A-LEVEL GEOGRAPHY TOPIC MASTER

COASTAL LANDSCAPES

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Series editor
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CHAPTER 1

Coastal system dynamics – flows of energy

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There is a great variety of landforms and landscapes located along the world's million or so kilometres of coastline. How these features have developed and continue to evolve is the result of the interaction of processes powered by various sources of energy. This chapter:

- analyses coasts as open energy systems
- investigates energy inputs: waves, tides and currents
- explores feedback and equilibrium in coastal systems
- assesses the relative importance of energy sources in the coastal system.

KEY CONCEPTS

Systems – groups of related components. In physical geography, they tend to be 'open', that is having both inputs and outputs. The coast is such a system with both energy and materials, such as sediment, flowing through it. Systems operate across all scales, from a small cove right the way up to the global oceanic system.

Equilibrium – the state of balance within a system. Any stretch of coastline can be investigated in terms of its equilibrium. Some locations might receive an increased level of wave energy due to a fierce storm and this could affect the intensity of wave erosion. In turn an increase in erosion could lead to a dramatic change in a cliff, leading to its collapse.

Feedback – an automatic response to change within a system. Positive feedback leads to further change, for example an increase in wave energy could scour the seabed, deepening the water and allowing yet more wave energy to enter the location, further increasing wave energy. Negative feedback reduces the effect of change, for example a decrease in wave energy entering the coastal zone could lead to deposition of sediment offshore, further reducing wave energy as more wave energy is lost to friction.

Threshold – critical 'tipping points' in a system. For example, a single wave can be considered as a system. As it approaches the shore, wave height increases until the threshold is reached at which the water cannot be supported and the wave breaks, resulting in a forward rush of water.

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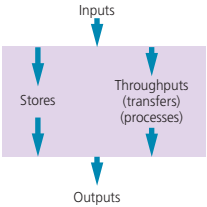
1 Coasts as open systems

▶ *How do inputs, stores and processes and outputs operate together to form the coastal system?*



▲ **Figure 1.1** An open system

An open system is one in which energy and materials move across its boundaries. Closed systems are those where only flows of energy occur across their boundaries.

All such open systems include:

- inputs, e.g. energy, sediment
- stores or components, e.g. sediment, water
- processes, e.g. weathering, erosion, mass movement
- throughput, e.g. energy, sediment, water
- outputs, e.g. energy, sediment

The application of systems when studying coasts has much potential as it focuses on knowledge and understanding of flows of energy and materials. These combine to create specific landforms such as cliffs and beaches. However, defining system boundaries is problematic. Can sections of a coast be sensibly divided up, and where does one section finish and another start? Where reasonable boundaries are established, it soon becomes apparent that a hierarchy of systems exists. For example, a sand dune system it is possible to sub-divide into different types of dunes – embryo, fore, yellow, grey. In turn, each individual dune ridge consists of two slopes or faces and a crest.

Using systems is not without its difficulties but it helps identify the various flows and components and understand how landforms and landscapes are created and interact.

Defining the coast

KEY TERM

Terrestrial Refers to the land rather than the sea or atmosphere.

Coasts are where sea, land and atmosphere meet. This unique combination may seem to offer a simple location to study but the reality is complex. Where tall cliffs plunge directly into the sea the boundary between land and sea appears clear. Other locations, such as extensive, low-lying estuaries, seem at times to be **terrestrial** but can change over the course of a few hours into a marine environment as the tide sweeps in.

The most useful context for a study of coasts is to think in terms of a coastal zone. This zone extends between the inland limit of marine influence – for example where sea spray can be blown – and the seaward limit of the land's influence, such as how far river water extends out to sea as an identifiable flow. However, not to be excluded are the marine processes that extend beyond such a zone, such as the circulation of sediment in an offshore cell.

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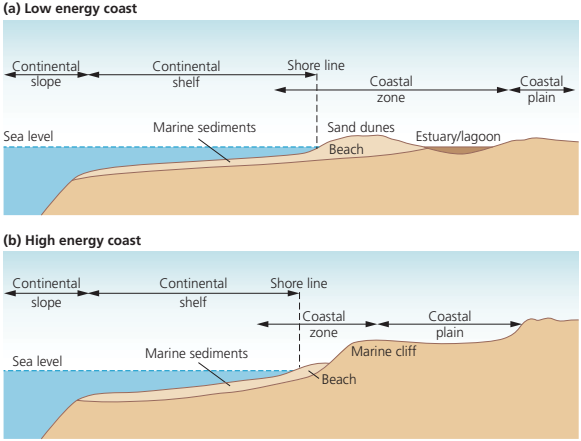
The term **littoral** can also be applied to coasts. However, there is no one single definition of coasts and the use of definitions varies. It can, however, be helpful to describe some spatial boundaries of the coastal zone and to appreciate that sub-divisions can exist (Figure 1.2).

KEY TERMS

Littoral The environment between the highest and lowest levels that tides reach.

Quaternary The most recent geological period, existing for the past approximately 2.5 million years.



▲ **Figure 1.2** Spatial sub-divisions at the coast

Not all the elements in each type of coast will necessarily be present in all locations. A lagoon does not exist along every low-lying coast as it does, for example, at Slapton, Devon. The impact of the advance and retreat of glaciers and ice sheets over the **Quaternary** has had a very significant role in defining the coastal zone. During this period, sea level has risen and fallen over 100 metres vertically many times. This has left a legacy of coastal processes and landforms both further inland and out to sea than the present-day coastline, something discussed in greater detail in Chapter 5.

The input of energy into the coastal system

Three sources of energy drive the coastal system:

1 Solar energy
2 Gravitational energy
3 Geothermal energy.

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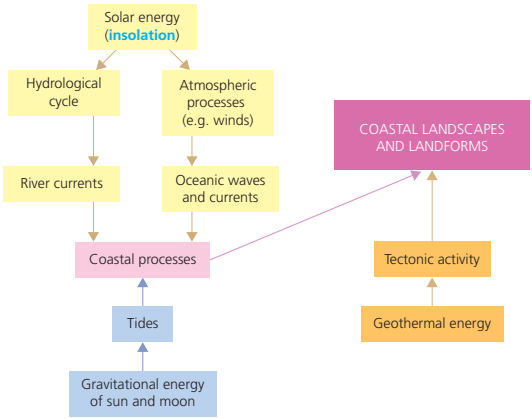

▲ **Figure 1.3** Energy inputs into the coastal system

1 Solar energy – this powers the hydrological cycle, which brings water off the land into the coastal zone, for example. It is also responsible for atmospheric processes such as winds which, in turn, generate waves and currents.
2 Gravitational energy – the gravitational pull of the sun and moon generates tides. Gravity is a key element in the movement of material down slopes, such as rock fall and underwater landslides.
3 Geothermal energy – responsible for tectonic activity that can cause uplift or submergence along a coast.

KEY TERMS

Archipelago A closely grouped cluster of islands.

Insolation Incoming solar radiation. Its intensity per unit area varies with latitude being highest around the Equator and lowest at the Poles.

It is important to recognise that energy inputs operate over very different time scales. At the geological scale (millions of years), geothermal energy can cause the convergence and subduction of plates along coasts. The southern coastline of the Indonesian **archipelago** and much of the west coast of South America receive such inputs of energy. Still over long time periods, but measured in hundreds of thousands of years, is the drowning of river valleys to create estuaries following a rise in sea level. At the other end of the time scale, winds and waves can be generated and die away in the matter of a few hours. An individual wave may take barely a minute to break on a beach.

▲ **Figure 1.4** Volcanoes along the Indonesian coastline

Energy allows 'work' to be undertaken. As it flows through the coastal zone, ecosystems function, sediments can be transported by water and wind, and waves break against a cliff face causing particles to be broken off. Changes in the energy available in the coastal zones changes the 'work' that can be achieved and in turn this affects the landforms and landscapes that develop.

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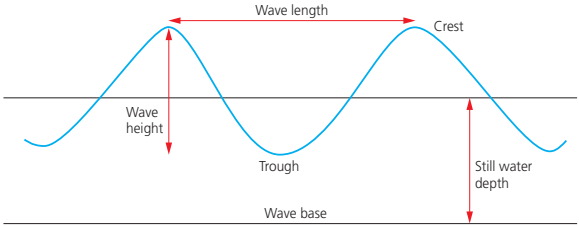
2 Energy inputs – waves, tides and currents

▶ *In what ways is energy brought into the coastal system by waves, tides and currents?*

Waves

All coasts are affected by waves to some extent but there are considerable contrasts from one location to another in the nature of wave activity. This is the case at all scales from the macro (global) to the micro (local). Waves represent a transfer of energy and are capable of carrying out much work in the coastal zone. This work includes erosion, transport and deposition of materials. Waves are described by their:

- height – the vertical distance between wave crest and wave trough
- length – the horizontal distance between consecutive crests
- wave period – the time taken for consecutive crests to pass a fixed point
- wave steepness – the ratio of wave height to wave length
- wave velocity – the ratio of wave length to wave period.



▲ **Figure 1.5** Wave characteristics

Wave height is a useful descriptor as it is commonly taken as an indication of wave energy. Two frequently used formulae for a measure of wave height are:

$$H = 0.031U^2$$

$$H = 0.36\sqrt{F}$$

where H = wave height, U = wind velocity (ms^{-1}) and F is the fetch (km). 0.031 and 0.36 are empirically derived constants.

The **fetch** is an important factor in the energy transfer from atmosphere to water. The greatest energy transfer occurs when strong winds blow in the same direction over a long distance for a long period of time; this generates the highest waves and so brings significant wave energy into the coastal zone.

KEY TERM

Fetch The distance of open water in one direction from a coastline, over which the wind can blow.

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The energy (E) of a wave in deep water is proportional to the product of the wavelength (L) and the square of the height (H):

$$E \propto LH^2$$

This formula indicates that a small increase in wave height will result in a proportionately much greater increase in energy. Because wave height varies greatly across the course of even a few minutes, a widely used measure of wave height is 'significant wave height'. This is the mean wave height of the highest third of the waves, averaging an instrument record taken over relatively short time periods (a few minutes).

Wave energy at the global scale

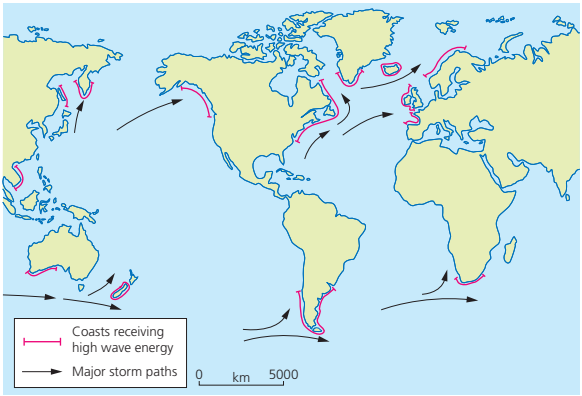
On the global scale, it is possible to identify coastlines exposed to different levels of wave energy on the basis of **prevailing winds**, fetch and **aspect**. The global distribution of high energy waves reflects the locations of substantial areas of open sea and the pattern of global winds.

Coastlines regularly receiving high wave energy are those of mid-latitude regions, north and south of the equator (Figure 1.6). Here atmospheric storms, circulating round the globe in westerly directions, occur regularly and frequently, generating large waves, that is, greater than five metres.

KEY TERMS

Prevailing winds The direction winds come from most often at a particular place, for example the prevailing winds for the British Isles are westerly.

Aspect The direction something faces, for example the aspect of the Egyptian coastline is northerly.



▲ **Figure 1.6** Location of coastlines receiving high wave energy

In the southern hemisphere, the area between 40 and 50 degrees south acquired the name the 'Roaring Forties'. Those on board sailing ships crossing these regions had to contend with severe storms and their accompanying waves. Such hostile conditions had considerable influences on flows of people and goods and the early developments of regional and global economic, social and political systems. Significant wave height around Cape Horn, at the

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southern tip of South America, is between five to six metres. In the northern hemisphere, the storms and sea conditions are still severe but not as extreme as in the southern hemisphere. This is because the large land masses of North America, Europe and Asia obstruct the airstream, whereas in the southern hemisphere there is less land to cause frictional drag on the wind.

Other coastlines experiencing storm waves include some in the lower, tropical and sub-tropical latitudes such as South-east Asia and areas around the Indian Ocean and Arabian Sea. Here, seasonal storms associated with the monsoons bring increased amounts of wave energy into the coastal zone.

Additionally, coastlines in areas where tropical storms and hurricanes (cyclones/typhoons) are generated receive very high levels of wave energy when these storms make landfall.

Beyond these areas, coastlines exposed to open stretches of water still receive significant inputs of wave energy. Significant wave height for the British Isles is between four and five metres. Where a sea is essentially enclosed, such as the Mediterranean, relatively low wave energy is experienced. Significant wave height here is between one and two metres. However, the lowest wave energy exists in polar regions where coastal sea ice is an extensive feature, such as Arctic coastlines.

Waves generated well away from land, for example out in the Pacific or Southern Ocean, become **swell waves**. These travel long distances in relatively regular progression. They are unaffected by local winds and can be seen moving against a local wind flow.

Dominant waves are key in understanding energy inputs from the ocean-atmosphere systems. Often these are the result of prevailing winds, but in some locations locally 'dominant winds' generate locally dominant waves. It is important, therefore, to consider influences at contrasting scales when investigating coastal landforms and landscapes.

KEY TERMS

Swell waves These are generated out at sea and have a long wave period.

Dominant wave The wave which has the greatest influence on a particular stretch of coast.

Storm surge An elevated sea surface near the coast, most often caused by extremely energetic storms such as hurricanes/typhoons/cyclones.

Storm surges

Three factors combine to create a **storm surge**:

- Extremely high onshore wind speed
- Very low atmospheric pressure
- The shape of the coastline.

The high wind speeds are usually associated with the passage of a tropical storm. If the storm reaches a coastal area at the same time as high tide occurs, sea level rises even higher.

When air in the lower atmosphere is rising, less mass of air presses down on the sea surface, thereby allowing the water to rise well above normal levels. Sea level rises approximately one centimetre for every one millibar fall in air pressure.

Along funnel-shaped coasts where there is a relatively shallow off-shore gradient, surges are more pronounced. Relatively straight coastlines are not as affected.

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Surges happen regularly along coastlines affected by tropical storms, such as around the Bay of Bengal or the Caribbean. However, surges can occur in other locations. On 5 December 2013, a storm surge affected coastlines surrounding the North Sea and through into the Channel. The two successive high tides were the highest experienced in some 60 years and led to the evacuation of thousands of people from low-lying locations in England, the Netherlands, Belgium and France. The impacts in the coastal zone included severe cliff, beach and sand dune erosion, loss of some properties and disruption to transport links (see page 132).

Seismic sea waves – tsunamis

KEY TERM

Tsunami A wave created when a large mass of water is suddenly displaced.

A **tsunami** can be triggered when vast quantities of water are displaced. This can occur due to an earthquake affecting the sea bed or a large-scale underwater mass movement, such as the collapse of an underwater steep slope. The earthquake needs to be of a type that moves the seabed vertically, so not all underwater earthquakes result in a tsunami.

In deep water, tsunamis are hardly noticeable, having a wave height that is usually less than one metre and a very long wavelength, up to 200 kilometres. They travel at very high velocities, up to 800 km h^{-1}. Out at sea, they can pass beneath a vessel with little, if any, effect, but as they close on the shore their power is focused into a forward rush of water. *Tsunami* is a Japanese word for 'harbour wave'. Their height can climb to many metres and when the tsunami wave breaks, vast amounts of energy are released on to the coastline. The tsunami generated by the earthquake off the coast of Aceh province, Sumatra in December 2004 is estimated to have delivered about 1000 tonnes of water per metre of shoreline. The four to five metres of vertical movement of the seabed is estimated to have displaced some 30 km^3 of water, which then radiated out along the entire 1200 km length of the rupture in the rocks making up the seabed.

Waves in deep and shallow water

▲ **Figure 1.7** The Great Wave off Kanagawa, woodblock print by Japanese artist Hokusai

Waves in deep water

As air moves across a water surface, the friction between the air and water allows a transfer of energy from the atmosphere to the sea. This action creates pulses of energy which pass through the upper layer of water. Each wave thus possesses potential energy due to its height from wave crest to trough and kinetic energy caused by the movement of water within the wave.

When looking at waves out at sea beyond the near shore, it appears that, as waves pass through, they move water forward. Individual water particles, however, move in a circular motion at an equal velocity in all parts of the orbit (Figure 1.8). An object in the water basically bobs up and down as a wave passes.

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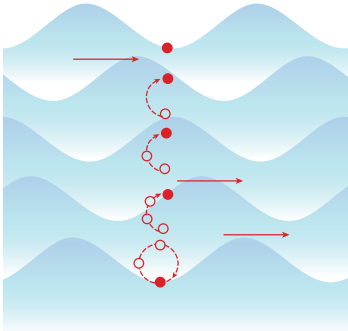

◀ **Figure 1.8** Circular motion in deep-water waves

The diameter of the circle travelled by a water particle decreases with increasing depth of water until a depth is reached at which the water is unaffected by the pulses of energy and conditions at the surface. This depth is known as **wave base**. Wave base is generally reckoned to be somewhere in the range of between one-half to one-quarter of the wave length. Wave base is important as above it waves are capable of eroding, transporting and depositing sediment, thereby carrying out considerable geomorphological work.

KEY TERMS

Wave base The depth at which water is unaffected by waves passing above.

Swash The forward movement of water once a wave begins to break.

Backwash The return flow of water away from the shore under the influence of gravity.

Waves in shallow water

As waves come close to the shore, they are modified as a result of decreasing water depth. The circular orbits of deep-water waves become more elliptical because of friction between the seabed and the water particles, with the forward element of the elliptical orbit being faster than the backward one. Wavelength and wave velocity both decrease. As energy has to be conserved, that is it can be neither created nor destroyed, it can only be transformed from one form to another. The wave's energy is transferred into an increase in wave height and consequently wave steepness. Eventually a situation is reached in which water is piled up to a height that over-steepens the leading part of the wave so that the orbits of the water particles are broken. The water rushes forward as the wave 'breaks' as **swash** followed by the **backwash**.

Types of breaking waves

Breaking waves are not all the same. The type of breaking wave depends on:

- wave steepness
- water depth
- the gradient of the shore.

Although various categories of waves exist, it is more realistic to think of wave type as existing on a continuum.

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Breaker type	Description
Spilling	Steep; gently sloping sea bed; break at some distance from the shore; foam forms at wave crest and becomes a line of surf as wave approaches the shore.
Plunging	Steep; moderately or suddenly changing sea bed shape; steep-fronted; tend to curl over and plunge down on to the shore, producing lots of foam.
Surging	Gentle; steep-angled shore gradient; tend not to break completely; top of wave breaks close to shore; water slides up and down the shore.

▲ **Table 1.1** Types of breaker

▲ **Figure 1.9** Spilling breakers, Mawgan Porth, Cornwall

▲ **Figure 1.10** Plunging breakers, Beer, Devon

▲ **Figure 1.11** Surging breakers, Valentia Island, Ireland

Quite often the terms 'constructive' and 'destructive' are applied to wave type.

Constructive breakers	Destructive breakers
Lower wave height	Higher wave height
Long wavelength	Short wavelength
Low frequency: 6–8 per minute	High frequency: 12–14 per minute
Swash energy > backwash energy	Swash energy < backwash energy

▲ **Table 1.2** Characteristics of constructive and destructive waves

The idea behind the use of these terms is that constructive waves push sediment landward adding to the volume of beach sediment, while destructive waves have the opposite effect. This is a rather simplistic view of wave action and does not truly reflect what happens in the real world (see page 13).

The relationship between process and form

The relationship between geomorphological processes, such as waves, and form, the shape or morphology of the landform such as a beach, is complex. Using terms such as constructive and destructive implies that the waves (the process) determines the shape of the beach (the form). However, one of the influences on wave type is the shape of the off-shore gradient, which includes the beach. Another influence on wave type is the particle size of

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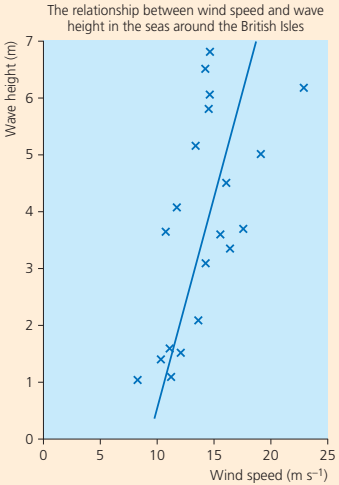
the sediment making up the beach, for example the contrast between small-grained sand and pebbles. It is also the case that the same beach will receive different types of waves through time. In addition, the angle of wave approach can vary markedly through time.

The important significance of breaker type is the amount of energy that each brings into the coastal zone and how this impacts on the shore landforms. High-energy waves are able to carry out more 'work', such as sediment transport or erosion, than low-energy waves. In many ways, the use of terms such as high and low energy reflects more closely how waves and landforms relate to each other.

ANALYSIS AND INTERPRETATION

Study Figure 1.12, the relationship between wind speed and wave height.



◀ **Figure 1.12** The relationship between wind speed and wave height

The data originate from the network of moored buoys, lightships and oil/gas platforms around the British Isles.

▶ Confidence values

Confidence limit	Critical value
0.05 level	0.388
0.01 level	0.549

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(a) (i) Describe the relationship shown in Figure 1.12.

(ii) Following statistical analysis, a correlation coefficient of $r = +0.556$ was obtained. Interpret this result.

GUIDANCE

When interpreting a scatter graph, two aspects of the graph need to be considered: the direction of the relationship and its strength. Direction refers to whether the two variables are positively or negatively related. Figure 1.12 shows a clear positive relationship, with wave height increasing as wind speed also increases. The strength of the relationship is seen in the scatter of individual points. When the points are relatively closely grouped along the line of best fit, then the relationship is strong. The opposite is the case when the scatter of points is dispersed and especially if there are some clear **anomalies**. The scatter in Figure 1.12 indicates a strong relationship with no real anomalies.

The inclusion of the result from a statistical analysis allows a deeper interpretation to be conducted as it indicates how reliable the result is, that is whether the relationship is significantly different from what could have occurred by chance. The actual result is well above the critical value for the 0.05 confidence level and just above the value for the 0.01 confidence level. This means there is a less than 1 in 100 chance of the result having occurred purely randomly. It is possible, therefore, to suggest with quite a high degree of certainty that there is a strong positive correlation between wind speed and wave height.

(b) Explain how wave energy entering the coastal zone is affected by different factors.

GUIDANCE

It is important to appreciate that even if a statistical test indicates a strong correlation between two variables, this does not necessarily mean that there is a cause-and-effect relationship between the variables. It just indicates that a correlation exists and acts as a green light for the analysis to go further, confident that the relationship is worth investigating.

This question calls for an explanation of the factors that could influence wave energy. Clearly wind speed is important. Waves represent the effects of the transfer of energy from the atmosphere (winds) to the sea. The friction resulting from the moving air passing over water results in the orbital motion of water particles being initiated. The direction of the wind, its duration and the distance over which it has blown are key factors determining wave energy. However, as the scatter graph and correlation coefficient indicate, atmospheric energy is not the only factor influencing wave energy arriving in the coastal zone. Water depth and the offshore gradient are two important factors. As soon as a wave enters an area where the depth of water is less than the wave base, the circular orbits of water particles in a wave are affected by friction with the seabed. This reduces wave energy. The aspect of a stretch of coastline, that is the direction it faces, will influence the level of wave energy reaching it. On the west coast of the British Isles, west-facing coasts receive the full force of wave energy arriving from the Atlantic. Any bays facing south-east or east will receive much less wave energy. Most of their wave energy is the result of winds blowing from the east and in this direction the fetch is less and wind speeds are, on average, much less than the westerly winds.

KEY TERM

Anomaly A point that lies some way from the line of best fit. Anomalies can be termed exceptions or outliers.

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Wave energy at the medium and local scales – wave refraction and diffraction

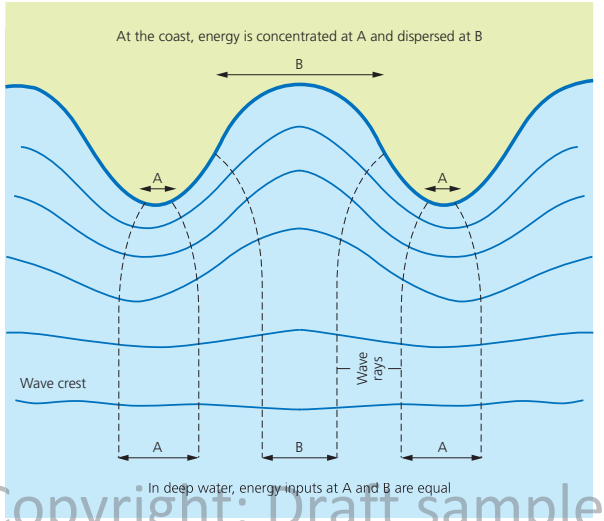
Wave refraction and diffraction are important factors because they affect the distribution of wave energy along a particular stretch of coast. This takes into account local factors such as the shape of the coastline.

Wave refraction

Whenever waves approach the shore at an oblique angle, the section of the wave in shallower water closer to the shore decelerates due to friction with the seabed. The remainder of the wave, in water deeper than the wave base, moves forward at a constant speed. As a result the wave bends or **refracts** so that its orientation is more parallel to the shape of the coastline. How well refracted waves become depends on factors such as the distance between where friction with the seabed begins and where the wave breaks.

The effect of energy inputs to the coastline can be seen when lines drawn at right angles to the wave crests are traced from offshore to the shore. These lines are known as **wave rays**.

▲ **Figure 1.13** Wave refraction along the Oregon coastline, north-west USA



◀ **Figure 1.14** Wave refraction and energy patterns

KEY TERMS

Wave refraction The reorientation of wave crests as waves enter shallow water so that the wave approach becomes parallel to the shoreline.

Wave rays Lines drawn at right angles to wave crests; they are an indication of energy patterns.

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Along relatively straight stretches of coastline, refraction is minimal, so energy distribution tends to be even along the shore. Waves approaching stretches of coastline consisting of bays and headlands are more subject to refraction and therefore variations in energy distribution. Energy is focused on the headlands where wave rays converge. Where wave rays diverge in bays, energy is more dispersed (Figure 1.14). Such variations in energy have significant implications for landform development.

Wave energy is also affected by the shape of the seabed in the coastal zone. The presence of deeper water over valleys or canyons allows waves to travel without losing their energy through friction with the seabed. Shallow areas offshore such as sandbanks mean that wave base is reached offshore and waves can start to break at some distance from the shore.

Wave diffraction

When a wave meets an obstacle, such as an island or a human-made offshore breakwater, **wave diffraction** occurs. Although the **lee** of the obstacle is protected from wave action, once the wave crest has passed the obstacle, energy is transfered into the sheltered area and wave action takes place. This impact of wave energy has implications for coastal management schemes that use offshore artificial reefs or breakwaters.

KEY TERMS

Wave diffraction Occurs when a wave passes an obstacle and its direction is altered so that wave energy is brought into the area behind the obstacle.

Lee The side of an object that is sheltered from a force such as wind or waves.

Tidal range The difference in water level between high and low water.

Semi-diurnal Refers to something having a twice-daily pattern.

Diurnal Refers to something having a daily or 24-hour cycle.

Tides

Tides are the result of the gravitational attraction on water by the sun and moon, the latter having about twice the effect of the former. Out in the deep ocean, tidal movements of water are hardly noticeable. In the coastal zone, however, tides play a very important role in shaping landforms and influencing ecosystems. Two aspects of tides are significant:

1 Tidal frequency
2 **Tidal range**.

Tidal frequency

The majority of coastlines experience **semi-diurnal** tides – two high and two low tides approximately every 24 hours. Some locations, for example California, experience a more varied pattern, where the two high or low tides can vary from each quite markedly. Antarctica is unusual as it has **diurnal** tides – one high and one low tide every 24 hours.

As the respective motions of the Earth, moon and sun go through regular cycles, the gravitational forces change and, therefore, so do the tides.

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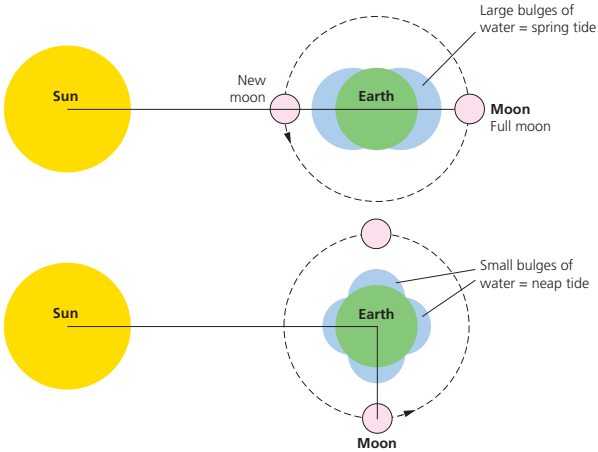

▲ **Figure 1.15** The formation of tides

Twice a month the sun and moon are aligned so that their gravitational forces are combined and act in the same direction. This produces **spring tides**, referring to the 'springing forth' of a tide. High tides are higher than average, low tides lower. Seven days later than a spring tide, the sun and moon are at right angles to each other with respect to the Earth. Their gravitational forces are therefore not acting together and so produce **neap tides**.

Tidal range

Tidal range is at its highest at the time of spring tides; neap tides produce the lowest range.

Tidal range varies considerably around the world (Figure 1.16). Enclosed seas such as the Mediterranean experience hardly any difference in sea level between high and low tides. On the other hand, the physical shape of the coastal zone including the underwater topography, can amplify tidal oscillation and generate tidal ranges over 10 metres. The greatest tidal range in the world occurs in the Bay of Fundy in north-east Canada, at around 16 metres. Around the UK, the Environment Agency maintains 44 tidal recording stations. The greatest tidal range in the UK occurs in the Severn Estuary, being between 14 and 15 metres.

KEY TERMS

Spring tides These are nothing to do with the season but are the above average tides generated when the sun's and moon's gravitational forces act in the same direction.

Neap tides Twice monthly smaller tides when high tide is lower and low tide higher than average.

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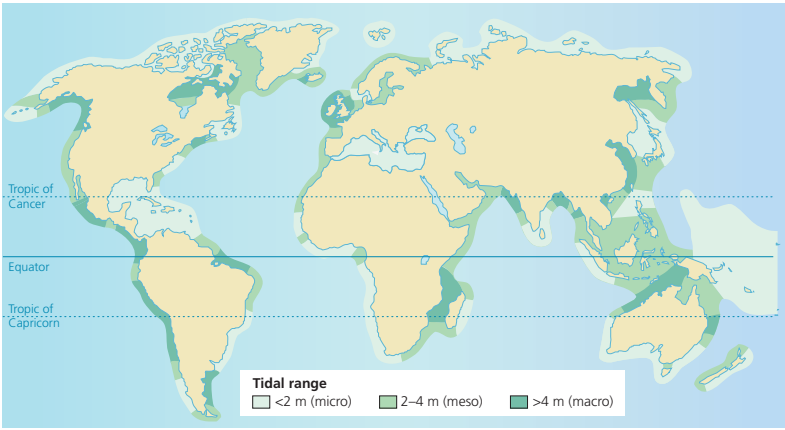

▲ **Figure 1.16** Global pattern of tidal ranges

The significance of a coastline's tidal range is because of its effect on the extent of the intertidal zone and the time interval between tides. Both these factors influence weathering processes and biological activity. With a high range, more of the coastal zone is exposed to the impacts of alternate wetting and drying of rocks and the waves operate over a greater vertical, extent bringing more energy into the coastal zone. Coasts with a high range tend to possess greater biodiversity in the intertidal zone as they provide more ecological niches. For example, a large tidal range is often associated with tidal flats and salt marshes.

Dynamic tide theory

As a tide is a wave of energy governed largely by interaction between the Earth and the moon, it might be expected that the crest of this wave lies directly under the moon as it orbits the Earth. However, this is not the case because of factors such as:

- ocean depth variations
- seabed topography
- shapes of the landmasses
- the ocean being broken up into deep basins (e.g. Atlantic, Pacific) separated by shallower shelves and continents.

The overall effect is that the tide is broken up into smaller-scale systems rather than one worldwide wave. As the gravitational pull of the moon passes across a basin, so does the tide. It is rather like holding a shallow dish of water and gently tipping it from side to side. The effect is that the water swirls around an **amphidromic point**. The greatest variations in tidal range occur furthest away from this point.

KEY TERM

Amphidromic point The point where tidal range is almost zero.

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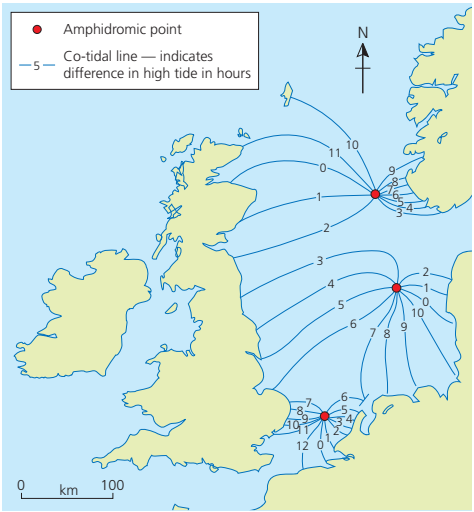
Because of the Earth's rotation, tides circulate around an amphidromic point: clockwise in the southern hemisphere; anti-clockwise in the northern hemisphere. Co-tidal lines join locations at which high tide occurs at the same time. Co-tidal lines radiate from an amphidromic point, usually being drawn at one-hour intervals starting at a particular point along a coast. High and low tide times therefore occur at different times along a coastline as the water swirls round the amphidromic point.

On the global scale there are six major amphidromic points, for example in the middle of the North Atlantic and halfway between South Africa and Antarctica. Smaller basins such as the North Sea also possess amphidromic points.



▲ **Figure 1.17** Amphidromic points and tidal patterns in the North Sea

Currents

There are several clearly identifiable flows of water in the coastal zone:

- Tidal currents
- Shore-normal currents
- Longshore currents
- Rip currents
- River currents.

Their water movements represent energy flows and so are important in the development of coastal landscapes and landforms.

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KEY TERMS

Flood tide The rising tide.

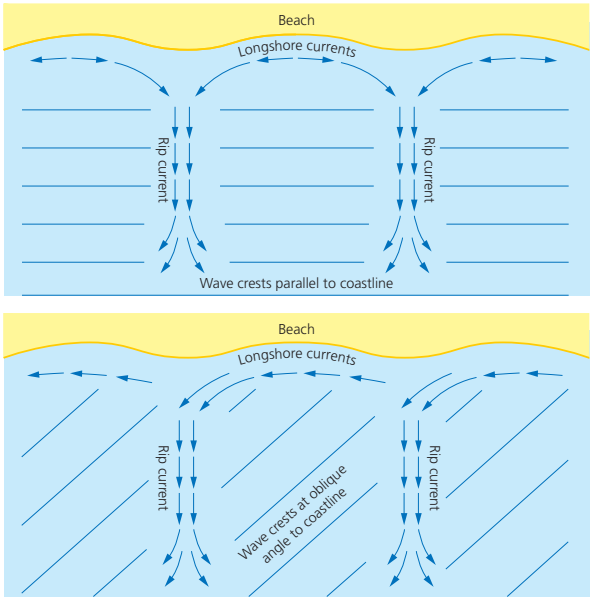
Ebb tide The falling tide.

Rip currents Powerful, narrow, fast-moving, seaward flows of water.

In estuaries, the **flood tide** can pick up (entrain) sediment and carry it inland. Once high tide is reached, the current reverses and the **ebb tide** takes over. The velocities of tidal currents are relatively low at the start and end of each cycle and peak in the middle of the flood and ebb tides.

Where waves approach the shore with their crests parallel to the shape of the coastline, shore-normal currents exist. Water is carried up the beach but there has to be a return flow of water. At fairly evenly spaced locations along the shore, **rip currents** take water back out to sea after moving along the shore for a short distance. Their velocities can easily reach 1 metre per second, which is faster than an Olympic swimmer.

Where waves approach the shore at angles other than parallel to the shore, rarely greater than 10°, the predominant current is a longshore one. Here also, rip currents can form, returning water out to sea.



▲ **Figure 1.18** Rip current formation

In estuaries, river flows can be energetic, especially after heavy rainfall inland. As these currents pass into the coastal zone they interact with seawater movements, potentially causing very disturbed conditions.

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3 Feedback, equilibrium and coasts

▶ *What happens to the coastal system when change occurs?*

Given that the energy inputs to the coast are so dynamic, change in the processes operating at, and landforms making up, the coast is inevitable. Such changes can be across the whole range of time scales, from the effect of a single wave breaking on a beach to the impact of tectonic adjustments that occur in geological time. Landforms develop a morphology (shape) which dissipates available energy. Too much energy leads to erosion and transport; too little to deposition. As energy inputs change, landforms adjust in their shape. Some changes take place in just a few hours; others occur across thousands of years.

KEY TERMS

Feedback An automatic internal response to change in a system.

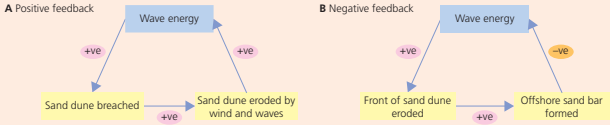
Positive feedback Amplifies change.

Negative feedback Restores a system to balance.

Feedback in the coastal system

Whatever the time scale involved, there is a very strong relationship between the energy coming into a location, the processes able to operate there and the landforms created. These process–form relationships involve **feedback**. Feedback takes place as a consequence of change in the system. Two types of feedback can be seen, **positive** and **negative**.

Positive and negative feedback examples



▲ **Figure 1.19** Feedback relationships between wave energy and sand dunes

Positive feedback can occur when wave energy increases, perhaps through a rising sea level. This leads to an increase in erosion of the dunes by removing the vegetation binding the sand. Wind action is thus able to erode the dunes further which makes the system more susceptible to wave action. The dune system therefore becomes more and more eroded.

Negative feedback can occur when wave energy increases. The increase in erosion of dunes by the waves releases sand which is then transported by the waves offshore. The sand is deposited as an offshore bar. As the incoming waves travel over the bar, the reduced depth of water means that more waves break before reaching the dune system. The reduction in wave energy allows the dune to recover as vegetation is able to establish and trap sand.

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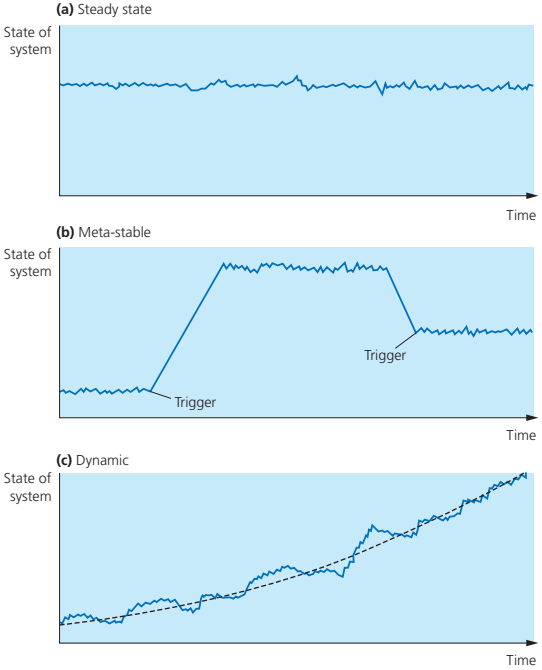
Equilibrium in the coastal system

KEY TERMS

Equilibrium The state of stability in a system.

Steady state equilibrium Exists when a system is essentially constant in its relationship between inputs and outputs. There might be variations in flows into and out of the system, such as seasonal, but on average the system is stable.

The concept of **equilibrium** extends the use of the idea of coasts as open systems. It focuses on the balance between inputs and outputs and attempts to describe ways in which a system might respond to changes in that balance.



▲ **Figure 1.20** Types of equilibrium

The amount of energy entering the coastal system may be equal to energy dissipation without any change in the morphology or shape of landforms (Figure 1.20a). This **steady state equilibrium** continues until there is a change in the energy environment. Where and when sea cliffs receive more or less the same atmospheric and marine energy, the profile of the cliff tends to stay the same from year to year. A beach receiving similar wave energy from one year to the next undergoes seasonal adjustments, but its average annual gradient stays the same.

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Sometimes a dramatic event occurs within the coastal zone that brings about substantial change to the coast. Sand and shingle can adjust rapidly to changing energy inputs. A high energy storm generating increases in wave height and periodicity can remove most of a beach in the space of a few hours. The result is a new shape, a wide flat beach. Subsequently the coastal zone adjusts to the new situation, a **meta-stable equilibrium** (Figure 1.20b). Wave energy is absorbed without any further net transfer of sediment.

Human activity can also bring about adjustment in the coastal zone. The construction of **groynes** over a six-month period triggers a change in the rate and volume of sediment moving along a coast. In turn this will influence the beaches and cliffs by the groynes and further along the coast.

Time scales of energy change of a few hours will make no difference on solid rock coastlines. In the same way that rivers cannot adjust their channels when flowing over solid rock, so waves will make no impression on solid rock coastlines over short periods. Even if significant erosion occurs during a single storm, it will take thousands of years to achieve anything approaching an equilibrium form.

Even on hard rock coasts, equilibrium could in theory be achieved providing environmental stability lasted for long enough, perhaps over several thousands of years. Cliff recession would eventually form a shore platform wide enough to dissipate all wave energy before reaching the cliff line. Cliffs would then degrade through weathering and slope processes to achieve a new equilibrium form. But given the enormous climatic shifts of the past two million years as ice sheets advanced and retreated, and the accompanying changes in sea level, equilibrium on such a time scale is unlikely.

But change can be more gradual within the context of long-term changes. The coast could be in a state of basic or **dynamic equilibrium** (Figure 1.20c). Rising sea level is an example of this as wave energy reaches higher up the shore. Cliff and beach profiles will adjust as a consequence. Sediment input can increase as a result of deforestation in the catchment area of the river draining to the coast. This might cause an estuary to silt up more rapidly, with salt marsh growth accelerating.

So, part of the coast is in equilibrium, and part is not and probably never will be. The system has the freedom to adjust to energy changes on short time scales by shifting sediments (similar to a river flowing across its floodplain within a channel made up from alluvium), but little if any to bring about equilibrium on rocky coasts. As a result, in stormy conditions, the coastal system has surplus energy. Much of this surplus will be expended battering cliffs. The evidence for this is erosional features formed by cliff recession, such as caves, arches and stacks.

KEY TERMS

Meta-stable equilibrium Exists where a system changes dramatically between one state and another after the influence of a trigger and adjusts to that new state.

Groynes Barriers running across a beach down into the sea.

Dynamic equilibrium Involves change in a system but in a more gradual way than the dramatic change in meta-stable equilibrium.

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We must not forget that wave energy also has an uneven spatial distribution on indented coastlines. Refraction concentrates wave energy on headlands but diffuses it in bays. Energy environments can change in just a few metres, adding further complexity to the coastal system. Thus variations in energy inputs are spatial as well as temporal.

4 Evaluating the issue

▶ *How is the relative importance of different energy sources in the coastal system assessed?*

Identifying possible contexts, data sources and criteria for the assessment

This chapter's debate focuses on a core component of all physical systems: energy. The coastal system demonstrates, in various ways, just how significant energy inputs are to the way that it functions. There are several energy sources which need to be clearly described and explained, and a decision taken as to how to assess their relative importance.

- Possible contexts – in geographical assessment, it is important to consider scale. In the case of investigating energy inputs to the coastal system, a range of spatial scales are relevant, from the macro or global, through various meso scales (regional) e.g. the North Sea, to the micro or local such as a small bay, beach or reef. Scale can also be in terms of time, stretching from the macro or geological, through various shorter time periods such as the recent ice age, down to the time scale of a tidal sequence or an individual storm.

  The greater range of spatial and temporal contexts will offer more opportunities to compare and contrast and thereby achieve an assessment of '…the relative importance of different energy sources.'
- Data sources – these will depend on the individual energy sources being considered. With a topic such as energy it is unlikely, if not impossible, to consider actual quantities of energy. However, there are some indicators of energy, such as wave height and wind speed.
- Criteria for assessment – as with data sources, quantifiable means of assessing relative importance are nigh on impossible to achieve. However, this does not mean that the issue is to be avoided – informed judgements should be made concerning such points as degree of erosion or deposition. Quantifiable evidence of possible outcomes of some energy inputs is available, such as rates of cliff recession.

Assessing the relative importance of solar energy

As for all natural systems, it is helpful to start with the key energy source of the sun. At the global scale insolation is not evenly distributed. The low latitudes receive more intense heating per unit of surface area than do the middle and particularly the high latitudes. Insolation in the polar regions is spread over substantially greater areas than at the equator. And for lengthy periods of time, virtually no energy from the sun enters these regions.

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The significance of solar energy is that it drives many other natural systems. Variations in the heating of the Earth's surface at the global scale result in the global pattern of winds, with air moving from areas of high atmospheric pressure to areas with low pressure. This global circulation of air results in prevailing westerly winds affecting western Europe, western North America and western Chile. Equatorial locations such as much of the Indian subcontinent's coastline receive much less wind.

On a small scale, the differential heating of land and sea during the day sets up local onshore and offshore winds on a 24-hour cycle. Although not a major influence, such changes have some effect on the coastal system.

The sun also powers the hydrological cycle. Without its energy evaporation would not take place. In turn, with no moisture in the atmosphere, no precipitation would fall. The importance of this is in the context of weathering processes and the role of water in mass movement.

Nearly all ecosystems rely on solar energy as their starting point. Primary producers convert this energy via photosynthesis into structures which are then the food source for consumers. Solar energy is thus transferred through food chains and webs. The significance of living organisms is not just in the importance of biodiversity but in the impacts they have on landscapes and landforms. Coral reefs, mangroves, salt marshes and sand dunes would not exist without organisms.

Assessing the relative importance of waves

Waves represent a transfer of energy from the atmosphere to the sea. In this, it can be argued that they are subordinate to solar energy, which powers the atmospheric system. However, waves are a critical component in the coastal system because of the 'work' they carry out. It is just as important to recognise the significance of the absence of wave energy in a particular coastal location as it is to discuss the presence of wave energy in other places.

The role of wave energy in the production of landforms and landscapes must not be underestimated. Erosional process such as hydraulic action, abrasion and attrition rely on energetic waves reaching the shore. Sediment transport relies to a considerable extent on wave energy. Traction, saltation and suspension in water cannot take place without that water moving. In addition, without sediment erosion and transport there would not be deposition.

The contrast between high and low energy coastlines is essentially made in the context of wave energy. It is this input of energy, or the lack of it, which determines the ways the respective landforms and landscapes of these contrasting coastlines develop, for example a rocky, cliffed coast compared to an estuary. On a smaller scale, the contrast between the seaward and landward sides of a spit is essentially defined by wave energy.

Assessing the relative importance of tides

Tidal patterns and, in particular, tidal range, are significant because they influence the extent of the intertidal zone both vertically and horizontally. The more shore that is exposed between high and low tide, the more erosion, transport and deposition can take place. Tidal flows of water are very significant in estuaries, for example altering the mixing of salt and fresh water, which then influences ecosystems.

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As with wave energy, tidal energy is related to the sun, though not in terms of insolation. Rather it is the gravitational influence of the sun that helps propel large-scale movements of water. However, the role of the moon is relatively more significant in tides than that of the sun. Although the sun is many times larger than the moon (diameter 400 times; volume 27 million times), its gravitational pull is less influential because it is so far away (400 times further away).

Assessing the relative importance of geothermal energy

Geothermal energy creates the rocks which are the foundation of a coastline. Rocks are created and destroyed in cycles. The rock cycle is a model that describes the formation, breakdown and reformation of a rock as a result of sedimentary, igneous and metamorphic processes. In addition, the role of tectonics has been and continues to be crucial. The opening and closing of oceans and land masses has affected the pattern of ocean currents. Present locations of land are made up of rocks formed under very different conditions to those being experienced today. The chalk cliffs of southern and eastern England relate to a time when these locations were much further south in the tropics. Many sandstones were formed in arid environments. Igneous and metamorphic rocks can be related to when the area they are found in was once an active plate boundary.

Tectonic energy has also brought about the folding and faulting of rocks. Without such massive releases of geothermal energy, many coastal landforms would not have developed as they have, such as various types of cliffs.

Over shorter time scales, such as the past few thousand years, tectonic forces have continued to exert a significant influence on the coastal zone.

- New land is created on the coast at locations such as Hawaii and Iceland as lava erupts and flows into the sea. Underwater earthquakes displace vast quantities of water, sending tsunamis racing across oceans. The impacts of the delivery of such enormous quantities of energy can completely remodel a coastline.
- Over the last ten thousand years or so, some coastlines around the UK have steadily risen upwards (at a rate of several mm per year), while others have sunk gradually. This is the result of isostatic rebound (see Chapter 5, pages 124–126), another process which depends on tectonic energy.

Arriving at an evidenced conclusion

The highly dynamic nature of the coastal system is down to the substantive transfers of energy that take place within its confines. Landforms and landscapes that develop along coastlines are so diverse because of energy variations over long, medium and short time scales.

There is no coastline without geothermal energy. Rocks need to be formed and lifted above the surface of the sea. No cliffs can exist without the rock cycle, nor any beaches. The very existence of the current pattern of land and sea is due to tectonics.

However, without insolation, neither the atmospheric system nor the hydrological cycle could function. Winds, waves, rainfall, water flowing off the land all rely on solar energy. In addition the biosphere relies on insolation to provide the energy that can then flow throughout ecosystems.

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A case can be made for solar energy to play the most significant role, through the agencies of winds and waves in particular. However, take away or alter any one component and feedback starts to operate, bringing about changes. It is this variation in relative energy within the coastal system that makes it so dynamic. No two waves are exactly the same, and the structures and lithologies of apparently identical rocks can vary in subtle ways that lead to slightly different landforms developing.

Finally, over the course of the past two hundred years, human activities have been intervening in the coastal system either deliberately or unintentionally, to add yet another source of 'energy' into the coastal system. Along increasingly densely populated coastlines, it is human activities that are perhaps the most significant factor. Perhaps the most dramatic influence is only just beginning, that of the rise in sea level associated with anthropogenic global warming.

KEY TERM

Isostatic rebound The upward movement of land as weight is removed, e.g. through the melting of ice or weathering and erosion of rocks.

Chapter summary

- ✔ Coasts function as open systems. Flows of energy and materials enter and leave the system; as these flows interact, distinctive coastal landforms and landscapes are produced.
- ✔ The time scales over which processes operate vary from millions of years to just a few seconds. A systems approach helps understand how such variation in time scale shapes landforms and hence landscapes.
- ✔ Waves generated by winds are a major energy input into the coastal system. As waves come close to shore, they break and their energy enters the coastal zone. The energy they bring varies both spatially and through time.
- ✔ Tides and currents move both water and sediment and vary around the world; tidal range is a significant component in a location's coastal system, influencing the distribution of processes across the coastal zone.
- ✔ The amount of energy coming into any part of the coastal zone influences the processes operating and the landforms and landscapes formed. Two types of feedback can occur, positive and negative, each being a response to something changing in the system. Equilibrium in the coastal system depends on the balance of energy within the system; stability or disturbance can occur.

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Refresher questions

1. Identify two of each of the following in the coastal system: inputs; stores; processes; outputs.
2. Outline how wave energy along a coastline is affected by the length of fetch.
3. Describe what happens to the pattern of water particle movement when a wave approaches and then reaches the shore.
4. Explain the significance of swash and backwash when considering the impacts of waves on a coastline.
5. Explain how wave refraction influences the distribution of wave energy along a coastline.
6. Outline the importance of tidal range to coastal processes.
7. Describe and explain the difference between positive and negative feedback.
8. Explain how dynamic equilibrium might operate within the coastal system.

Discussion activities

1. Discuss how energy inputs from past events can continue to influence the contemporary coastal system. You could focus on a stretch of coastline known to you. Research its geology and then draw a timeline covering the periods when the rocks of the coast were formed. Identify key events/periods in the past when there were significant energy inputs.
2. Consider the advantages and disadvantages of using a systems approach to understanding coastal landforms and landscapes. Focus on the value of looking at flows of energy and materials through a system. Then think about how human beings interact with the coastal environment and how such interactions can be included in a systems approach.
3. In small groups, discuss variations in wave energy due to aspect and fetch that coastlines around the British Isles are likely to receive. Use an atlas map and images from Google Earth as the basis of your discussion.
4. Discuss what elements in the coastal system are likely to respond either rapidly or only slowly to changes in energy inputs.
5. Discuss ways in which wave energy influences informal representations of places. For example, research pictures painted by artists that represent different 'moods' of the sea, such as a storm. Additionally, find pieces of music or excerpts of fictional text that portray contrasting levels of wave energy.

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Investigating the ways that elements in the coastal system respond to changes in energy and/or material inputs is not straightforward. Possible opportunities are suggested in subsequent chapters, for example in the context of beaches. It is possible to look at changes in the outline of a stretch of coastline as evidence of how feedback processes might be operating. Comparing maps over a time period of 100 or more years can reveal significant adjustments in the coast. Ordnance Survey maps date back to the early nineteenth century and can be supplemented by maps drawn in earlier times. When comparing maps across such a range of time, it is important to notice any differences in scales so that you are comparing like with like as regards distances for example. For some locations, coastal change might also be investigated by analysing old postcard images. These secondary sources could be compared to the present-day context, which would be your primary data source.

Further reading

British Geological Survey – various pages on the site offer much detailed information about geology: see www.bgs.ac.uk The marine science area has some dedicated pages offering information about seabed geology.

Channel Coast Observatory : https://www.channelcoast.org

Coastal Wiki: http://www.coastalwiki.org/wiki

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