Contents

Review questions

1. Distinguish between the terms erosion and weathering.
2. Explain the role of erosion in the formation of shore platforms.
3. How does weathering contribute to the formation of stacks?
4. Explain why beach profiles vary a) from place to place and b) over time.
5. How do flows of energy and materials influence aeolian processes?

Key idea

→ Coastal landforms are interrelated and together make up characteristic landscapes

Case study: A low-energy coastal environment: the Rhone Delta, France

Location

The River Rhone flows into the Mediterranean Sea just to the west of Marseilles in southern France. The delta lies between the two major distributaries of the River Rhone; the Grande Rhone and the Petit Rhone, which diverge 4 km north of Arles. In the 30 km between this point and the sea, the Rhone splits into many further distributaries to form a delta. The east branch, the Grand Rhone, is the largest of the two branches and carries 85 per cent of the river's water into the Mediterranean Sea.

See pages 17–22 for full explanations of the formation of the coastal landforms listed below.

How the delta formed

The Rhone delta has formed over the last 7000 years since the sea level rise at the end of the last ice age finished. The current shoreline began to take shape at the beginning of the eighteenth century when a flood moved the course of one of the channels of the Rhone to its present-day position. This led to material at the mouth of the abandoned channel being moved to form the Beauduc Spit. In the nineteenth century the mouth of the Grand Rhone changed position due to human management reducing it from three channels to one. The total length of coastline is 90 km and covers an area of 1740 km^2. It is a lobate shaped delta that is dominated by waves (rather than the tide or river), meaning that waves re-shape the delta by moving sediment at the edge of the delta by longshore currents. The deposits are typically sand and silt, with coastal beaches of fine sand.

This is a low-energy coastal environment:

- The enclosed shape of the Mediterranean Sea means fetch distances are relatively short in all directions. The longest fetch is about 900 km from the SW, although that is interrupted by the presence of the Balearic Islands.
- The dominant wind direction (NW) typically has low wind speeds.
- As a result of both of the above, waves tend to be low in height and energy.
- The high levels of sediment accumulation from river deposition have created a gently sloping coastal landscape. Waves break early on the shore and their energy is dissipated by the beach and delta sediment.

Deposition was estimated to be 17 million m^3/year or 50 tonnes/min in 1900. The river flow does vary seasonally with a typical discharge of 1500 m^3/sec, with up to 6000 m^3/sec in high flow conditions, and so deposition varies seasonally, too. The high deposition rate is due to the flocculation of clay particles. The Mediterranean is very saline, and when salt water mixes with fresh water, any clay particles present become adhesive and stick together forming larger, heavier clumps which can no longer be held in suspension. The small tidal range (0.3 m) also creates very few currents to carry material away. However, the amount of material carried fell during the twentieth century as the Rhone River was managed to prevent flooding and for hydro-electricity production. In 2000 it was estimated that the river was only carrying 1.5 million tonnes per year.

Landforms of the Rhone Delta

Waves come from two main directions (Figure 1.28 on page 24). The most frequent wave direction is SW (30 per cent of the total regime), but these waves are of rather low energy with heights of 0.5 to 1 m in 80 per cent of cases, making this coast a low energy environment. Waves from SSE and ESE are less frequent and represent 16 per cent and 11 per cent of the total annual regime, respectively. These are higher energy waves, more than 2 m high in more than 40 per cent of cases. They are associated with onshore winds from SSE and SE, whose speeds can exceed 100 km/h.

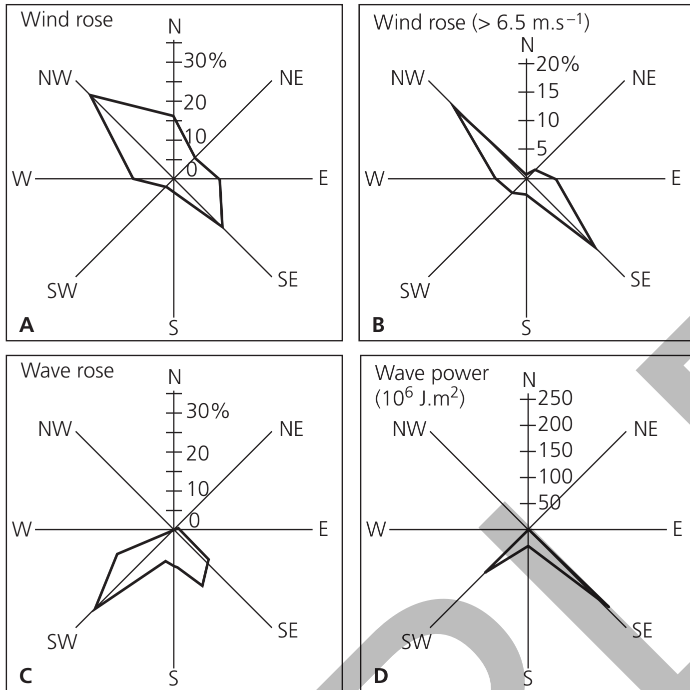

Figure 1.28 Wind and wave data

The pattern of sediment transport is split up in to four cells (Figure 1.29).

See pages 2–3 for information about how sediment cells operate.

Cell 1 is dominated by SW–NE longshore drift which has formed the Gracieuse spit across the entrance to Port St-Louis at Marseilles. Cell 3 has converging longshore drift currents, and this has resulted in the formation of onshore bars. All along the coast, areas of lagoons (known locally as étangs) can be seen where longshore drift has moved sand to create lagoons trapped behind the onshore bars and spits.

The delta is very gently sloping. The coastal beaches are narrow with low dunes behind them (see Figure 1.30). Behind the dunes are the brackish ponds/lakes and lagoons. In the nearshore area there are longshore bars where backwash removes sand and deposits it, and between these there are longshore troughs.

Dunes form when the winds blow from the sea, and dry sand is moved up the beach by saltation. The sand becomes trapped by obstacles on the berm or the point of the highest spring tides. Gradually these sand deposits

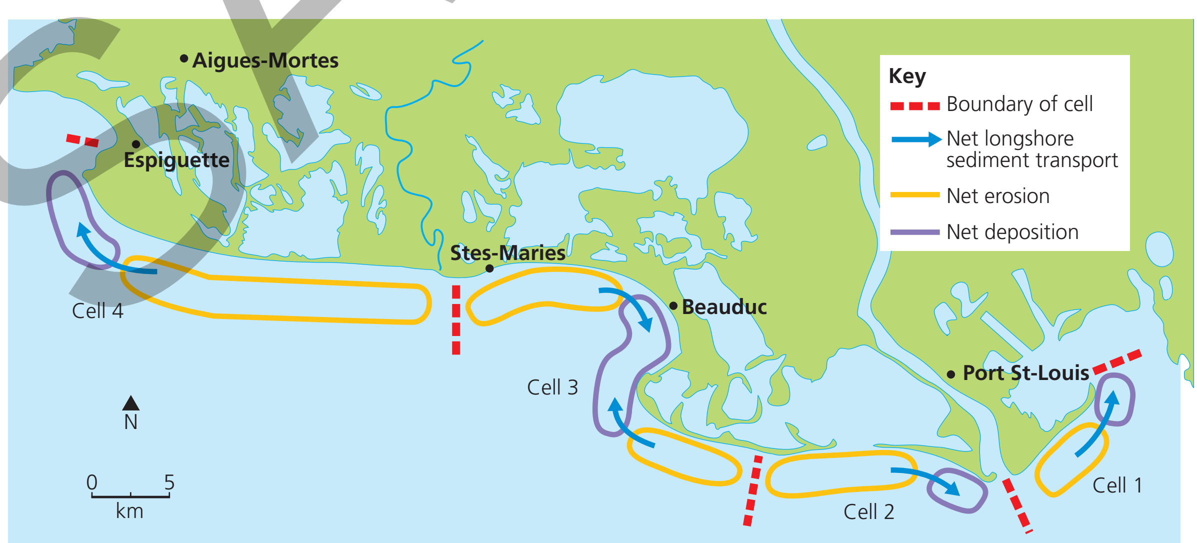

Figure 1.29 Sediment cells

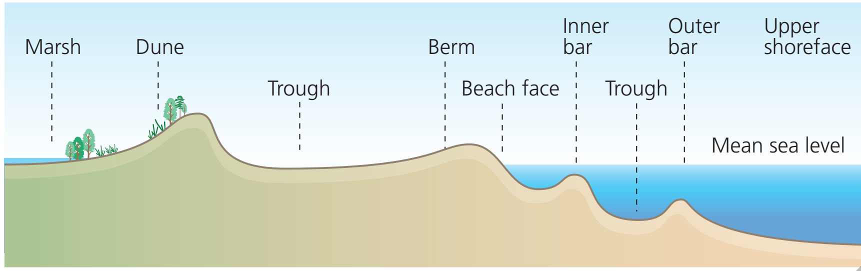

Figure 1.30 The coastal plain

will build up and become colonised by plants, such as marram grass, which are adapted to salty conditions and have long roots to help them survive on shifting sands. The grasses trap more sand, forming an embryo dune. These grow to form a ridge. Over time, dunes stabilise and the plants colonising them change as soils become established. The delta is covered by areas of brackish, saltwater marshes behind sand dunes and around the edges of the étangs.

Recent changes

Climate change and the increase in temperatures are having an impact on the Mediterranean. A rise in sea level of 2 mm/year since 1950, plus increased storm activity have affected the delta, leading to increased rates of erosion of beaches and dunes. Although the tidal range is small, winds from the SE can result in large wave surges. This, along with the reduced sediment input from the rivers, has led to a change in the relationship between sediment inputs and outputs in the system, resulting in rates of coastal retreat of between 2 and 8 m, notably at Stes-Maries (Saintes-Marie-de-la-Mer) (Figure 1.29). Authorities have spent €15 million on coastal protection, including groynes, rip rap and sea walls to try to restore the equilibrium in the system.

Activities

1. Describe the shape and structure of the Rhone Delta.
2. Explain how the delta formed.
3. Describe and explain the recent changes to the sediment budget of the delta.

Case study: A high-energy coastal environment: Saltburn to Flamborough Head, Yorkshire

The coastal environment between Saltburn and Flamborough Head is a rocky, upland area (Figure 1.31). This 60 km long coastal environment displays many coastal landforms and its characteristics reflect the influence of the high wave energy it receives.

Geology

The environment is strongly influenced by its geology. The adjacent North York Moors rise up to 400 m above sea level and comprise mainly sandstones, shales and limestones formed during the Jurassic period as well as some carboniferous rocks. Flamborough Head, at the

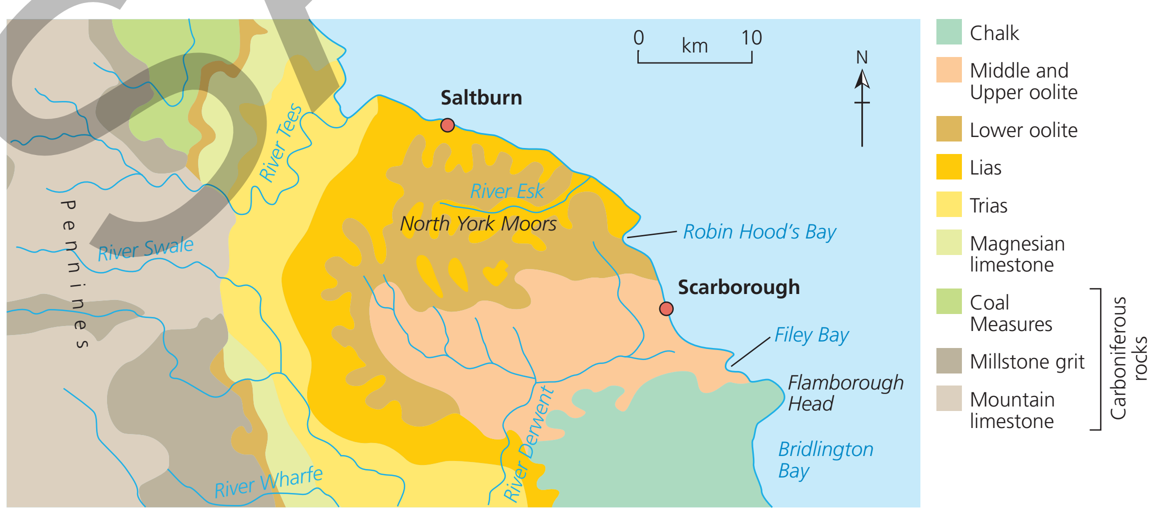

Figure 1.31 Geology of the Saltburn to Flamborough Head coast

southern end of this stretch of coastline, is a large chalk headland. Its spectacular cliffs are topped with till, a superficial deposit left behind by glaciers during the Devensian glacial period. Differences in rock resistance are responsible for the varied coastal scenery, notably the high cliffs and the bay and headland sequence.

During the late cretaceous and early tertiary periods, tectonic processes caused uplift of the sedimentary rocks leading to folding and faulting. This exposed the rocks and affected resistance to geomorphic processes.

Energy

The dominant waves affecting this coastline are from the north and northeast, with a fetch of over 1500 km. The most exposed parts of the coast are those that are north-facing, such as the area nearest to Saltburn, and so these receive the highest inputs of wave energy. Rates of erosion vary, partly due to these differences in wave energy inputs, but also due to variations in the resistance of the different geologies. Areas of relatively weak shale and clay experience erosion rates of 0.8 m per year on average, while the more resistant sandstones and limestones only erode at rates of less than 0.1 m per year.

Stretch and challenge

Average rates of erosion may hide significant variations in rate over time. On resistant geologies such as those on this coastline, occasional rock falls and landslides produce very significant cliff retreat in a few seconds (i.e. a very high rate) which may then be followed by long periods of stability (low rate).

Monitoring of wave height using floating buoys in Whitby Bay during 2010–11 revealed that wave height often exceeded 4 m, even during summer months.

The high-energy inputs are also responsible for significant longshore drift from north to south along the coastline. In places, this sediment movement is interrupted by headlands, and sand and shingle then accumulate to form beaches in the bays, such as in Filey Bay.

Sediment sources

The coastline between Saltburn and Flamborough is sub-cell 1d of the major sediment cell 1, which extends south from St Abbs in southern Scotland to Flamborough. Some of the sediment in sub-cell 1d has come from the nearshore area, driven onshore as sea levels rose at the end of the last glacial period. Sediment is also supplied by cliff erosion, including sandstone and chalk from the resistant rock outcrops and the boulder clay deposits which yield significant amounts of gravel. The only large river, the Esk, enters the North Sea at Whitby. This supplies limited amounts of sediment due to the construction of weirs and reinforced banks along its course (Figure 1.32). This is an example of the relatively limited influence of human activity as a factor on this stretch of coastline.

Beach surveys have found that there had been a net increase in beach sediment of 9245 m^3 between 2008 and 2011 at Saltburn. Zones of both beach erosion and accretion were observed within Filey Bay, which reflect the influence of winter storm systems, with erosion at the back of the beach being particularly significant in the winter of 2010–11.

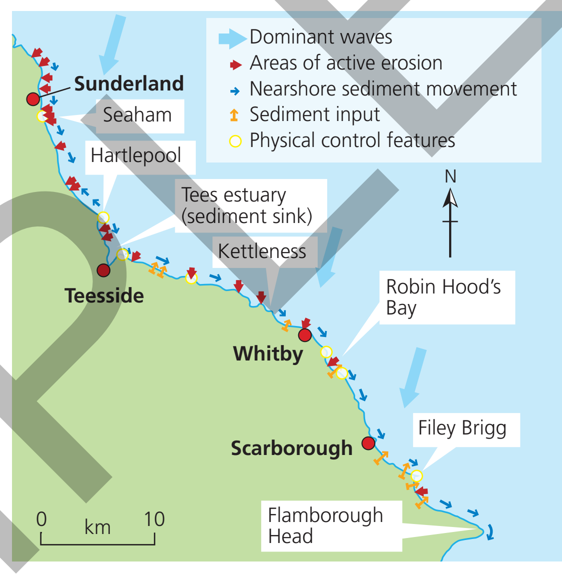

Figure 1.32 Erosion and sediment movement of the coast of northeast England

See pages 13–17 for full explanations of the formation of the coastal landforms listed here.

Cliffs

The sedimentary rocks of this coastline are horizontally bedded, and as a result the cliff profiles tend to have a vertical face. Most cliffs are overlain by a layer of weak glacial till, which has a much lower angle. Cliffs at Flamborough (Figure 1.33) are made of chalk, which is physically very strong with tightly bonded mineral particles. The vertical cliffs are typically 20–30 m high, with the overlying till lowered by mass movement processes to an angle of about 40°. Further north, between Robin Hood's Bay and Saltburn, the cliffs are much higher, but often with a stepped profile, reflecting the more varied geology. The steeper slope segments are formed in the more resistant sandstones and limestones, with gentler slopes corresponding to the weaker clays and shales, again lowered by mass movement processes.

Figure 1.33 Cliffs at Flamborough Head

Shore platforms

High-energy waves and active erosion mean that cliffs are retreating along this coastline, leaving behind rocky shore platforms. A good example can be seen at Robin Hood's Bay (Figure 1.34), eroded into Lower Lias shales. The platform slopes at a typical angle of 1°, although ramped sections are as steep as 15°. The platform has a maximum width of about 500 m, but extends much further into the off-shore zone. Based on current rates of erosion and retreat, it is quite possible that platforms such as these could have been formed within the last 6000 years, during times of predominantly stable sea levels. However, some experts suggest that they are relict features, formed during earlier inter-glacial periods when sea levels were similar to those of today.

Headlands and bays

The variation in rock type along this coastline has led to the formation of a series of bays and headlands as part of a discordant planform. Robin Hood's Bay (Figure 1.34) has been eroded into relatively weak shales with more resistant bands of sandstone either side forming the

Figure 1.34 Cliffs and shore platform at Robin Hood's Bay

headlands of Ravenscar, to the south, and Ness point, to the north. Further south, Filey Bay has developed in weak Kimmeridge Clay and is flanked by more resistant limestone and chalk. The prominent headland at Flamborough is formed of chalk, with deep bays either side formed from clay.

Landforms on headlands

As a result of wave refraction, wave energy is concentrated on resistant headlands that project into the North Sea. Weaknesses, such as large joints or faults, are then exploited by the erosive action of the waves, enlarging them to form caves and arches. These features are clearly visible in Selwick's Bay at Flamborough Head (Figure 1.35), where a master joint in the chalk has been enlarged. Green Stacks Pinnacle is an excellent example of a stack, isolated at the end of the headland following the collapse of an arch roof. Over 50 geos have formed along this coastline, with most of them aligned to the NE or NNE, facing the dominant wave direction. Blowholes have developed where vertical master joints in the chalk have been enlarged. Subsequently chalk and boulder clay have collapsed into the underlying sea caves, leaving funnel-shaped depressions on the cliff tops. On the north side of Selwick's Bay several blowholes appear to have merged and the intervening chalk has collapsed to produce a complex inlet.

Beaches

There are very few well-developed beaches along this stretch of coastline. The best examples are found in the sheltered, low-energy environments such as Scarborough and Filey Bay. Elsewhere deposits of sand and shingle accumulate slowly owing to the low input of sediment from rivers and the slow rates of erosion of the resistant rocks. High-energy waves also remove sediment before it can accumulate. Although longshore drift is considerable, the coastline lacks spits and other drift-aligned features. This is due partly to the high tidal range of around 4 m, and the lack of estuarine environments that would provide sediment sinks.

Figure 1.35 Landforms at Selwick's Bay: (top) cave and arch, (bottom) stack.

Activities

1 Explain the influence of geology on the planform of the coastline between Saltburn and Flamborough Head.
2 Why does this coastline have so few beaches?
3 Identify the main sediment sources in this coastal system.

1.3 How do coastal landforms evolve over time as climate changes?

Changes in the volume of water in the global ocean store are known as **eustatic** changes. These changes are influenced by variations in mean global temperatures, affecting both the amount of water in the ocean store and its density.

However, it should be appreciated that sea level change is relative as it is also affected by changes in land level. These changes, known as isostatic, are not considered here.

There are a number of physical factors that can affect changes in global temperature and the volume of water in the oceans. They include:

- variations in the Earth's orbit around the Sun, typically every 400,000 years

- variations in the amount of energy produced by the Sun, with a solar maximum every eleven years or so
- changes in the composition of the atmosphere due to major volcanic eruptions which reduce incident solar radiation
- variations in the tilt of the Earth's axis, occurring every 41,000 years.

Activities

1 Describe the relationship between temperature and sea level shown in Figure 1.36.
2 Explain this relationship.

Key idea

➜ Emergent coastal landscapes form as sea level falls

Climate change and sea level fall

A decrease in global temperature leads to more precipitation being in the form of snow. Eventually this snow turns to ice and so water is stored on the land in solid form rather than being returned to the ocean store as liquid. The result is a reduction in the volume of water in the ocean store and a worldwide fall in sea level.

As temperatures fall, water molecules contract, leading to an increased density and a reduced volume. It is estimated that a 1°C fall in mean global temperature causes sea level to fall approximately 2 m.

About 130,000 years ago, during the Tyrrhenian inter-glacial period, global mean annual temperatures were almost 3°C higher than today and sea level was about 20 m above today's position. Temperatures then fell during the onset of the Riss glacial period, reaching a minimum about 7°C lower than today about 108,000 years ago. As a result of this temperature decrease, less water was returned to the ocean store and sea levels dropped by over 100 m, making them about 83 m lower than the present day (Figure 1.36).

Emergent landforms

Landforms shaped by wave processes during times of high sea level are left exposed when sea level falls. As a result they may be found well inland, some distance from the modern coastline.

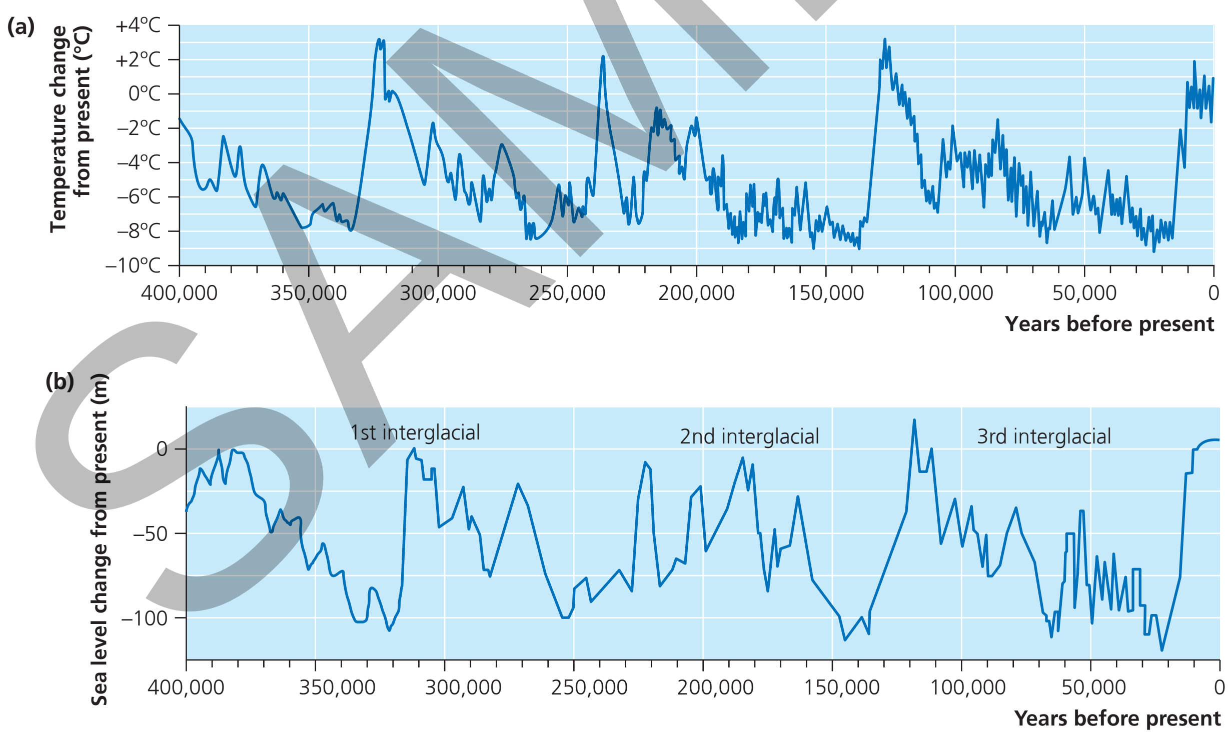

Figure 1.36 (a) Temperature change and (b) sea level change during the last 400,000 years

Raised beaches, marine terraces and abandoned cliffs

Raised beaches are areas of former shore platforms that are left at a higher level than the present sea level. They are often found a distance inland from the present coastline. Behind the beach along emergent coastlines it is not uncommon to find abandoned cliffs with wave-cut notches, caves and even arches and stacks. Marine terraces are much larger scale landscape features than raised beaches, which are quite small scale and localised at the base of relic cliffs. Terraces do not necessarily have cliffs above them. Their formation, however, is essentially the same as raised beaches – marine erosion during a previous period of higher sea level.

On the southern tip of the Isle of Portland near Weymouth in Dorset there is a distinct raised beach (Figure 1.37) at a height of about 15 m above the present day sea level. This is thought to have been formed around 125,000 years ago during the Tyrrhenian inter-glacial period when sea levels were much higher than today's. The Portland limestone here was eroded by hydraulic wave action, partly through the exploitation of the bedding plane weaknesses. Erosion rates at that time are estimated to have been as much as 1 m/year. Other raised beaches at Portland are thought to date to about 210,000 years ago.

Marine terraces are formed by very similar processes as raised beaches, but often acting over much longer time scales. This means they tend to be substantially larger in extent.

Modification of landforms

After their emergence, these landforms were no longer affected by wave processes. However, they continue to be affected by weathering and mass movement.

Figure 1.37 Raised beach on the Isle of Portland, Dorset

Figure 1.38 Cryoturbations in limestone below the raised beach, Isle of Portland, Dorset

On top of the abandoned cliff on the Isle of Portland is a 1–1.5 m layer of frost-shattered limestone debris deposited when the area experienced periglacial conditions during the last glacial period. At the same time, the cliff face itself was gradually degraded by frost weathering processes, leading to rock fall from the cliff face. Evidence of other periglacial processes, such as **cryoturbation** (Figure 1.38), is also evident as contortions in fragmented limestone. They are the result of freezing and thawing of the permafrost in the subsoil during the late Pleistocene period, the final glacial phase.

In the post-glacial period, warmer and wetter conditions have led to the development of vegetation cover on many such exposures, often making them more difficult to recognise. With further warming of the climate predicted for the future, continued degradation is likely to occur with chemical weathering perhaps becoming more influential, especially by carbonation of limestone cliffs and platforms. Biological weathering on the raised beach may also become more significant with the colonisation of the surface by increasing numbers of marine organisms, such as limpets and whelks.

If temperatures increase sufficiently, the associated sea level rise could lead to these emergent landforms again being found much closer to, or even at, the coastline. They would then be subjected to wave processes once more.

Review questions

1. How does a cooling climate affect global sea level?
2. Explain the formation of abandoned cliffs.
3. How and why might abandoned cliffs be modified in the future?