Geo Factsheet

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The Importance of Sub-Aerial Processes in the Formation of Coastal Landforms

Introduction

Coastlines around the world are changing. These changes can occur at different rates, scales and are due to various factors and processes. The resultant landforms that we see provide information about the mechanisms at work. For example, a sand spit tells us about the direction of longshore drift and the supply of sediment, whilst a coastal stack provides clues about a diminishing headland. In order to understand what these landforms show, we must consider the variety of factors that can shape them.

Table 1 Classification of common coastal landforms

Erosional landforms		Depositional landforms	
Cliffs	Geos	Beaches	Tombolos
Platforms	Blowholes	Spits	Bars
Headlands	Stacks	Marshes	Deltas
Arches	Stumps	Dunes	Cuspate forelands

Coastal landforms are usually grouped into two categories according to the primary process behind their formation (see **Table 1**). In reality, erosion and deposition are closely connected and, to some extent, both will play a role in the formation of all of these landforms. For example, whilst a beach is clearly a depositional feature, the sand from which it is made may well have been eroded from local cliffs. Indeed, even the term 'erosional landform' is somewhat misleading given that it is usually not just erosion that leads to its formation. It is the relationship between marine erosion and the sub-aerial processes of weathering and mass movement, along with several other factors, that determines the nature of these erosional landforms (see **Figure 1**).

It is also worth noting the relationship that **time** has with processes and landforms within the coastal landscape. Artificial management of coastlines aimed at reducing marine erosion is likely to have impacts felt within decades, as will many mass wasting events such as the slumping witnessed in Dorset. More significant changes to a coastline such as the development or denudation of various rocky features may take hundreds or thousands of years.

Underlying all these geologically rapid events are changes to entire land masses, where tectonic movements can force changes to the relative positions of land and sea.

Sub-aerial processes

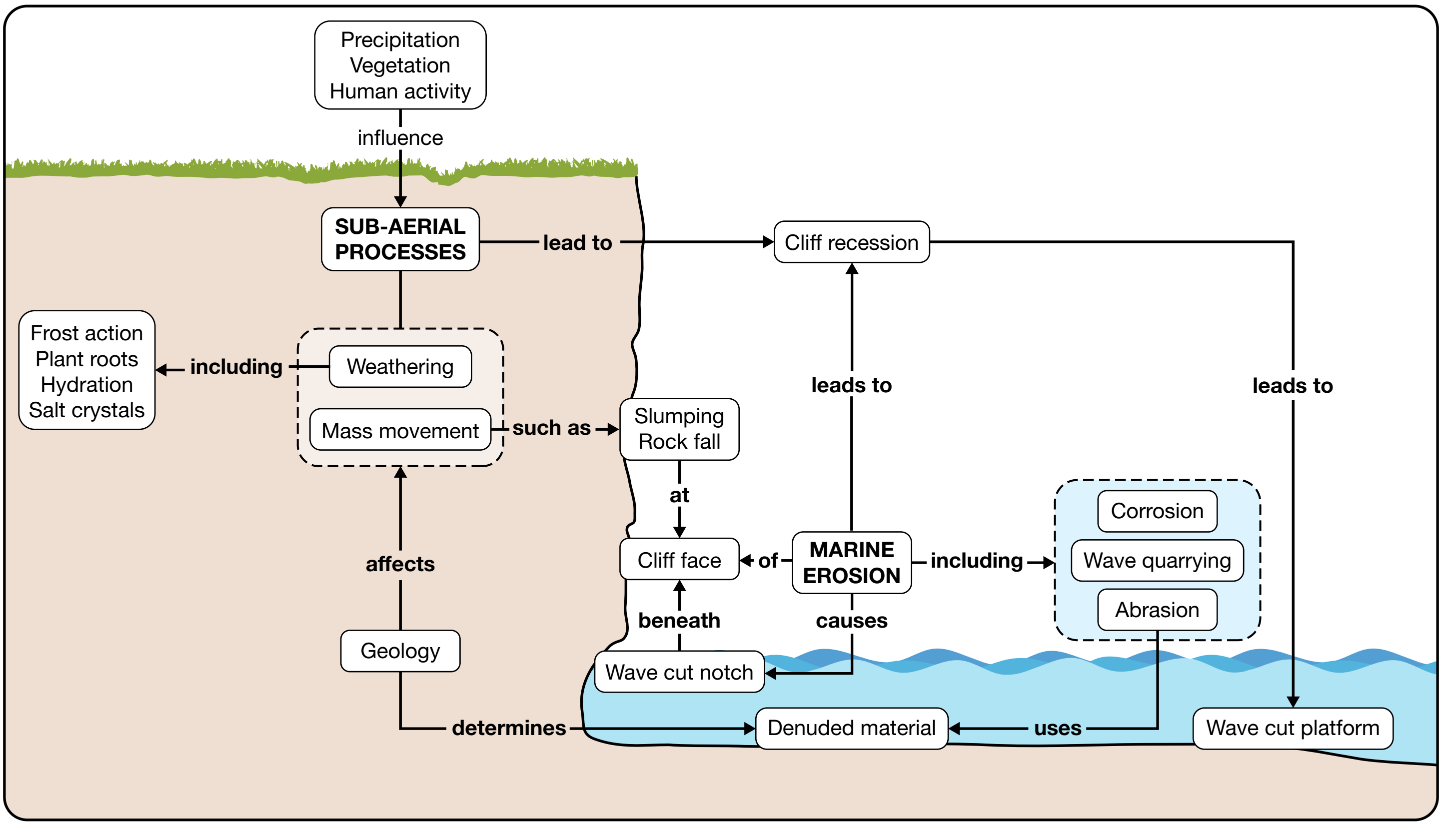
Sub-aerial (literally "under the air") processes are the combination of weathering and mass movement, which work together to **denude**, or remove, the earth's surface. They are not exclusive to coastal environments and are found at work inland too. At the coast, however, they are aided by marine erosional processes that act in tandem with them on exposed coastal surfaces.

Weathering is the breaking down of rocks *in situ* which means that, unlike erosion, there is no additional force acting on the rocks, such as waves or rainfall. Weathering is usually categorised into three groups:

- Physical Weathering is the **disintegration** of rocks into smaller pieces.
- Chemical Weathering is the **decomposition** of rocks by a chemical reaction.
- Biological weathering is the result of action from plants and their roots.

There are a number of factors that determine the type and rate of weathering. Climate is the major control of weathering but there are too many other variables to see a clear relationship. **Table 2** summarises the main controls. This complex combination of controls explains why there is such variation in the shape of coastlines around the world.

Figure 1 Relationship between sub-aerial processes and marine processes



Physical weathering: freeze-thaw

Freeze-thaw, or frost shattering, occurs when water that has settled into cracks, joints or pores in the rock freezes. Water expands by 9% when it freezes and this exerts immense pressure on the surrounding rock. Freeze-thaw is most effective when the water seeps into a rock's pores before freezing and the stress this generates exceeds the rock's tensile strength. A regular frost cycle, where the water freezes and then thaws, provides the optimal conditions for freeze-thaw.

Physical weathering: salt-crystal growth

Salt-crystal growth occurs when salt-laden water moves into the pores of rock. As the water evaporates, the salt crystals left behind grow and aggregate creating internal pressure within the rock. It is particularly common in arid regions where evaporation rates are high. The process has been shown to be most effective in temperatures of 27°C where crystals expand up to 300%.

Physical weathering: hydration

The repeated wetting and drying of rock will affect its minerals in different ways according to their nature. If a rock's minerals expand and then contract at varying rates this will lead to internal stresses that eventually contribute to the rock's disintegration.

Chemical weathering: carbonation

Carbonation affects limestone and chalk coastlines because they both contain calcium carbonate. Rainfall absorbs atmospheric carbon dioxide to create a weak carbonic acid, which then reacts with the calcium carbonate in the rock. Calcium bicarbonate is produced, which can then be washed away in solution.

$$H_2O + CO_2 \rightarrow H_2CO_3$$

$$H_2CO_3 + CaCO_3 \rightarrow Ca(HCO_3)_2$$

Chemical weathering: hydrolysis

Hydrolysis occurs when a mineral within a rock reacts with water to produce a new substance. A good example is when the feldspar found in granite reacts with acidic water and forms kaolin, a soft clay. Quartz, one of the other minerals found in granite, is resistant to chemical weathering, which is why it is one of the most common minerals found in sedimentary rocks.

Biological weathering: root action and burrowing animals

Plants and animals can lead to both the disintegration of rocks (e.g. through plant root action) and the decomposition of rocks (e.g. through the release of humic acids by decaying vegetation). A layer of leaf litter on a forest floor can also provide a 'blanket' that keeps the soil beneath warm and damp enough to increase the rate of chemical weathering.

Figure 2 Peltier Diagram

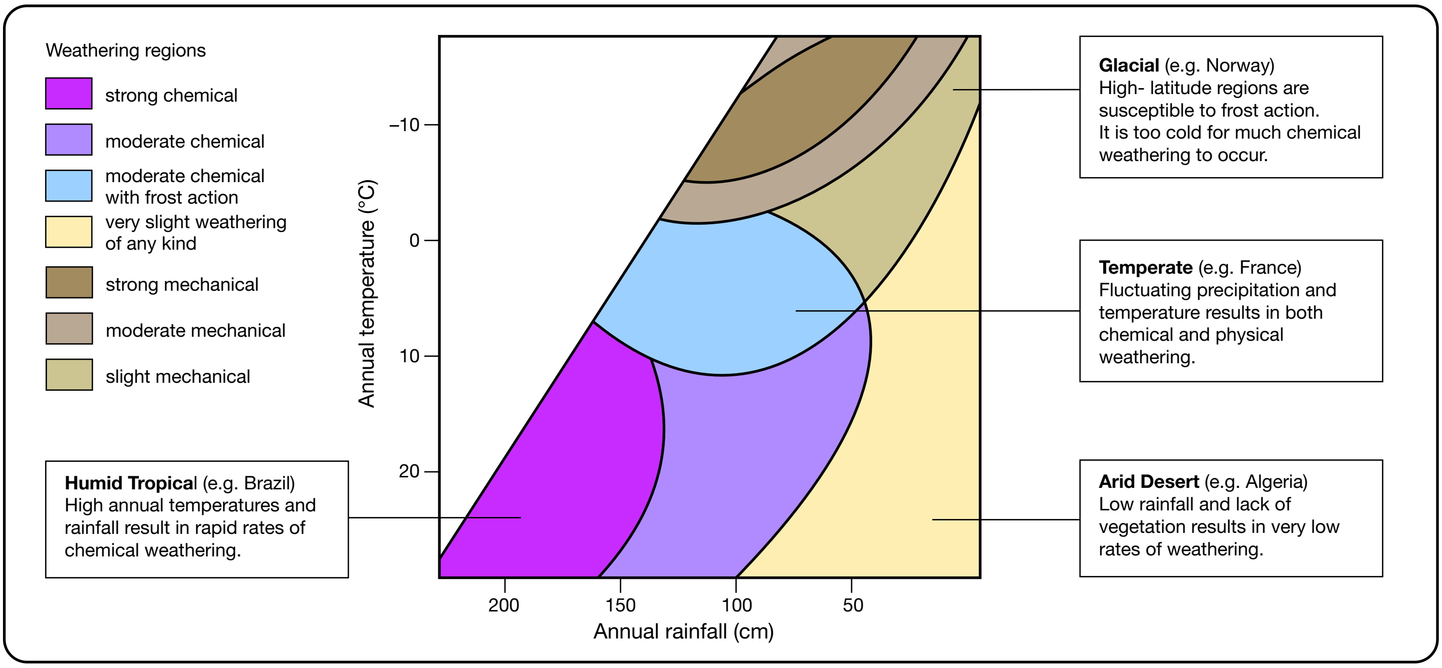


Table 2 Controls of Weathering

Factor	Explanation
Climate	The type and rate of physical and chemical weathering is affected by temperature and the presence of water.
Rock structure	The presence of joints, bedding planes or faults allow water to penetrate into the rock. Sedimentary rocks have bedding planes that make for natural slip planes (see **Figure 5**).
Rock type	Rocks are made up of a variety of minerals which will weather at different rates. For example, limestone is susceptible to carbonation due to the presence of carbonate minerals.
Vegetation	The presence of vegetation generally increases the rate of chemical weathering by providing a leaf litter 'blanket' and humic acids released during plant decomposition.
Human activity	Increased outputs of gases such as carbon dioxide and nitrogen increase the acidity of rainfall which can accelerate the rates of processes such as carbonation.

In 1950 Louis Peltier created a diagram (see **Figure 2**) to show how the temperature and amount of rainfall in a place determines the type of weathering that will happen there. His diagram shows that:

- Physical weathering will occur where rainfall and temperatures are low.
- Chemical weathering will occur where rainfall and temperatures are high.
- Very slight weathering will occur where rainfall is low, and temperature is high.

His diagram does have limitations, as it seems to be based on freeze-thaw as being the only type of physical weathering. However, it does show that chemical weathering generally increases with higher temperatures and more rainfall.

Mass movement

Along with weathering, the other sub-aerial process at work on the coast is mass movement, which is the downslope movement of material under gravity. The nature and rate of the movement is dependent on a range of factors such as the climate, topography, vegetation, and the material itself. In coastal areas, mass movement works in conjunction with weathering and marine erosion to denude slopes of material. In the case of a typical cliff face, marine erosion and weathering weaken and break down the rock, whilst mass movement removes the loose material to expose new rock surface for further work from erosion and weathering.

Types of mass movement

Rock falls occur on steep slopes, especially on dry bare rock faces that have been exposed to processes such as freeze-thaw that works in joints and cracks. Along coastlines, cliffs are subjected to undercutting by the marine erosion of waves at their base. Rock falls are very fast and often occur after heavy rains have added additional weight by seeping into the rock. The rate and regularity of rock falls may vary, as the debris from one event may reduce the likelihood of another by acting as protection from further marine excavation.

Slumping is common along coastlines made of softer, less-resistant materials. Rocks that are more permeable absorb rainwater which adds weight to the slope, as well as providing a lubricant for the movement. Slumping is also known as a rotational slide due to the concave nature of the downward movement (see **Figure 5**). Individual portions of the collapsed slope remain relatively undisturbed as the ruptures tend to follow internal weaknesses such as joints or fractures. The resultant blocks are often tilted inwards, thus collecting rainwater and increasing the likelihood of further slope failure. Slumping can occur very rapidly, hence the warning of danger along the Jurassic coast (see **Figure 4a**).

Figure 3 Rockfall at the White Cliffs of Dover

Case Study:

The White Cliffs of Dover are an iconic feature of Britain's coastline. They are commonly associated with wartime defence and a romantic reminder of home. However, like all other cliffs, they are subject to sub-aerial processes and marine erosion. This results in regular rockfalls, like the one shown in **Figure 3**, which occurred in March 2012. Rockfalls are common along chalk cliffs, particularly in the winter months when their permeability and wet weather allow for wetting and drying cycles to take effect. This internal stress weakens the cliff making slope failure more likely.

Figure 4a Dorset County Council warning on social media

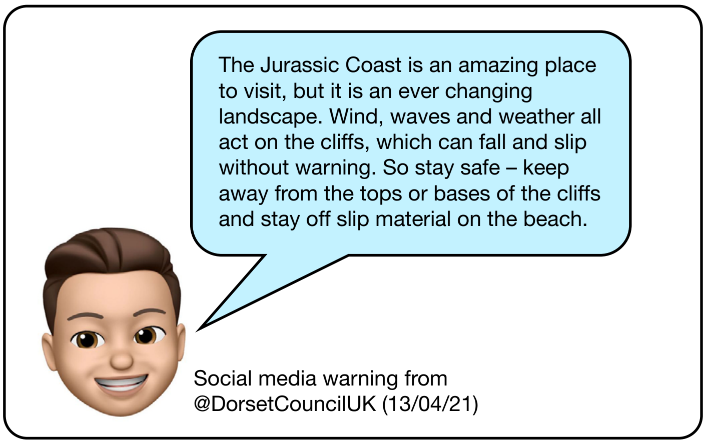


Figure 4b Systems diagram of cliff recession

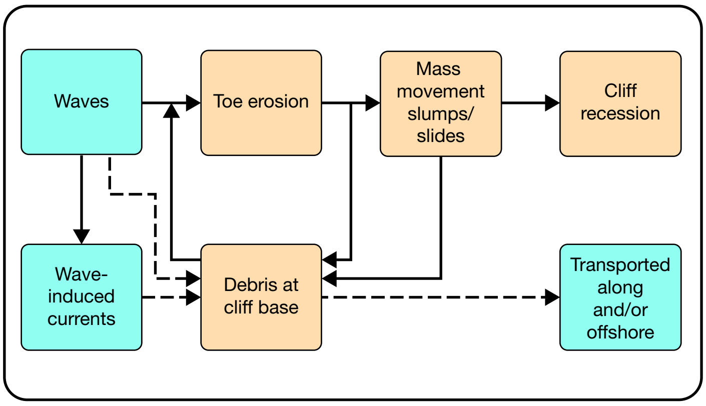
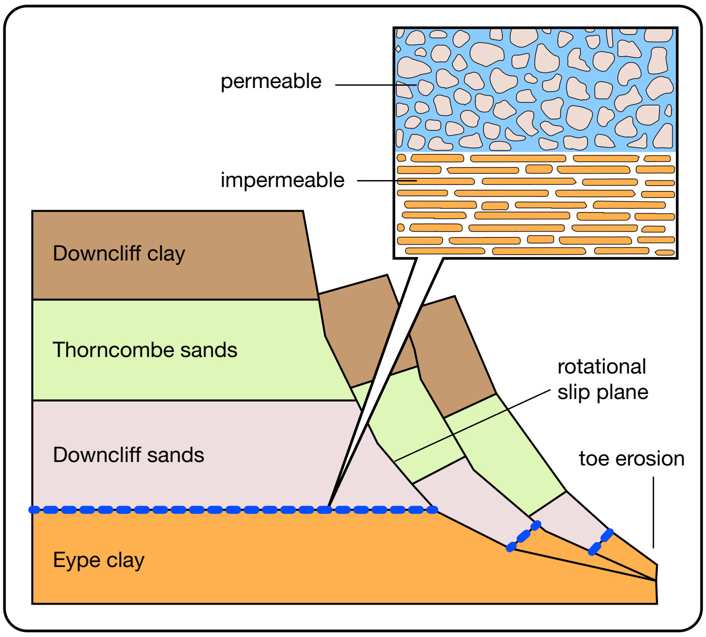


Figure 5 Slumping diagram (Jurassic Coast). Note the blue dotted line representing the lubricated boundary between saturated sandstone and impermeable clay



Case Study:

The Dorset coastline is well documented for its range of coastal features and is no stranger to mass movement. On the 13th April 2021, the largest cliff failure in 60 years saw 4,000 tonnes of rock slump down onto the beach below, with a 300m stretch of cliff affected. **Figure 5** shows a simplified cross-section of the affected cliff made up of layers of sands and clays. The more porous sandstone absorbed rainwater making it heavier. The impermeable layer of Eype Clay at the base acted as a slide plane along which the mass movement occurred.

Sub-aerial processes and erosional landforms

No two coastlines are the same. Whilst two coastlines may both have cliffs and wave-cut platforms, those landforms will inevitably differ.

Cliffs are steeply sloping surfaces that cover about 75% of the world's coastlines. The wide range of cliff size and shape suggests that there are several controls that determine their **morphology** (structure). Sub-aerial processes and marine erosion are the two main factors that shape cliffs, but the local geology, vegetation and climate will also influence their development.

Figure 6 shows a model of how cliffs develop over time. Note the increasing height of the cliff as it recedes. Their profiles are variable and are controlled by a number of different factors. For example, the rock type, presence of jointing or bedding planes, and the climate can all influence a cliff's morphology. Similarly, the presence of a beach at the base of a cliff could also affect the impact that waves can have on erosion or transportation of denuded material. It is the balance of these controlling factors that will determine whether it is sub-aerial processes or marine erosion that is the dominant influence, and therefore determine the shape of the cliff.

Figure 6 A model of cliff formation and modification

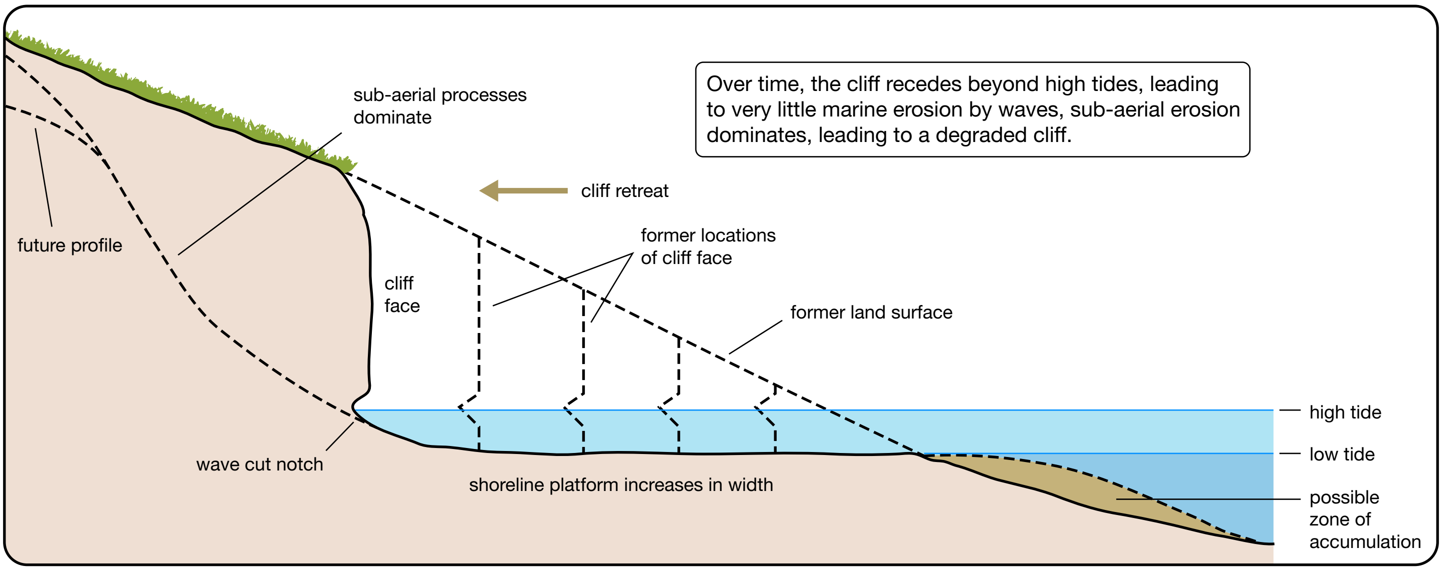
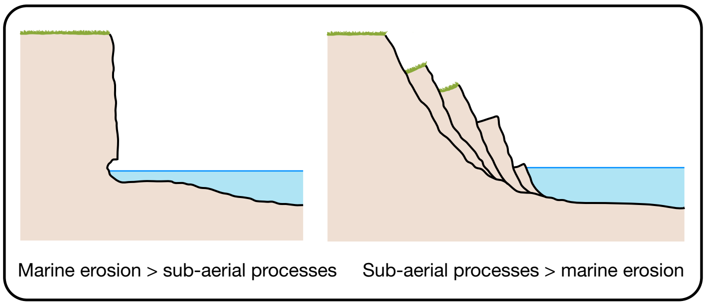


Figure 7 shows a comparison of two cliffs. In the case of the first cliff, there is relatively little weathering or mass movement, resulting in a steep cliff. The rate of marine action compared to sub-aerial processes is such that any denuded material is removed before any significant build up at the base of the cliff. The balance between supply and removal at the second cliff is the opposite. That is, there is considerable weathering and mass movement resulting in a gently sloping cliff with a significant build-up of material at the base, that protects the cliff from basal excavation.

Figure 7 Cliff profiles



Wave-cut platforms

Wave-cut platforms are misnamed. A growing number of coastal geomorphologists suggest that waves actually only play a limited role in the formation of these gently sloping platforms that are left behind as a cliff retreats. Given the importance in sub-aerial processes in cliff recession then perhaps they should more accurately be called **Shore platforms** or **Coastal platforms**. **Figure 8** shows low tide at Kimmeridge Bay in Dorset and the recognisable gently sloping area covered in rock pools, which have been carved out by a combination of marine abrasion and corrosion. Both **Figures 1 and 6** show the process by which this platform was formed.

Figure 8 Shore platform at Kimmeridge Bay, Dorset. Note that the precise form of the shore platforms is controlled by lithology

Figure 9 shows the impact changing sea levels can have on a coastal landscape. The small fishing village of Bleik in Norway is situated on the edge of a **raised platform**. This platform would once have been formed in the usual way as the cliffs, just visible to the left of the photograph, receded. As sea levels dropped relative to the land, the platform was raised out of reach of the sea allowing vegetation and eventually human settlement. Indeed, the flat area has provided ideal land for agriculture and even a golf course with the whole cliff recession cycle starting again at the base of the new sea level. Sub-aerial processes will dominate on the raised beach and former cliff.

Caves, arches and stacks

These marine features are also modified by sub-aerial processes. A **cave** may develop where an exposed notch or fault along a cliff face is deepened and widened by repeated marine erosion. If this occurs along a narrow headland then two back-to-back caves may eventually join to form an **arch**. There are many spectacular examples of arches around the world, and they make for great tourist attractions. Eventually, however, they will collapse as the processes that created them continue to wear away at the arch's roof and sides until gravity forces the roof to drop, leaving a **stack**. These tall, isolated pillars of rock are a residual feature of cliff recession.

Figure 9 Raised platform at Bleik, Norway

The factors affecting the rate of change to these features are the same as described earlier: geology; climate; vegetation and human activity. Wave refraction is also likely to play a part, whereby the shape of the coastline causes incoming waves to focus their energy onto the sides of the headland, increasing their impact. As with all coastal landforms, it is a combination of marine erosion and sub-aerial processes that are responsible.

Sub-aerial processes and depositional features

As this Factsheet has tried to show, it is difficult to explain one coastal feature or process without appreciating the role that a variety of other factors will have played. This holds true with the depositional features listed earlier in **Table 1**. We might expect only the processes of transport and deposition to have created these features but without erosion, mass-movement and weathering, beaches would not exist. Most beaches around are made of quartz-rich sand. This is due to quartz's relative stability and resistance to weathering. For example, whilst the other minerals in exposed rocks, such as feldspar, are broken down by hydrolysis, quartz minerals are left over and eventually find their way into the oceans. Over time, these minerals may be transported slowly by sea currents and longshore drift until they are deposited in a low-energy environment, such as a beach.

Conclusion

This **Geo Factsheet** addresses the role that sub-aerial processes play in the formation of a variety of coastal landforms. It examines the relationship between sub-aerial processes and marine erosion, as well as discussing the factors that determine the rate of weathering and mass movement. The list of weathering and mass movement used is not exhaustive, and there are numerous other factors and influences involved. For example, human activity is increasingly becoming more significant in the changing coastal landscape. Growing populations and a warming climate are now significant factors. The increasing acidity of rain and seawater may be altering the rates of chemical weathering; and the rapid urbanisation of coastal settlements can lead to deforestation and soil mismanagement that may, in turn, affect a number of sub-aerial processes including rates of mass movement.

Exam Style Question

"Assess the relative importance of sub-aerial processes in shaping rocky coastlines."

This is frequently accompanied by a photo resource. It is vital that you really use the resource. It is also important that you assess the relative importance of other processes for maximum AO2 marks.

Points to consider:

- This type of question requires not only an appreciation of what sub-aerial processes are but also an understanding that they work in tandem with marine erosion.
- A range of other factors should also be considered. Geology, climate, vegetation, and human activity all help shape a coastline.
- There is no "right" answer. However you choose to structure your answer, a range of factors should be given to demonstrate a clear understanding of the topic, backed up by examples such as the case studies referenced above.

References and Further Research

- **National Geographic summary of types of weathering:** https://www.nationalgeographic.org/encyclopedia/weathering/
- **Introduction to Coastal Processes and Geomorphology by Robin Davidson-Arnott:** https://doi.org/10.1017/CBO9780511841507
- **Deadly cliffside collapse underscores California's climate-fueled crisis:** https://www.theguardian.com/us-news/2019/aug/06/california-collapsing-beach-deaths-highlight-climate-fueled-erosion-crisis
- **Seatown Landslide – Jurassic Coast Trust:** https://jurassiccoast.org/what-is-the-jurassic-coast/staying-safe-while-enjoying-the-coast/seatown-landslide/
- **The Physical Geography of Landscape:** Collard, Roy. Collins Educational (1988)
- **Process and Landform:** Clowes, Alan and Comfort, Peter. Oliver and Boyd (1997)

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