Chapter 2 The geomorphology of the coastal cliffs of Great Britain — an introduction

K.M. Clayton, E.C.F. Bird and J.D. Hansom

Introduction

The published research literature on coastal cliffs in Britain is relatively limited, receiving surprisingly little attention in textbooks despite the high proportion, 80% (Emery and Kuhn, 1982), of the world's coastline that is cliffed. Carter (1988) is typical of this under-representation, with the subject of cliffs and shore platforms covered in 12 pages, or just 2% of the text. Specialized texts concerning cliffs are also few in number; the two most significant in English being by Trenhaile (1987) and Sunamura (1992). As well as the lesser need for coastal protection measures, the main reason for this lack of attention seems to be the slow geomor- phological evolution of hard rock cliffs and thus the obvious limitations of a process-based approach in describing and interpreting them. More work has been done on the rapidly evolving cliffs cut into weak rocks, such as London Clay (Hutchinson, 1973) or Chalk (So, 1965; May, 1971a; May and Heeps, 1985), and the glacial deposits of East Anglia (Hutchinson, 1976) and Holdemess, Yorkshire (see GCR site report, present volume). Indeed, much of Sunamura's text reports experiments carried out on cliffs, or models of cliffs, cut in *weak* rocks. Even so, field measurement and quantification are uncommon, despite the pioneering work of Robinson (1977a—c) and Mottershead (1989, 1998).

With the exception of 'plunging cliffs', which descend into deep water (Figure 2.1)a and (Figure 2.2)D, cliffs rise above a shore that may be irregular and rocky, or above a more or less well-developed shore platform created by the retreat of the parent cliff (Figure 2.1)b. This platform may sometimes be obscured by boulders, or, in weak rocks especially, by a shallow veneer of beach material, such as at Holderness (Figure 2.1c). Whatever the form of the shore adjacent to the cliffs, more attention has been paid to the cliffs themselves than adjacent platforms or other shoreline elements, yet they have evolved together and may share common processes. Over time, platforms are lowered by a variety of erosional processes, and are widened as the cliff retreats (Figure 2.2)A. Thus platform width may be related to cliff retreat at any one sea level. However, the relationship is complicated by erosion of the seaward edge of the platform (thus underestimating the amount of retreat), or by inheritance of the platform from a previous sea level (thus overestimating the rate of retreat over the Holocene Epoch (Trenhaile *et al.,* 1999).

More work has also been published on coastal landslides than on the geomorphology of coastal cliffs *per se,* partly because today active landslides in Britain are far more common on the coast than inland (Hutchinson, 1972, 1976; Brunsden and Jones, 1980; Hutchinson *et al.,* 1991; Chandler and Brunsden, 1995). Hutchinson (1973) shows that the rate of basal cliff erosion is a fundamental control on the different processes of cliff-slope erosion (and thus the varying slope forms) on lithologically uniform sediments like the London Clay. Because complex landslides and mudflows are best-developed and most easily examined at the coast, much of the work in such mass movements has tended to treat the cliff-slope processes for their intrinsic interest, neglecting or even ignoring marine processes at the cliff foot.

Coastal landslide GCR sites represent almost one-third of all sites selected for the *Mass Movements in Great Britain* (Cooper, in prep) and form an important supplement to the weak-rock sites selected for the GCR described in the present volume. For example, descriptions of the coastal cliffs subject to landslipping at Hallaig (Raasay), and along the Dorset coast (Axmouth to Lyme Regis, Black Ven, and Blacknor on the west side of the Isle of Portland), are included in the *Mass Movements* GCR volume. Only Lyme Regis to Golden Cap (see GCR site report) has been selected explicitly for the GCR both for its coastal geomorphology and mass movements features. Other sites covered in the *Mass Movements* volume include Trimingham, Norfolk, in Quaternary glacial deposits, Folkestone Warren, Kent, (Chalk over Gault Clay), Warden Point, Isle of Sheppey (London Clay) and the relict 'abandoned' cliffs, now fronted by saltmarsh at High Halstow, Kent.

One type of weak-rock cliff well represented in the GCR is cut in chalk, the commonest rock of south-eastern England and cropping out in coastal cliffs along a considerable length of the coast from the Isle of Thanet to Devon, as well as at

Flamborough Head, Yorkshire, and in a short coastal cliff at Hunstanton, Norfolk, where the Red Chalk is well exposed. There is considerable variety of form within these representative sites, yet, despite a number of local studies, no integrated geomorphological study of our chalk cliffs has yet been attempted.

Because of the more rapid rate of retreat and the larger number of buildings along the cliffs on weaker rocks, they are often modified by drainage works and coastal engineering structures. If the value for research of as yet undisturbed cuffed coasts is to be maintained, and if their value in providing sections of geological importance is to continue, then engineering intervention must be minimized. For example, Hutchinson's work on the London Clay cliffs provides what is now a historical record of a series of coastal sectors that have been entirely modified by engineering works. Today that work would be impossible to carry out and it is therefore increasingly important that our remaining cliffed sites on weak rocks remain in their natural state.

Inland and coastal cliffs

It is perhaps obvious, but rarely stated, that coastal cliffs dominate the population of cuffed slopes, particularly in Britain. Inland cliffs are mainly of glacial origin, but there are also inland cliffs of tectonic origin in mountainous areas, and those that are the headwalls of active landslides. Other inland slopes occur as isolated features on the outer bluffs of active river meanders and as natural rock outcrops on steep slopes, as in the Weald. In all cases cliffs may form, and persist, where active basal removal continues where material at the foot of the slope is removed by erosion, so maintaining the cliffed slope above. If this does not occur, the cliff will in time degenerate into a talus slope that progressively covers the cliff beneath (Figure 2.2)F. This process is relatively slow on erosion-resistant rocks and much quicker in unconsolidated sediments. Yet glacially formed cliffs, on both trough sides and within conies, rise above talus slopes and only where streams erode their base do they stand as true cliffs from bottom to top of the slope.

That cliffs, even in the most resistant rocks, have been modified by talus accumulation within the postglacial period (at most 15 000 years, but commonly the 10 000 years of post-Loch Lomond Stade time) emphasizes the importance of active, ongoing basal removal of talus as an important factor in the maintenance of steep *coastal* cliffs. Even where part of the slope may survive from an earlier interglacial period of high sea level (commonly determined from the occurrence of dated interglacial deposits (emerged beaches or sediments accumulated in caves), if the cliffs descend to a shore platform without any large accumulation of talus obscuring their base, they probably owe part of their present form to Holocene basal erosion. The point is emphasized where, in areas covered by ice in the last glaciation, stacks rising from the shore platform now occur seawards of a talus-free cliff. Many such features (e.g. the Old Man of Hoy, Orkney) are Holocene in age, having been trimmed since sea level rose to its present position about 6000 years ago. However, there are also many cliffs and stacks that are till covered (and emerged stacks with till plugs, for example at Tarbat Ness, Ross and Cromarty) that clearly pre-date the last glaciation. Some of these have also been elevated as a result of local tectonic, and especially continuing glacio-isostatic, movements within the Holocene Epoch.

The fact that steep and active slopes are far more common on the coast than elsewhere has led many of those interested in slope processes and morphology to work on coastal cliffs. Often these researchers have had little interest in the process of marine erosion that maintains the slope as an active landfonn and it is common to find differences in process linked to slope angle without any reference to the rate of marine basal erosion. None of this helps to clarify the limited and often conflicting literature on coastal cliffs. In system terms, the cliff face processes are a cascade, by which the removal of sediment from the base by waves produces instability that is propagated upwards to the cliff top, (Figure 2.3), where rates of erosion are most readily observed and measured. The lack of understanding of this process of cascade is widespread. It has been stated more than once by those living at the top of 40 m-high cliffs in Norfolk, 'You can tell these falls have nothing to do with the sea — they are all at the top of the cliff'.

In a similar way, continued removal of sediment from the beach at the foot of cliffs undergoing erosion produces more instability (Figure 2.3) and persistent coastal retreat may only be maintained if the sediment is removed as rapidly as it is produced. Indeed, cliffs undergoing erosion may become protected by the formation of a wide and high beach, allowing their slopes to decline. Whereas the finer-grained sediment moves offshore, the coarser material (sand and gravel) forms a cliff-foot beach that may protect the cliff or be moved by alongshore drift. For example, estimates of material lost from the Norfolk cliffs suggest that about 25% of the sand and gravel moves directly offshore, while the remainder may travel as much as 60 km alongshore. In this particular case it is not the rate of removal of beach sediment that controls the rate of cliff recession, because the sections undergoing the most rapid erosion are also the highest (Cambers, 1973).

Coastal slope processes

As noted above, coastal slopes and cliffs can be defined simply as subaerial slopes that have been modified at their base by marine processes (Hansom, 1988), with the development of shore platforms at the foot of the cliffs representing the eroded remnant of the original coastal slope. Cliff and shore platform morphology is then dominated by the balance between marine processes and sub-aerial slope processes (Figure 2.3). However, this is an oversimplification since the efficiency of operation of both sets of processes derives in part from the relative resistance of rocks of different strengths (Table 2.1) and in part from the position of sea level on the profile. In hard-rock cliffs, it is often microstructures that control most of the differences in erosion rates. As a result, although cliff profiles vary greatly, there appears to be little correlation between rock hardness and cliff angle, steepness being as much a function of basal erosion rate as of rock resistance (Young, 1972). The position of sea level is also important since this controls not only the spatial location of process operation on the cliff-face, but also temporal shifts in such locations. Some cliffs plunge vertically into relatively deep water yet, in contrast, many other relict cliffs stand behind staircases of platforms that have emerged as a result of uplift or changes of sea level as occurs in Islay, Argyll and Bute.

Coastal slopes are affected by all of the main types of mass-movement processes that occur as slopes try to attain stable, equilibrium forms. However, they may possess shorter-term stability than their inland relatives because of undercutting, over-steepening, and the removal of basal debris by marine processes. Mass movements, ranging from the quasi-continuous fall of small debris to infrequent but extensive landsliding, play an Important role in the development of rock cliffs. Fresh rock faces and the presence of talus at the base of cliffs attest to the importance of rockfalls on many coasts. Although they are more frequent than deep-seated slides, rockfalls tend to be smaller and more widespread and are probably the dominant form of mass movement on most rock coasts (Trenhaile, 1987). Rockfalls involve the detachment and fall of surficial material from steep rock faces and typically occur in well-fractured rock, especially where wave-cut notches have developed in lithologically or structurally weaker rocks at the cliff base. Rockfalls and coastal subsidence may occur where deep cave systems have penetrated into the cliff. Slab-falls occur in massive cohesive rocks with deep tension cracks parallel to the cliff face. Toppling or forward tilting is a common process in the Torridonian sandstone cliffs of Sutherland, and is characteristic of rock structures that consist of columns or are well-defined by joints, cleavage or bedding planes (Figure 2.4). All of these mass movements are essentially surficial failures induced by frost action and other types of subaerial weathering, basal erosion of the cliff and unloading and hydrostatic pressures exerted by water in the rock clefts (Trenhaile, 1997). A high percentage of falls are consequent upon ongoing cliff erosion and retreat: the formation of tension cracks parallel to the erosion surface arises from reductions in confining pressures as surface rock is removed. The 1999 failure of the chalk cliff at Beachy Head is a good example of this process.

(Table 2.1) Likely recession rates in different materials (compiled by Carter, 1988, from data in Sunamura, 1983).

Lithology	Recession rate (m a^{-1})
Granite	10^{-3}
Limestone	10^{-3} to 10^{-2}
Shales and flysch	1^{0-2}
Chalk	10^{-1} to 1
Tertiary sedimentary	10^{-1} to 1
Quaternary sedimentary	1 to 10
Recent volcanic rocks	10 to 10^{2}

Deep-seated mass movements are common in some coastal regions, where geological conditions are suitable, particularly where the compressive strength of the rock is exceeded by the load it must bear. Easily sheared rocks with low bearing strength are particularly susceptible to landslides and, as a result, they are more frequent in soft rocks and less common in resistant rocks (Trenhalle, 1987). However, a relatively common type of landslide in hard rock occurs where the cliff is characterized by seaward-dipping beds or alterations of permeable and impermeable strata, or where massive rocks overlie rocks with low load-bearing strength. In such situations, translational slides and 'dip-slip' slides, where failure occurs along a slope-parallel failure surface or bedding plane, produce large but often shallow features whose failure may often have been triggered by high pore-water pressures following prolonged rainfall. Spectacular examples of such landslides occur in the 30° westward-dipping beds of the Aberystwyth Grits near Aberystwyth, Wales.

Brunsden (1973) and Brunsden and Jones (1976, 1980) showed how complex coastal slopes may develop on coastal landslides. The cliffs of west Dorset are noted for the spectacular landslide systems that truncate NE–SW-trending ridges rising to between 140 and 170 m. The ridges are formed in chert and Upper Greensand overlying unconformably interbedded Lower Jurassic clays, marls, mudstone and thin argilla-ceous limestones. Large arcuate landslide scars form the upper part of the slope and are separated from nearly vertical sea cliffs by an under-cliff marked by small rotational landslides, mudslides, large gullies and accumulations of debris. The landslide scars and the sea-cliffs retreat at similar rates despite the continually changing relationships and forms of the individual components of the landslide. Within these landslide areas, the role of the sea is crucial, the most active landslides occurring where marine action is most effective. In contrast, where landslides transport large boulders, the foot of the cliff may become protected by this natural rock armouring. In weaker rocks, Cambers (1976) demonstrated that on the Norfolk coast the highest rate of cliff retreat due to landslides is found where there is the greatest frequency of tides reaching the base of the cliff Whether the slope maintains a particular angle or becomes gentler or steeper depends on the balance between the production of material by weathering and the rate at which it is transported out of the system (Carson and Kirkby, 1972). The role of the sea is critically important both for bedrock erosion and in removing sediments derived from slope processes (Figure 2.4).

Processes of marine erosion of cliffs and shore platforms

Four main groups of marine erosion processes operate on cliffs and shore platforms: mechanical wave erosion; weathering; solution and bio-erosion (Pethick, 1984; Hansom, 1988, Trenhaile, 1997). Although, these processes are often recognized and described, there remain relatively few quantitative estimates of their relative and absolute rates of operation with, for example, the studies of Trudgill (1986), Trenhaile (1987), Jerwood *et al.* (1990a,b), Sunamura (1992) and Stephenson and Kirk (2000a,b) as notable exceptions. Indeed, the relative importance of erosional processes has often been inferred from morphological evidence that is itself ambiguous (Trenhaile, 1980).

Mechanical wave erosion comprises two processes, wave quarrying and abrasion. Wave quarrying is the prising or pulling away of pieces of rock by the shock of impact of breaking waves. Secondary processes, such as pressure release and the pneumatic effects of air pressure in rock crevices, may also be involved in propagating rock failure along the crack-tip. Geological structure is important in this process since rocks with well-developed joints and fractures are more susceptible to quarrying. One of the few attempts to measure both the erosive process and the rates of cliff recession, so that a quantitative model could be prepared, is that of Sunamura (1975, 1977, 1981). Experiments on a model cliff in a wave tank and comparison with field data show that the pressure exerted by breaking waves causes maximum quarrying; broken waves are the next most effective; and unbroken waves reflected by the cliff in deep water cause negligible erosion (Figure 2.5).

Maximum wave quarrying is found on cliffs fronted by narrow, steep beaches, which induce wave breaking. However, over time, the production of a shore platform and beach composed of eroded debris, means that waves are progressively excluded from the cliff foot and the rate of erosion reduces (Sunamura, 1975). Freshly smoothed and scoured rock surfaces close to areas of loose sediment at the foot of cliffs are the most obvious demonstration of abrasional processes, particularly seen adjacent to the rough and angular appearance of sediment-free quarried surfaces (Tjia, 1985). Experiments reported in Sunamura (1992) show that abrasion rates are closely linked to beach elevation. Where production of sand from cliff erosion leads to the development of an embryo beach, abrasion erosion rates increase at first and then fall abruptly as enhanced beach volumes begin to protect the underlying rock (Figure 2.6). Clearly quarrying and abrasion work best together and in time produce notching and undercutting of the cliff base.

Cliffs and shore platforms are subject to two types of weathering process: water layer weathering and subaerial weathering. The first of these relates to the tidal wetting and drying of the cliff and platform by waves, spray and tides and may include chemical processes, such as hydration and oxidation, and mechanical rock breakdown caused by salt crystallisation or the swelling of rock grains. Pitting or honeycombing of cliff faces within the spray zone is evidence of these processes and is particularly noticeable in sandstones or other sedimentary rocks where the cementing material becomes decomposed. Salt weathering in conjunction with frost action is a fairly potent force in the splash and spray zones and widespread cracking and spoiling of a chalk shore platform in southern England was noted by Robinson and Jerwood (1987a-c). Jerwood *et al.* (1990a,b) used laboratory simulations to demostrate how efficaceous such process combinations could be in weathering softer rocks. Subaerial weathering relates to the normal weathering processes that loosen rock surfaces and deliver debris to the cliff foot. Subaerial weathering may affect rocks down to the level of permanent saturation (Bartrum, 1916); this weathered material is then easily removed by wave action. Russell (1971) notes that the water table marks a boundary between resistant rock below and weathered, easily erodible rock above.

Although they occur on all coasts to varying degrees, solutional and bio-erosional processes are most visible on tropical coasts. Since these processes often work in conjunction, the relative effects are difficult to separate. Solutional processes are most important in calcareous rock types where seawater, heavily charged with carbon dioxide in solution, aggressively dissolves the coastal rock. Work by Trudgill (1987) on the Irish coast has shown that, since seawater is undersaturated with respect to calcium carbonate, solutional activity is only prominent at night and in intertidal pools. As a result, on European coasts at least, chemical weathering is probably outweighed by the effects of a suite of biological processes. Such bio-erosion results from the activities of a huge range of organisms that either graze on algae on rock surfaces or bore into the rock in search of food or shelter. A range of overall erosion rates, ranging usually from about 0.5–1 mm a^{-1} on vertical and horizontal limestone surfaces (Trenhaile, 1997), has resulted from these studies but a key point is that bio-erosion serves to link the biological and geomorphological features, not only morphologically but also functionally. Organisms erode rock that then becomes involved in biogeochemical cycling, where abrupt changes in ecology or geomorphology will force the other components to react (Viles and Spencer, 1995). In some areas of the British Isles, such bioerosion may be favoured by particular structural arrangements. Low-angled bedding planes in the limestones of County Clare, Ireland give rise to a series of stepped benches that control the vertical zonation of bio-eroders (Trudgill, 1987) and the same occurs in Welsh limestones at Hunts Bay and Rhossili Point. In turn, whereas the macro-scale controls on platform development are provided by structure, the meso- and micro-scale platform geomorphology is produced by bio-eroders. In spite of some very clear associations between geomorphology and biological processes, the effects of wave-related processes and their relationship with rock strength generally overshadow the impact of solutional and biological processes in Great Britain. The resultant cliff and platform morphology reflects this.

The form of coastal cliffs

The detailed form of a cliff coast is produced by a complex interaction of controls shown in (Table 2.2), amplified below.

Geological controls on cliff form

The overall form of coastal cliffs depends strongly upon the nature of the materials forming them, but given the variety of contexts in which these occur, attempts to characterize cliff form have not met with much success. The many combinations of process, lithology and structure and the variety of controls on cliff form in different climatic and sea-level situations make generalization of cliff form inherently difficult. Nevertheless, some types of cliff are more common in particular morphogenetic regions than in others. Steep cliffs are common in the wave-dominated environments of the north and west coast of Great Britain where the accumulation of cliff-foot sediment is restricted by wave-transport. Where wave activity is weaker and subaer-ial weathering stronger, coastal slopes tend to be gentler and more convex in form.

(Table 2.2) Primary, secondary and tertiary controls on cliff form (based on May, 1997a).

FIRST ORDER	SECOND ORDER	THIRD ORDER
Geological structure and lithology	Weathering and transport slope processes	Coastal land-use Resource extraction
Wave climate	Slope hydrology	Coastal management
Subaerial climate	Vegetation	
Water-level change (sea level and tide)	Cliff-foot erosion	

Geomorphology of the hinterland (landforms into which the cliffs are cut)	Cliff-foot sediment accumulation
	Resistance of cliff-foot sediment to attrition and transport

It is also possible to classify active sea-cliff profiles according to the interaction of process and geology. Emery and Kuhn (1982) propose a matrix of cliff-forms produced as a result of varying bedrock homogeneity and the relative importance of marine and sub-aerial processes (Figure 2.7). However, the shape and gradient of cliffs are also profoundly influenced by dip, strike, lithological variation, and structural weaknesses. Steep cliffs generally develop in rocks that are either vertically or horizontally bedded, whereas intermediate bed angles tend to produce more moderate slopes. Lithology also influences cliff morphology — high cliffs tend to be associated with more resistant rocks such as unbedded, impermeable, crystalline rocks that are highly resistant to wave erosion, whereas sedimentary rocks are more susceptible to wave quarrying, especially where dissolution of the rock cement or exploitation of weaker bedding planes aids disintegration. As a result of this complexity, the available models, although useful simplifications, take limited account of the infinite possibilities of structural variation. The topography of the cliff hinterland adds another dimension (see p. 44).

Characteristic medium-scale features of cliffs

The rate of mechanical wave erosion is particularly sensitive to variations in rock structure. Small bays, inlets and narrow gorges that develop along joint and fault planes and in the fractured and crushed rock produced by faulting are generally the result of accelerated erosion along these lines of structural weakness. Narrow inlets or geos, caves, arches and stacks are often found in close association with each other on coasts with well-defined and well-spaced planes of weakness. However, these features are less likely to develop in *very* weak rocks or in rocks with a *very* dense joint pattern, since the rock must also be strong enough to produce high, near-vertical slopes or to support the roofs of caves, tunnels and arches. If the joints or planes of weakness are very dose together then long, narrow inlets develop such as the geos of northern Scotland. The angle of dip of the plane of weakness affects the occurrence and form of the erosional feature produced. For example, geo-like gorges with vertical sides are common in many horizontally bedded rocks with predominantly vertical joint planes such as occurs around the coast of Hoy in Orkney or at Skirza Head, Caithness (see GCR site report, Chapter 3). In steeply dipping rocks, where the planes of weakness are usually inclined, geos may either fail to develop or will be irregular in shape (Steers, 1962). Although joints and faults account for most narrow inlets, on igneous rock coasts geos may develop as a result of differential erosion of dykes and sills as occurs, for example, at Geo na h-Airde on St Kilda (see GCR site report in Chapter 3).

The occurrence of marine caves is again usually determined by structural weaknesses such as: joints; faults; breccias; planes; unconformities; irregular sedimentation; or the internal structure of lava flows. The form of caves, which can be tunnel or dome-shaped, reflects the num ber and inclination of these structures (Figure 2.8). Caves are particularly common in places where the rock is strongly jointed (Trenhaile, 1987) and vertical bedding or jointing tends to produce tall, narrow caves (Fleming, 1965). Lithology may account for the formation of some caves and they may develop as a result of the differential erosion of dykes that are weaker than the adjacent rock. Large caves in limestone regions may also have been formed by underground solution and later inherited and modified by wave action as a result of cliff retreat and changes in relative sea level. However, most sea caves are relatively small and have been excavated by wave quarrying, particularly during storm periods, in association with abrasive and hydraulic processes. If a cave becomes connected to the surface through a joint or fault-controlled shaft, a blowhole can develop, through which fountains of spray are blown out during storms and high tides, such as occurs at the Bullers of Buchan, Aberdeenshire. The presence of pebbles around the tops of blowholes in north-eastern Scotland (Steers, 1962) testifies to the enormous pressures generated during storms in narrow marine caves. In common with the cliffs into which they are cut, most caves, although modified by contemporary processes, may well pre-date present sea level and some (for example in the Gower peninsula, South Wales) are at least as old as the last interglacial period (Davies, 1983).

Tunnels and natural arches may develop from marine caves where wave erosion of either, or both, sides of a promontory may succeed in excavating a tunnel, usually along the line of a geological weakness, to produce a sea arch (Figure 2.8). The term 'sea tunnel' is appropriate when an arch is considerably longer than the width at the entrance. A typical example of a sea tunnel runs for about 100 m along a fault zone at Merlin's Cave, Tintagel, Cornwall (see GCR sitre report in Chapter 3; Wilson, 1952). Collapse of the roof of the arch or tunnel leads to the formation of a stack (Figure 2.8). Sea arches are ephemeral landforms, especially where they occur in weak rocks. For example, map evidence suggests that the Old Man of Hoy, in the Orkney Islands, developed from a promontory, since it did not exist prior to 1600. Yet by 1819 a prominent feature had developed with a stack and an arch with the twin legs that gave The Old Man its name (Hansom and Evans, 1995). The debris from an earlier roof collapse now litters the connecting platform between the base of the stack and the parent cliff One of these legs was destroyed in a major storm in the early 19th century to produce a monolithic stack and the process has continued into the late 20th century with a large segment of its upper structure now in danger of collapse. Stacks often form quite quickly and sometimes can persist once they have become isolated from the mainland and the abrading effects of cliff-foot sediments. However, it is difficult to be precise about the age of stacks and in general it seems that most arches and stacks are short-lived features, judging from the rapid changes of morphology documented in many locations. Some arches last several hundred years (The Old Man), some only tens of years (e.g. Byrne, 1964) and others last barely over one year (Bird and Rosengren, 1986). The spectacular collapse of part of a famous double limestone arch at London Bridge, on the coast of Victoria, Australia, occurred on 15 January 1990, leaving the other arch as an islet and stranding two tourists who were later rescued by helicopter. Stacks are generally produced from the collapse of sea arches, however some also survive as emerged or exhumed forms. When stacks eventually collapse, their bases will often survive for a time as reefs until these too merge into the developing coastal platform.

At a smaller scale, a wide range of features such as crevices, caves, clefts, and blowholes can form, together with even smaller-scale features such as tafoni and weathering forms.

Influence of inland topography on cliff form

It is also important to appreciate the role of hinterland landforms in determining cliff pattern and height. The obvious example of this is the site at Seven Sisters on the Channel coast of Sussex where an almost straight cliffline truncates the 'dip-slope' of the South Downs, crossing a series of dry valleys, the seven ridges between them forming the Seven Sisters (see (Figure 2.9)). Cliff height here is a function of the height of the land traversed by the cliff, not of the erosional energy of the waves at their foot. At Beachy Head, the eastern end of this line of cliffs, the maximum cliff height is *c.* 160 m and major rockfalls and/or landslides are relatively common, yet the sea remains able to sweep clear the coastal platform at the foot, although for very large failures this clearance may take several years. Lower cliffs in Chalk are more stable and rockfalls occur less frequently (Hutchinson, 1972).

Whereas the role of landform in the varying height of the Seven Sisters is clear, this is more easily overlooked on a coast where varying geology has allowed development of a dissected landform where valleys grade to sea level. Commonly in southern England, lower and wider valleys are found in weaker mudrocks, and higher ground in the more resistant rocks. The Holocene drowning of this landscape has allowed the sea to cut high cliffs in Chalk and other more resistant rocks, whereas the clays and mudrocks that crop out within indented valleys and bays have much lower cliffs or none at all. Some accounts suggest that the sea has eroded these deep bays, rather than inheriting them in much their present form by the partial submergence of a subaerially dissected landform.

A similar situation is the drowned and glacially sculptured landscape of western Scotland. Here cliff-like slopes on the sides of sea lochs, the deep fjord inlets, have been relatively little modified from the form left by the retreating ice, and similar forms occur on open coasts as in northern Skye. In other areas, the sea has partly drowned a glacially eroded landscape of low relief as at the Loch Maddy GCR site in the Western Isles.

High-energy coasts — for example those exposed to the largest waves of the North Atlantic Ocean, as on St Kilda, or on the western coast of Orkney — have cliffs that extend to the full height of the eroded land and also plunge into deep water at their base. The highest cliff in Great Britain is Conachair, St Kilda, reaching 430 m in height. Such cliffs seem to be limited in height only by the elevation of the land behind the coast.

Elsewhere, cliffs only trim the lower part of the seaward slope, perhaps because the rock is particularly resistant to erosion, or because incident wave energy is restricted by limited fetch or shallow water, or because there is a lack of abrasive material. Plunging cliffs also retreat more slowly than cliffs that possess a shore platform, so these may not rise to the full height of the coastal slope. In some cases cliffs may be limited by the short time that the present-day coast has been exposed to wave attack. This is true of parts of the Scottish mainland coast, where Holocene emergence following crustal unloading shortened the period of sea-level standing dose to its present position.

Clearly, cliffs are cut into a variety of pre-existing topographical situations (e.g. river or glacially scoured valleys and interfluves at all angles to the coast) and into a variety of geological structures (e.g. alternating layers of resistant and less-resistant, faulted and folded rock strata). Consequently, three-dimensional predictive models of cliff morphologies have not yet appeared.

Shore platforms

Many cliffs undergoing erosion (other than plunging cliffs) stand behind shore platforms, sometimes wide, sometimes narrow, sometimes rather steeply inclined, but often rather gently sloping seawards (Figure 2.2). The platform is commonly intertidal, but a few plunging cliffs stand above a drowned shore platform that is not far below low tide level. Most weak-rock cliffs such as chalk have a platform in front of them (though it may be obscured by beach sediment). Plunging cliffs are found mainly on resistant rocks in the situation where the combination of wave energy and duration of the current sea level stand has been unable to develop a shore platform of any kind, and where any platform or rocky shore created in an earlier interglacial is not situated at present-day sea level. Once established, shore platforms may be readily extended, for they are exposed to quarrying, abrasion, weathering, solution and bio-erosion.

Despite the significance of shore platforms and their relationship to the cliffs behind them, they have received less attention from researchers than the cliffs themselves. Accounts in textbooks such as those by Trenhaile and Sunamura are incomplete. Nevertheless, the description by Trenhaile (1987, pp. 206–39) of platform morphology, and of rates of erosion is a good summary to which little has been added in more recent literature. Thus the sites described in the present volume represent potential for future research. Most well-developed British shore platforms slope relatively steeply, and where the stratification or jointing of the rock imposes structural control, they are rather irregular.

Wide, sub-horizontal platforms seem underrepresented in Great Britain, probably because weathering processes are relatively less effective than wave processes and the forms are less likely to survive. Nevertheless, impressive sub-horizontal shore platforms occur within Robin Hood's Bay on the soft Jurassic rocks of North Yorkshire.

The processes involved in forming shore platforms have been much debated in the scientific literature, although it is now recognized that these are similar to those affecting marine cliffs, and, as a result, have largely been accounted for above. In common with cliff forms, a great range of shore platform morphologies created by local conditions occur. However, two fundamental types emerge: sub-horizontal platforms and sloping ramp platforms (Trenhaile, 1997; (Figure 2.2)).

Sub-horizontal platforms tend to have surfaces lying at either high or low-tide levels and terminate seawards at a low tide cliff whereas ramp platforms slope between the two tide levels with no major break in slope (Figure 2.2). In much of the literature, high-tide platforms (Figure 2.2)B are thought to be produced by water-layer weathering and develop best where rocks are permeable and horizontally bedded, where evaporation rates are high and where tidal characteristics allow a long drying period (Pethick, 1984). Since quarrying and abrasion processes rapidly destroy the features produced by slower weathering, high-tide platforms are thought to be best preserved where mechanical wave erosion is limited, and thus are rare in Britain. Low-tide platforms are thought to be produced by solutional and biological processes and are common in tropical areas, although they are also found on mid-latitude limestone and chalk coasts. Sloping intertidal platforms are very common in the storm-wave environments of the mid-latitudes (e.g. many parts of the British coast) and are produced by mechanical processes such as quarrying and abrasion. The slope or 'ramp' from the two tide levels is rarely regular, as variations in rock type and structure are exploited by wave erosion to produce an irregular surface.

Work by Trenhaile (1974a,b, 1978, 1987, 1997) has cast doubt on the traditional interpretations of shore platform types by highlighting the important, and perhaps controlling, role of tidal range in platform morphology. There is a strong positive relationship between platform gradient and tidal range, particularly in the storm-wave environments, but also in other climates and wave regimes (Figure 2.10): where tidal ranges are great, gradients are correspondingly steep. Such work suggests that, as a result, low tidal ranges can produce sub-horizontal platforms whether or not they occur in storm-wave environments (Trenhaile, 1997). Similarly, solutional, biological, water layer weathering, or even frost action in the intertidal zone may well produce platforms, but they are probably secondary to, and work via, the control of tidal range.

Trenhaile and Layzell (1981) suggested that the rate of intertidal erosion is determined by the time that still-water level occupies each elevation within the tidal range (the tidal duration factor), by an erodibility factor related to wave energy and rock hardness, by platform gradient and by the rate of submarine erosion. It was suggested that platforms develop best at mid-tide level because tidal duration, and thus erosion, is greatest in this zone (Figure 2.11). Carr and Graff (1982), however, demonstrated that maximum tidal duration is bimodal and associated with times of high and low water. Since tidal level varies most rapidly at the mid-tide position, wave action, and thus erosion, is least effective there. Trenhaile (1982) accepted this modification of the basic Trenhaile and Layzell model and added that this was consistent with the observations of Chastain (1976).

Relationships between morphology and factors other than tidal range are less clear and much of the field evidence is contradictory, particularly at the local scale. So (1965) described the varying slope of the coastal platforms of the Isle of Thanet in Kent, surveying them before the very extensive sea defences were completed. Platforms were found to decrease in height from headlands towards embayments and this was attributed to the greater energy of storm waves at headlands, allowing planation to a higher level. This was supported by the observation that platform height also varied with coast alignment, being highest where the coast faces northeast. Transverse gradient was greater in embayments than off headlands, and most platforms showed an upper concave and a lower convex form. Platform width, from their upper limit to the common low-tide cliff (locally a submerged cliff at the outer edge), was greatest on more resistant Chalk, and lowest on the weaker beds. So concluded that the very existence of a platform indicated that the recession of the cliff foot to form the platform was faster than the rate of landward recession of the low-tide cliff. It is remarkable that in the last 30 years no wider- scale work has been done on the English Chalk coastal platforms to confirm or modify the conclusions reached by So for the Isle of Thanet in Kent.

Geological effects, both structural and lithological, are clearly responsible for detailed variations in areas where the morphogenetic conditions are similar. Rock types that provide debris to the platform contribute to platform abrasion, yet large quantities of debris accumulating on the platform also serve to reduce abrasion and protect the surface (Sunamura, 1976; (Figure 2.6)). Robinson (1977b,c) found that platforms in north-east England became progressively narrower as sandy beaches, bare rock, boulder beaches and talus cones built up at the cliff foot. In addition, the compressive strength of the host rock needs to be matched against the stresses placed on it by mechanical wave processes. Other things being equal, igneous rocks such as granite or basalt have higher compressive strengths than sedimentary rocks such as limestones, chalk and sandstone and so are likely to be more resistant to wave erosion. Modelling suggests that platform morphology owes a great deal to structural control with fastest rates of erosion and thus of platform width associated with horizontally bedded rocks and where the dips are moderate and the strike is perpendicular to the rock face (Trenhaile, 1987). Slower rates are associated with vertical strata that strike obliquely or parallel to the cliff face. However, in some cases, mechanical strength may be secondary to chemical processes such as hydration. For example, although some mudstones are mechanically strong, they are susceptible to flaking due to hydration and dehydration (Suzuki *et al.*, 1970).

Some measurements have been made of the rate of lowering of coastal Chalk platforms using micro-erosion meters. However, since most platforms are stepped, erosion also occurs through the detachment of blocks from the front edges of steps and this also needs measurement if the real average rate of lowering is to be calculated. Observations near Brighton, Sussex (Robinson and Jerwood, 1987a,b) showed that frost contributes to the erosion of coastal platforms in Chalk, the combined effect of salt crystallization and frost-induced spilling declining towards low-water mark as the time for freezing within each tidal cycle is reduced.

On the cliffs in the Jurassic strata of North Yorkshire, Robinson (1977c) described four types of shore platform:

1. a sub-horizontal plane downwasting at 1–2 mm a–1;
2. a similar plane, with a ramp (slope >2.5°) at the foot of the cliff;
3. a ramp with beach and no plane to seaward;

4. complex forms dominated by geological structure, with no clear development of either ramp or plane, i.e. a rocky shore.

Platforms here ranged from 90 to 200 m in width; sandy beaches were only found landwards of wide platforms. He discovered older ramps above the present platform represent former cliff-foot positions, the ramp and platform both extending landwards over time by parallel retreat — i.e. preserving their angle of slope.

That platform width might represent the balance between the rates of basal recession and recession of the seaward margin below low tide level complicates the interpretation of measurements of platform width. Many authors assume that the current width represents the total retreat of the cliff since the completion of the Holocene marine transgression and others argue that platform inheritance from earlier interglacials means that the current rate of cliff retreat is dose to zero. Comparison of the south and north sides of the Bristol Channel highlights the issue. The widest platforms occur on the southern side where energy levels are low. On the southern side, energy levels may be sufficient for basal erosion of the cliff-platform junction, but insufficient to erode the seaward edge of the platform at the same rate, so that the platforms have become very wide. In contrast, narrow platforms on the northern side (e.g. at Nash Point, Glamorgan) might be the result of effective erosion both at the outer edge of the platform as well as at the cliff base. Even over such short distances comparisons are problematic since it is possible that the Nash Point shore platform has evolved from a series of higher platforms and is thus partly inherited (Trenhaile, 1972, 1974a,b).

Evidence of inheritance

Many cliff forms may also owe much to changes in sea level and climate in the geologically recent past and it is this diversity that creates some of the most spectacular and geomorphologically important cliffs in Britain. For example, some cliff profiles are 'compound', consisting of two or more major slope elements, whereas 'multistoried' cliffs have two or more steep faces separated by more gentle slopes (Figure 2.12). Bevelled or 'slope-over-wall' cliffs are characterized by a convex upper slope above a steep lower face (Davies, 1980; Griggs and Trenhaile, 1994). Given the common occurrence of equifinality in geomorphology it is unlikely that a single explanation can account for all the British cases, let alone others elsewhere in the world. Nevertheless, many such cliffs have developed in resistant rocks over long periods and may be unrelated to the bevelling produced where a balance exists between marine and sub-aerial processes in the Emery and Kuhn (1982) model. Cotton (1951) suggested that, during the Quaternary Period, variations in sea level resulted in cliffs developed during high interglacial sea levels being abandoned during sea-level fall and then buried by ice or subject to paraglacial processes. This produced convex slopes above and an accumulation of talus below. When sea level rose again to interglacial highs, marine processes removed the talus to produce steep, lower cliff faces. As a result, there is a good match between the occurrence of bevelled cliffs and ice limits in the British Isles (Griggs and Trenhaile, 1994; (Figure 2.13)). Griggs and Trenhaile (1994) suggest that bevelled cliffs resulted where the talus reached the cliff top during the last glacial but that multi-storied cliffs resulted where the talus reached only partly up the cliff face (Figure 2.12).

However, our knowledge of past sea levels is incomplete and for British sites that were unaffected by isostatic recovery following the Last Glacial Maximum (*c.* 18 000 years BP) (or in Scotland, the Loch Lomond Stadial (11 000 years BP)), sea level during the last interglacial was probably between 3 and 6 m higher than present sea level. Earlier interglacial sea levels were closer to present sea level.

The assumption is that the normal situation is where sea level rose over the Holocene Epoch to reach the present coastline about 6500 years BP, with the shore platform of the last interglacial some 3–6 m above present mean sea level. However, there are very few cliffs where the sedimentary record (and completed research) allows detailed confirmation of this situation: sites with a well-established sea-level record tend to be low coasts. Present-day sea level around the British coast is rising at 1.5–2 mm and although this has probably only been the case over the last 100 years or so, this has likely led to accelerated marine erosion of shore platforms and cliffs. Shennan (1989) draws isobases showing much of the Scottish mainland still rising slowl (see (Figure 1.8)b. However, over much of the coast this is currently less than the annual rate of sea level rise (Dawson *et al.,* 2001), so apart from the heads of Scottish inlets and estuaries, relative sea level in Britain is now either currently stable or rising everywhere.

Departures from the assumed normal pattern described above occur where land movements have been sufficient to affect the height and/or timing of Holocene sea levels. These movements are mainly glaclo-isostatic and neotectonic movements of structural origin.

Glacio-isostasy delayed the arrival 'of the sea at its present elevation, though in many cases this has meant that the Holocene maximum was locally much higher than present-day level, achieved as a result of continuing slow uplift as the land has recovered from its ice load. For example, at Culbin on the Moray Firth coast of Scotland, the Holocene maximum reached 8 m OD and the cliff cut in glacial deposits is now elevated. Holocene emergence over much of the Scottish coast has limited the time available to create shore platforms adjusted to present-day sea level, especially in comparison with more stable areas in England and Wales. On the other hand, the western and northern isles of Scotland, including St Kilda, did not suffer such late glacial unloading (or as large an ice load) and may have been assisted by relative sinking of the land (Flinn, 1969). As a result they have had considerably longer time periods available for shore platform formation. Yet in spite of this, shore platforms are relatively rare even in these locations and too little is known to say why.

Sea level is also influenced by neotectonic movements of the land, a relatively neglected area of study from the geomorphological perspective in Britain. Embleton (1993) concluded *inter alia* that Tertiary tectonism has continued into the Quaternary Period and is manifested today as seismic activity with maximum rates of present neotectonic movement being about 0.5 mm a^{-1}. Clayton (1998) came to very similar conclusions, though adding to tectonic causes the effects of uplift as a result of denudational unloading through erosion of the land.

Clayton and Shamoon (1999) propose that parts of the coast may have moved independent ly over the last 5 Ma or so. Whether they are still moving independently today, and whether the rate of movement has been enough to affect coastal landforms, remains to be established. The maximum rate of 0.5 mm a^{-1} postulated by Embleton (1993) implies a maximum movement since the end of the Holocene transgression of some 3 m, so the effect is small. Nevertheless, the influence of neotectonic movements on the form and elevation of individual cliffs and shore platforms, and on the hinterland processes such as fluvial incision, should be acknowledged even if it is difficult to quantify at present.

One emerging route to establishing the age and influence of neotectonism and coastal emergence is the dating of fluvial incision into hard rocks by means of cosmogenic isotope analysis. This may allow dating of erosional surfaces such as shore platforms, to establish whether they are old or young. However, old platforms that have been retrimmed will yield young ages.

From the above, it follows that there are two schools of thought relating to cliff and shore platform development and age. The first is that most of our hard-rock cliffs and platforms are contemporary and the result of erosion since Holocene sea levels stabilized some 6500 years ago. The counter-argument is that till-draped cliffs and stacks, as well as emerged caves and beaches that date to earlier interglacials, indicate that many cliffs and associated forms pre-date present sea level even though they are now trimmed by it.

Many cliffs and shore platforms in Britain, particularly those developed in softer and weaker rocks (such as the Holderness coast of Eastern England), are certainly Holocene in age and are well-adjusted to present day processes. Nevertheless, since several interglacial sea levels have occurred at similar altitudes to present, we must also acknowledge that many cliffs and shore platforms that now occur at present-day sea level may be inherited or partly inherited erosional surfaces that have been exhumed (Trenhaile, 1987). Certainly, many cliffs and shore platforms in the British Isles are demonstrably older than the last glaciation since they are draped with glacial till only partly removed by present-day wave activity (for example at Tarbat Ness and along the coast of Islay and Jura). Depending on the date and rate of elevation, emerged platforms may merge imperceptibly into the present-day shore platforms (e.g. on Islay, and at Dunbar).

Since Scottish coasts are affected by isostatic readjustments of various amounts away from the former ice depression centres, it is not surprising that inherited shore platforms and cliffs adorned with stacks and caves are variously elevated, submerged or consonant with the altitudes of the present platforms. Plunging dills are another aspect of the legacy of inheritance. Waves reaching such cliffs tend to be unbroken and so most wave energy is reflected, little erosion takes place and erosion rates may be correspondingly low. For example, the cliffs of Shetland and Orkney are thought to be largely inherited features (Flinn, 1974; Hansom and Evans, 1995). Although the cliff faces are composed of freshly exposed rocks owing to a combination of storm waves affecting the cliff-top (Hansom, 2001) and the current rise in sea level, the macro-profile and setting shows these cliffs to plunge into deep water. Thus there exists either no erosional step at present-day sea level or a very limited one, in spite of some 6500 years of erosion in often very exposed and high-energy positions.

The key point of disagreement may be identified using the apparent considerable retreat of the Orkney sandstone cliffs. Rapid retreat does and can occur; the Old Man of Hoy can be fairly convincingly dated as 400 years old (Hansom and Evans, 1995), yet the Orkney cliffs, like those of St Kilda and Shetland, are almost certainly inherited from previous sea levels and are now retrimmed to look new. Similarly, on the Gower limestones in Wales, steep cliffs are presently trimmed by waves at the headlands (e.g. Rhossili, Oxwich and Hunts Bay) yet the same el iffline can be traced into bays where they are relict and buried by either glacial till, periglacial deposits or Holocene beach deposits. In such situations whereas the cliffline is inherited, it includes some cliff forms that may be young.

Nowhere does inheritance produce a more distinctive coastal geomorphology than in those locations where relative sea-level rise has submerged, but not necessarily modified, land surfaces initially shaped by glacial, fluvial or subaerial terrestrial processes. For example, Holocene submergence of the network of glacial troughs on the western seaboard of Scotland, has produced a spectacular fjordic coast that extends from Cape Wrath to the Firth of Clyde. The areally scoured glaciated erosion surfaces in north-west Sutherland and in the Loch Maddy area of North Uist, are now submerged to produce a bewildering, though distinctive, complex of aligned and moulded coastal forms and islets, skerries and streamlined ridges set within a range of sheltered and exposed coastal environments.

Given the conflicting evidence concerning the effect of interglacial inheritance versus Holocene development of cliff and platform in Great Britain, it seems clear that only through measuring the past and present rate of change on shore platforms and cliffs will clarification be achieved. Indeed only when this work has been done at a large number of locations, on different rocks, with varying wave energies and tidal ranges, can a satisfactory and convincing explanatory account of British cliffs and their shore platforms be assembled. For the present time, the site descriptions and interpretations assembled here provide some of the context for that work.

Sea cliffs as biological SSSIs and Special Areas of Conservation (SACS)

N.Y. Ellis and C.R. McLeod

In Chapter 1, it was emphasized that the SSSI site series is constructed both from areas nationally important for wildlife, and GCR sites. An SSSI may be established solely for its geology/geomorphology, or its wildlife/habitat, or it may comprise a 'mosaic' of biological and GCR sites that may be adjacent, partly overlap, or be coincident. There exist a number of sea cliffs that are of crucial importance to the natural heritage of Britain on account of their wildlife value but, implicitly, will have some features of regional importance for coastal geomorphology. Such sites are not included independently in the present geomorphologically focused volume because of the 'minimum number' and 'national importance' criteria of the GCR rationale (see Chapter 1).

Many sites that have been selected for the GCR for features other than coastal geomorphology are to be found on the coast of Britain. For example, where coastal cliffs provide sections through the successions of strata that are important for the geological research, the best, most representative sections have been chosen for stratigraphical GCR selection categories.

(Table 2.3) Candidate and possible Special Areas of Conservation in Great Britain supporting Habitats Directive Annex I habitat 'Vegetated sea cliffs of the Atlantic and Baltic coasts' and/or 'Submerged or partially submerged sea caves' as qualifying European features. Non-significant occurrences of these habitats on SACs selected for other features are not included. (Source: JNCC International Designations Database, November 2002.)

SAC name	Local authority	Cliff habitat extent (ha)

Ardmeanach	Argyll and Bute	125.9
Beast Cliff–Whitby (Robin Hood's Bay)	North Yorkshire	156.1
Berwickshire and North Northumberland Coast	Northumberland; Scottish Borders	†
Buchan Ness to Collieston	Aberdeenshire	62.2
Cape Wrath	Highland	299.6
Cardigan Bay/ Bae Ceredigion	Ceredigion; Penfro/ Pembrokeshire	†
Clogwyni Pen Ll■n/ Seacliffs of Lleyn	Gwynedd	65
Dee Estuary/ Aber Dyfrdwy*	Cheshire; Fflint/ Flintshire; Wirral	1
Durham Coast	Durham	120.4
East Caithness Cliffs	Highland	310
Exmoor Heaths	Devon; Somerset	85.6
Fair Isle	Shetland Islands	129
Flamborough Head	East Riding of Yorkshire; North Yorkshire	315.6
Glac na Criche	Argyll and Bute	50
Glannau Ynys Gybi/ Holy Island Coast	Ynys M6n/ Isle of Anglesey	111.1
Great Orme's Head/ Pen y Gogarth	Conroy	13.9
Hastings Cliffs	East Sussex	55.1
Hoy	Orkney Islands	94.9
Isle of Portland to Studland Cliffs	Dorset	579
Isle of Wight Downs	Isle of Wight	18.4
Limestone Coast of South West Wales/Arfordir Calchfaen de Orllewin Cymru	Abertawe/ Swansea; Penfro/ Pembrokeshire	349.5
Lundy	Devon	†
Mousa	Shetland Islands	†
Mull of Galloway	Dumfries and Galloway	137.6
North Rona	Western Isles/ Na h-Eileanan an lar	31.4
Overstrand Cliffs	Norfolk	28
Papa Stour	Shetland Islands	†
Pembrokeshire Marine/ Sir Benfro Forol	Penfro/ Pembrokeshire	†
Pen Ll■n a'r Sarnau/ Lleyn Peninsula and the Sarnau	Ceredigion; Gwynedd; Powys	†
Polruan to Polperro	Cornwall	192
Rigg-Bile	Highland	450.8
Rum	Highland	216.7
Sidmouth to West Bay	Devon; Dorset	807.5
South Devon Shore Dock	Devon	238.7
South Hams	Devon; Torbay	3.8
South Wight Maritime	Isle of Wight	198.6
St Abb's Head to Fast Castle	Scottish Borders	122.4
St Albans Head to Durlston Head	Dorset	28.7
St David's/ T■ Ddewi	Penfro/ Pembrokeshire	303.9
St Kilda	Western Isles / Na h-Eileanan an Iar	738.8
Strathy Point	Highland	169.3
Stromness Heaths and Coast	Orkney Islands	63.5
Thanet Coast	Kent	†
The Lizard	Cornwall	149.8
Tintagel–Marsland–Clovelly Coast	Cornwall; Devon	1457.9

Y Fenai a Bae Conwy/ Menai Strait and Conwy Bay	Conwy; Gwynedd; Ynys Mon/ Isle of Anglesey	†

* Possible SAC not yet submitted to EC.

† SAC proposed for sea caves; sea cliffs not a qualifying feature.

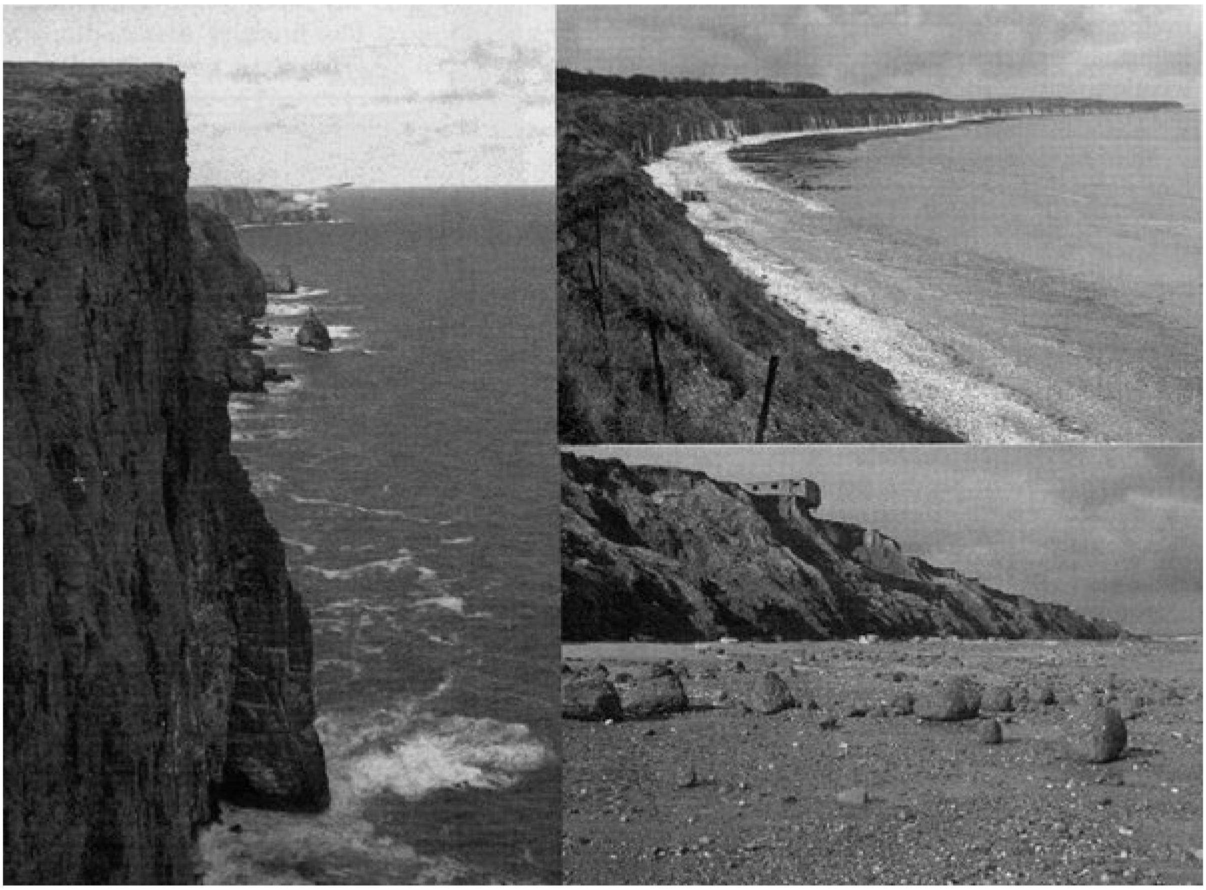
Bold type indicates a coastal geomorphological GCR interest within the site.

Cliffs in even the weakest rocks, such as at Alum Bay on the Isle of Wight and Barton Cliffs in Christchurch Bay where Tertiary rocks provide key exposures uncommon enough for these to be the type sites of the relevant Tertiary strata. The full list of selection categories can be found in Ellis *et al.* (1996). Ongoing coastal erosion at these sites is important in providing 'fresh' faces of rock to study. However, there are problems in balancing the need for maintaining a 'fresh' geological exposure with the fact that over time it may be eliminated by the very erosion that originally created the exposure in the cliff.

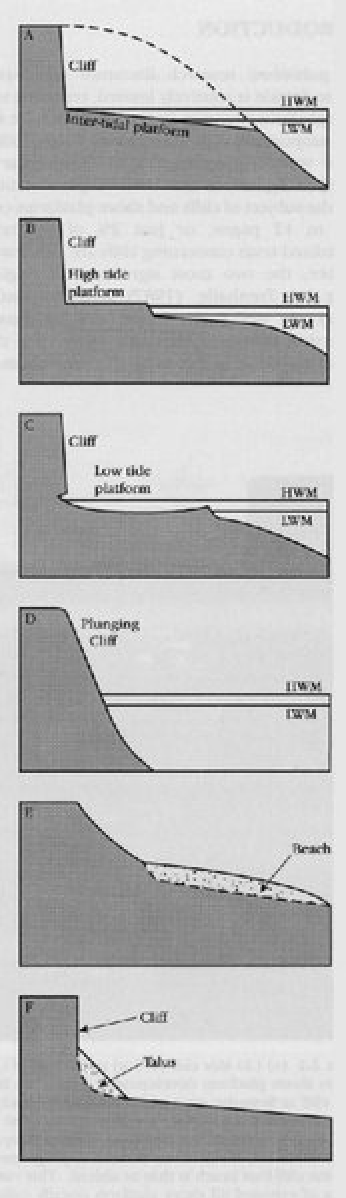
In addition to being protected through the SSSI system for their national importance, 'Vegetated sea cliffs of the Atlantic and Baltic coasts' are a Habitats Directive Annex I habitat, eligible for selection as Special Areas of Conservation (see Chapter 1). Two further Annex I habitats, 'Submerged or partially submerged sea caves' and 'Reefs', are important features of some cliff coasts. Furthermore, some sea cliffs are of international importance for breeding seabirds, and for this reason may be designated Special Protection Areas under the Birds Directive.

Sea cliff SAC site selection rationale

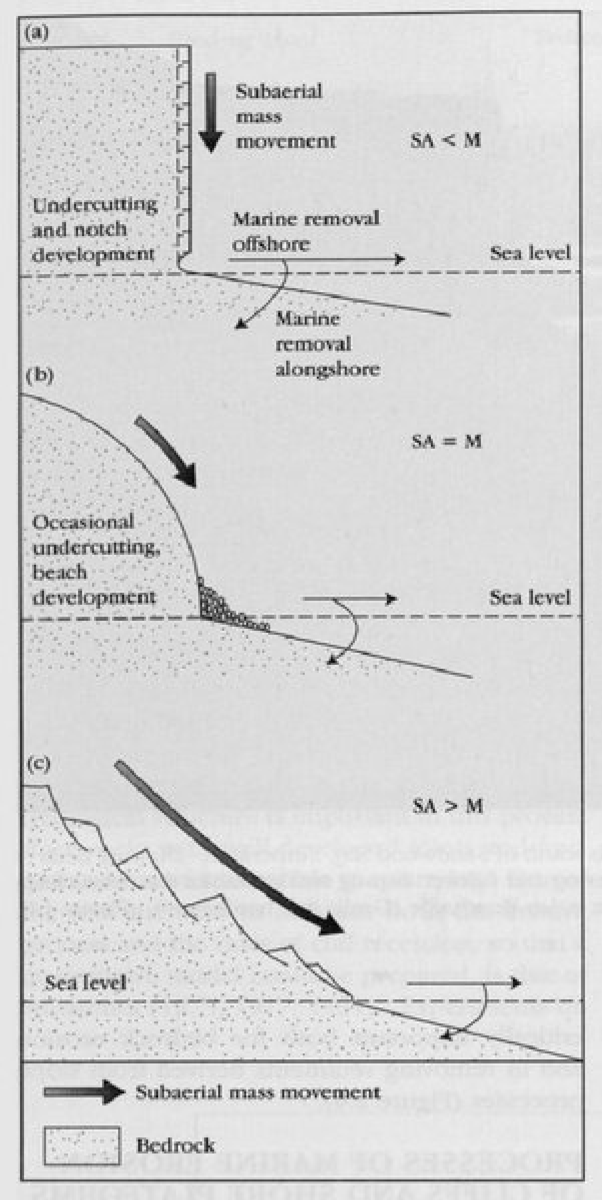
The UK supports a significant proportion of EU sea cliff vegetation (The National Vegetation Classification (Rodwell, 2000) describes 12 maritime cliff NVC types). In particular, the coast of England holds a major proportion of the European coastal Chalk exposures (113 km, compared with 85 km in France and shorter lengths in the Baltic area). All the selected SACs are extensive and have an exceptionally well-developed zonation of vegetation. They reflect the very wide ecological variation of the habitat type across the UK arising from the variability of cliff structure, geology and levels of maritime exposure. The SAC series includes rock types that range from unconsolidated drift or clay through soft shales, mudstones, limestones and Chalk, to acid igneous formations. In addition, both sheltered east-facing sites and exposed west-facing sites are included.



(Figure 2.1) (a) Clò Mór cliff (193m) to the east of Cape Wrath, Sutherland is a good example of a plunging chit with no shore platform development, which has been inherited from former sea levels. (b) Recession of the Chalk cliff at Sewerby, west of Flamborough Head, Yorkshire, has produced a steep lower cliff with a sloping shore platform whose upper junction is obscured by a gravel beach composed of chalk gravels together with glacial gravels derived from bevelling of the cliff-top till. (c) Rapid erosion of the soft and unconsolidated glacial till cliff at Atwick, Holdemess, Yorkshire, progresses by undercutting and rotational failure that is accentuated when the cliff-foot beach is thin or absent. This view looking north shows a very thin upper beach veneer over an area of exposed till shore platform (locally called an 'ord') whose surface is strewn with till blocks eroded from the cliff. (Photos: J.D. Hansom.)



(Figure 2.2) Coastal cliffs and their related shore platforms. A, cliff with intertidal ramp platform; B, cliff with shore platform at about high tide level; C, cliff coast with shore platform at about low tide level; D, plunging cliff with no shore platform; E, relict cliff with platform marked by emerged beach; F, typical inland cliff with talus at foot. (After Bird, 1984.)



(Figure 2.3) Processes of cliff retreat. SA = subaerial erosion of material, symbolized by the large arrow; M = marine erosion, symbolized by the fine arrows eroded material is removed offshore and alongshore by marine process. (a) SA<M; here steep cliffs, undercut by marine processes, develop. (b) SA=M; here a balance between the two sets of processes allows small beaches to develop at the toes of sloping cliffs; (c) SA>M; here subaerial mass movements by sliding produce a low stepped profile and marine transport of plentiful debris. On most coastal slopes, the rate of erosion of material falls far short of the ability of waves and tides to remove it, so that the slope angles are maintained (a,b). However, on weaker rocks (c) material is delivered at a rate controlled in large part by the ability of the sea to maintain removal and thus the rate of basal erosion, in which case slope angle will decline until sediment input matches the rate of removal. (After Hansom, 1988.)

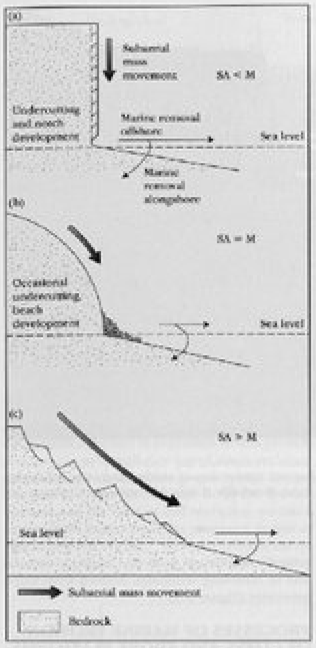


Figure 2.3 Processes of cliff retreat. SA = subaerial erosion of material, symbolized by the large arrow; M = marine erosion, symbolized by the fine arrows – eroded material is removed offshore and alongshore by marine process. (a) SA<M; here steep cliffs, undercut by marine processes, develop. (b) SA=M; here a balance between the two sets of processes allows small beaches to develop at the toes of sloping cliffs; (c) SA>M; here subaerial mass movements by sliding produce a low stepped profile and marine transport of plentiful debris. On most coastal slopes, the rate of erosion of material falls far short of the ability of waves and tides to remove it, so that the slope angles are maintained (a,b). However, on weaker rocks (c) material is delivered at a rate controlled in large part by the ability of the sea to maintain removal and thus the rate of basal erosion, in which case slope angle will decline until sediment input matches the rate of removal. (After Hansom, 1988.)

Table 2.1 Likely recession rates in different materials (compiled by Carter, 1988, from data in Sunamura, 1983).

Lithology	Recession rate (m a^{-1})
Granite	10^{-3}
Limestone	10^{-3} to 10^{-2}
Shales and flysch	10^{-2}
Chalk	10^{-2} to 1
Tertiary sedimentary	10^{-1} to 1
Quaternary sedimentary	1 to 10
Recent volcanic rocks	10 to 10^{2}

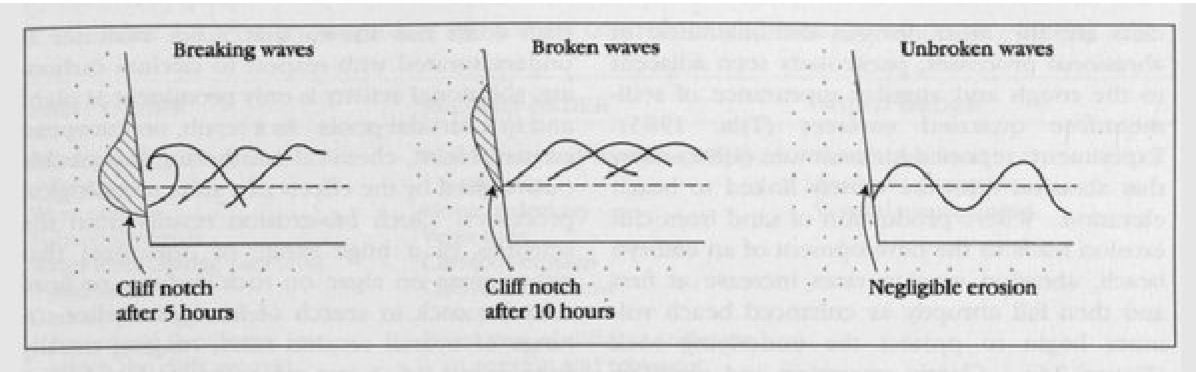
retreat: the formation of tension cracks parallel to the erosion surface arises from reductions in confining pressures as surface rock is removed. The 1999 failure of the chalk cliff at Beachy Head is a good example of this process.

Deep-seated mass movements are common in some coastal regions, where geological conditions are suitable, particularly where the compressive strength of the rock is exceeded by the load it must bear. Easily sheared rocks with low bearing strength are particularly susceptible to landslides and, as a result, they are more frequent in soft rocks and less common in resistant rocks (Trenhaile, 1987). However, a relatively common type of landslide in hard rock occurs where the cliff is characterized by seaward-dipping beds or alterations of permeable and impermeable strata, or where massive rocks overlie rocks with low load-bearing strength. In such situations, translational slides and 'dip-slip' slides, where failure occurs along a slope-parallel failure surface or bedding plane, produce large but often shallow features whose failure may often have been triggered by high pore-water pressures following prolonged rainfall. Spectacular examples of such landslides occur in the 30° westward-dipping beds of the Aberystwyth Grits near Aberystwyth, Wales.

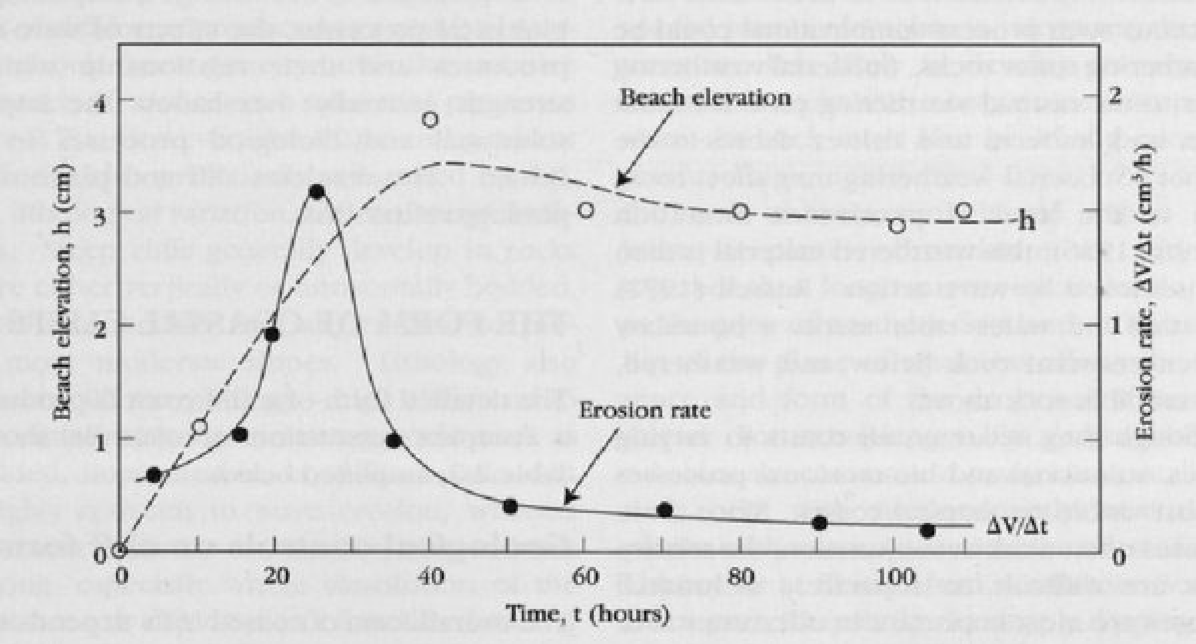
Brunsden (1973) and Brunsden and Jones (1976, 1980) showed how complex coastal slopes may develop on coastal landslides. The cliffs of west Dorset are noted for the spectacular landslide systems that truncate NE–SW-trending ridges rising to between 140 and 170 m. The ridges are formed in chert and Upper Greensand overlying unconformably interbedded Lower Jurassic clays, marls, mudstone and thin argillaceous limestones. Large arcuate landslide scars form the upper part of the slope and are sepa-

(Table 2.1) Likely recession rates in different materials (compiled by Carter, 1988, from data in Sunamura, 1983).

(Figure 2.4) Toppling in the Torridonian sandstone cliffs south of Sandwood Bay, Sutherland. Dipping beds of well-jointed sandstones are subject to subaerial weathering and failure. Strong surf prohibits the debris from accumulating at the cliff foot. The stack in the distance is Am Buachaille (Gaelic for 'herdsman). (Photo: J.D. Hansom.)



(Figure 2.5) Cartoon depicting erosion of a vertical cliff under breaking-, broken- and unbroken-wave attack. Breaking waves cause the greatest amount of erosion. (Based on Sunamura, 1983, 1992 and Hansom, 1988.)



(Figure 2.6) Temporal variations in abrasion rate (AV/At), and beach elevation, h, expressed by the thickness of sand deposited at the cliff base, using data from wave-tank experiments. AV/At = volume of eroded material per unit time. (After Sunamura, 1976.)

Table 2.2 Primary, secondary and tertiary controls on cliff form (based on May, 1997a).

FIRST ORDER	SECOND ORDER	THIRD ORDER
Geological structure and lithology	Weathering and transport slope processes	Coastal land-use
Wave climate	Slope hydrology	Resource extraction
Subaerial climate	Vegetation	Coastal management
Water-level change (sea level and tide)	Cliff-foot erosion	
Geomorphology of the hinterland (landforms into which the cliffs are cut)	Cliff-foot sediment accumulation	
	Resistance of cliff-foot sediment to attrition and transport	

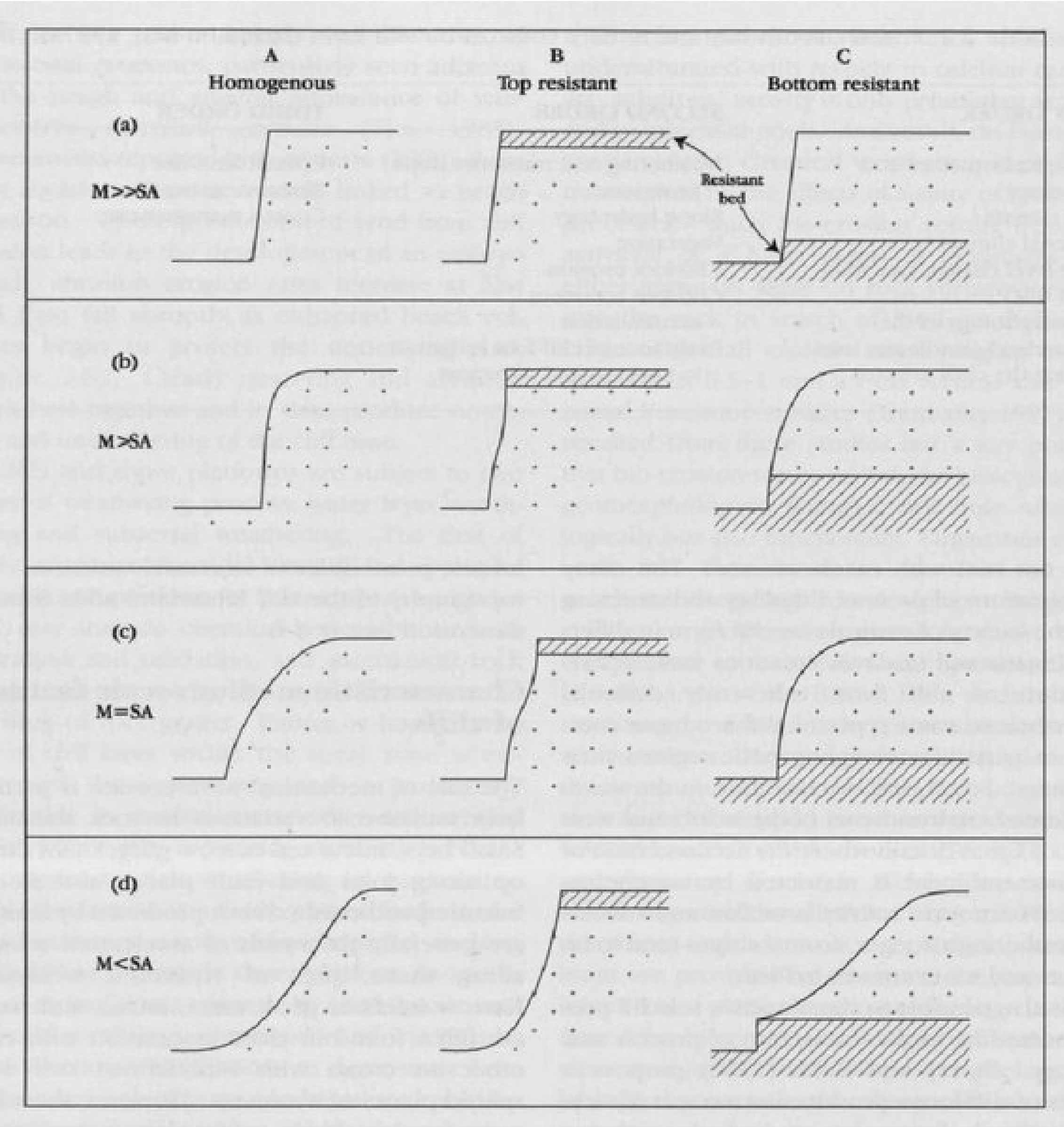
have not met with much success. The many combinations of process, lithology and structure and the variety of controls on cliff form in different climatic and sea-level situations make generalization of cliff form inherently difficult. Nevertheless, some types of cliff are more common in particular morphogenetic regions than in others. Steep cliffs are common in the wave-dominated environments of the north and west coast of Great Britain where the accumulation of cliff-foot sediment is restricted by wave-transport. Where wave activity is weaker and subaerial weathering stronger, coastal slopes tend to be gentler and more convex in form.

It is also possible to classify active sea-cliff profiles according to the interaction of process and geology. Emery and Kuhn (1982) propose a matrix of cliff-forms produced as a result of varying bedrock homogeneity and the relative importance of marine and sub-aerial processes (Figure 2.7). However, the shape and gradient of cliffs are also profoundly influenced by dip, strike, lithological variation, and structural weaknesses. Steep cliffs generally develop in rocks that are either vertically or horizontally bedded, whereas intermediate bed angles tend to produce more moderate slopes. Lithology also influences cliff morphology – high cliffs tend to be associated with more resistant rocks such as unbedded, impermeable, crystalline rocks that are highly resistant to wave erosion, whereas sedimentary rocks are more susceptible to wave quarrying, especially where dissolution of the rock cement or exploitation of weaker bedding planes aids disintegration. As a result of this complexity, the available models, although useful simplifications, take limited account of the infinite possibilities of structural variation. The topography of the cliff hinterland adds another dimension (see p. 44).

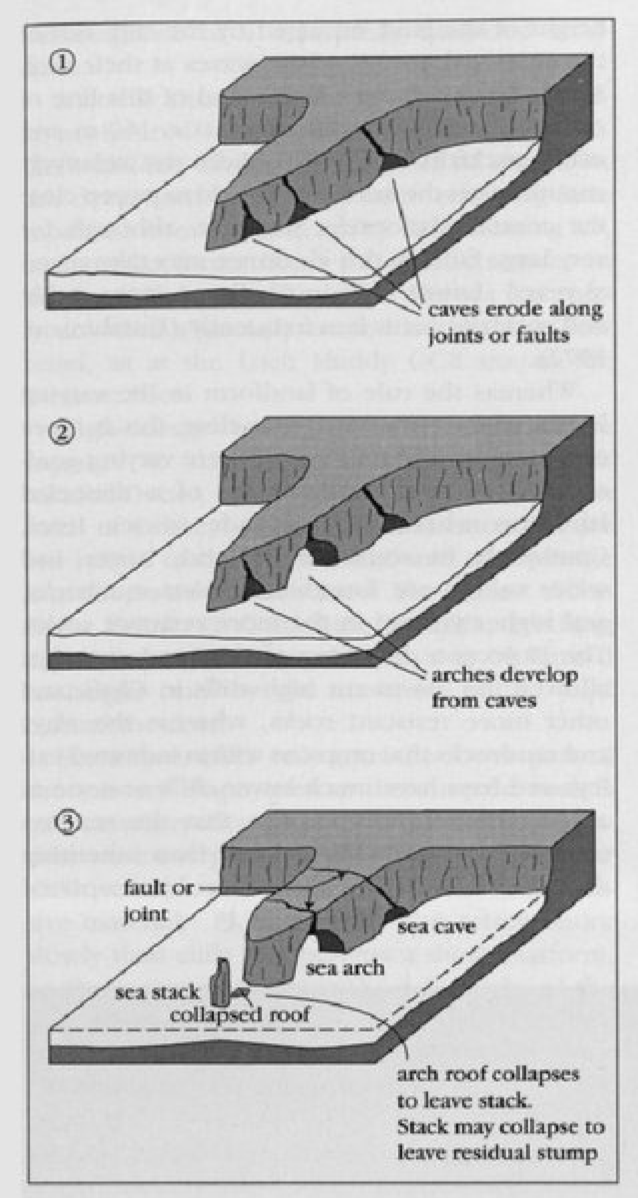
Characteristic medium-scale features of cliffs

The rate of mechanical wave erosion is particularly sensitive to variations in rock structure. Small bays, inlets and narrow gorges that develop along joint and fault planes and in the fractured and crushed rock produced by faulting are generally the result of accelerated erosion along these lines of structural weakness. Narrow inlets or geos, caves, arches and stacks are often found in close association with each other on coasts with well-defined and well-spaced planes of weakness. However, these features are less likely to develop in *very* weak rocks or in rocks with a *very* dense joint pattern, since the rock must also be strong enough to produce high, near-vertical slopes or to support the roofs of caves, tunnels and arches. If the joints or planes of weakness are very close together then long, narrow inlets develop such as the geos of northern Scotland. The angle of dip of the plane of weakness affects the occurrence and form of the erosional feature produced. For example, geo-like gorges with vertical sides are common in many horizontally bedded rocks with predominantly vertical joint planes such as occurs around the coast of Hoy in Orkney or at Skirza Head, Caithness (see GCR site report, Chapter 3). In steeply dipping rocks, where the planes of weakness are usually inclined, geos may either fail to develop or will be irregular in shape (Steers, 1962). Although

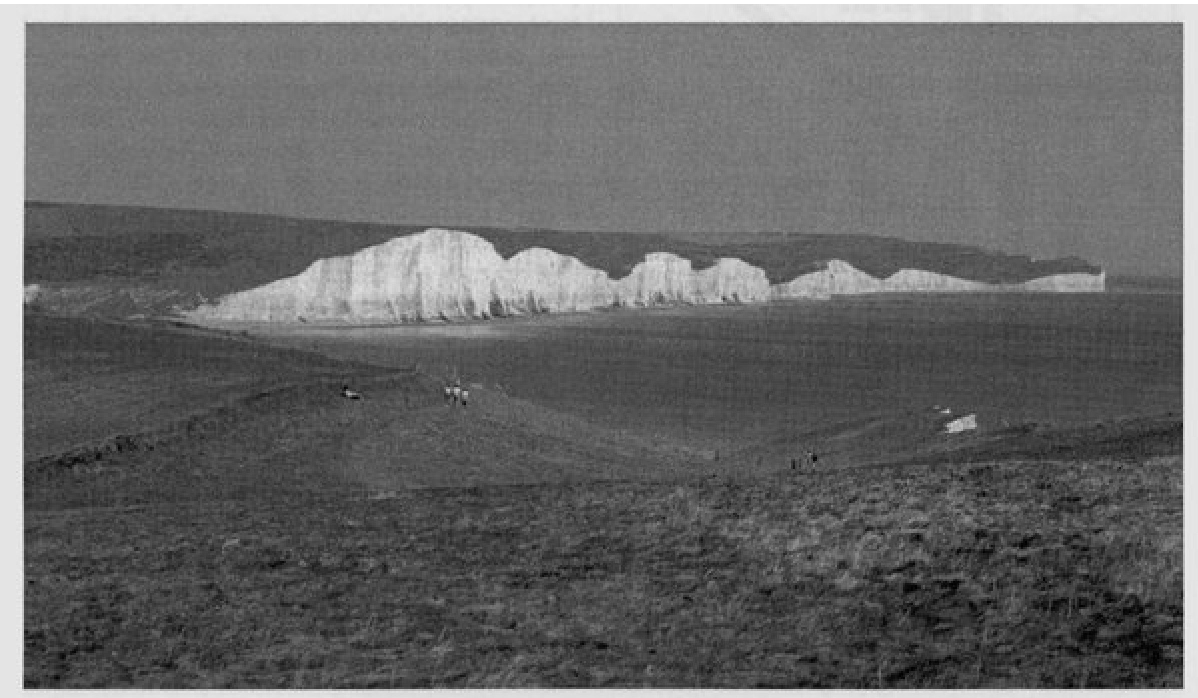
(Table 2.2) Primary, secondary and tertiary controls on cliff form (based on May, 1997a).



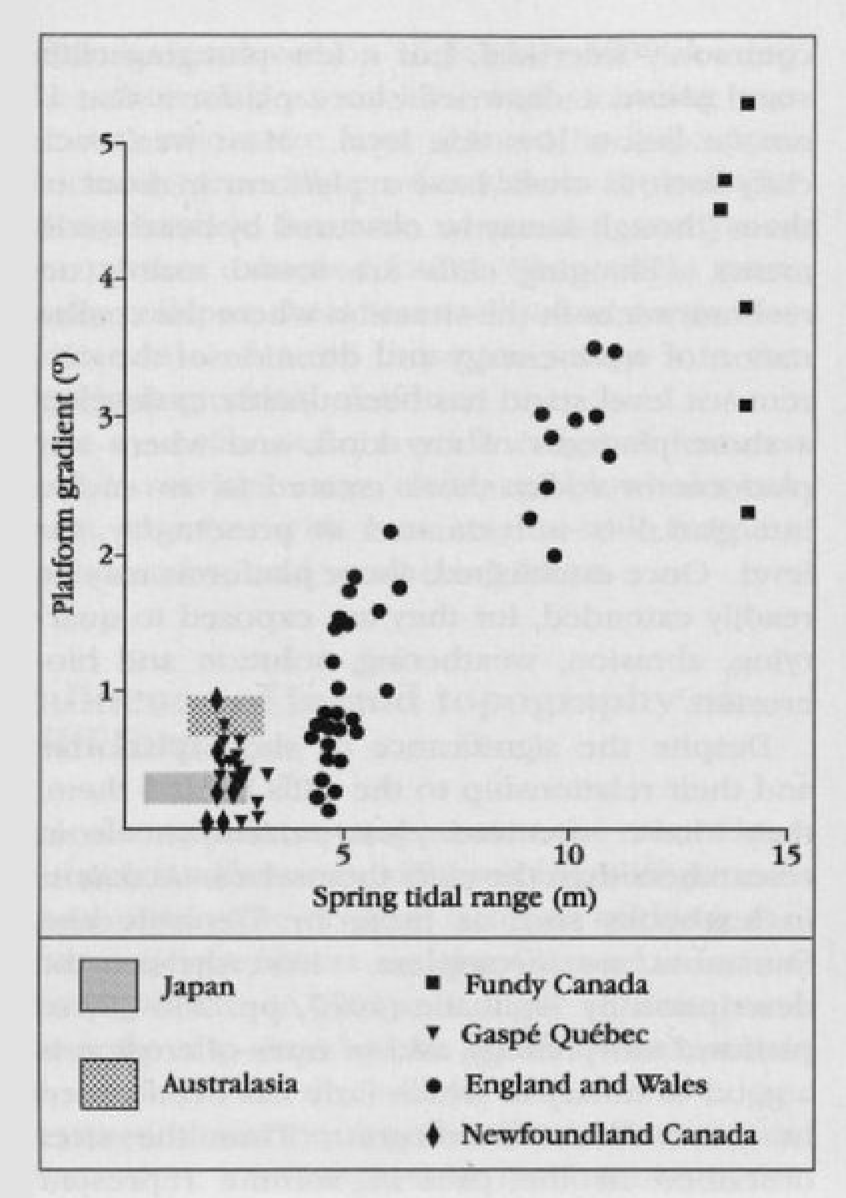
(Figure 2.7) A classification of active sea-cliff forms according to comparative rates of subaerial erosion and marine erosion (SA = subaerial erosion; M = marine erosion). Type 'A' profiles are for cliffs of uniform resistance to erosion; type 'B', where a more resistant rock layer is present at the top; and type 'C', where there is a layer of more resistant rock at the base. (Based on Hansom, 1988, after Emery and Kuhn, 1982.)



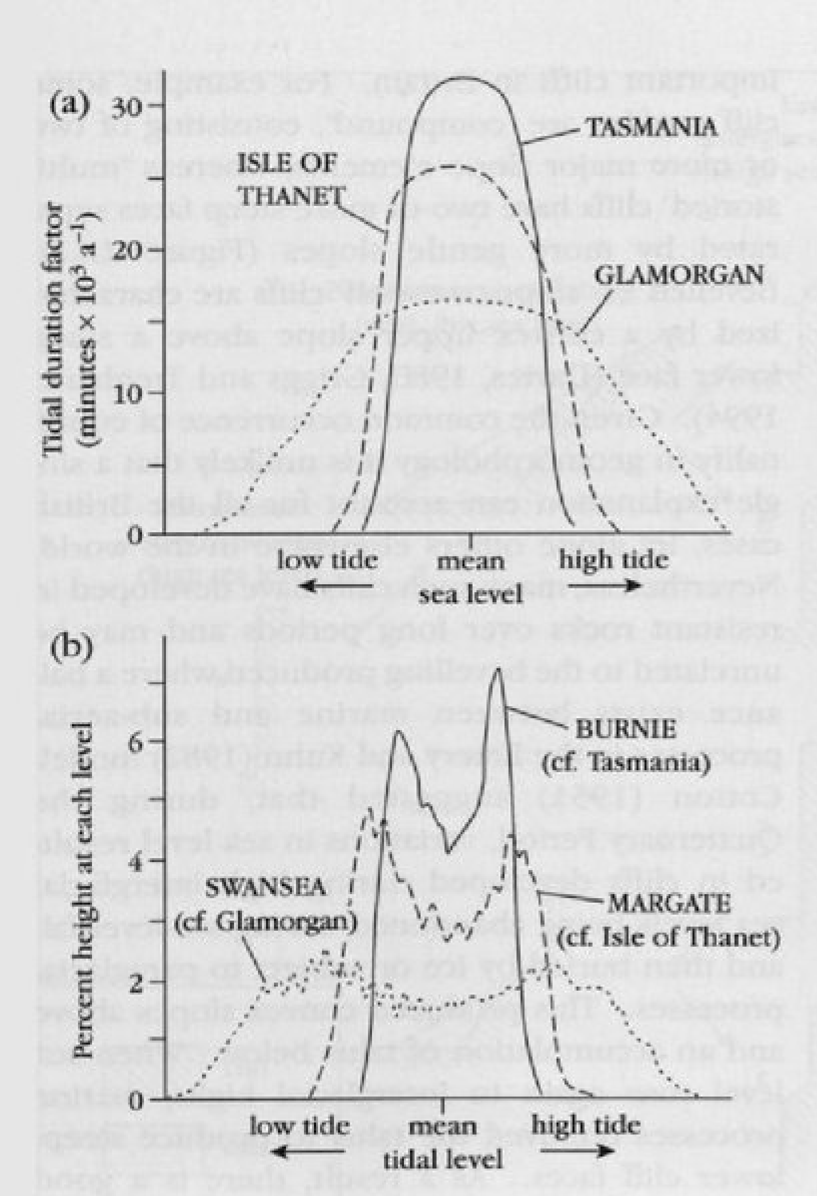
(Figure 2.8) The development of caves, arches and stacks. Wave erosion is more effective along faults and joints where the rock is weaker, and so caves become excavated along these lines of weakness.



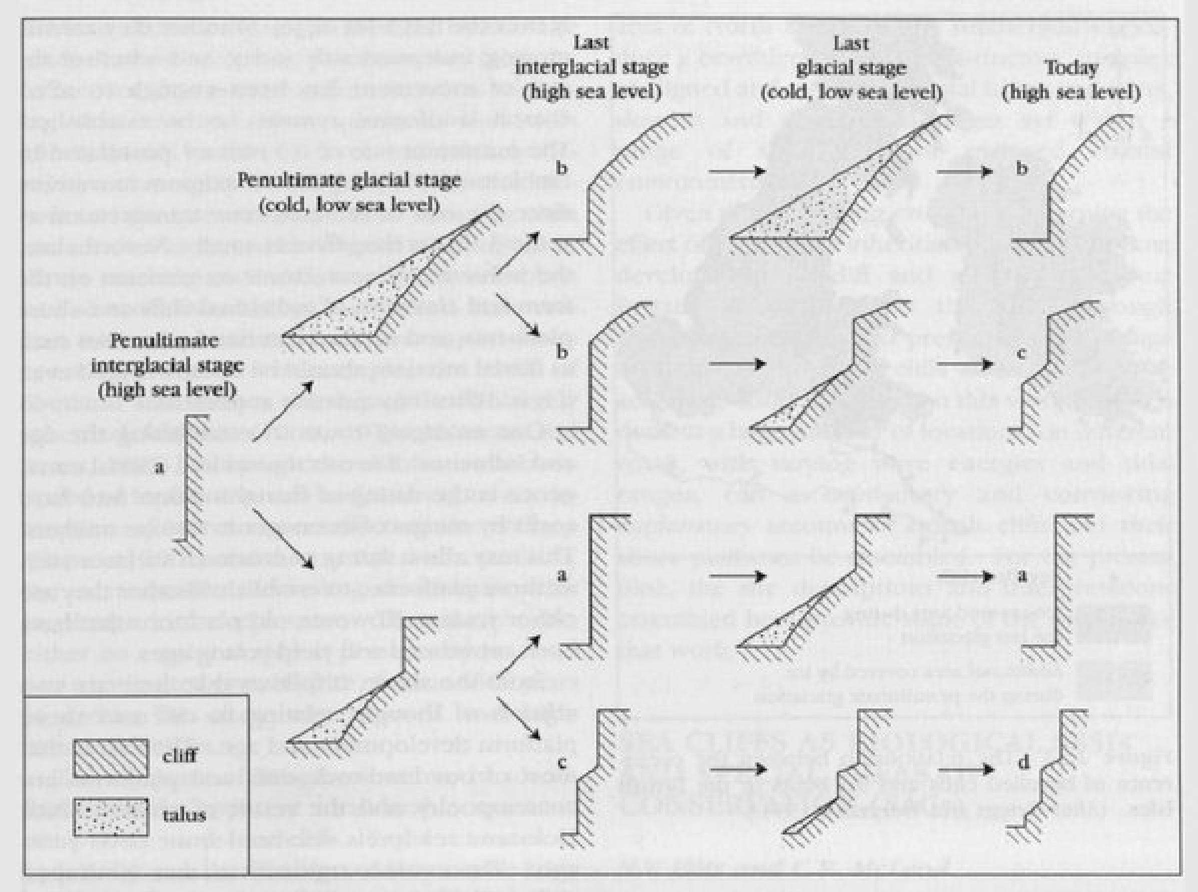
(Figure 2.9) Cliff height, and to some extent cliff form, is a function of the height of land cut by the cliffline. The photograph shows the cliff form of the Seven Sisters, Sussex, an almost straight cliffline truncates a series of dry valleys, the seven intervening ridges forming the Seven Sisters. (Photo: V.J. May)



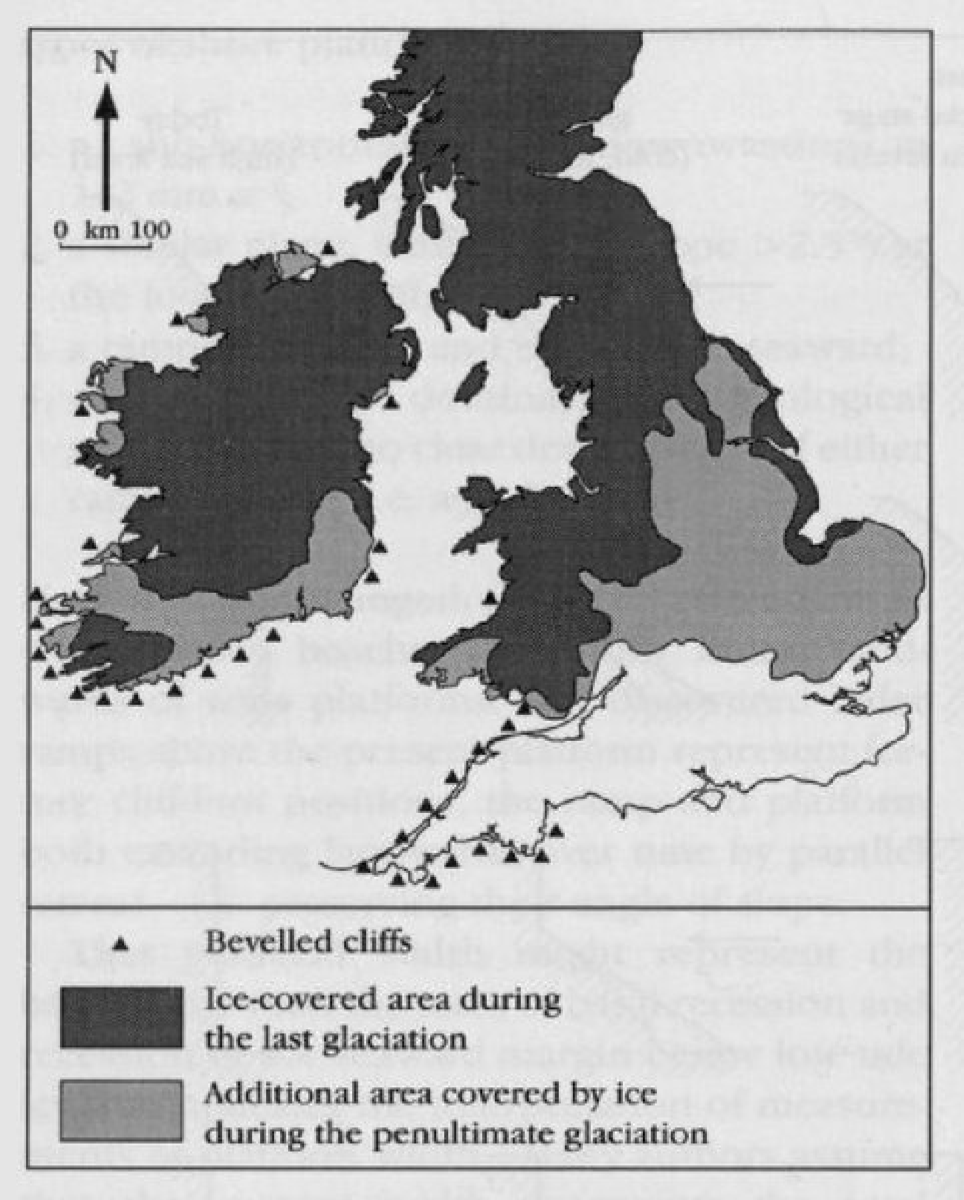
(Figure 2.10) Plot of platform gradient against tidal range. Each point is a regional average of many surveyed profiles and suggests a direct relationship between gradient of platforms and spring tidal range. (After Trenhaile, 1987, p. 207.)



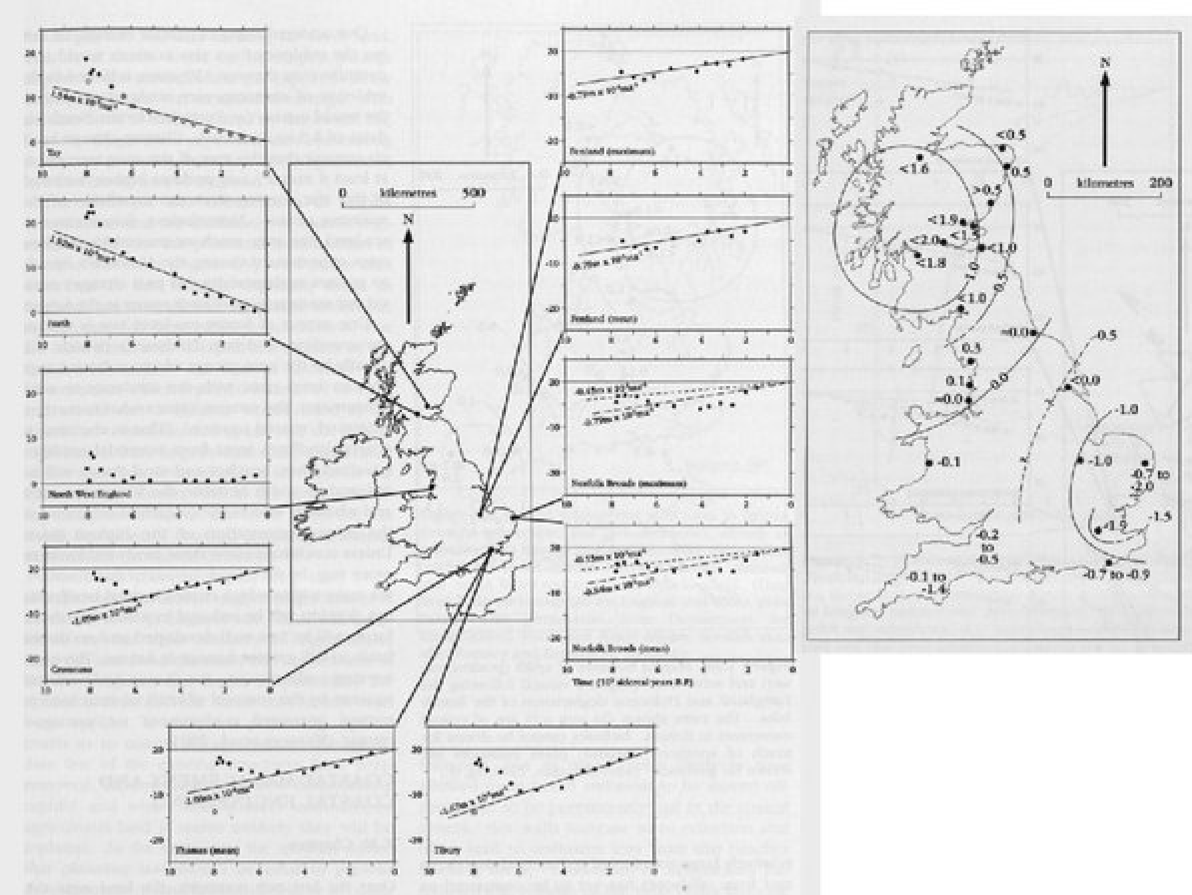
(Figure 2.11) Tidal duration curves from three locations as plotted in varying detail by two sources. Tidal duration is the length of time that still-water level occupies each elevation within the tidal range. (a) After Trenhaile and Layzell (1981); (b) after Carr and Graff (1982).



(Figure 2.12) Flow-diagram model of coastal cliff development over two glacial/interglacial cycles, starting from a vertical, unbevelled cliff profile, (a). During low sea levels, periglacial activity results in talus accumulation at the bases of cliffs. During high sea levels, the talus is removed and the cliff trimmed and stepped, and bevelled profiles (b) develop where the talus reached the cliff top during the last glacial stage, whereas multi-storied profiles (c) develop where the talus extended only part of the way up the cliff face. Both (b) and (c) cliff forms can be affected by a subsequent interglacial–glacial cycle, leading to the numerous possible complex stepped profiles (d) that depend on the resultant level of talus development between cycles. (After Griggs and Trenhaile, 1994.)



(Figure 2.13) The relationship between the occurrence of bevelled cliffs and ice limits in the British Isles. (After Griggs and Trenhaile, 1994.)



(Figure 1.8) a. Uplift and subsidence, based on trends in sea level around the coast of Britain. These trends are established by comparing local sea-level curves with the eustatic trend shown in Figure 1.7b. Open circles indicate that the data were obtained by the author by extrapolation. The vertical scale on the graphs is in metres OD, the horizontal scale is in 10^3 sidereal years before present. (After Tooley and Shennan, 1987, p.136, fig. 4.9.) b. Map of isobases of uplift (positive values) and subsidence (negative values) following the Lateglacial and Holocene deglaciation of the British Isles. The rates shown (in mm a^{-1}) are of crustal movement in Britain. Isobases cannot be drawn for much of southern England; point estimates are shown for guidance. (After Sherman, 1989, fig. 9.)

Table 2.3 Candidate and possible Special Areas of Conservation in Great Britain supporting Habitats Directive Annex I habitat 'Vegetated sea cliffs of the Atlantic and Baltic coasts' and/or 'Submerged or partially submerged sea caves' as qualifying European features. Non-significant occurrences of these habitats on SACs selected for other features are not included. (Source: JNCC International Designations Database, November 2002.)

SAC name	Local authority	Cliff habitat extent (ha)
Ardmeanach	Argyll and Bute	125.9
Beast Cliff–Whitby (Robin Hood's Bay)	North Yorkshire	156.1
Berwickshire and North Northumberland Coast	Northumberland; Scottish Borders	†
Buchan Ness to Collieston	Aberdeenshire	62.2
Cape Wrath	Highland	299.6
Cardigan Bay/ Bae Ceredigion	Ceredigion; Penfro/ Pembrokeshire	†
Clogwyni Pen Llŷn/ Seacliffs of Lleyn	Gwynedd	65
Dee Estuary/ Aber Dyfrdwy*	Cheshire; Fflint/ Flintshire; Wirral	1
Durham Coast	Durham	120.4
East Caithness Cliffs	Highland	310
Exmoor Heaths	Devon; Somerset	85.6
Fair Isle	Shetland Islands	129
Flamborough Head	East Riding of Yorkshire; North Yorkshire	315.6
Glac na Criche	Argyll and Bute	50
Glannau Ynys Gybi/ Holy Island Coast	Ynys Môn/ Isle of Anglesey	111.1
Great Orme's Head/ Pen y Gogarth	Conwy	15.9
Hastings Cliffs	East Sussex	55.1
Hoy	Orkney Islands	94.9
Isle of Portland to Studland Cliffs	Dorset	579
Isle of Wight Downs	Isle of Wight	18.4
Limestone Coast of South West Wales/ Arfordir Calchfaen de Orllewin Cymru	Abertawe/ Swansea; Penfro/ Pembrokeshire	349.5
Lundy	Devon	†
Mousa	Shetland Islands	†
Mull of Galloway	Dumfries and Galloway	157.6
North Rona	Western Isles/ Na h-Eileanan an Iar	31.4
Overstrand Cliffs	Norfolk	28
Papa Stour	Shetland Islands	†
Pembrokeshire Marine/ Sir Benfro Forol	Penfro/ Pembrokeshire	†
Pen Llŷn a'r Sarnau/ Lleyn Peninsula and the Sarnau	Ceredigion; Gwynedd; Powys	†
Polruan to Polperro	Cornwall	192
Rigg–Bile	Highland	450.8
Rum	Highland	216.7
Sidmouth to West Bay	Devon; Dorset	807.5
South Devon Shore Dock	Devon	258.7
South Hams	Devon; Torbay	3.8
South Wight Maritime	Isle of Wight	198.6
St Abb's Head to Fast Castle	Scottish Borders	122.4
St Albans Head to Durlston Head	Dorset	28.7
St David's/ Tŷ Ddewi	Penfro/ Pembrokeshire	303.9
St Kilda	Western Isles / Na h-Eileanan an Iar	758.8
Strathy Point	Highland	109.3
Stromness Heaths and Coast	Orkney Islands	63.5
Thanet Coast	Kent	†
The Lizard	Cornwall	149.8
Tintagel–Marsland–Clovelly Coast	Cornwall; Devon	1457.9
Y Fenai a Bae Conwy/ Menai Strait and Conwy Bay	Conwy; Gwynedd; Ynys Môn/ Isle of Anglesey	†

* Possible SAC not yet submitted to EC.
† SAC proposed for sea caves; sea cliffs not a qualifying feature.
Bold type indicates a coastal geomorphological GCR interest within the site.

(Table 2.3) Candidate and possible Special Areas of Conservation in Great Britain supporting Habitats Directive Annex I habitat 'Vegetated sea cliffs of the Atlantic and Baltic coasts' and/or 'Submerged or partially submerged sea caves' as qualifying European features. Non-significant occurrences of these habitats on SACs selected for other features are not included. (Source: JNCC International Designations Database, November 2002.)