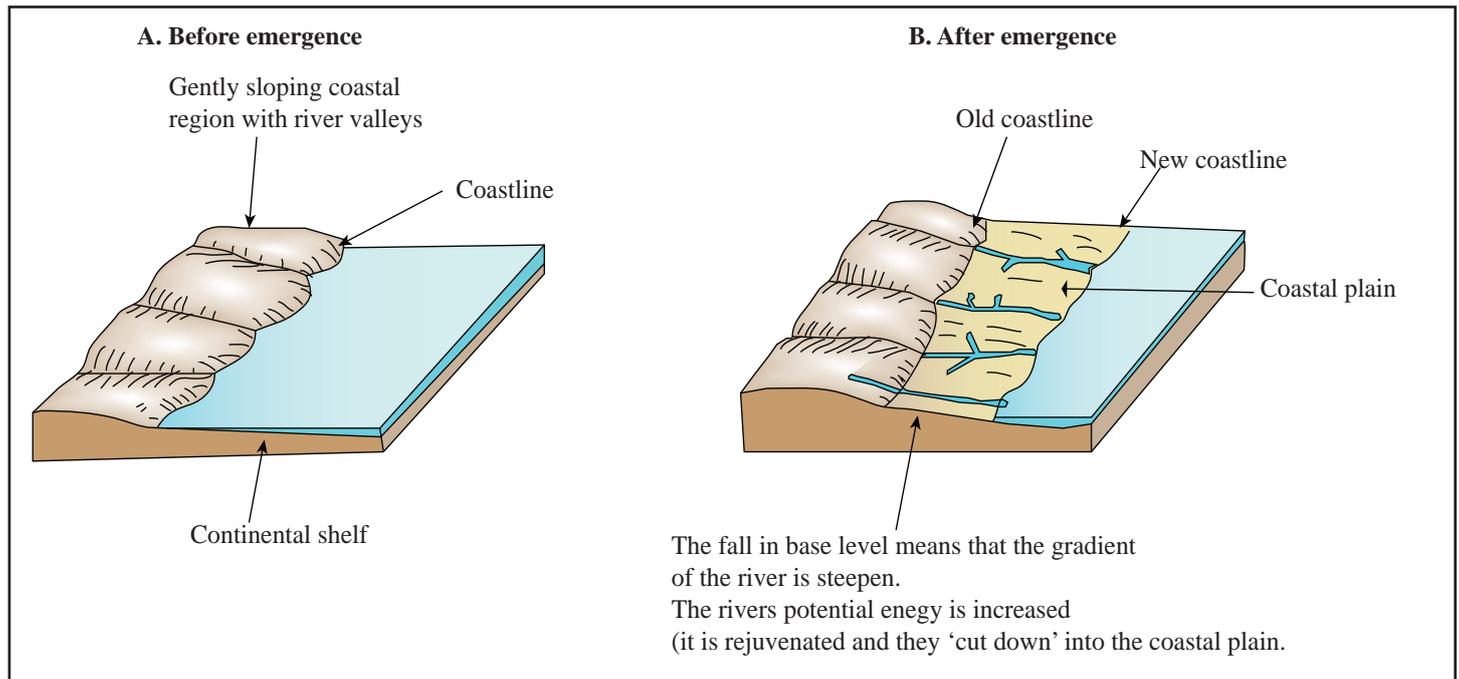
Figure 4. Typical features associated with a raised beach



The coastal **lagoons** which emerge will eventually shrink as they shallow due to their water source being cut off with increasing height and distance from the sea.

Low-lying coastal regions can also be shaped when sea levels fall. When global sea levels fell to a low point around 18,000 years before present, continental shelves surrounding the world's continents were exposed (**Figure 5**). They extended the coastline as they emerged as smooth, gently sloping, broad coastal plains which have simple, even shorelines. At this time, the British Isles became a peninsula, attached to Western Europe above sea level and Tasmania and New Guinea were similarly linked to Australia (Bird 2008). Rivers had further to travel to reach the sea and **base level** (the maximum point to which rivers will vertically erode or 'cut' downwards to, usually marked by sea level) was lowered. This meant that the rivers' capacity to erode vertically was rejuvenated, meaning that the coastal plains were incised, creating deeper channels and valleys. The more landward portions of these low-lying coastal areas may be shaped by glaciation at this time (see *fiards*).

Figure 5. Typical features of a low-lying emergent coastline



Landforms on submergent coastlines

Positive changes in sea level mean that the overall shape of the coastline will be changed; river and glaciated valleys and lowlands can be drowned, creating inlets and bays and the uplands may create coastal promontories. The sea may isolate some areas of land to form islands, for example, during the Holocene, as sea levels rose, Britain became separated from Europe and Tasmania and New Guinea separated from Australia; a reverse of the events described above.

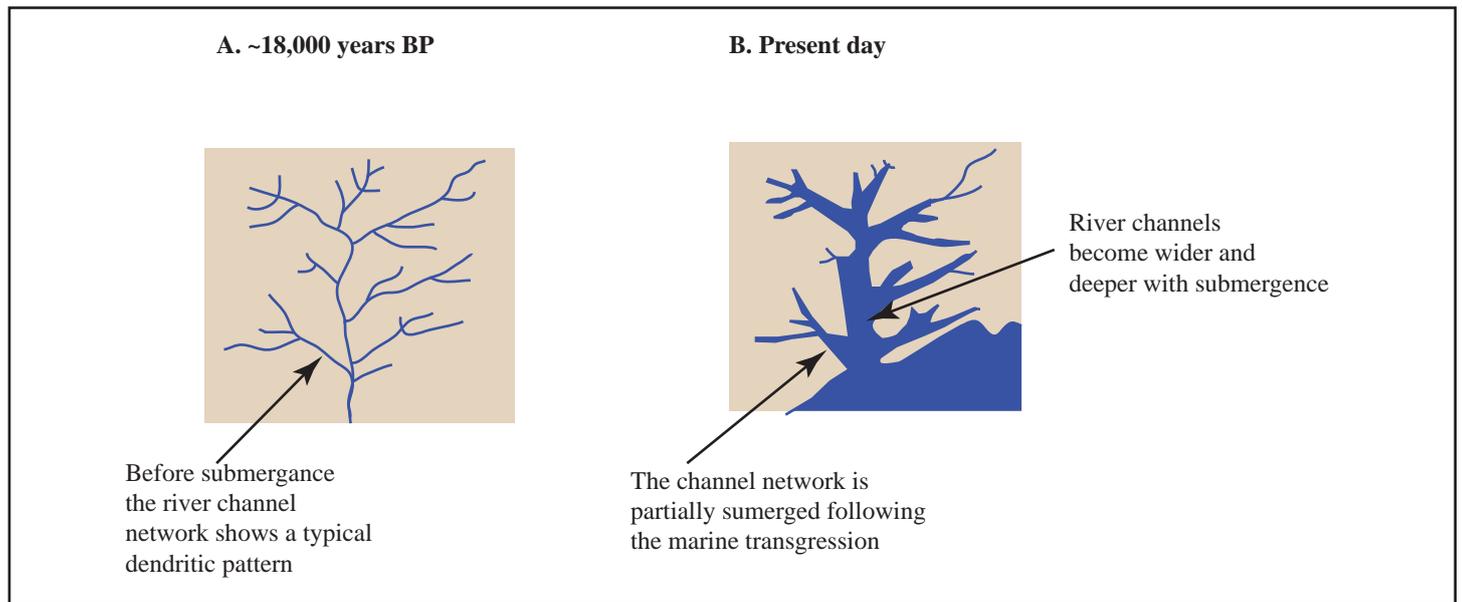
When sea levels rise, from either eustatic sea level rise or tectonic subsidence, some features originally formed at sea level when the seas were lower than present are completely submerged. Many of the incised coastal plains created when continental shelves were exposed during times of lower sea level were submerged as the sea level rose during the Flandrian transgression.

The incisions may form submarine canyons when submerged at depth. Abrupt changes in slope below current sea level are believed to be 'drowned' cliffs which have been submerged as sea levels have risen. These cliffs are linked to submerged wave-cut platforms, and there may even be 'stairways' of drowned terraces, similar to those raised terraces formed by a fall in relative sea level. Beaches and their associated deposits may also be submerged. Many of these submarine features are not preserved as they are worn down by wave action and burial by deposits during their submergence.

The most commonly discussed landforms of coastal submergence are rias and fjords and the variations of these landforms. **Rias** are 'drowned' river valleys which have been (partially) submerged during a period of marine transgression. They have a branching or *dendritic* pattern when seen in their plan view (**Figure 6**).

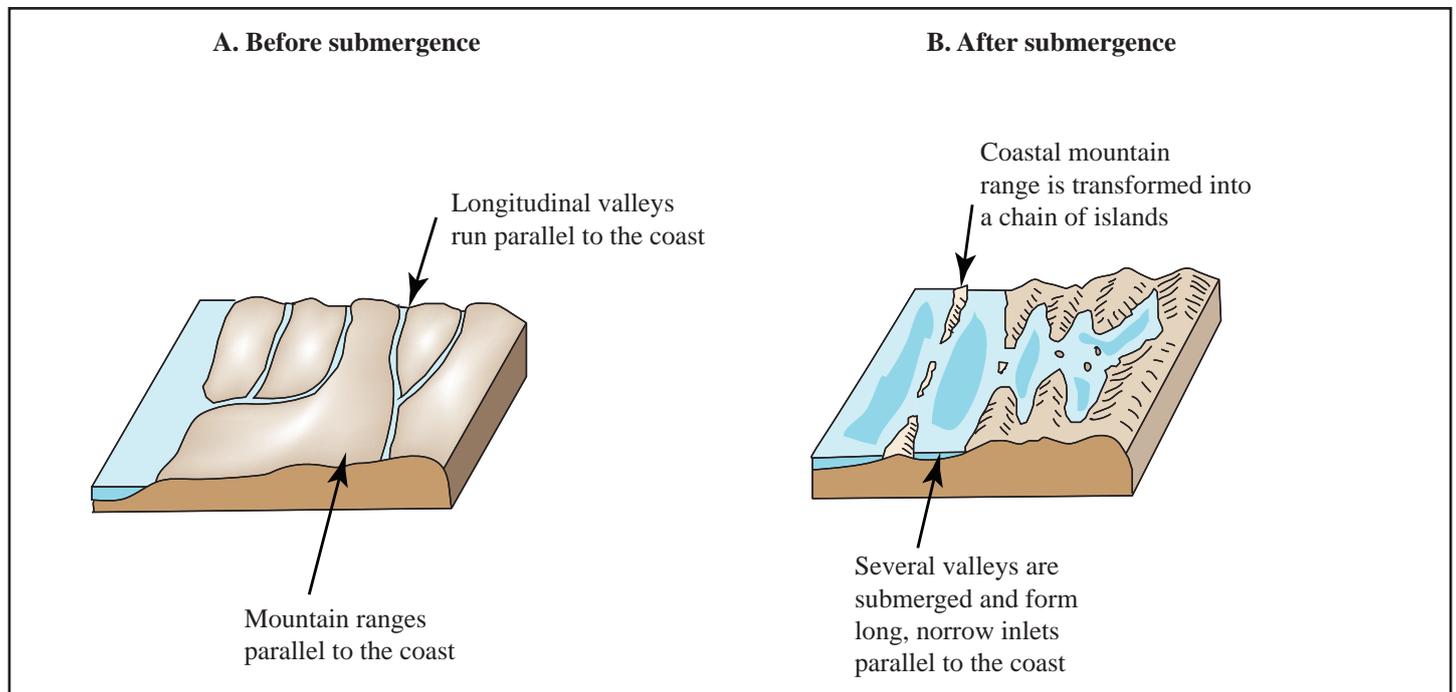
Rias are more common along discordant coastlines where geological strata, mountains and hills trend at right angles to the coastline. When global sea levels were lower than present, base level was lowered, giving rivers a renewed or 'rejuvenated' potential energy to cut downwards. Rivers will therefore erode deep river valleys during these times of lowered sea levels. Once sea levels begin to rise again, the deepened segments of the river situated at the coast are filled as the sea level increases, creating the drowned river valley with its characteristic dendritic drainage pattern. In Western Europe, rias tend to be found on the peninsulas of Cornwall, south-west Ireland, north-west Spain and Brittany in France. Specific examples of rias include Milford Haven in Pembrokeshire, south-west Wales and Kingsbridge estuary in Devon.

Figure 6. A typical ria in plan



Features similar to rias but formed when rivers flow almost parallel to the coast are called **Dalmatian coasts** or sometimes longitudinal coasts. They are formed on concordant coastlines where geological strata, hills and mountains trend parallel to the shore. Rather than rias being formed on these concordant coastlines, wide, open bodies of water called sounds develop, which have islands or ridges of raised land between them. A classic example of the features, and where the name 'Dalmatian coasts' originated from, can be found off the coast of Croatia where many narrow, long islands lie parallel to the shore (**Figure 7**).

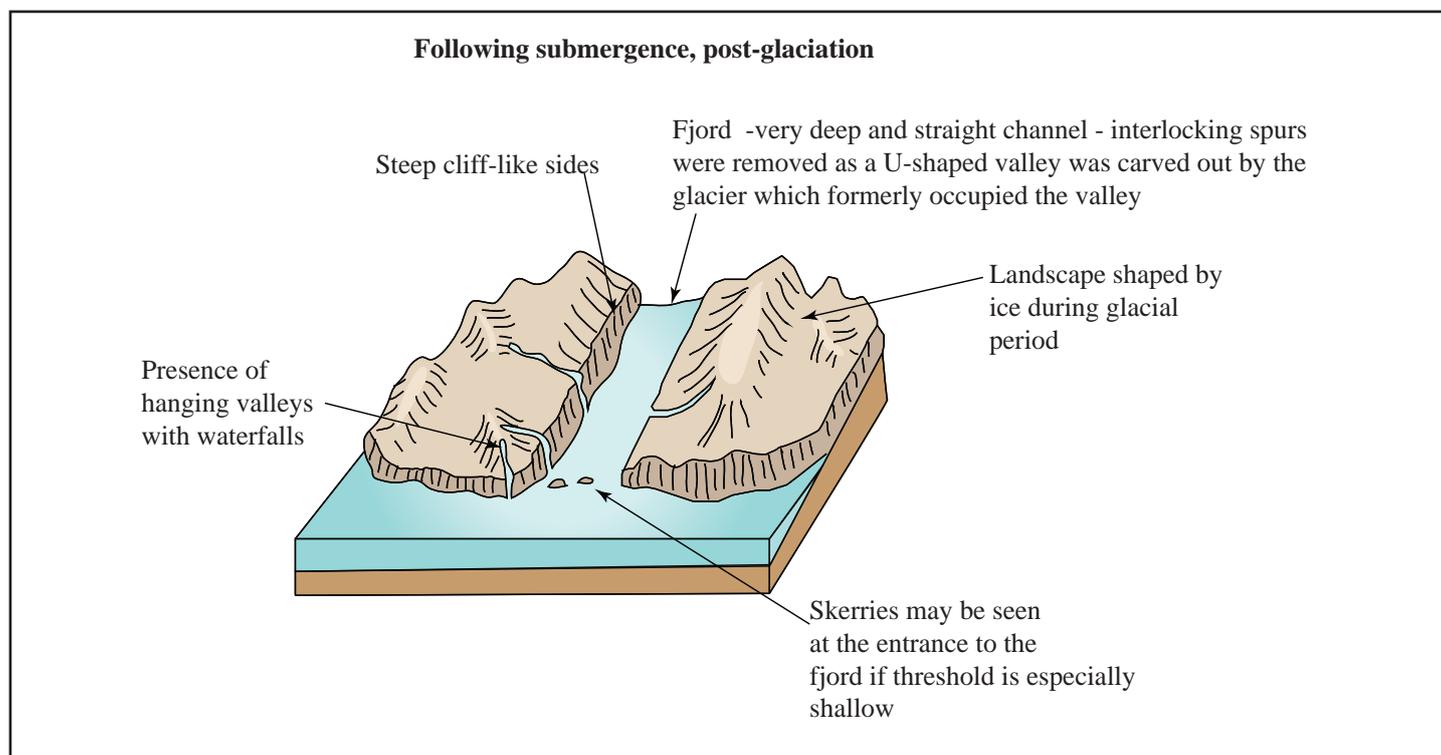
Figure 7. The formation and features of Dalmatian coasts



Fjords (or *fiords*), sometimes known as sea lochs, are **drowned glacial valleys** which have been shaped by the action of ice and submerged during the Holocene. The deep, steep-sided glacial troughs carved out by moving ice are submerged as sea levels rise. The deep troughs are best formed at higher altitudes where the effects of ice have been more profound; in some upland coastal areas they can reach in excess of 1200m in depth. Fjords have steep sides and flat bottoms, typical of the U-shaped valleys of glaciated landscapes. They are relatively straight-sided and narrow compared with rias. Also typical of glaciated areas, fjords may have hanging valleys and waterfalls (**Figure 8**). Ridges of scree and moraine may also line the fjord's shores, providing evidence of its glacial heritage. Fjords have a shallow entrance called a **threshold**. The threshold is occasionally less than 100 metres in depth. If the threshold appears at the water's surface it may manifest as islands called skerries; a **skerry** is a small rocky outcrop. The origin of the threshold is disputed. It could be a large terminal moraine, which is material 'bulldozed' by the moving glacier, marking its furthest point of advance during the glacial period, or it could be, the point where the glacier's snout was thinner, or perhaps were the glacier began to float, each of the latter two scenarios giving the glacier reduced erosive power.

Examples of fjords can be seen in high latitude locations such as Norway, where Sognefjord is located; the most northerly parts of North America and south Chile as well as in western Scotland. *Fiordland* in the south-west part of South Island, New Zealand has fourteen fjords including the well-known Milford Sound. **Fiards** are submerged *lowland* areas which have been glaciated in the past. They are much wider, shallower and less branched than fjords. They lack the steep cliff-like valley sides of fjords and also differ with the presence of low-relief features such as marshes, mud-flats and floodplains. Glacial deposits and features such as drumlins can also be submerged as sea levels rise and inundate the low-lying areas. Examples of fiards are found in the Oslo Fjord region and the Baltic coast of Sweden. Specific examples include Strangford Lough in Northern Ireland and Somes Sound in Maine on the north-east coast of the USA.

Figure 8. The key features of fjords



Depositional features can also be shaped by submergence. **Mangroves** and **salt marshes** which are widened by emergence may shrink as they are eroded by the transgressing sea. The tidal creeks that cross them will increase in size as sea levels rise and more water can periodically inundate the ecosystems. When there is a rise in sea level, the lower reaches of rivers will be submerged and at the point at which a river network reaches this new sea level, there will be deposition, providing that sediment is in great enough supply, creating a **delta**. Sea level increase during the Holocene has also formed **submerged forests** where peat layers and tree remains, usually stumps still in their position of former growth, are submerged. An example of a submerged forest is at Borth in Mid Wales.

Finally, **coral atolls** (ringed coral reefs) can develop as sea levels rise. Fringing reefs develop around the shallow shores of volcanic islands in warm tropical ocean environments. As the sea level rises, either due to eustatic changes or a relative rise in sea level due to subsidence of the land, often due the crust being depressed under the huge weight of the volcano, reefs are able to grow upwards, leaving a ring-shape reef once the volcanic island has been submerged. Examples of atolls include those that make up the Maldives and many Pacific Islands

Summary

Sea level can change on a long-term basis due to movements of the sea, and vertical movements of the land, leading to a change in relative sea level. *Rises* in sea level create **submergent** coastlines. When coastlines shaped by rivers are submerged, rias are formed on discordant coasts, while Dalmatian coastlines are created on concordant coasts. Glaciated uplands form fjords when submerged, and fiards form on the formerly glaciated lowlands. Other features of coastal submergence include submerged forests and atolls. *Lowering* of sea level can create **emergent** coastlines where raised beaches and associated features are common. Incised river channels may be carved into lowland coastal plains if continental shelves emerge.

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