Coastal Geomorphology of Great Britain

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Chapter 4

Soft-rock cliffs – GCR site reports

INTRODUCTION

V.J. May and K.M. Clayton

Cliffed coastlines undergoing rapid erosion characterize much of the south-eastern British coast where they are cut into relatively 'soft' geological materials such as sandstones, clay, shale and chalk, as well as many weak superficial deposits, notably the extensive glacial till of the east coast of England (see Figure 1.2 and Table 4.1). There are also many locations around the British coast where short lengths of rapidly changing cliffs occur wherever softer materials crop out, for example part of the coastline between Weymouth and Lulworth (see GCR site report for the Dorset Coast, Chapter 11). It is also common for bayhead cliffs in upland coasts to be formed in weak materials, often of glacial or fluvio-glacial origin, which produce pocket beaches. In such locations, pocket beaches are often entirely dependent on the erosion of truncated valley deposits as local sources of sediment, for example at Crackington Haven, Cornwall. In contrast, some pocket beaches may depend entirely on adjacent headlands as their sole source of sediment. Additionally, small cliffs, of up to a metre or so in height, often develop at the margins of saltmarshes (see Chapter 10), exhibiting on a micro-scale many of the features of the larger soft cliffs described in this chapter.

Many cliffs are associated with shore platforms that may extend seawards for several hundred metres from the cliff foot. Most actively developing platforms are associated with cliffs that are undergoing active retreat, and so many of the sites described in this chapter are also important for their platforms. A discussion of platform development is provided in Chapter 2 of the present volume.

The selection of soft-cliffs for the GCR used the following classification, based on the cliff lithology, form, and recession rates. It is comparable to the later Jones and Lee (1994) classification of cliffs on the basis of coastal recession.

1. Cliffs that are steep in profile and are retreating rapidly. Their steep profile is largely a function of the rapidity of retreat, which commonly exceeds 0.04 m a^{-1} and may attain 1.82 m a^{-1}. Formed mainly in weak or unconsolidated sands, clays, and gravels, the sediments are often of glacial origin. They are significant sources of beach sediment, for example along the Yorkshire and East Anglian coasts. Their mass-movement features are well represented at Trimingham (described in the *Mass Movements* GCR volume; Cooper, in prep.).
2. Cliffs cut into stiff mudrocks, such as Kimmeridgian clay, the Gault Clay, and Tertiary clays such as the Barton Clay. Often affected by shallow slides and mudslides, these cliffs provide very little sediment for beaches because most of the fine-grained material is carried into deeper water as the toe of slides is removed. They typically retreat at rates between 0.25 m a^{-1} and 1.50 m a^{-1}. As coastal features they are represented best by parts of the cliffed coasts of the south-west Isle of Wight and Dorset, although the best example of the mass-movement features is at Warden Point on the Isle of Sheppey (Dixon and Bromhead, 1991; Cooper, in prep.).
3. Cliffs cut into sandstones, shales and chalk that retain steep profiles despite a variety of retreat rates, which range from very slow to 1.20 m a^{-1}. Parallel retreat (over a timescale of 5 to 10 years) is their most common behaviour. Although they provide potential beach sediments, these are often quickly reduced by attrition to sand or smaller-sized particles. Chert, flint and other hard materials within these rocks may provide important components for beaches. In contrast, when the cliff failures produce boulders, they may form substantial elements of the intertidal landscape and may persist for very long periods of time. These cliffs are often associated with wide shore platforms which have attracted a substantial literature. The effects of small-scale structural features such as faults and joints often contribute to the formation of buttresses, caves, arches and stacks in these coasts. Stacks are often the most distinctive persistent elements of otherwise rapidly retreating coasts.
4. Major landslides in clay that carry extensive volumes of more-resistant overlying material such as chalk, greensand, flint and chert to the shoreline and provide major inputs of potential gravel beach sediment. Typically they retreat at rates in excess of 0.35 m a^{-1}. The harder components of the debris delivered to the beach provide very important beach material, whereas the fine-grained materials are usually quickly dispersed off-

Soft-rock cliffs

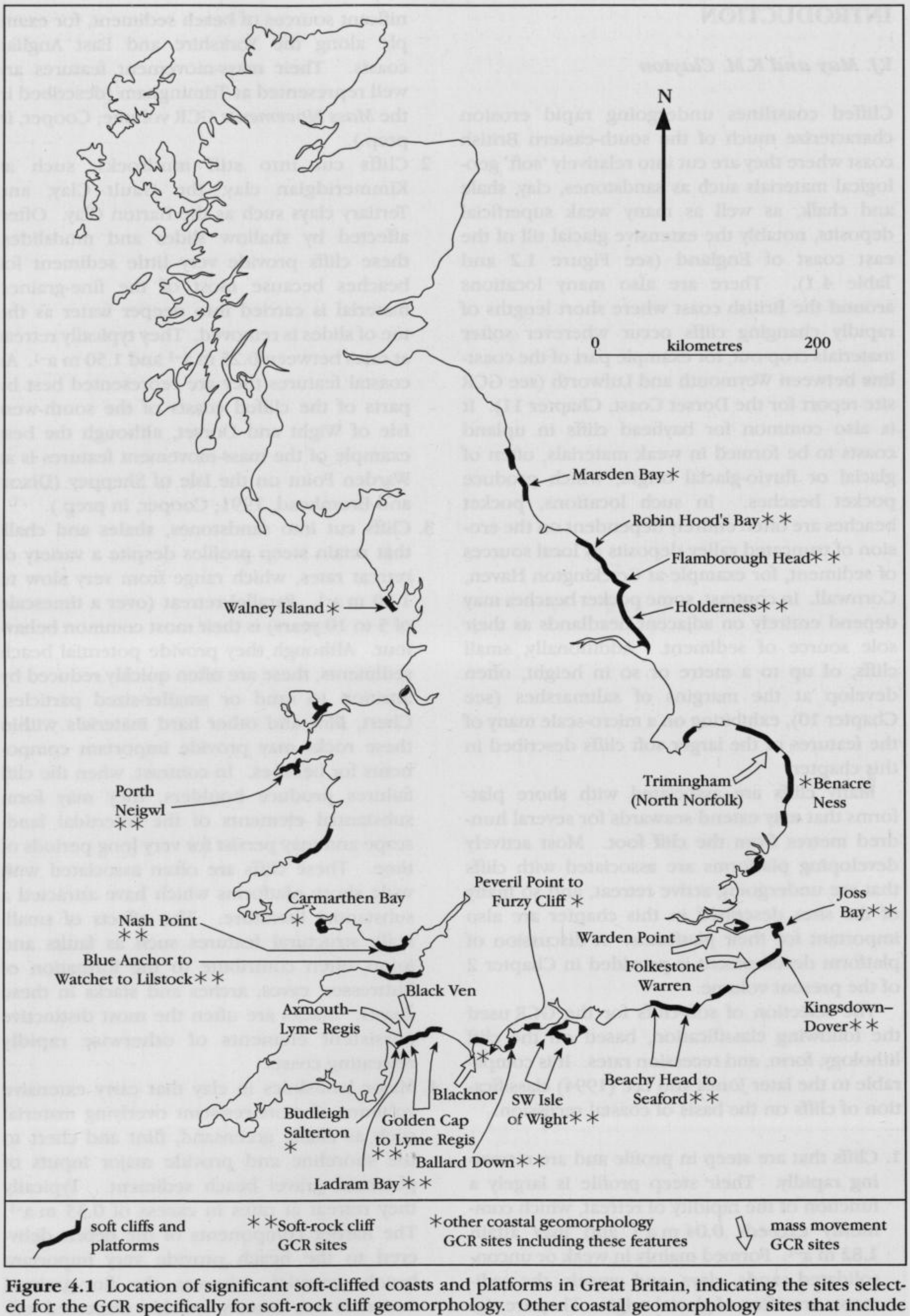


Figure 4.1 Location of significant soft-cliffed coasts and platforms in Great Britain, indicating the sites selected for the GCR specifically for soft-rock cliff geomorphology. Other coastal geomorphology sites that include soft-rock cliffs and sites selected for the Mass Movements GCR 'Block' that occur on the coast are also shown.

Table 4.1 The main features of soft-rock cliff coastal geomorphology GCR sites, including coastal geomorphology GCR sites described in other chapters of the present volume that contain soft-rock cliffs in the assemblage. Sites described in the present chapter are in **bold** typeface.

Site	Main features	Other features	Mean rate of cliff-top retreat (m a^{-1})	Tidal range (m)
Budleigh Salterton	Cliff erosion feeding Budleigh Salterton Pebble Beds into local and regional beaches	Shingle beach (see Chapter 6)	0.30	4.0
Ladram Bay	Cliff–stack–platform development in Triassic sandstone and mudstone		0.20	3.7
Robin Hood's Bay	Cliffs in till resting on Liassic shales. Till/platform junction	Platform across Liassic shales	0.03	4.8
Blue Anchor–Watchet–Lilstock	Rapid retreat in Liassic shales with very unusual 'washboard' topography in macro-tidal environment	Platform development	Up to 1.20	9.4
Nash Point	Rapid cliff retreat in Liassic shales. Cave development	Platform development	0.2–0.10	6.0
Lyme Regis to Golden Cap	Intensively researched landslide and related beach coast	Major mass-movements	0.60–0.96	3.5
Peveril Point to Furzy Cliff	Rapidly eroding cliffs in range of materials from Chalk to Oxford Clay. Longitudinal coast	Semi-enclosed beaches. Submarine rock reefs. Landslides)	0.00–0.41	1.7 (east)–2.0 (west)
South-west Isle of Wight	Differential erosion in materials from Chalk to Wealden. Contrasts between relict and modern beaches. Stacks. Chines	Major mass-movements	0.20–2.10	3.3 (east)–2.2 (west)
Kingsdown to Dover	Cliff and beach development in high (over 30 m) cliffs. Recent beach depletion	Flow failures	0.20–0.60	5.9
Beachy Head to Seaford	Cliffs of variable height in Upper Chalk. Narrow platforms. Locally limited sediment supply. Recent beach depletion		0.40–1.26	5.3
Ballard Down	Classic cave–arch–stack site in Upper Chalk. Transverse coast	Pocket beach formation	0.01–0.60	1.7
Marsden Bay	Cliffs and stacks	Beach phases		4.2
Flamborough Head	Highly complex chalk cliffs overlain by Devensian till. Caves and stacks	Extensive platforms	0.30–0.90	4.0
Joss Bay	Cliff and platform development in Upper Chalk		0.30	4.0

Table 4.1 – *contd*

Site	Main features	Other features	Mean rate of cliff-top retreat (m a^{-1})	Tidal range (m)
Carmarthen Bay	Both hard-rock cliffs and easily eroded cliffs	Major dunes, sand-spits and barrier beaches, rias, emerged beaches, intertidal sandflats, saltmarsh		8.0
North Norfolk Coast	Rapidly eroding cliffs in chalk and till, latter feeding regional sediment budget	Major spits, beaches and saltmarsh (see Chapter 11)	0.30–0.42	4.7 (E)–6.4 (W)
Benacre Ness	Rapidly eroding till cliffs resulting from longshore movements of ness and subsequent reduction of natural protection	Shingle ness (see Chapter 6)	0.42–0.96	2.1
Porth Neigwl	Rapidly retreating glacial drift cliffs, chines, beach cusps	Contemporary beach cementation (see Campbell and Bowen, 1989)	Up to 1.00	3.9
Walney Island	Till cliffs, rapid erosion	Barrier islands, recurved spits		9.0
Holderness	Rapidly eroding cliffs, mainly in till	Till shore platform, ords, thin beach	Up to 2.22	4.0

shore. The coastline between Golden Cap and Lyme Regis is the best representative of this coastal system, but the mass movements are especially well-represented by Folkestone Warren and the coastline between Axmouth and Lyme Regis (Cooper, in press).

Each of these types is represented by a GCR site, or GCR sites described in the present chapter (Figure 4.1, Table 4.1).

Retreat in soft-rock cliffs

Cliffs in weaker materials retreat at rates that range from 0.01 m a^{-1} to over 3 m a^{-1}. Although average values for cliff retreat have been used to compare the magnitude of retreat in weak cliffs, it is essential to recognize that the rate of change in such cliffs, or indeed in any cliffs, is rarely regular (see Figure 4.2). Competing types of geomorphological processes affecting soft cliff sites operate at different rates, or are episodic, so the local form of cliffs can change quite considerably over time; it is common to observe morphological change seasonally. Many of these cliffs are affected by large mass-movements, which produce temporarily protective areas of debris at the cliff foot, or enhance beach volumes sufficiently to provide protection against wave attack for a time. Table 4.1 identifies both the sites that represent soft-cliff coasts specifically and those which are described in other chapters or in the *Mass Movements* GCR volume (Cooper, in prep.).

Two examples demonstrate the irregularity in the long-term mean and short-term variations of cliff recession. At Birling Gap, six-monthly surveys of the cliff top over a decade (from 1952 to 1961) showed that there had been considerable temporal and spatial variation in the amounts lost, although over the ten-year timescale there is a high degree of consistency in the average retreat rate overall (see Table 4.2; May, 1971a). However, at Hengistbury Head, rates of retreat – as well as cliff-face changes – were recorded by the author at both the cliff top and foot, and these measurements demonstrate that although there is also a close similarity between cliff-top and cliff-foot retreat rates, there are considerable variations in the magnitude and frequency of the retreat event. These two examples show that the mixture of materials, structures, wave climates, beach characteristics and platform development is such that rapid retreat cannot be ascribed to any single rock type or location. Cliffs cut in rocks that retreat at the highest rates in one loca-

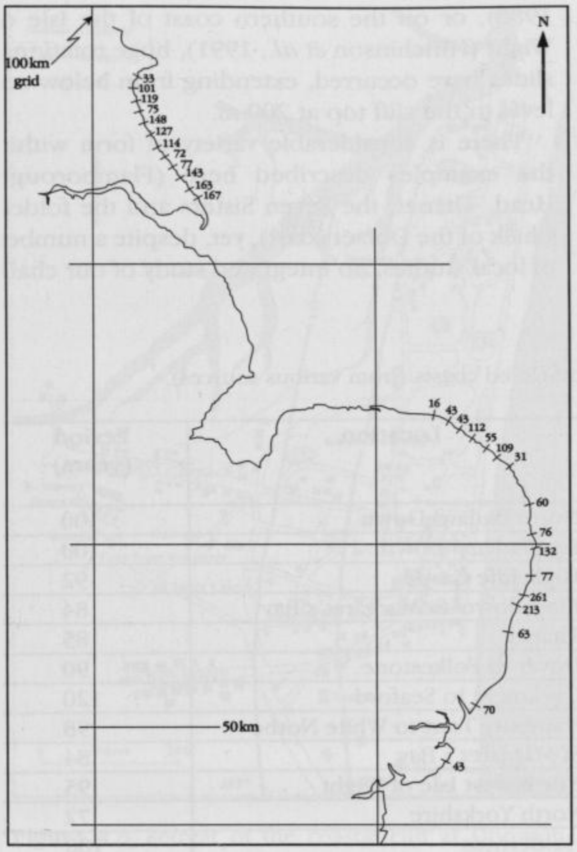


Figure 4.2 Rates of retreat along the North Sea Coast of England from Bridlington to Clacton-on-Sea. Rates are shown as averages for each length of cliff; where the length of cliff exceeds 5 km, values are every 5 km along the coast. Values are totals (metres) for 100 years to 1980. See also Table 2.1 and Table 4.2 (Compiled by K.M. Clayton)

tion may show minimal rates of change elsewhere.

It is also easier to reconstruct the development of the rapidly changing cliffs of Holderness and East Anglia, largely cut into glacial deposits, than the hard-rock cliffs of western Britain. Rates of erosion vary from 0.25 m a^{-1} to 3.5 m a^{-1} in Holderness (Figure 4.2), and an average of 6 m a^{-1} since the 1930s at Covehithe in Suffolk. Such cliffs undergoing rapid erosion suffer cliff failure in large part by rotational landslides, and their significance for study of these processes has formed a major reason for their inclusion as GCR sites. Thus many are described in the GCR volume on mass movement sites (Cooper, in press.).

From the marine-process viewpoint, two features are particularly noteworthy. First, the pattern of erosion over time and space is complex (Cambers, 1973). Despite such spatial and temporal variations, overall data for the whole of the Norfolk cliffs imply a long-term average rate of retreat close to 1 m a^{-1}. Certainly cliff positions are difficult to establish prior to the first Ordnance Survey maps, but evidence of vanished villages near Cromer in Norfolk described in the Domesday Survey (1086 AD), or maps showing the steady erosion of the streets of the medieval town of Dunwich since 1589 AD (Robinson, 1980a; Figure 4.3) strongly suggests long-term persistence of an erosion rate comparable with that found today. This implies both the long-continued effectiveness of the longshore and offshore removal of sediment, and the continuation of wave-energy levels at the coastline similar to those today.

Yet, second, when the extent of coastal retreat since the slowing of the Holocene rise in sea level at about 6000 years BP is considered, it is clear that a third factor has been at work – the gradual and persistent deepening of the offshore zone. Along the North Sea coast of England (e.g. Holderness and north-east Norfolk), some of this change has been contributed by relative sea-level rise, but part may also be attributed to sea-floor erosion, probably by abrasion and bio-erosion. Insofar as the rate of cliff retreat has been sustained, the gradual deepening of this submerged offshore zone (from both erosion and sea level rise) and so the maintenance of offshore gradients may well have been the basic control on wave energy and so on the rates of coastal erosion. Along these coasts a shore platform also underlies the beach, but it is often seen only after severe storms, since erosion contributes enough sediment to maintain a thin covering beach (Figure 2.1c).

An intermediate position is held by the Chalk cliffs of England. Chalk is the commonest rock of south-eastern England and crops out in coastal cliffs along a considerable length of the coast from the Isle of Thanet to Devon, as well as at Flamborough Head and at Hunstanton, Norfolk, where the Red Chalk is well exposed. Several lengths of Chalk cliffs are included in the GCR sites described in this chapter, including the steeply dipping (and rather resistant) Chalk of the Isle of Wight and Dorset. The rate of retreat tends to be ≤1 m a^{-1} with the more sheltered sites undergoing erosion at about 0.2 m a^{-1}. Chalk cliffs differ from weaker rocks (where the platforms are usually buried by a beach) in commonly displaying shore platforms at their foot.

Sand can usually only accumulate in bays, although considerable lengths (as for example the Seven Sisters, Sussex) can be fronted by a rather patchy beach of flint pebbles or cobbles. In addition, the greater coherence of Chalk means that cliff failure is generally by falls (toppling) rather than by rotational slides, although where mudrocks underlie the cliff section, as at Folkestone Warren (Hutchinson *et al.*, 1980), or on the southern coast of the Isle of Wight (Hutchinson *et al.*, 1991), huge rotational slides have occurred, extending from below sea level to the cliff top at 200 m.

There is considerable variety of form within the examples described here (Flamborough Head, Thanet, the Seven Sisters and the folded Chalk of the Dorset coast), yet, despite a number of local studies, no integrated study of our chalk

Table 4.2 Rates of cliff-top retreat of soft-cliffed coasts (from various sources).

Cliff-top retreat (m a^{-1})	Rock type	Location	Period (years)
0.01	Upper Chalk	North Ballard Down	100
0.01	Upper Chalk	East Ballard Down	100
0.03	Bracklesham Beds	Highcliffe Castle	92
0.07	Upper Chalk	Kingsdown–St Margaret's Bay	84
0.07	Upper Chalk	Thanet	85
0.09	Middle/Lower Chalk	Dover to Folkestone	90
0.16	Upper Chalk	Cuckmere to Seaford	120
0.18	Chalk	Hambury Tout to White Nothe	98
0.19	Upper/Middle Chalk	St Margaret's Bay	84
0.27	Hamstead Beds	North-west Isle of Wight	95
0.28	Glacial drift	North Yorkshire	72
0.29	Glacial drift	Holderness	100
0.37	Jurassic clays	Furzy Cliff–Shortlake	98
0.39	Kimmeridge clays and shales	Kimmeridge	100
0.41	Upper Chalk	Newhaven–Rottingdean	89
0.41	Wealden	South-west Isle of Wight	125
0.41	Kimmeridge clays	Ringstead	99
0.42	Glacial drift	Weybourne–Cromer	100
0.57	Glacial drift	Gorleston–Corton	100
0.57	Glacial drift	Holderness	100
0.58	Barton Clay	Barton	62
0.68	London Clay	Reculver	79
0.83	Glacial drift	Gratby–Caister	100
0.85	Glacial drift	Holderness	100
0.88	London Clay, crag and glacial drift	The Naze	100
0.96	London Clay	Northern Isle of Sheppey	79
0.96	Glacial drift	Cromer–Mundesley	100
1.05	Glacial drift	Pakefield–Kessingland	100
1.06	Chalk	Beachy Head	90
1.08	Sandstone	Cliffend	75
1.11	Glacial drift	Holderness	100
1.19	Hastings Beds sandstones	Ecclesbourne Glen	75
1.20	Glacial drift	Holderness	100
1.22	Chalk	Birling Gap	120
1.26	Chalk	Seaford Head	120
1.43	Hastings Beds clays	Fairlight Glen	75
1.75	Glacial drift	Holderness	100
1.96	Glacial drift	Holderness	100
2.22	Glacial drift	Holderness	100
3.00	Glacial drift	Covehithe	100

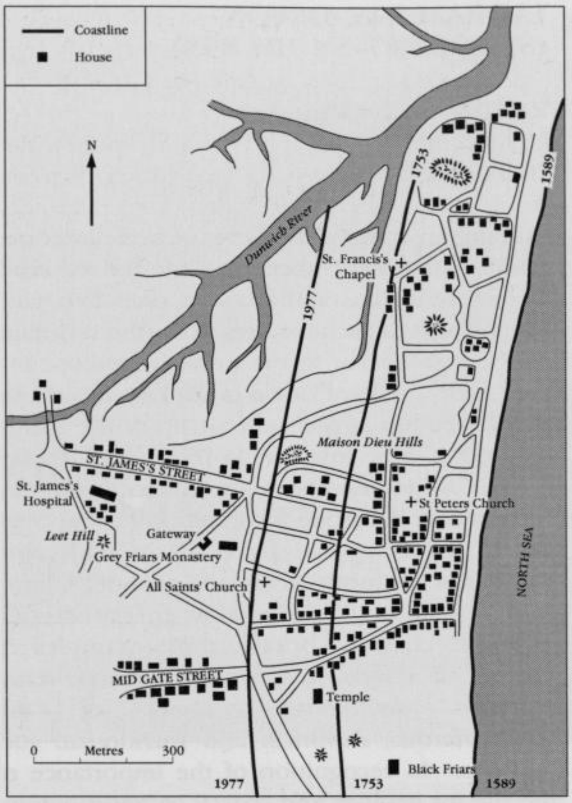


Figure 4.3 Retreat of the coastal cliff at Dunwich, Suffolk, plotted on the 1589 map of Agas; the 1977 cliff top as surveyed by A.H.W Robinson. (After Robinson, 1980a, p.141)

cliffs from a geomorphological viewpoint has yet been attempted (the stratigraphy of the Chalk is described in the GCR volume by Mortimore *et al.*, 2001). Again, the present GCR volume may stimulate such work.

As mentioned above, several of the weak-rock cliff sites are described within the *Mass Movements* GCR volume. Further soft-rock cliff sites in the GCR are those important for the sections that they provide in deposits reviewed in the Quaternary GCR volumes (Campbell and Bowen, 1989; Gordon and Sutherland, 1993; Campbell *et al.*, 1998).

Anthropogenic influences

Because of the co-incidence of soft-rock cliffs and human occupation of the south and east coasts of England, these areas are commonly modified by drainage works and coastal engineering structures aimed at arresting erosion. Current rules for funding these works are making coastal protection works more difficult to justify than has been the case over recent decades. Nevertheless, it remains important for undisturbed cliffed coasts to be protected from anthropogenic intervention if their value for geomorphological research is to be maintained, and indeed if their value in providing sections of importance to geological research is to continue. 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 basal 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 naturally changing state. To some extent their designation as Sites of Special Scientific Interest (SSSIs) can help to facilitate debate on options available to avoid intervention or manage the land in a way sympathetic to the conservation of the scientific features of interest.

There are now few locations along the coast between the Exe estuary and the mouth of the Tees where rapidly retreating cliffs remain unaffected by human intervention. Even in areas where they have not been affected by the construction of sea-walls, their dynamics have been altered by the obstruction of longshore sediment transport. Thus erosion of the chalk coasts of the South and North Downs has been re-invigorated by a reduction in cliff-foot beaches following the construction of major harbour walls and coast protection works at Newhaven, Seaford, Folkestone and Dover. The south-west Isle of Wight is one of the very few coastlines where there has been minimal modification both to the cliffs and the sediment transport system.

In contrast to many soft cliffs that have been investigated in detail before coast protection works were emplaced (e.g. Clements, 1994; Barton, 1991), some of the remaining unprotected cliffs have been less well investigated, despite their critical role as feeder-bluffs.

Although much interesting work has been published, there is still more research needed before we achieve an integrated understanding of the links between cliff-foot erosion, rock type, slope processes and slope form on cliffs in weak rocks. At least on the steeper cliffs (and these are usually those undergoing the most rapid erosion) within each rock type, landslides are the major process delivering material down the cliff slope. This reflects magnitude rather than frequency, though they are spatially common along the coast concerned. As a result, casual inspection of the cliffs, especially in winter when the cliffs are wet, will suggest that small streams and mudflows contribute proportionately more to slope transport than is actually the case, for though they are common, they are individually far smaller in size than the landslides (e.g. Cambers, 1973).

The conservation value of soft-rock cliff coasts

The geomorphological significance, and hence the Earth science conservation value, of soft-cliff coasts arises from their importance to our understanding of three linked processes:

1. the processes of retreat in cliffs that are cut into rocks of varying resistance;
2. the processes of platform development;
3. the processes of supply and transport of sediments from cliffs to beaches both below the cliffs and alongshore.

The rates at which cliffs and platforms produce sediment and the rate at which it is reduced and/or transported provides a strong feedback mechanism on cliff recession and platform lowering. The three processes are linked first by the sediment pathway from cliff to cliff foot to beach to down-drift beaches, second by the role of the sediment pathway from platform to beaches, and third by the inter-relationship between beach sediments and platform morphology and development. It is not usual to regard the erosional slope extending across the intertidal zone in poorly consolidated materials as a platform, but it is predominantly a surface of active erosion and a source of sediments. It exerts considerable effects on wave-energy dissipation, runoff and sediment transport. On many soft coasts, the erosion of cliffs provides the major source of beach sediment. Without erosion of cliffs, many beaches will cease to exist. Thus the continuing conservation of many sand and gravel beaches depends upon the continuation of cliff erosion.

In the present chapter, sites are arranged so that the soft-rock cliffs cut into the oldest rocks are described first, followed by others in decreasing stratigraphical age; in this way the important Chalk cliffs sites are grouped together and the Chapter ends with the cliffs cut into the Quaternary sediments of the Holderness coast.

LADRAM BAY, DEVON (SY 096 847–SY 104 858)

V.J. May

Introduction

Ladram Bay comprises a series of well-developed stacks, cliffs and platforms cut into the red sandstones of the Triassic succession, one of very few assemblages of such features in southern Britain. To the east, similar forms are well developed in the Chalk at Ballard Down in the Isle of Purbeck, at the Needles at the western tip of the Isle of Wight and near Joss Bay in the Isle of Thanet (see GCR site reports in the present volume). Ladram Bay is unique in Britain in having been cut in the comparatively easily eroded sandstone, but the forms have been preserved largely because this is a relatively low-energy site. On the west coast of Britain, most examples of stacks and associated forms are cut into more resistant sedimentary rocks of the Carboniferous, Devonian and Torridonian successions. In recognition of the importance of the site for geology and coastal geomorphology, it is part of the Dorset and East Devon Coast World Heritage Site.

The cliffs vary in height from about 25 m to over 40 m. The shore platform is rarely wider than 150 m, even where it extends below low tide levels. A beach of large shingle and cobbles masks the cliff–platform junction at some points, there being a tendency for the beaches to be better developed where the platform is absent or narrow. The platforms are structurally controlled to the extent that some surfaces co-incide with near-horizontal joint planes. Erosion along near-vertical joints has played a major role in the isolation of the stacks from the mainland.

Description

Ladram Bay is a small site comprising cliffs, stacks and platforms between Smallstones Point (SY 096 847) and High Peak (SY 104 858; see Figure 4.1 for general location). The southern part of the site (just over 1 km in length) has cliffs that are, for the most part, about 25 m in height, whereas they rise to over 120 m at High Peak. The lower cliffs here, as elsewhere in the site, are steep (with angles of inclination generally in excess of 80°). At High Peak, however, the upper part of the cliff is more complex, with

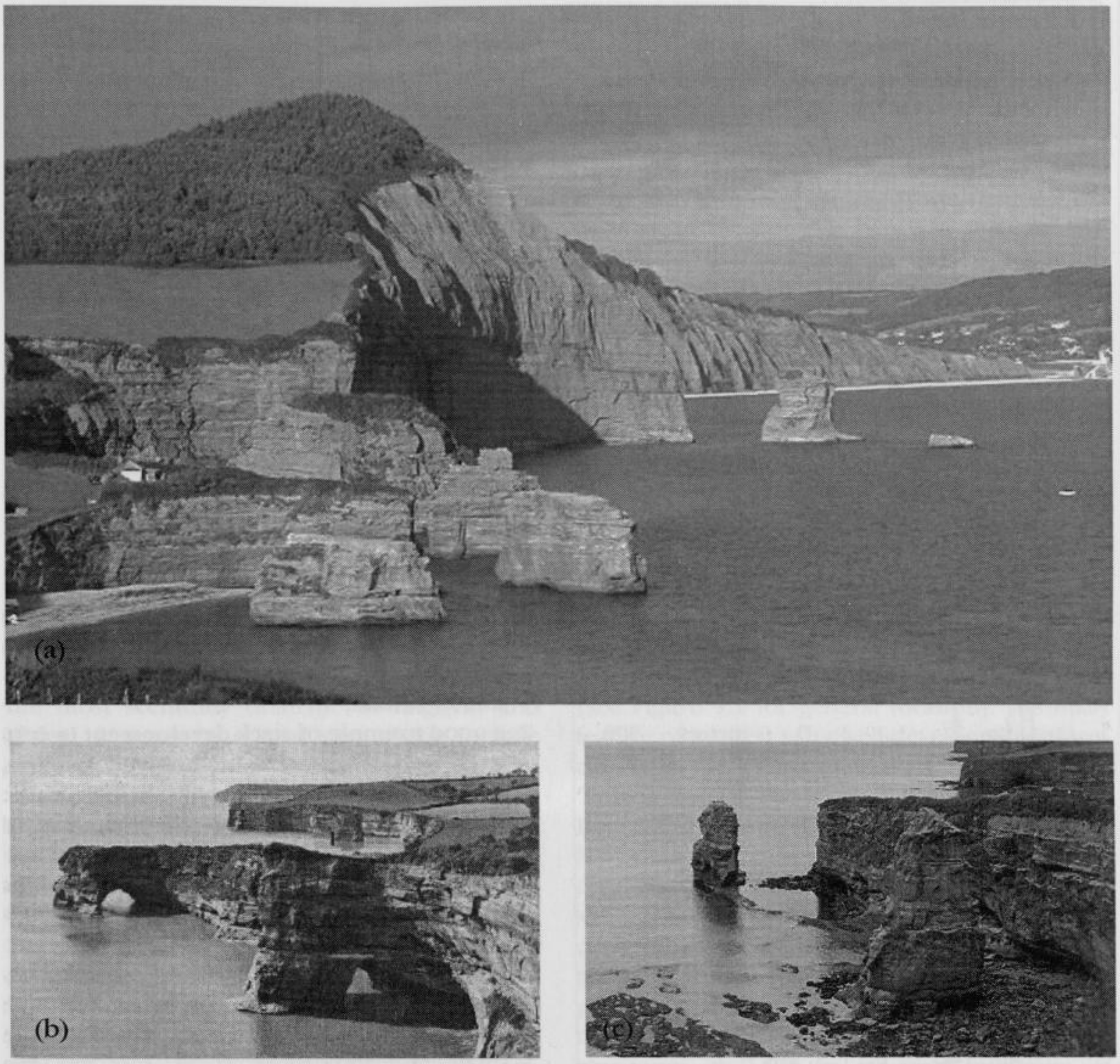


Figure 4.4 (a–c) Undercutting of the cliffs at Ladram Bay. (a) General view looking north showing the stacks associated with headlands; small pocket beaches occupy the bays (b) Two natural arches as they appeared at the beginning of the 20th century in a picture postcard, and (c) the present-day equivalent, view looking SSW. The strata are dipping seawards. (Photos (a,c): V.J. May.)

multiple mass-movements producing a stepped profile (Figure 4.4a). Stacks occur at Ladram Bay itself, and off High Peak, where they are known as 'Little and Big Picket Rocks'.

A series of platforms occur at Smallstones Point, at Ladram, and below High Peak in association with more resistant layers of the sandstone. Their slope reflects the dip of the beds forming them (about 4°). Erosion along near-vertical joints appears to have been important for the separation of the stacks from each other. Therefore, this is a coastline that is strongly controlled by structure. Between the headlands, there are small pocket beaches composed mainly of large mostly locally derived shingle and cobbles, but very little flint. Any sand that occurs is derived locally from rock outcrops.

Interpretation

The development of stacks and associated forms in the more easily eroded materials such as chalk and sandstone depends upon the ability of the sea to exploit weakness in the rocks and the

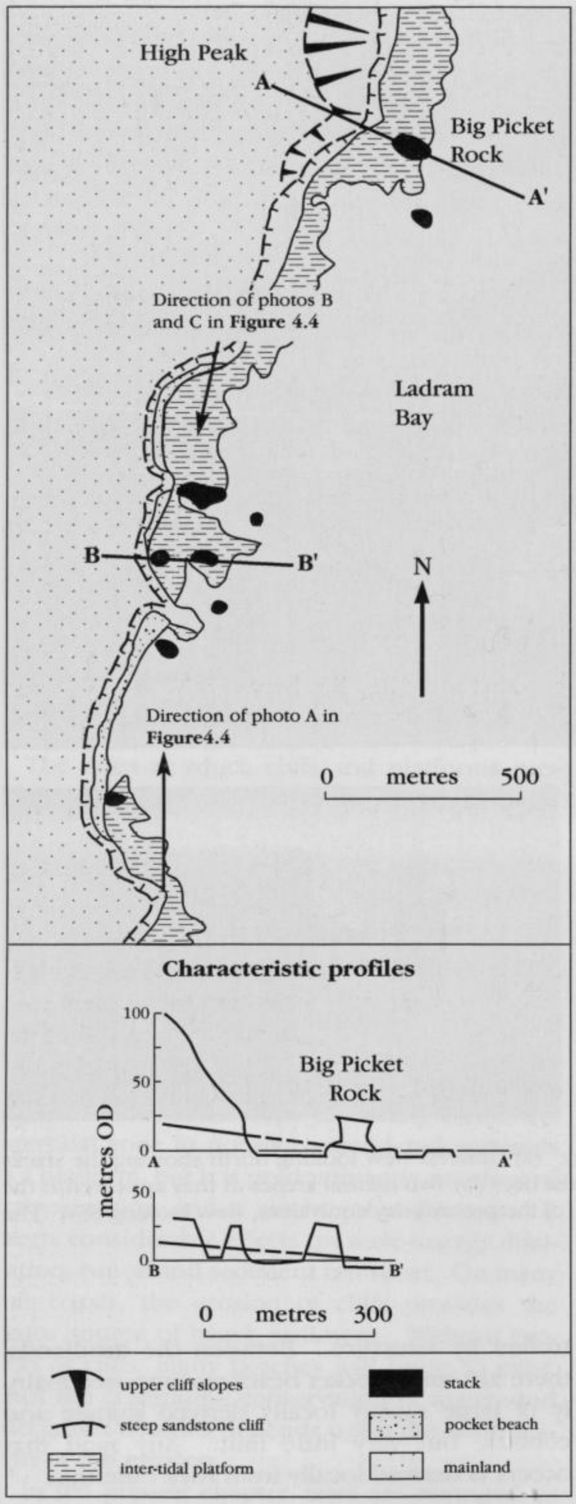


Figure 4.5 The cliffline, platforms and stacks at Ladram Bay. Characteristic profiles are shown (A–A' and B–B'). Of particular note are the absence of stacks below the high cliffs, the presence of strata with fewer discontinuities in the lower stacks, and the tendency for stacks to be associated with headlands.

resistance of the rocks to undercutting at the points where the stacks occur. At Ladram Bay, the stacks appear to result from a combination of:

1. local structural weaknesses,
2. wave energy sufficient to exploit rock weaknesses,
3. the occurrence of resistant strata at the base of the stacks. Owing to the dip of the strata, stacks only occur where the harder strata crop out at sea level (Figures 4.4 and 4.5).

The combination of mass-movements and a platform is unusual, according to Wright (1969), yet at High Peak both occur. It could be argued that the existence of the platforms here owes more to structural effects than to marine processes. This site is scientifically important as:

1. a representative of the coastal landforms in the Triassic and in sandstone, both of which crop out only to limited extent on the coastline of Britain;
2. a good example of stack development in relatively weak material in a sheltered location, the nearest comparable site being in the rather less well-sheltered chalk at Ballard Down;
3. an excellent example of the relationships between structural features and the development of stacks and platforms;
4. part of a suite of erosional landforms in contrasting energy and rock settings, namely the Magnesian limestone at Marsden Bay, the Chalk at Flamborough Head, Joss Bay, the Needles, and Ballard Down and more resistant materials at Gwithian Towans and Tintagel.

As a result, this is an important site in the national GCR network of coastal landforms which, although not as well documented as coastal sites within the Chalk, demonstrates how erosional features such as stacks and arches may develop in low-energy environments when a resistant gently-dipping basal stratum, with intersecting vertical joints or faults, and less resistant upper strata occur together. The presence of the slightly harder pedestal-forming bed appears to be particularly important to stack formation in relatively weaker strata no matter what the wave climate may be.

Conclusion

Ladram Bay is a small but important locality for geomorphology, because of the development of stacks and associated features in lithologies different from many better-known examples. The site demonstrates the role of slightly harder pedestal-forming beds in the formation of stacks in generally more easily eroded coastlines such as those comprising sandstone and chalk. The site is unusual in that mass movements and platforms are found together.

ROBIN HOOD'S BAY, YORKSHIRE (NZ 965 030)

V.J. May

Introduction

The coastline of the North York Moors is one of the most scenically dramatic in England and Wales. It transects a large part of the Jurassic succession from the Lower Lias (Lower Jurassic) strata at Saltburn-by-the-Sea in the north to the Corallian (mid-Upper Jurassic) deposits at Filey in the south. Few parts of this coast have been examined geomorphologically in detail, except for the cliffs and shore platforms around Robin Hood's Bay, where well-developed platforms cut across outcrops of Liassic shales. The cliffs mainly comprise till resting on the Lias and are subject locally to considerable mass-movement and rapid cliff-retreat. Much of the geomorphological interest in the site arises from the platforms and their relationship to the cliffs. Robin Hood's Bay contrasts with other 'active platform' sites: first, it is affected exclusively by the North Sea wave climate; second, it has been subject to glacial and postglacial processes prior to sea level reaching its present position, and third, it is close to the point along the east coast where isostatic stability rather than uplift or subsidence is predominant.

Studies of shore platforms have been a major focus of geomorphological research since the 1960s (e.g. Agar, 1960; Trenhaile, 1972, 1974a,b, 1983; Trenhaile and Layzell, 1981; Robinson, 1977a–c; Sunamura, 1983) and this GCR site has been among the most frequently examined in such studies. It forms an essential member of the network of 'active platform' GCR sites because, although Liassic shales are represented elsewhere at other GCR platform sites, no other North Sea site includes such a marked relationship between upper till cliffs and an underlying pre-glacial bedrock platform that is currently being reworked. In addition Robin Hood's Bay is by far the most studied site, particularly because of the contrast between this site and others in the 'active platform' network in England and Wales (Trenhaile, 1974b). It has been identified as the only location in 225 km of platformed coast with a continuous platform extending around a well-defined headland–embayment sequence (Trenhaile, 1974b). Unusually, the rate and nature of erosion in a cliffed coast with extensive platforms has been the focus of attention (Agar, 1960; Robinson, 1977a–c).

Description

Robin Hood's Bay lies between NZ 956 051 and NZ 908 037 on the north-east coast of Yorkshire (see Figure 4.1 for general location). Its main feature of interest is its well-developed platform cut across the geological structure known as the 'Robin Hood's Bay Dome' comprising Lower Lias shales (Figure 4.6). The bay is backed by low cliffs in the shales overlain by extensive deposits of till. The southern boundary of the site lies at South Cheek where the Peak Fault is crossed by the platform and exposes a small area of ferruginous shales. From calculations for four points around the bay, Agar (1960) estimated that the coastal retreat rate varied from a maximum of 0.305 m a^{-1} to a minimum of 0.046 m a^{-1}. Here, as elsewhere along the north Yorkshire coast, bays were retreating more rapidly than headlands (Table 4.3). In addition, there was a considerable difference between the rates of retreat of the till and the Lower Liassic strata at the cliff foot.

The cliffs are about 50 m in height in the northern part of the bay where they are cut by two steep-sided valleys, Mill Beck and Stoupe Beck (see Figure 4.6). These are cut mainly in till. Although the Lias forms the lower part of the cliff, it is commonly masked by debris from the landsliding clays above it, and by a storm beach of shingle. South of Stoupe Beck, the cliffs rise steadily to reach a maximum of 107 m at the southern end of the bay. Here the Lias forms most of the slope, with near-vertical lower cliffs comprised entirely of Lower Lias rocks.

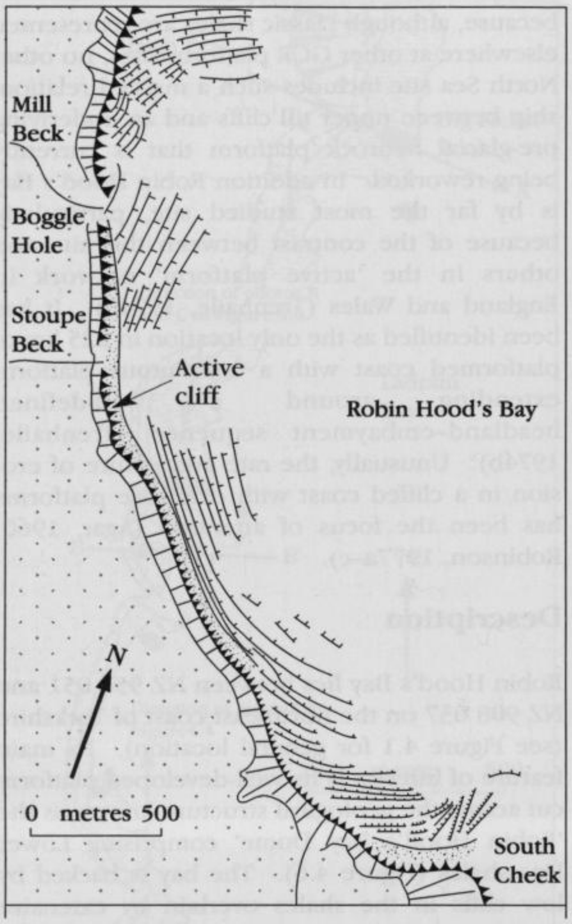


Figure 4.6 Pattern of seaward-facing micro-cliffs on the landward-dipping strata (the strike of the strata is indicated) on the low-gradient intertidal platform in Robin Hood's Bay.

The Peak fault runs through South Cheek, with the result that the southern part of the cliff is dominated by Toarcian rather than Pliensbachian shales. Agar (1960) did not measure change here although his paper suggests that erosion was substantially less than elsewhere in the bay.

The platform is distinguished by a series of curving ridges and troughs that reflect the differential erosion of the shales and the structural form of the Robin Hood's Bay Dome (Figures 4.6 and 4.7). Trenhaile (1974a) suggests that the platform on the northern side of the bay is concave in form, a feature that he attributes to ramp development. However, rather than having a truly concave form, the platform is made up of two elements. The ramp is related to harder material forming the upper part of the platform. Elsewhere in the bay, linear forms up to 500 m in width are more characteristic of the platform (Trenhaile, 1974b) and extend for considerable distances offshore with a gradient of about 1 in 100 to depths of about 40 m (Agar, 1960).

Interpretation

The broad geological structure of the Robin Hood's Bay Dome has not affected the macro-morphology of the platform cut across it, whereas the micro-morphology of the platform is strongly dependent upon the structure across the Dome (Figure 4.7). In contrast to the platforms between Watchet and Lilstock (see GCR site report for Blue Anchor–Watchet–Lilstock in the present chapter), this site does not have a well-developed 'washboard' surface but demonstrates well how spatial arrangements of the micro-morphology are controlled by the varying dip and strike of the beds of the outcrops. In detail this may affect the refraction of waves, especially at lower stages of the tide. In turn this affects the transport of sandy sediment within the intertidal zone. The development across a very complex structure of platforms that display similar characteristics to those cut across simpler ones gives this site an important place in the debate about shore-platform development.

Most writers have concentrated on the development of the cliffs and the platform, rather than the links between the platform and geomorphological processes. The single exception is Robinson (1977c, see below). Agar (1960) used his measurements of cliff erosion in combination with an assessment of the degree to which the upper cliff had changed in postglacial (Holocene) times to judge the development of the coastline over the past 10 000 years. He regarded present-day conditions as 'optimal', i.e. the sea breaking on the gradually sloping foreshore and attacking the vertical face of the cliffs at high tide to develop a cliff-foot notch. Erosion rates could thus be interpreted as being maxima. Agar argued that a slightly lower sea level would result in the action of the waves being concentrated on the platform and having a much less important role in coastline retreat. A higher sea level would similarly have only a limited effect because waves would be reflected from the vertical cliffs. Taking account of the contemporary interpretations of the curve of sea-level change, he argued that apart from a short period around 7000 BP, the past few centuries are the only postglacial period 'in which favourable conditions for formation of the present foreshore have existed' (Agar, 1960, p. 422). Extrapolating from the measured rates of retreat, he argued that most of the local erosion has occurred only during the last six centuries. As a result, many profiles, including those of South Cheek, would have been affected by only limited postglacial erosion. Their upper slopes were not regarded by Agar as contemporary forms, but as probably of last interglacial age. Both the discussion following Agar's paper and later comments cast doubts on his interpretation of the coastal features.

Straw and Clayton (1979) consider that if Agar is correct then the present coastline must approximate in location to that of the Ipswichian (Eemian) interglacial. They cite the resistance of the rocks to marine erosion and recognize the difficulty of ascribing the platform solely to late Holocene marine erosion. They thought it inevitable that the platforms must have been prepared during preceding interglacial periods. However, Robinson (1977c) was not convinced by the view that many of the platforms have been reworked and that notches revealed beneath the till show that the platforms are at least Weichselian in age. Robinson counters by arguing that many of the features are recent, some less than 200 years old, and that much of the alleged pre-Weichselian glacial form has been buried by postglacial landslipped material that has then been removed, exhuming the pre-talus surface.

In a wider discussion of shore platforms, Trenhaile (1974b) describes this site as the only location in 225 km of platformed coastline with 'a continuous shore platform extending around a well-defined headland–embayment sequence'. He also records that the platform gradient increases towards the headlands, especially in the north, typically from about 35' to 2.5°. The headland site is more rugged than the Lower Lias shales of the embayment and is also more exposed to greater wave activity. From such evidence here and on other shore platforms around the coastline of England and Wales, Trenhaile (1974b) concludes that the platform gradient is being maintained in dynamic equilibrium. This appears to cast doubt on the claim that many of these platforms, including the platform at this site, have been inherited from previous forms (Trenhaile and Layzell, 1981). However, they argue that the evidence suggesting that shore platforms are partially inherited features is not incompatible with the evidence indicating that they are at or close to a state of dynamic equilibrium with a morphology finely tuned to their present environments. Despite some debate (Carr and Graff, 1982; Trenhaile, 1982), this argument appears to hold good for Robin Hood's Bay – that the platforms are likely to be be reworked earlier platforms, retrimmed by Holocene seas. Unfortunately neither Agar, nor Trenhaile and Layzell, take sufficient note of the role of debris on the platforms either in its erosional, or its protecting and roughening, role.

Robinson (1977a–c) argued that the morphology of the platforms resulted from the presence of sand debris rather than the nature of the rocks forming the platform. The width of the platform is controlled primarily by the protection afforded to the cliffs by the deposits at their foot (Figure 4.7). Where debris is absent, the platform has a low angle of inclination, characteristically about 1°. Robinson calls this the 'plane'. In contrast, where there is a beach, the slope is greater, usually up to 15°. This is the 'ramp'. Trenhaile (1974b) believed that the steeper ramp was produced by harder materials. Robinson identified five erosion processes here:

1. micro-quarrying;
2. the expansion and contraction of clay mineral lattices by hydration and desiccation. He estimated that processes 1 and 2 together low-

Table 4.3 North Yorkshire coast cliff retreat rates in m a^{-1} (based on Agar, 1960).

		Cliff top	Cliff foot
Whole coast		0.02	0.05
Headlands only		0.01	0.04
Bays only		0.04	0.07
Robin Hood's Bay	Lower Lias	0.02	between 0.07 and 0.16
	Glacial drift	0.31	between 0.05 and 0.31

Figure 4.7 Shore platform at Robin Hood's Bay looking east from Mill Beck (see Figure 4.6 for location). (Photo: J.D. Hansom.)

ered the platform by 0.144 cm a^{-1};

3. wave-quarrying, by which removal of small blocks from the cliff foot lowered the platform surface by 2.3 cm a^{-1};
4. corrasion: direct abrasion of the in-situ rock by wave-transported sediment lowered surfaces by 5.79×10^{-3} cm $tide^{-1}$;
5. wedging, in which small sediment particles forced into cracks in bedrock gradually force it apart. This lowered surfaces by 11.05×10^{-3} cm $tide^{-1}$.

Robinson (1974) showed that erosion was more rapid when a thin beach was present, but seasonal variations in wave action also affect the efficiency of erosion of the ramp. In contrast the plane is affected by desiccation and contraction at low water – especially in summer – and expansion at high water. The annual rates of lowering estimated by Robinson's use of a micro-erosion meter are about 1.5 times faster than those obtained by longer-term comparisons of platform levels on the Chalk around the Isle of Thanet (see GCR site report for Joss Bay in the present chapter).

Conclusions

Robin Hood's Bay is a very important site for study of platformed coastline development, because the platform cuts across a complex structural geological structure, the 'Robin Hood's Bay Dome'. Despite the complexity of the underlying structure, the platform displays many of the features observed elsewhere in much simpler structures. Unlike many other platforms, it has been the focus of detailed investigation of the erosion processes, in particular the varying role of beach sediments in either erosion or protection of the platform and cliff foot. It demonstrates well a relationship between headland and embayment in which preglacial erosion of the platform may have produced an equilibrium form that is being reworked today. This remains, however, the paradox of this site, for it is not possible to determine the extent to which the platform is being exhumed or reworked. The cliffs are cut both into the Lower Lias bedrock and glacial materials and provide an excellent example of a cliffed coastline where the comparatively recent weaker sediments reveal older features as they are eroded. The erosion of these cliffs is important to our understanding of the late Quaternary history of soft-rock coasts.

BLUE ANCHOR–WATCHET–LILSTOCK, SOMERSET (ST 034 436–ST 070 438 AND ST 116435–ST 169 455)

V.J. May

Introduction

The southern cliffed coastline of the Bristol Channel between Blue Anchor and Hinckley Point contrasts with the higher hog's-back cliffs of the Exmoor coast and the low, estuarine, wide mudflats and fringing dunes around the mouth of the River Parrett to the east. This site, which comprises two areas east and west of Watchet, is characterized by cliffs rising to a maximum of 84 m and fronted by a particularly well-developed series of intertidal platforms varying in width from 120 m to over 500 m. At St Audrie's Bay, the cliff has been proposed as the type locality and section for the base of the Jurassic System (Warrington *et al.*, 1994). The base of the Hettangian Stage at the base of the *Planorbis* chronozone is placed at the horizon in which ammonites of the genus *Psiloceras* appear.

The platforms are veneered in part by shingle, sand and mud, and reflect in detail the variable resistance to erosion of the Turassiched Marls, Penarth Beds and Lower Lias bedrock. A key feature of the platforms is their development in a macrotidal environment and their different exposure from narrower platforms in similar rocks on the northern side of the Bristol Channel at Nash Point. Whereas there has been considerable research into the nature of the platforms on the northern side of the Bristol Channel, it has been singularly lacking on the southern coast. Ussher (1908) was the first to describe the main features and Steers commented that the cliffs and shore features were of 'considerable interest' (Steers, 1946a, p. 211).

Description

The western part of the site extends from the eastern end of the sea-wall at Blue Anchor (ST 034 436) to just west of Watchet (ST 070 438). Near-vertical cliffs rise eastwards to Blue Anchor Point (ST 040 437) where they give way to higher cliffs that are much affected by many small landslips. From their highest elevation of 84 m, they fall steadily towards sea level at Watchet. At Warren Bay (ST 057 434), they truncate a valley that is left hanging about 25 m above the base of the cliffs.

The alignment of the coastline of the western part of the site has little relationship to the direction of wave attack from the Atlantic Ocean. The coastal plan is primarily a function of the varying strengths and structures truncated by the cliffs and platforms. Differential erosion is a dominant force both in the general form and the detail of the coastal features. The platform varies between 300 m and 500 m in width. The general slope of the platform reflects the process of marine planation in cutting across the outcrop, but the varying strength, dip and strike of the beds give rise to a varied micro-relief. Parts of the platform warrant the description 'washboard-like relief', a form that has been described elsewhere (for example, Suzuki *et al.*, 1970), but rarely reported in Britain (Figure 4.8).

The eastern part of the site extends from the eastern side of St Audrie's Bay (ST 116 435) to Lilstock (ST 169 455). Much of the cliff is near-vertical, rising from about 25 m to over 50 m in height at Quantocks Head. The cliffs decline in height to near sea level at Kilve Pill (ST 143 444) and then maintain a height of about 30 m to the eastern boundary of the site. The platform is between 120 m and 300 m in width, and demonstrates similar relationships between rock type, structure and micro-relief to the area west of Watchet. This part of the site, however, shows a stronger relationship to the prevailing direction of wave attack from the WNW, both in the alignment of a shingle beach on the eastern side of St Audrie's Bay and in the alignment of the cliffs to the north-east of Kilve Pill.

Interpretation

Although the coastline is one on which erosion dominates, there have been few measurements of change. Mackintosh (1868) estimated the rate of cliff retreat on the Lias cliffs as 1.2 m a^{-1}. Retreat is far from uniform, with very little change at some points whereas others attain current rates of change comparable to those noted by Mackintosh. The platforms here are of considerable interest and they warrant further inves-

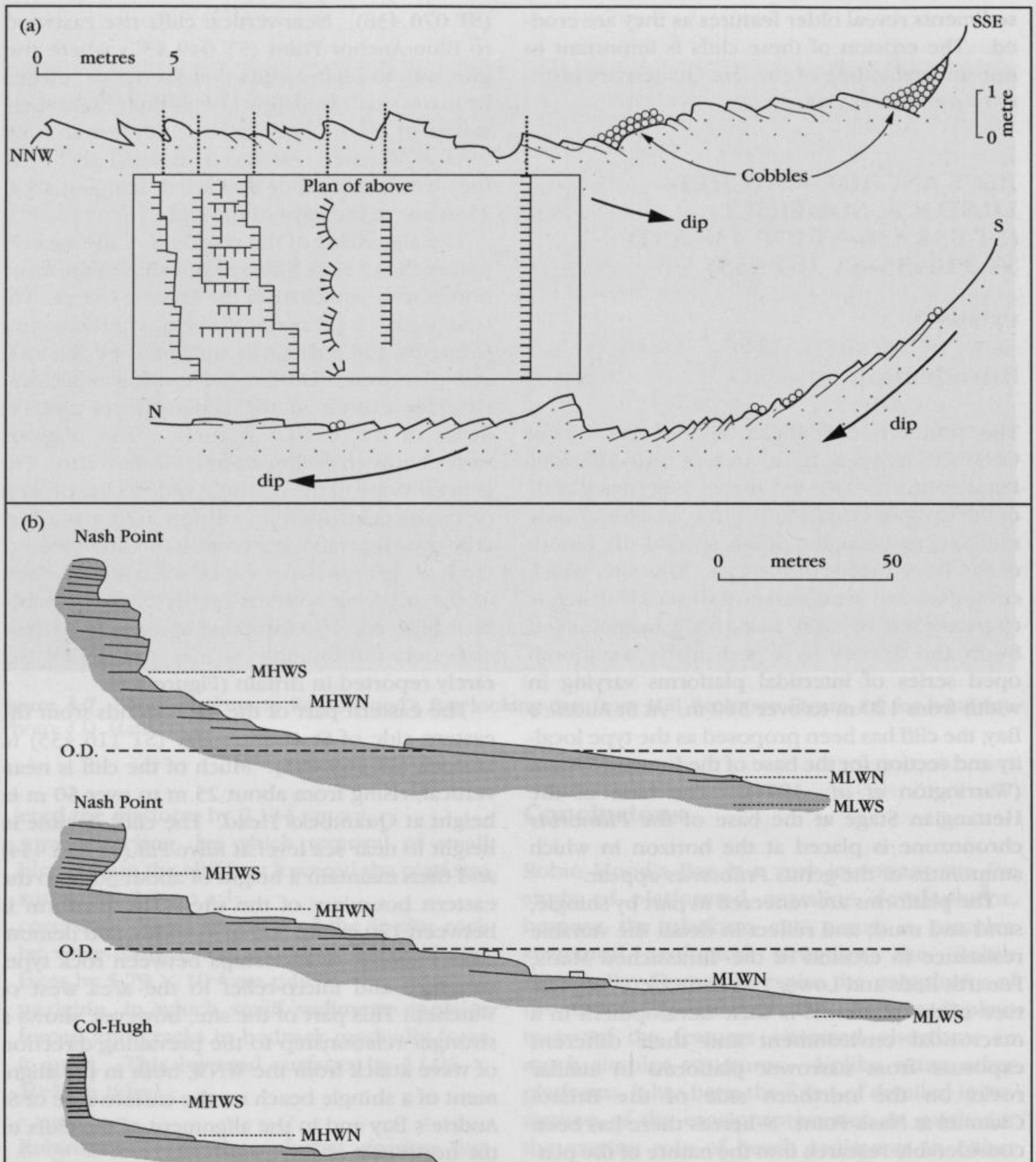


Figure 4.8 (a) Cross-sections, showing characteristic forms of the platform east of Watchet, where the dip of strata to landward or seaward strongly affects the pattern of micro-cliffs, (b) three characteristic platform profiles at Nash Point, Vale of Glamorgan (see GCR site report in the present chapter) where dip of strata is more uniform than at Watchet. Mean high- and low-water spring tide levels (MHWS and MLWS) and mean high- and low-water neap tide levels (MHWN and MLWN) are shown. (Part (b) is after Trenhaile, 1972.)

Figure 4.9 Cliffs and shore platform at Kilve, Somerset (Photo: V.J. May)

tigation. Both the platforms and the cliffs in the Lias on the northern side of the Bristol Channel have been investigated in some detail (see GCR site report for Nash Point below). Although the Watchet sites lie in a similar tidal regime to that of Nash Point, they are much less exposed to the high wave-energy levels reported by Williams and Davies (1987). The maximum fetch of this site is just over 300 km to the WNW, whereas Nash Point has a maximum fetch of 5000 km to the south-west. Atlantic waves approaching the Watchet sites undergo considerable refraction and approach the shore at an angle, whereas Nash Point receives the full undiminished energy of Atlantic storms. In the less vigorous environment of Watchet, processes of intertidal weathering are more important and there is less movement of particles broken from the bedrock.

The detailed nature of the platform reflects the minor structures of the rocks forming it, as well as the dip of the strata (Figure 4.8a). For example, parts of the platform are distinguished by a blocky structure in which large numbers of small vertical joints about 0.25 m to 0.35 m apart create a series of irregular three- to six-sided polygons. The platform cuts across folded strata that dip variously seawards, landwards (Figure 4.9) and alongshore, and there are important variations in both the platform morphology and its effects upon wave action and shingle and cobble movements. Where the strata dip landwards, for example east of Kilve, the intertidal area is characterized by a series of micro-cuestas, up to 1 m in height (Figure 4.8). As the edges of these up-tilted strata have been broken up by marine erosion and intertidal weathering, they form a cobble field between the minor cuestas. The size of material in the cobble fields varies from the almost unaltered newly-quarried blocks, through sub-rounded and rounded blocks and pebbles to sand. Because the beds are rarely horizontal and often lie at an angle across the beach, many of them also show signs of the action of flowing water along the base of the micro-cuesta dip-slope. The blocky nature of the beds also imposes a maximum height on the micro-cuestas. As soon as a block is partly undermined it begins to slide along the joint surfaces and frequently topples forward. Wave action is insufficient to remove most of the blocks, which appear to remain close to their original site, until they have been worn down to a threshold size and shape which allows movement.

Where the strata dip seawards, for example, west of Watchet and between Quantocks Head and Kilve, the lower cliff sometimes forms a sloping rampart formed by unbroken strata. On the platform, micro-cuestas are formed with the scarp facing landwards, and large accumulations of shingle and cobbles are retained on the landward side of the micro-cuestas. Most erosion of the scarps is achieved by wetting and drying processes; the erosional product is readily transported along the sloping micro-vales. The scarps are very effective in preventing shingle and cobbles moving down the slope of the platform towards the sea. Even where the scarp is no higher than 0.1 m, its alignment is clearly marked by the line of cobbles resting against it.

Where the strata dip alongshore, the platform is also marked by micro-cuestas, but this pattern allows waves to reach well up the shore along the micro-vales between ridges. The most active parts of the cliffs characteristically co-incide with these more exposed locations, for example to the west of Lilstock. Although they differ between seaward-and landward-dipping topographies, the large inter-cuesta sediment fields in this site contrast very strongly with comparatively bare platforms on the northern side of the Bristol Channel. Although this probably reflects the lower wave-energy environment of the Watchet sites, the morphology and slope of the platforms is also important. Most of the clasts are subangular. The only smoothed surfaces occur on the more resistant strata at the foot of the cliff, which are commonly cloaked by large beaches of more rounded clasts.

The platforms in this site show a morphological pattern in which the harder and wider, jointed and bedded strata form the upstanding forms. Suzuki *et al.* (1970) found that, in contrast to the generally expected relationship of rock hardness or strength to the extent to which strata protruded above the platform, the micro-cuestas at Arasaki, southern Japan, were formed in an apparently weaker tuff than the surrounding mudstones. The ability of the mudstone to absorb greater quantities of water, and the greater stresses that occurred as a result, caused them to be eroded more efficiently than the tuffs, which became the micro-cuestas. On the Watchet sites, the micro-relief is strongly controlled by the thickness of the in-situ strata, so that only those beds that are thicker than about 0.25 m form micro-cuestas. The variation (between 0.5 m and 0.02 m) in bed thickness, which characterizes the Lias in this site, thus appears to be the critical factor in the development of the washboard-like relief of these platforms. They warrant detailed study to develop a fuller understanding of the complex relationship between platform relief and the role of sediment as an abrasional agent.

Conclusions

This is a fine example of shore platforms developed in a macrotidal environment. The site includes one of the best examples in Britain of 'washboard' platform relief. The development of the platforms depends on the way in which the cliffs retreat. Although the site has received very little attention in the literature, the rapidity of retreat along much of this coastline is important for geomorphological study. Similar features have not been described elsewhere on the British coast, partly because platform studies have concentrated upon the gross morphology of platforms rather than their micro-forms, but also because such forms are comparatively rare. The platforms at Robin Hood's Bay are comparable, but are affected by a tidal range almost half that of this site. The other shore platforms, especially those in the Chalk, lack the resistant strata to produce micro-cuesta topography, and the platforms in the Carboniferous Limestone and Portland Stone are more commonly affected by weathering by dissolution. This site is thus important to the network of active platform sites both in its macrotidal location and its varied morphology.

NASH POINT, GLAMORGAN (SS 934 677–SS 905 699)

V.J. May

Introduction

Much of the coastline of the Vale of Glamorgan is formed of cliffs cut in the Lias limestones and mudstones and fronted by platforms that attain widths in excess of 500 m. The line of cliffs is broken by a number of small steep-sided valleys. This site (see Figure 4.1 for general location) comprises the cliffed coastline east and west of Nash Point and is cut mainly in limestone and mudrocks of the Blue Lias. The cliffs vary in height from 62 m to less than 30 m, and are commonly near-vertical, even overhanging in places. Intertidal platforms are generally between 200 m and 250 m in width (Figure 4.10). Although they slope seawards, their micro-relief is largely controlled by the relative strength of the limestones and the argillaceous beds across which they are cut. Variations in cliff-form are not always directly associated with variations in rock type. Similarly, the coastal plan does not always accord with the terrestrial landforms that it transects. Because of its exposure to the Atlantic Ocean, this is a high-energy environment; both the cliffs and the platforms have been the foci of much recent investigation (Trenhaile, 1969, 1971, 1972, 1974a,b, 1983; Trenhaile and Layzell, 1981; Carr and Graff, 1982; Sunamura, 1983; Williams and Davies, 1984, 1987; Davies and Williams, 1986; Davies *et al.*, 1991; Williams *et al.*, 1993).

Nash Point has been described as an example of a site with structurally controlled platforms (Davies, 1972). Trenhaile (1969, 1971, 1972, 1974a,b, 1983) and Sunamura (1983) debated shore-platform development by reference to this and other British sites, and cliff and beach features were described by Williams and Davies (1987). A review of the literature suggests that the processes operating on this site have probably received more direct and regular attention than any other vertical cliff site in the UK (Mackintosh, 1868; Keatch, 1965; Trenhaile, 1969, 1971, 1972; Williams and Davies, 1984, 1987; Davies and Williams, 1986; Williams and Caldwell, 1988).

Description

The site extends from the western side of St Donat's Bay (SS 934 677) to Cwm Nash (SS 905 699). To the east of Nash Point, the continuous line of cliffs is broken by the valley of the Marcross Brook. The western cliffs are aligned

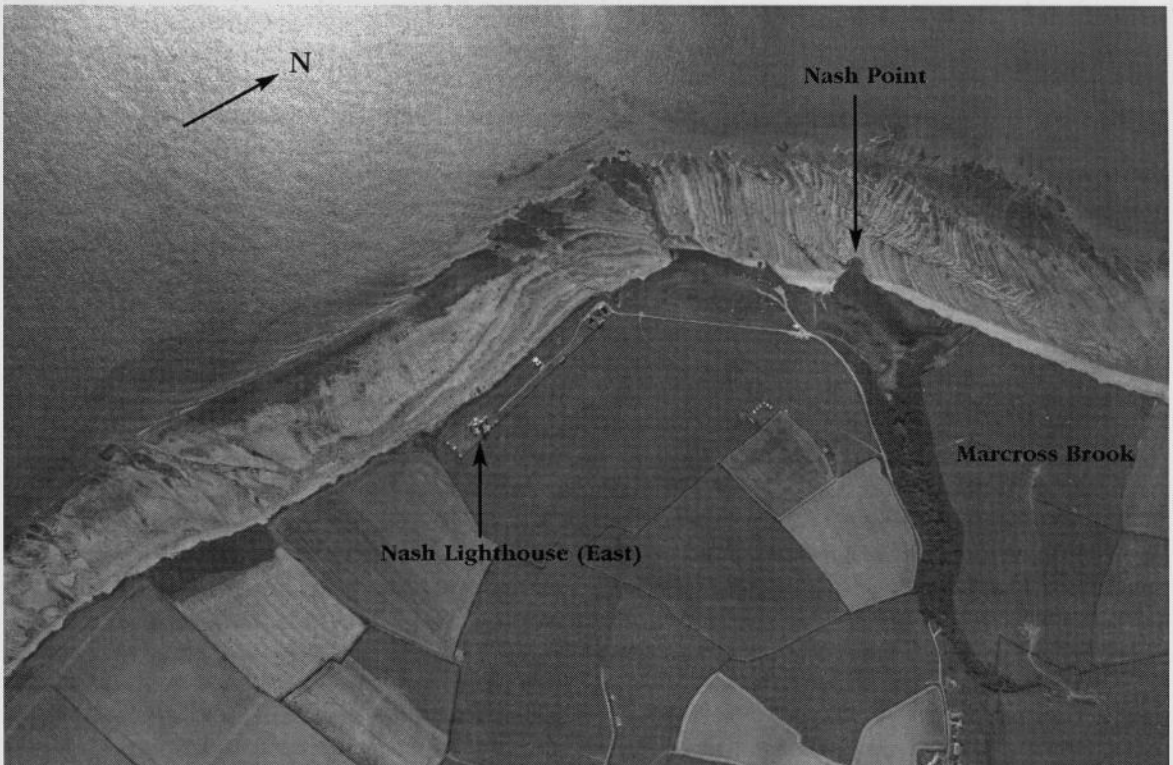


Figure 4.10 Nash Point, this view from directly above the site demonstrates the near-vertical nature of the cliffs and the width of platforms at low water. The micro-relief of the shore platforms is controlled largely by the the relative strengths of alternating beds of limestone and argillaceous rocks and jointing patterns, on this photograph particularly noticable in the vicinity of Nash Point itself (see also Figure 4.8b). (Photo: CCUCAP, © the Countryside Council for Wales.)

towards the south-west, facing the dominant and prevailing wind (over 40% of all winds) across a fetch of 5000 km. The eastern cliffs trend east–west. The dominant and prevailing winds blow alongshore but the southerly onshore winds have a fetch of only 24 km. According to Trenhaile (1972), this part of the coastline is characterized by longshore drift.

The tidal range is 6 m. Surges associated with low atmospheric pressure have been recorded, increasing water levels by up to 1.5 m (Williams and Davies, 1987). This is a relatively high-energy environment, having recorded cumulative wave energy densities of 68 × 105 joules m^{-1} crest $width^{-1}$ over one day, and wave power of 85,000 joules m^{-1} s^{-1} (Williams and Davies, 1987). Assuming a still-water level at mean high-water neap tides, the total breaking wave force recorded in one storm was of the order of 7 × 10^5 Pa (7 bars). Cliff retreat has been estimated by several writers (summarized by Williams and Davies, 1987) and varies between 0.1 m a^{-1} and 0.02 m a^{-1}.

The Lias around Nash was divided by Trueman (1922, 1930) into:

1. The *Arietites bucklandi* biozone – thick concretionary limestones alternating with thin mudstones, and
2. the *Sclotheimia angulata* biozone – mainly thick mudstones alternating with thin limestones.

The limestone beds reach almost 1.0 m thick in places, whereas the mudstones rarely exceed 0.5 m. There are three main groups of near-vertical joints trending NNE–SSW, NE–SW, and SE–NW. Joints resulting from pressure-release rebound lie most commonly parallel to the cliff face (the direction of greatest stress release). The platforms grade seawards at low angles (i.e. around 2°), and are broken only by small scarps and shallow solution features (Trenhaile, 1972). The platforms owe much of their uniformity to the exposure of single beds of limestone and so contrast dramatically with the platforms in the Lias on the southern side of the Bristol Channel. Characteristic profiles and the location of major breaks of slope are shown in Figure 4.8b. On the platforms, small scarps (generally less than 0.25 m in height) are associated with erosion of thin shale horizons and undercutting of the thicker beds.

Interpretation

A substantial literature concerning this site has focussed on two separate morphological units of the coast, the platform and the cliff. Trenhaile (1974a,b) discussed the development of shore platforms here and elsewhere in Britain (for example Robin Hood's Bay, see GCR site report in the present chapter). At Nash Point, the shore platform has probably evolved from the destruction of a series of higher platforms and is partly an inherited feature (Trenhaile, 1972). However, the rate of cliff recession and the present erosion of the platform indicate that more extension of the platforms has occurred than in the southern part of Gower. The development of platforms around Nash Point contrasts also with that on the southern side of the Bristol Channel. The platforms at Nash Point are strongly related to the dip of the strata, their surfaces being structural, whereas on the Somerset coast they are cut across steeply dipping strata. At Nash Point, lowering of the platform is mainly brought about by retreat of low steps, and Trenhaile (1972) concluded that contemporary scarp retreat is of the order of magnitude necessary to bring about parallel slope retreat. The platforms could be regarded as an example of the principle that the timescale of observation affects the significance of time in landform development (Schumm and Lichty, 1965): Johnson's (1919) model of platform development is not necessarily supported by the evidence from this site when long periods of time are considered. Over shorter timescales (i.e. under 100 years), there is a trend towards dynamic equilibrium in which there are 'fairly high correlations' between platform gradient and elements of platform morphology.

Williams and Davies (1984, 1987) demonstrated that retreat of the cliffs and thus extension of the platforms at high-water level resulted from several processes. Large-scale cliff failures usually occurred as a result of toppling and translation failures. The latter are usually very complex, low frequency and high magnitude events. The detachment of joint blocks also affects the cliffs. Although small in extent, their product is removed quickly by wave action, and so it is difficult to estimate the volumes of individual movements. Williams *et al.* (1993), having analysed rockfalls along 22 km of adjacent coastline, developed numerical models of cliff failure. Translation failure was predicted in cliffs where the *angulata* series formed a high proportion of the cliff mass and where cliffs are buttressed by limestone of the *bucklandi* biozone. Toppling failures were predicted for vertical and overhanging cliffs that were undercut at the base.

Caves cut into the cliffs are restricted to the low-energy environment of the W–E-trending cliff sections. Davies and Williams (1986) showed that interaction between the presence of particular limestone beds at the cliff base and within the cliff, and protection from the most direct wave attack is crucial. The most suitable basal limestone strata are the most massive (Trueman Bands, 28, 39, 47, 48 (Trueman, 1922/1930), but other limestone strata also form cave lintels. Caves do not develop where there is a high proportion of mudstone, requiring an average of over 66% limestone strata in exposed cave walls. Caves do not usually develop where there is a wide or low angle shore platform. 76% of the caves are associated with joints perpendicular to the cliff face. Cave retreat appears to operate at a similar rate to cliff recession. This examination of cave development is especially important to coastal geomorphological studies, because it goes beyond the usual suggestion that caves are associated with lines of weakness. Furthermore, the role of the basal beds can be shown to be consistent with the characteristics of arch and stack development described elsewhere in the present chapter (see GCR site reports for Flamborough Head, Ballard Down and Ladram Bay in the present chapter). The rate of cliff retreat may be the controlling factor, since any general retreat of the cliff will increase the wave energy available for cave excavation, and lowering of the platform in front of the cave will enhance the available wave energy. The three morphological units, the platform, the cliff, and the cave therefore appear to be functionally linked, but further investigation is required.

In terms of exposure to wave energy, this is the most-exposed, and best-documented Lias cliff site in southern Britain. It contrasts with other Lias sites at Robin Hood's Bay and Watchet (see GCR site reports in the present chapter) in its exposure and relatively high-energy environment. Although platforms around the Chalk (for example, Joss Bay) have also been described in some detail (So, 1965), they rarely display the marked alternation between hard and weaker beds that characterize the Lias and produce the sloping stepped form of the platforms at Nash Point. Although caves are a common feature of many cliffed coasts, few are described in the geomorphological literature, and Nash Point is an exception.

Conclusions

Nash Point is situated in a relatively high wave-energy environment and is dominated by platforms over 500 m in width and vertical cliffs over 60 m in height. The cliffs have received much less attention in the geomorphological literature than the platforms, but have many features in common with other cliffs undergoing active erosion. This is one of few sites where cave development has been investigated in detail. Like the platforms of the Isle of Thanet, the platforms at Nash Point are simple in form when compared to others elsewhere on the British coast. The initial surveys by Trenhaile (1969, 1971, 1972, 1974a,b) provide a basis upon which later studies have been able to build. As a result the site is important within British coastal geomorphological studies because of both the repeated surveys and an increasing understanding of the processes that occur here. Few vertical-cliff sites have been as examined and the processes so elucidated as at Nash Point, and, as a result, it is internationally important for its coastal geomorphology.

LYME REGIS TO GOLDEN CAP, DORSET (SY 380 927–SY 428 913)

V.J. May

Introduction

Between Ridge Cliff, to the east of Seatown, to Lyme Regis, there are four main cliffed areas, Ridge Cliff, Golden Cap, Cain's Folly and Black Ven, separated by valleys at Seatown, St Gabriel's Water and Charmouth (see Figure 4.1 for general location, and Figure 4.11). There are two pocket-type beaches, the larger between Golden Cap and Lyme Regis, the smaller to the east of Golden Cap at Seatown. This group of cliffs and beaches is geomorphologically important because:

1. The cliff changes (especially the landslides at Black Ven) are probably the most fully investigated of any in the world. The international

contribution to geomorphology is outstanding.
2. There are excellent examples of arcuate beach ramparts, formed by the boulder content of landslides.
3. The beaches are fed by chert and flint from the cliffs, so that it is possible to monitor the links between landslides, cliff erosion and beach-sediment budgets.

The landslides of this coast are well documented (Arber, 1941, 1973; Lang, 1914, 1928, 1942, 1944, 1955; Wilson *et al.*, 1958; Brunsden, 1973, 1974, 1996; Brunsden and Jones, 1972, 1976, 1980; Conway, 1974; Denness *et al.*, 1975; Brunsden and Goudie, 1981; Allison, 1990, 1992; Koh, 1992; Lee, 1992; Brunsden and Chandler, 1996; Brunsden *et al.*, 1996; Pile, 1996). Many coastal texts refer to the landslides here (e.g. Bird, 1984; Steers, 1964a, 1981), but there has been much less attention to the beaches (Lang, 1914; Bird, 1989; Bray, 1986, 1990a,b, 1996) and the offshore zone (Darton *et al.*, 1981).

As well as its geomorphological significance, the site is famous stratigraphically and palaeontologically and it is one of the GCR sites that form the Dorset and East Devon Coast World Heritage site, established in 2001.

Description

In general, the coastline truncates a series of NE–SW-orientated ridges that rise to between 140 m and 170 m OD. The area is composed of interbedded, firm, fissured clays, mudstones, marls and thin bands of hard argillaceous limestone of Lower Jurassic age. These are overlain unconformably by silty clays, fine-grained silty sands and chert beds of the Cretaceous Gault and Upper Greensand. Whereas the Lias dips ESE at 2–3°, the plane of the unconformity and the Cretaceous beds above it dip to the southwest at 2–2.5° (Brunsden and Jones, 1976). The sides of the ridges have a thick cover of solifluction and landslide debris. The ridge-tops are covered by a superficial layer of flint and chert head.

The eastern limit of the site is Ridge Cliff (SY 428 913) where the cliffs attain a height of 100 m in sands and clays of the Upper and Middle Lias. They decline westwards towards Seatown where a small stream, the River Winniford, enters the sea. They then rise to the highest point on the Dorset coast at Golden Cap (188 m OD; Figures 4.11 and 4.12). Here the Upper Greensand forms a steep upper section to the cliff profile, but the main part of the cliff is formed by the Eype Clays. It has been greatly affected by landsliding, but less dramatically than the cliffs to the west. The intertidal area is characterized by rock ramparts that represent the remnants of landslides that have carried Upper Greensand blocks to the foot of the cliff. Whereas the clays that form the bulk of the slide debris have since been eroded, the curved boulder aprons remain. Darton *et al.* (1981) indicated that similar features occur offshore, and Bray (1996) has confirmed this. At both St Gabriel's and Ridge Water small streams flow in hanging valleys at about 65 m before finding their way across the slipped cliff face. To the east of Charmouth, the cliffs at Cain's Folly rise to 145 m, whereas to the west their highest point is 177 m.

Seatown Beach, to the east of Golden Cap, is formed mainly in flint and chert shingle, but it also contains pebbles of Lias shales and limestones. It lies between two headlands that inhibit longshore transport of sediment both into the beach from the west and out of it towards the east (Figure 4.12). The beach gravels are sparse and poorly sorted at the western end and there are patches of sand and exposures of the underlying strata (Bird, 1989). Towards the centre of the beach at Seatown itself, the predominantly flint and chert pebbles are found in zones of contrasting size parallel to the beach face. Cusps are often well developed. At the eastern end of the beach, beneath Ridge Cliff, the beach is higher and wider with coarser and better-sorted shingle, but following periods of easterly wind can be denuded to reveal a deeply incised platform (D. Brunsden, pers. comm.).

Over the period 1901 to 1987, this beach had an input of 190 000 m^3 of shingle, mostly from intermittent transport around Golden Cap, particularly between 1932 and 1962 when the annual input was up to 8600 $m^3\ a^{-1}$ (Bray, 1996). In the past shingle was mined from Seatown Beach (Bird, 1980). Bray (1996) estimated that between 125 000 and 175 000 m^3 were extracted during World War II and a further 34 000 m^3 between 1956 and 1986. The extraction permit expired in 1987. Extraction of shingle, together with modest entrapment and attrition losses, has produced a complex series of volumetric changes with an overall deficit. Bray (1996) esti-

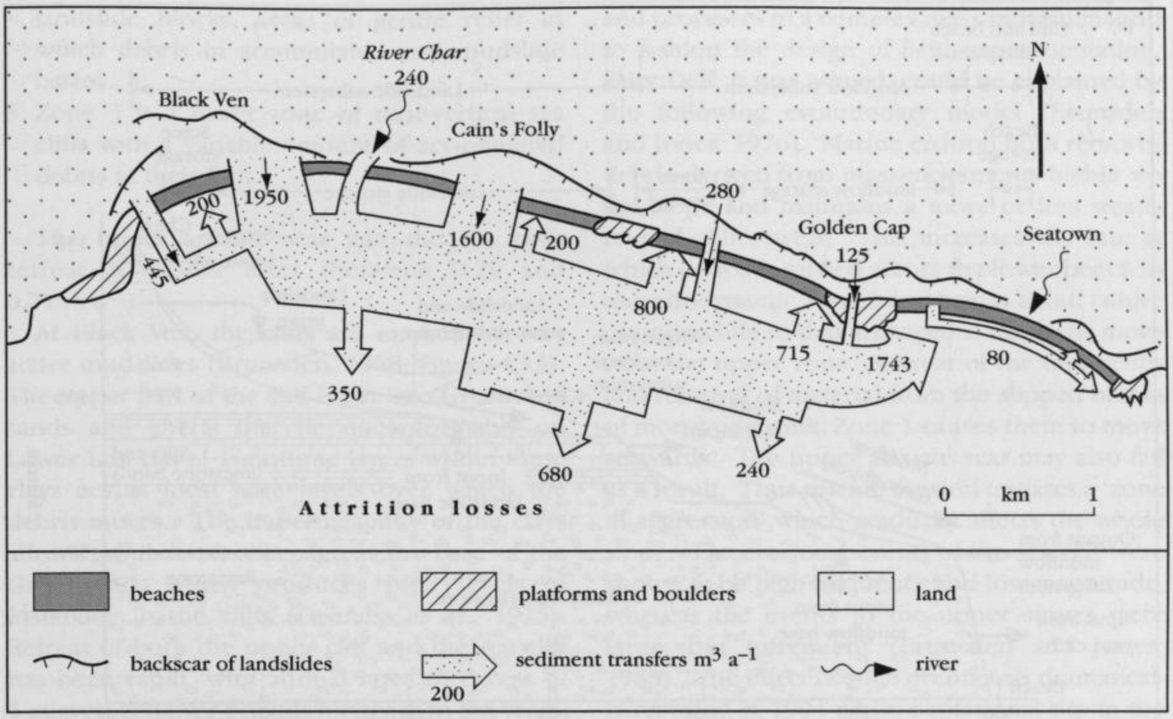


Figure 4.11 The sediment budget of beaches between Lyme Regis (to the westmost part of the map) and Seatown. (After Bray, 1990a.)

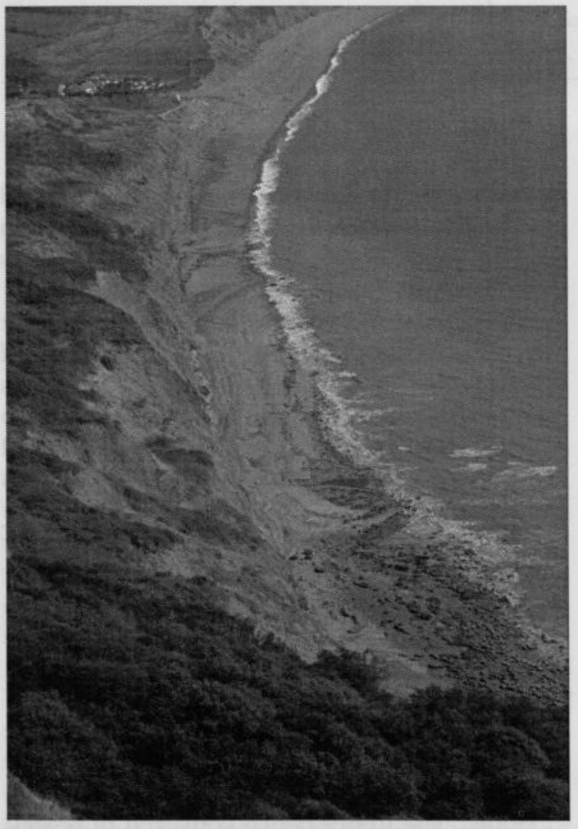


Figure 4.12 View looking south-east from Golden Cap, showing the depleted shingle beach at Seatown, platforms that are cut across folded strata, and the residual boulders at the west end of the beach (foreground). (Photo: V.J. May.)

mated that, with the cessation of extraction and no input from the west, the net deficit had fallen to 39 $m^3 a^{-1}$ by 1989. An unaccounted factor in beach and cliff erosion is the erosional lowering of the platform when it is intermittently exposed.

To the west of Golden Cap, the beaches are interrupted beneath the landslides by large lobes of debris from the slides and mudflows, but they give way westwards to an intertidal area that is dominated by structurally controlled shore platforms, especially just to the east of Lyme Regis. Most of the beach material is derived from the cliffs. Bray (1986) estimated that between 1901 and 1987, about 420 000 m^3 of mainly chert gravel with a B-axis greater than 10 mm was eroded from the cliff back-scar between Lyme Regis and West Bay. The beach between Golden Cap and Charmouth is well-sorted laterally, changing from a mixed sand and shingle beach at Charmouth to a predominantly cobble beach below Golden Cap (Bird, 1989). Supply of gravel is concentrated at the western end of this site, with transport towards the east. The volume of the beach increases towards

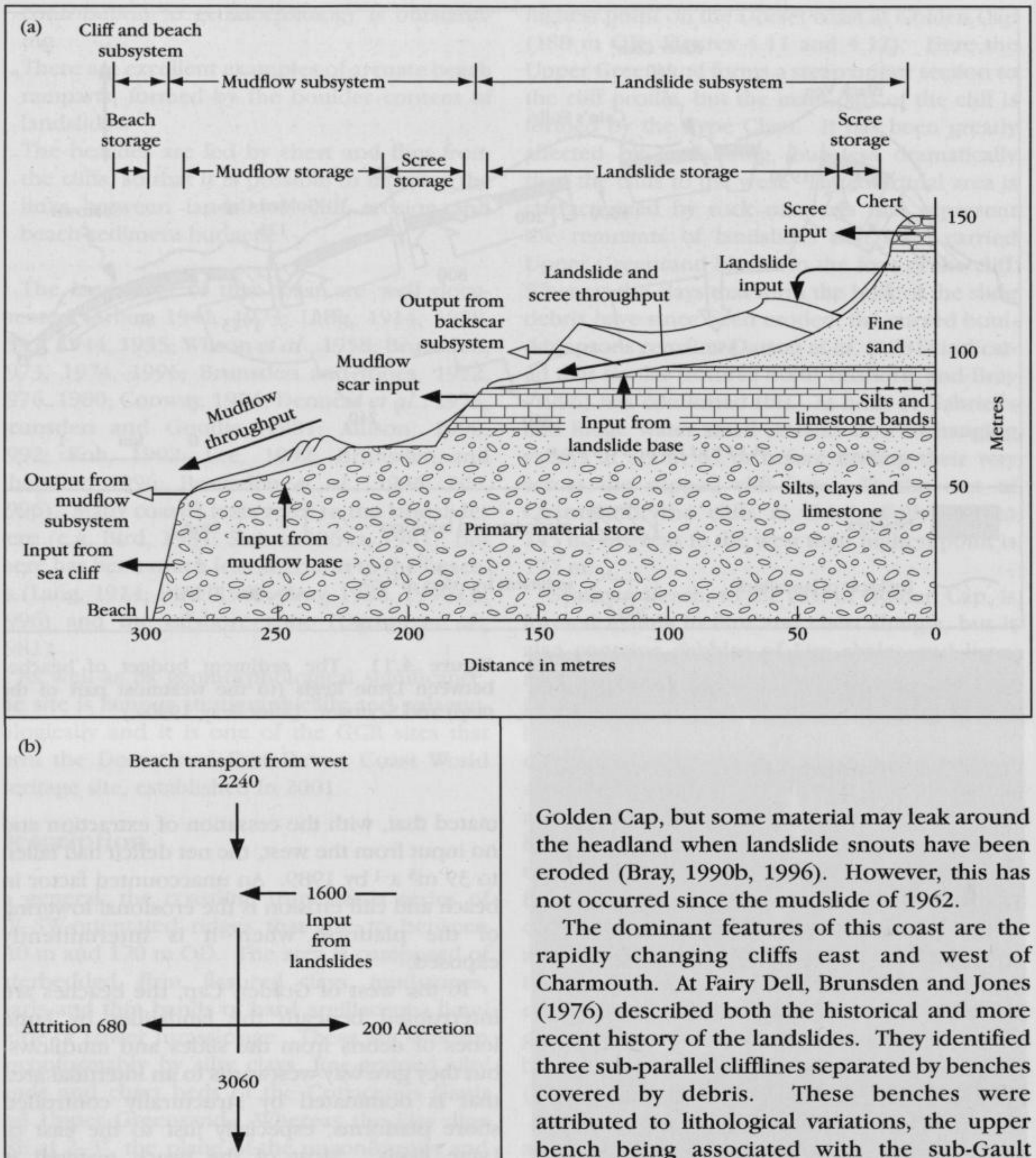


Figure 4.13 (a) Cross-section of the Black Ven system (Lyme Regis to Golden Cap GCR site) and sediment supply to its beach. See also Figure 4.11. In (b) the volumes of sediment (in $m^3 a^{-1}$) moving through the Black Ven beach are given. (Based on Brunsden, 1973 and Bray, 1990a.)

Golden Cap, but some material may leak around the headland when landslide snouts have been eroded (Bray, 1990b, 1996). However, this has not occurred since the mudslide of 1962.

The dominant features of this coast are the rapidly changing cliffs east and west of Charmouth. At Fairy Dell, Brunsden and Jones (1976) described both the historical and more recent history of the landslides. They identified three sub-parallel clifflines separated by benches covered by debris. These benches were attributed to lithological variations, the upper bench being associated with the sub-Gault unconformity and the lower bench with the outcrop of the Green Ammonite Beds. Three morphodynamic zones were identified.

1. Zone 1, an upper zone with an arcuate scar up to 45 m in height. The lower part of the scar was covered by a partially vegetated scree slope. The upper bench consisted of several large rotational landslide blocks separated by screes of chert.
2. Most of the central Zone 2 is extremely complex with deep V-shaped gullies, rotated

landslide blocks, areas of gentle relief in which debris in accumulated and mudslide basins.
3. Zone 3 is a lower zone of near-vertical sea cliffs with a variable amount of accumulated debris at their foot.

The upper arcuate scar and the sea cliffs retreat at similar rates (between 0.29 and 0.71 m a^{-1}).

At Black Ven, the cliffs are marked by very active mudslides (Brunsden, 1968; Figure 4.13). The upper part of the cliff is cut into Greensand sands and cherts that lie unconformably on Lower Lias clays. Limestone layers within these clays act as local base levels over which the debris moves. The impermeability of the clays allows groundwater seepage at the base of the Greensand, which produces high levels of instability in the cliffs (Denness *et al.*, 1975). Retreat of both the upper cliff and the sea cliff has been rapid, with annual rates in excess of 1 m averaged over periods longer than ten years. Over shorter periods of about two years the rate of retreat has been greater than 5 m a^{-1}. The present rapid activity is a relatively recent phenomenon, for large parts of the present upper cliff had been relatively stable prior to the major failures of 1957 and 1958 (Bray, 1996).

Interpretation

The cliffed coastline and landslides of West Dorset are important internationally because they have been the focus of research that has influenced understanding of both geomorphology in general and the coastal system in particular. Brunsden, and other workers, have demonstrated the applicability of 'systems methodology' to rapidly changing complex landforms and this led to a better appreciation of timescales in geomorphology. Denness (1972) discussed the reservoir principle of mass-movements in relationship to the cliffs at Black Ven, and later work identified the importance of secondary reservoirs to an understanding of complex mass-movements (Denness *et al.*, 1975). Bray (1986, 1990a,b, 1996) has described the sediment budget of the beaches and shown how they both depend upon and affect the landslides.

At Fairy Dell, Brunsden (1973) demonstrated how the application of system theory could be used both to elucidate the inter-related forms and processes in a complex mass-movement and to fashion the design of field experimentation. Fairy Dell, it was argued, could be explained by the following evolutionary model (Brunsden and Jones, 1976). Marine erosion both removes debris derived from mass-movements higher up the slope and maintains a more or less steady rate of cliff retreat. This increases the rate at which debris is carried across the lower bench in morphodynamic Zone 2 and brings about failure of undercliffs so that arenaceous materials move from the upper zone. Retreat of the undercliffs and removal of material from the slipped blocks of morphodynamic Zone 1 causes them to move seawards. The upper arcuate scar may also fail as a result. Thus marine erosion initiates a 'zone of aggression' which gradually affects the whole slope. The erosional events of the sea cliff were shown to be high frequency and low magnitude, whereas the events in the upper slopes were large, but infrequent (Brunsden and Jones, 1980). The effect of such events was dramatically revealed in 1994 when a rotational slip in the upper cliff at Black Ven loaded debris below and triggered a high-velocity sand avalanche across the beach west of Charmouth. The dry sand-fall fluidized and flowed seawards over a distance of 800 m (Brunsden and Chandler, 1996).

Cambers (1976) demonstrated that large landslides often provide large sediment stores at the foot of the landslide slope. Until sufficient sediment has been removed for unloading of the slope to occur, landsliding will be reduced. Thus, sediment storage can have a critical role in regulating the transmission of the 'zone of aggression' through the landslide system. Brunsden and Jones (1980) developed this point further to illustrate the concept of the 'formative event', which shapes the landform most effectively. At Fairy Dell, the formative events are the large movements that both produce large features in the slope and are recognizable over long periods of time, except in the sea cliffs where the formative events are small and frequent. As a result the sea cliff lacks sediment storage and has a relatively smooth form, but the mass-movement slopes are distinguished by considerable storage of sediment and great irregularity. The landslides at The Spittles (Figure 4.14) and Black Ven have been described by Brunsden and Chandler (1996) as re-activated features from the last interglacial period.

Denness (1972) and Conway (1974) examined the relationship between groundwater

Figure 4.14 The Spittles, east of Lyme Regis. (A) Main landslide scar – sand and chert cliff; (B) landslide storage and throughput system; (C) sea cliff and mud flows; (D) beach; (E) dissected shore platform. (Photo: V.J. May.)

flows and the extensive instability of the cliffs at Black Ven. The reservoir principle of mass-movement argues that where a permeable rock capable of holding and discharging ground water rests on an impermeable layer, a supply of water, independent of rainfall is introduced into areas of instability. Not only is landsliding more rapid than if surface water alone is involved, but there may be accelerated weakening of the rock fabric. At Black Ven, this 'primary reservoir' is the Upper Greensand resting on the Gault Clay. Debris accumulations within both active and relict mass movements can also act as more localized 'secondary reservoirs'. At Charmouth, the Higher Sea Lane landslip involves re-activation of relict mudflows that overlie the Lias clay (Denness *et al.*, 1975). The mudflows, acting as a secondary reservoir, supply water to the Lias and movements take place perpendicular in direction to the original flows. Thus, as the sea cuts the cliffs back into valley-side slopes, which are characterized by older inactive mass movements, new formative events have been triggered.

Analysis of 12 000 beach pebbles from beaches in this site shows that west Dorset beaches have similar pebble lithology and size distributions. Littoral drift from the west is suggested by an increase in roundness and sphericity towards the east (Bray, 1990b, 1996). Taken together these characteristics suggest that the beaches, including Chesil Beach, were probably interconnected in the past at a lower sea level, about 5000 years ago.

The beach most variable in volume over time is at Charmouth, which, in spite of being closest to the input from the landslides, has rapid throughputs of sediment because of the dominant drift towards the east. Accretion of shingle reduces erosion of the foot of the cliff and the landslides, and retreat rates diminish. Reduced retreat rates lessen the input of shingle to the beach and so accretion is also reduced. As a result the zones of active landsliding may migrate in the direction of longshore drift, as exemplified by an eastward shift in the area of intensive activity from the Spittles to the central part of Black Ven during the first half of the 20th century (Bray, 1990b). However, the lack of sediment at the western extremity of this beach at Lyme Regis and the progressive installation of groynes has aided the extension of landsliding towards Lyme Regis. Although not part of this site, Lyme Regis itself is underlain by numerous slides and shows substantial activity (Lee, 1992; Pile, 1996).

Within the Lyme Regis to Golden Cap GCR site, the application of systems modelling can be further developed, first by examining the sensitivity of the cliffs to high magnitude, low-frequency oceanographic events, and second, by investigating the entrapment processes within the boulder arcs left by erosion of landslide lobes. At Golden Cap, the Greensand has a much more restricted outcrop than on the cliffs between Lyme Regis and Charmouth. Mass-movements are more infrequent. The foot of the cliff is protected by a substantial accumulation of boulders, many of them in arcuate ramparts (Bird, 1985; Bray, 1986, 1990a,b, 1996), which also occur on the sea floor (Darton *et al.*, 1981; Bray, 1990a, Brunsden *et al.*, 1996). Thus this part of the coastline becomes more irregular as its formative events occur less frequently. Moreover, the modification of waves by refraction over such boulder zones concentrates wave energy around the flanks of the headland. Some of the sand- and shingle-sized product from the landslides travels alongshore and may accumulate against the updrift side of debris fans, thus offering some additional protection to the foot of the cliff. Lateral sorting of the beach sediments has been described (Bird, 1989), and the effects of different local sediment sources outlined, but this requires further examination. Future work should not only continue to elucidate the development of the cliffs, but also develop Bray's (1990b) integrated sediment-budget model of the whole site so that the effects of debris inputs at the western end upon the behaviour of the cliffs farther east can be predicted better. Similarly, the effects of surges in the English Channel and large waves such as those reported at Chesil Beach warrant further investigation, for until now most geomorphological investigation at this site has considered the terrestrial processes rather than integrating them with the marine processes. Recently, these cliffs have been used for the development of a model that aims to estimate the future erosion of soft-rock cliffs with accelerating rates of sea-level rise (Bray and Hooke, 1997).

This is a very actively changing site that has a long record of geomorphological investigation upon which future research and education can build. It offers opportunities not only for fine-tuning and evaluation of existing models of cliff behaviour but also the development of more complete models of the whole coastal system from cliff top to offshore. Although other cliffed coasts which are affected by mass-movements occur around the British coast, some have been greatly modified by coast protection works (for example at Folkestone Warren) and in some the longshore sediment-transport system has been modified significantly (for example on parts of the East Anglian coast). This site has been little affected by human modifications although the coast protection works at Charmouth have introduced a salient that acts as a barrier to sediment eastwards, thus further subdividing the system. The landslides between Lyme Regis and Charmouth have been investigated in more detail than any other site worldwide and as a result the complex inter-relationships between active mass-movements, marine erosion and beach development are better understood here than elsewhere. The comparatively well-understood modern processes at this site are also important in throwing light upon the development of the other coastal features of Start Bay, especially Chesil Beach, Slapton Beach and Hallsands. All these beaches contain flint and chert clasts, yet only in this site can they be shown to be contemporary in origin, and the rate of supply estimated. As a result it becomes possible to judge the extent to which beaches in this area were formerly interconnected (e.g. Bray, 1996).

The significance of this GCR site to the study of coastal geomorphology is considerable, since the research here has:

1. focused attention on the appropriate timescale for coastal studies in this site, i.e. 100 years;
2. demonstrated the critical role of the processes at the cliff foot in activating the larger, formative events of the landslide systems;
3. examined the role of the beaches in affecting

the process alongshore;
4. developed models and concepts that have much wider application.

Conclusions

Major landslides at Golden Cap, Fairy Dell and Black Ven dominate this cliffed coast, but the site is also of particular interest because, unusually, the sediment system from cliff top to beach has been investigated more thoroughly than any other site in Britain, and probably worldwide. This is a very important site for coastal geomorphological studies, especially as it is possible to interpret both terrestrial and submarine landforms. Estimates of the sediment budget at the site have integrated the cliff system with the associated beaches, making this a site of considerable importance for monitoring the effects of medium-term change.

SOUTH-WEST ISLE OF WIGHT (SZ 493 755–SZ 306 852)

V.J. May

Introduction

The south-west coast of the Isle of Wight (see Figure 4.1 for general location) is geomorphologically rich in features of interest. It contains examples of most of the cliff types undergoing active erosion described from other GCR sites. The site demonstrates well how coastal processes have produced different cliff forms related not only to variations of lithology and geological structure, but also variations in the intensity of coastal processes and the timescales over which coastal evolution occurs.

Much of the coast of the Isle of Wight is affected by rapid retreat and landslides. Damage to property remains a constant hazard and stabilization has been a priority on the urbanized parts of the coast (Clark *et al.*, 1993). However, the GCR site area is mainly unprotected, except at Freshwater Bay.

The site extends from Chale in the east (SZ 493 755) around the Needles (its westernmost point at SZ 289 849) to Alum Bay (SZ 306 852; see Figure 4.15) and crosses outcrops of Chalk, Upper Greensand, Gault, Lower Greensand and the Wealden exposed on both sides and in the core of the Brighstone anticline. The general plan of the coastline is controlled by the relative resistance of the Chalk in the west and the Upper Greensand in the east, and the effectiveness of the prevailing and dominant south-westerly wave systems in maintaining the alignment of the shoreline. There are many, small irregularities associated with locally resistant outcrops, and the beaches comprise both locally derived materials and some residual flints. Erosion has been rapid, so that small streams have been unable to keep pace with continually steepening gradients. 'Chines' (small coastal gorges) and waterfalls are common.

The cliffs vary in height from about 15 m in Brook Bay to over 145 m at Tennyson Down. At Freshwater Bay, the former Yar Valley is truncated and coast protection works have been constructed, but elsewhere interference with the beach system and its feeder bluffs has been negligible. The structural impact of variations in dip and rock strength is well exemplified in the stacks at Freshwater Bay and the Needles, as well as in the differential erosion of the Chalk itself along Tennyson Down.

Platforms are poorly developed on the Chalk coast, the cliff foot being masked by extensive boulder accumulations. However, parts of the coast intersecting the Greensand and Wealden strata have large platforms, for example at Hanover Point, whose seaward extensions affect wave refraction locally. This is one of six major south-west facing beach systems in the English Channel. It is distinctive by reason of its rapid retreat and the differential feeding of sediment to it, as well as a limited flint content. Flint is important only on the beach between Atherfield Point and Blackgang where major landslides feed the beach. The Chalk cliffs in the north are very slow to change; they feed very small quantities of flint into the beach, except at Scratchell's Bay and on the northern side of Tennyson Down.

Research has focused on the cliff processes, with increasing emphasis on the landsliding (Lyell, 1835; Steers, 1946a; May, 1964; Hutchinson, 1965, 1987, 1991; Hutchinson *et al.*, 1981; Barton, 1990, 1991; Clark *et al.*, 1993; Bromhead *et al.*, 1991; Chandler, 1991; Hutchinson, 1991), and the development of chines (Englefield, 1816; Lyell, 1867; Bristow, 1889; Bury, 1920; Cotton, 1941; Steers, 1953a; Flint, 1980, 1982).

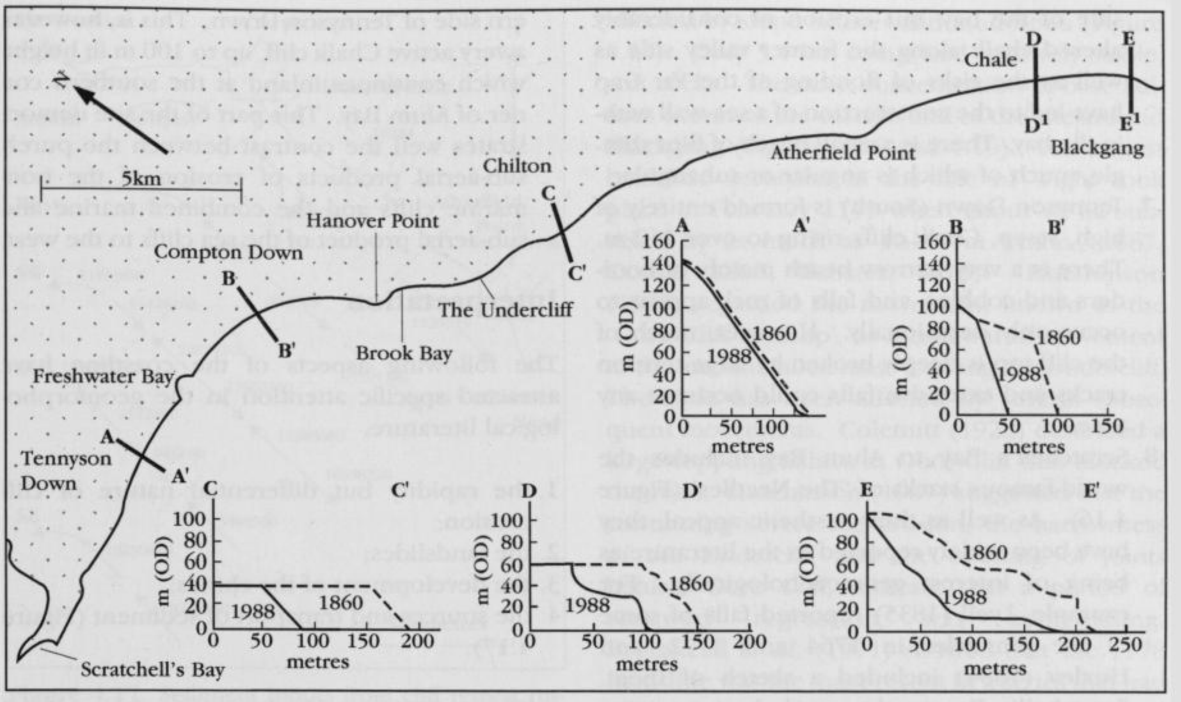


Figure 4.15 Variations in the rates of cliff retreat from Blackgang to the Needles (to the west of Scratchell's Bay), Isle of Wight. Cliff profiles for sections A to E are shown. (After Hutchinson, 1984.)

Description

The site can be divided into eight sections (Figure 4.15), as follows.

1. St Catherine's Point to Blackgang Chine, forming the western part of the Undercliff, which rises to over 180 m in height. The steep upper cliffs comprise mainly Upper Greensand, underlain by Gault Clay and Lower Greensand, all dipping gently to the south-east. There have been many large landslides (Hutchinson, 1965).
2. Blackgang Chine to Atherfield Point. Cliffs that are undergoing very active erosion at the eastern end give way westwards to steep fairly stable cliffs in the Ferruginous Sands. Two chines break the cliffline. This is the only substantial fringing flint-shingle beach within the site.
3. Atherfield Point to The Undercliff (Brighstone Bay) is dominated by active cliffs in the Atherfield Clay and the Wealden beds. The rate of cliff retreat has been estimated at greater than 1 m a^{-1} (May, 1964). Chines are distinctive features both here and in the next two segments of the coast.
4. Brook Bay, which is cut mainly into the Wealden Marls (Wessex Formation). Its eastern side is marked by an undercliff of slipped blocks up to 7 m thick known as 'Roughland'. On its western side, the cliffs are about 16 m in height. The dip of the strata is to the south.
5. Hanover Point to Freshwater Bay. The cliffs vary in height from about 15 m at Hanover Point to over 80 m at Compton Down. The dip is towards the north and so there is a gradual transition from the Wealden Marls and Shales (Wessex and Vectis formations) through the Lower Greensand to the Chalk at Compton Down. This is a very active coastline and the coast road at Compton Down is so seriously threatened that complete realignment has been considered (Barton, 1990). Chalk from the eroding cliffs is transported south-eastwards towards Hanover Point, but is virtually absent within 1 km of the Chalk cliffs.
6. Freshwater Bay forms a small semi-circular bay between relatively resistant Chalk headlands. Stacks and caves have formed on either

side of the bay, but erosion of considerably altered chalk along the former valley side as well as the risks of flooding of the Yar Gap have led to the construction of a sea-wall within the bay. There is a small beach of flint shingle, much of which is angular or subangular.

7. Tennyson Down (South) is formed entirely of high, steep, Chalk cliffs rising to over 140 m. There is a very narrow beach mainly of boulders and cobbles, and falls of rock appear to occur only occasionally. However, much of the cliff top is deeply broken by large tension cracks and extensive falls could occur at any time.
8. Scratchell's Bay to Alum Bay includes the world-famous stacks of 'The Needles' (Figure 4.16). As well as their aesthetic appeal, they have been widely reported in the literature as being of interest geomorphologically. For example, Lyell (1835) reported falls of some of the pinnacles in 1764 and 1772, and Huxley (1884) included a sketch of them. Scratchell's Bay to the south has a narrow beach of flint and chalk shingle, but there is limited beach development along the northern side of Tennyson Down. This is, however, a very active Chalk cliff, up to 100 m in height, which continues inland at the southern corner of Alum Bay. This part of the site demonstrates well the contrast between the purely sub-aerial products of erosion of the non-marine cliffs and the combined marine and sub-aerial product of the sea cliffs to the west.

Interpretation

The following aspects of the coastline have attracted specific attention in the geomorphological literature.

1. the rapidity but differential nature of cliff erosion;
2. the landslides;
3. the development of the chines;
4. the sources and transport of sediment (Figure 4.17).

The rapidity and diversity of erosional processes around the coastline of the Isle of Wight is especially well demonstrated along its

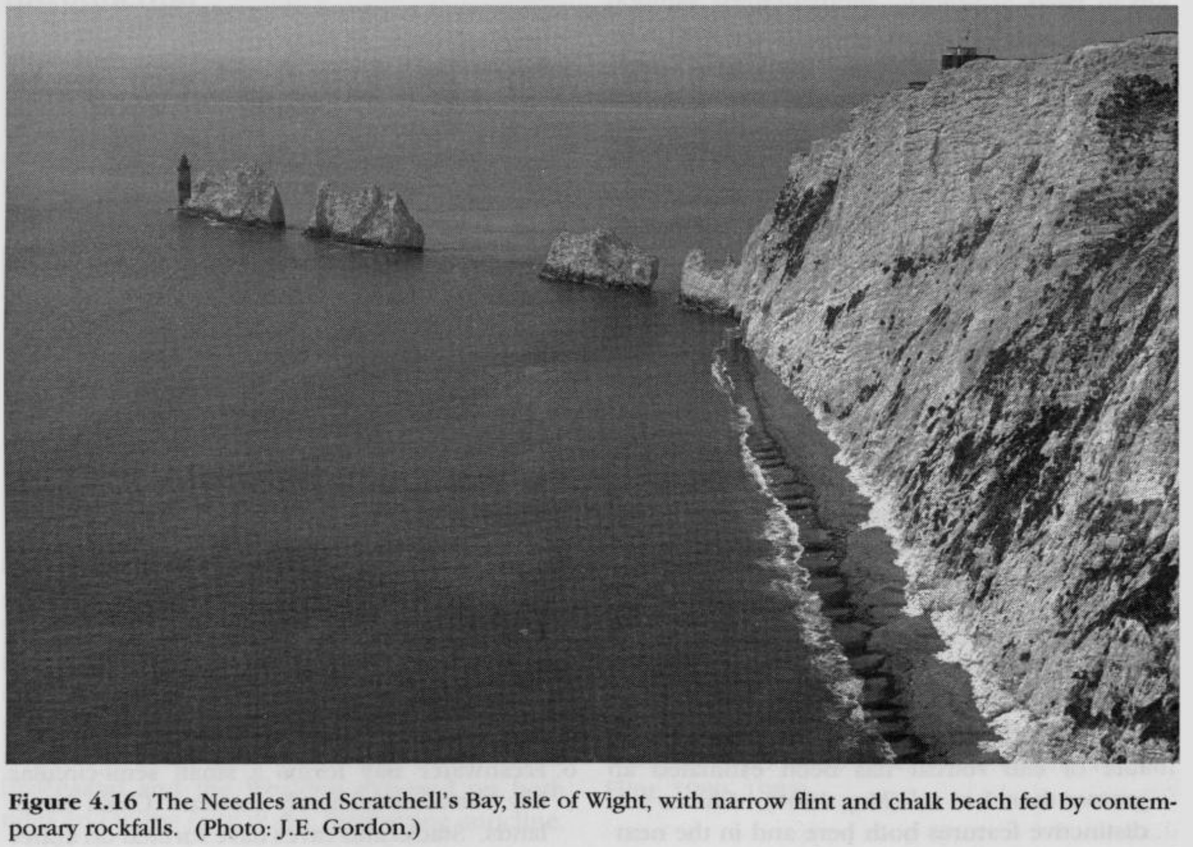


Figure 4.16 The Needles and Scratchell's Bay, Isle of Wight, with narrow flint and chalk beach fed by contemporary rockfalls. (Photo: J.E. Gordon.)

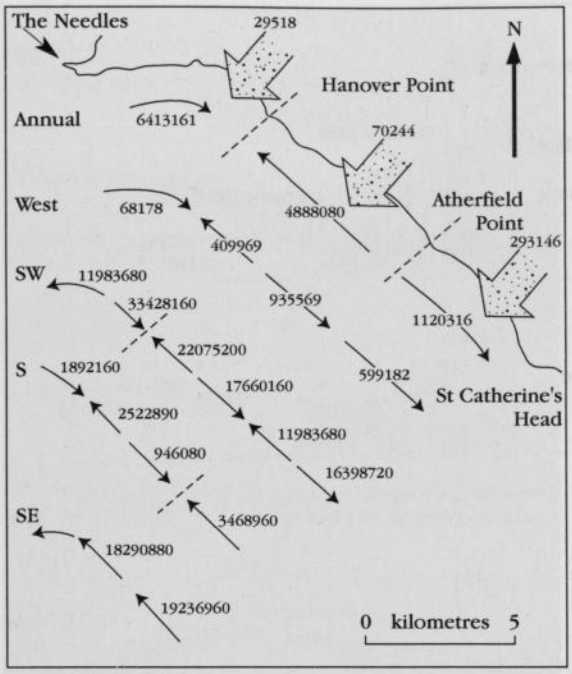


Figure 4.17 Sediment inputs from cliff retreat (m^3 a^{-1}) annual longshore potential sediment transport and variations with wind direction. See text for explanation. Total sediment input = 392 908 m^3 a^{-1} (After Davies, 1997.)

south-western coast. May (1964) summarized the main features and estimated that rates of cliff retreat during the previous 100 years ranged from 0 to more than 2 m a^{-1}. The resistance of the intertidal area and the cliff foot to erosion are particularly significant, for it can be shown that the more resistant layers (such as the Perna Bed hard band and the 'Pine Raft' at Hanover Point) not only form platforms but also reduce rates of cliff retreat. Thus headlands have formed at Hanover Point and Atherfield Point where the cliffs are formed in materials that are intrinsically weak. Their existence as headlands owes much to the greater relative resistance of the cliff foot and intertidal platforms. Much of the cliff consists of easily eroded materials, and so variations in the resistance of the cliff foot or platforms associated with these slightly harder bands play a very important role in the overall outline of the coast.

Hutchinson (1965) reconnoitred the documented landslides of the Isle of Wight indicating that this site contained 13.5 km affected by rockfalls, 0.6 km affected by seepage erosion, about 4.25 km affected by base failures, and 5.5 km affected by slope failures and mud-flows (Figure 4.18). Only 5.1 km comprised relatively stable, soft rocks. The main concentration of base failures occurs at the eastern end of the site around Blackgang (Figures 4.18 and 4.19). The largest landslide recorded in the Isle of Wight took place in February 1799 when about 40 ha subsided by as much as 10–12 m (Anon., 1887; Cooke, 1808; Webster, 1816). Hutchinson (1965) regarded the movement, known as the 'Gore Cliff landslip', as a renewal of movement in the ancient failed mass forming the Undercliff. The slide has been affected by several subsequent movements. Colenutt (1928) described a large toppling failure at Gore Cliff that blocked the road. Hutchinson (1987) suggested that the continuing severe toe erosion, the narrowness of the Undercliff and the opening of joints behind Gore Cliff, indicate that a period of renewed regression was approaching. Bromhead *et al.* (1991) showed that the 1978 landslide was the most recent in a series that had affected the coastline between Rocken End and Blackgang Chine during the last 200 years. It had a basal slip surface controlled by bedding about 18 m above the base of the Gault Clay and re-activated earlier slides. The large landslides that form the Undercliff result from the interaction between marine erosion initiated during the Holocene transgression and the seaward-dipping synclinal structure and detailed lithology of the Cretaceous rocks (Hutchinson, 1991).

To the north-west, seepage erosion appears to have been most important in giving rise to benches in the cliff profile. Fitton (1847) suggested that less permeable beds within generally more permeable strata would encourage water from these beds to undermine the cliff. As a result, the cliff is characterized by an upper active cliff, a bench and a lower sea-eroded cliff. The upper cliff and the sea cliff retreat at different rates, and the rates of recession trebled from the 19th to the 20th centuries. Hutchinson *et al.* (1981) and Hutchinson (1987) describe the processes in detail, as follows. The upper scarp of the Ferruginous Sands cliff at Walpen collapses as a result of seepage erosion in fine layers in the Foliated Clay and Sand. The resulting debris moves across the undercliff bench, usually obliquely, by compound slides and by rotational slips in its seaward edge. Mudslides and stream action also carry debris across the undercliff. As the bench surface dips below sea level towards the south-east, the bench is broken by deep-seat-

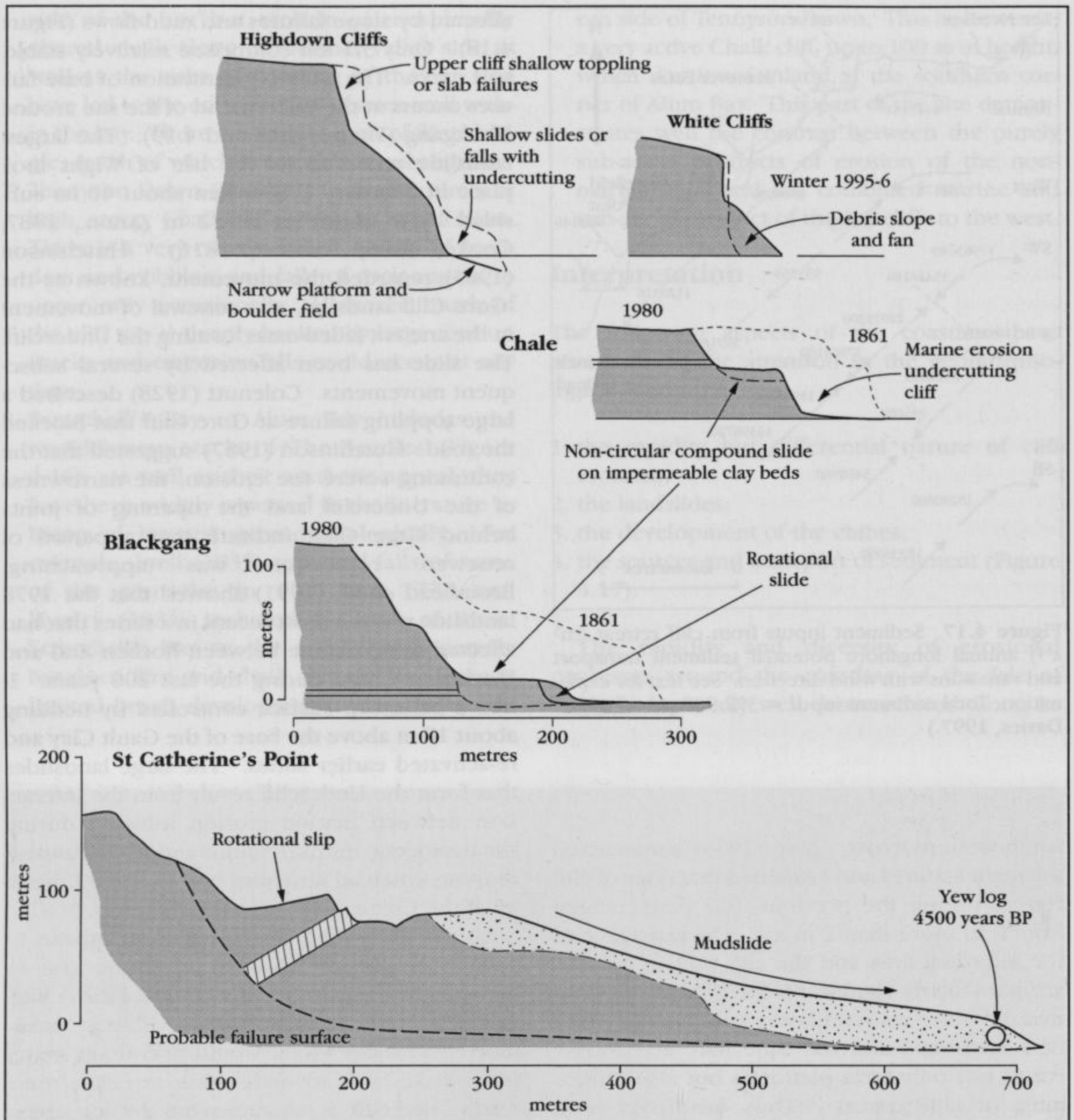


Figure 4.18 Differences of failure in the cliffs of south-west Isle of Wight, ranging from large rotational slides to shallow failures. (After Hutchinson, 1984.)

ed base failures.

North-westwards from Atherfield Point, the cliffs are marked by many slides, some shallow, others more deep-seated and giving rise to 'staircases' of slipped blocks, but they have received rather less attention in the geomorphological literature than the cliffs around Blackgang. The cliffs towards Alum Bay also warrant much fuller examination, not only because of the threats to roads at several points, but also because there is considerable evidence in the cliff-top tension fissures, particularly on Tennyson Down, that major cliff failures could occur (Figure 4.21). At Compton Down, the chalk cliffs are undergoing more active erosion than any other part of the chalk section of this coastline. Cliff failure

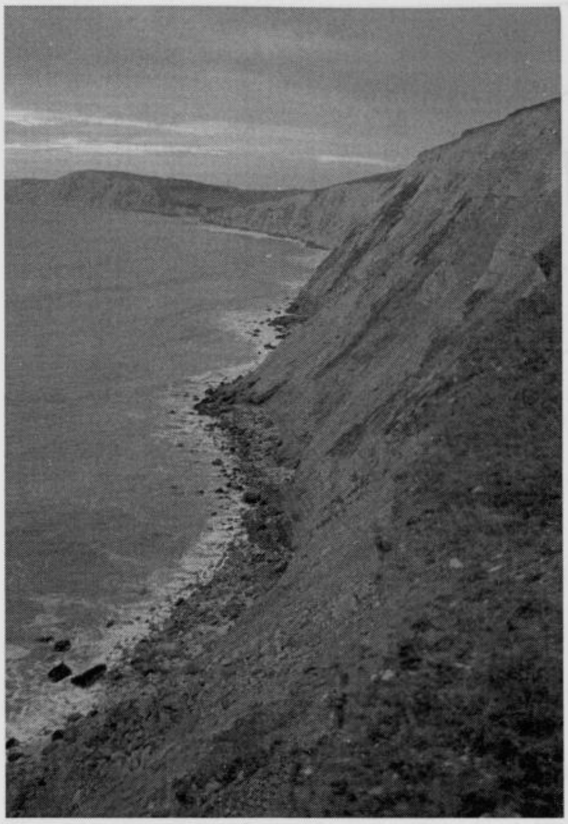


Figure 4.19 Characteristic slope failures at Compton Down, looking west, showing shallow slides in chalk rock. (Photo: V.J. May.)

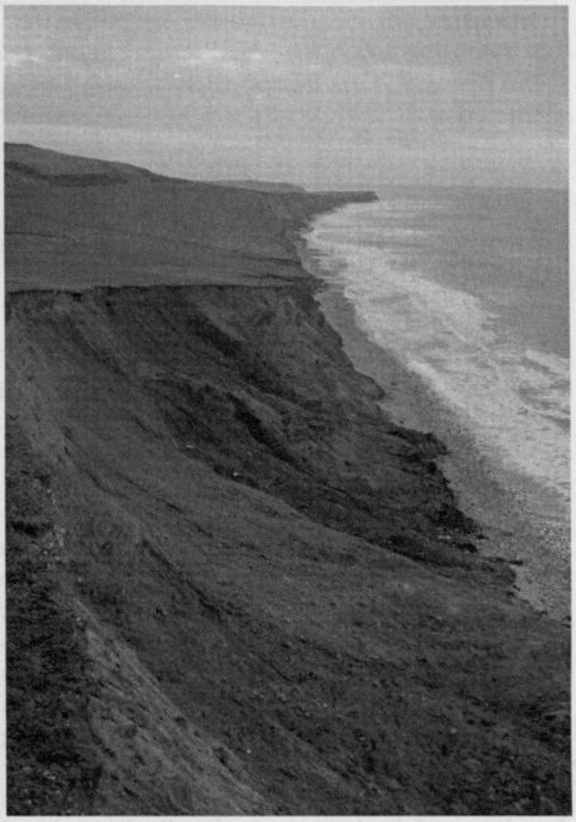


Figure 4.20 View looking east from Compton Down where chalk pebbles typically survive for little more than 1 km owing to their erosion during longshore drift. Well-developed cusps commonly characterize this beach. (Photo: V.J. May.)

occurs in massive units that give rise to open fissures behind the cliff edge (Figure 4.20; Barton, 1990).

Explanations for the origins of the chines range from landsliding (Lyell, 1867), enlargement after rainfall (Gardner, 1879), wind erosion (Englefield, 1816), and spring-sapping (Bristow, 1889). Bury (1920) concluded that they were formed recently, but did not suggest their probable age. In his view, where the rate of headward erosion was faster than that of cliff retreat the chines were lengthening. The valley-within-a-valley form he attributed to the role of much larger volumes of water forming the upper open valleys whereas the chines were the result of present-day conditions, the size of the chines being a function of their present-day small streams, which misfit the larger upper valleys. He argued that the different levels were a result of changes of sea level, a view supported by Steers (1953a). Flint (1980, 1982) concluded, in contrast, that they are a function of basin characteristics (stream power and geology) and cliff retreat-rate, not the result of cliff retreat alone. The critical drainage basin area for the maintenance of a base-levelled chine varies with rock type. In sands, this area is about 2.5 km^2, in marls 0.64 km^2 and in shales greater than 0.73 km^2. Below these values, stream power decreases, waterfall height increases and the chine is removed by cliff retreat (Flint, 1980). Landsliding is not a primary agent in initiating chines. Flint (1980, 1982) refuted Bury's (1920) view that the different levels of the chines were due to sea-level changes alone.

Because of the variety of beds, the sources of beach material can often be identified comparatively easily. Apart from Scratchell's Bay, there is no part of the Chalk coastline that has a beach composed solely of flint and chalk shingle.

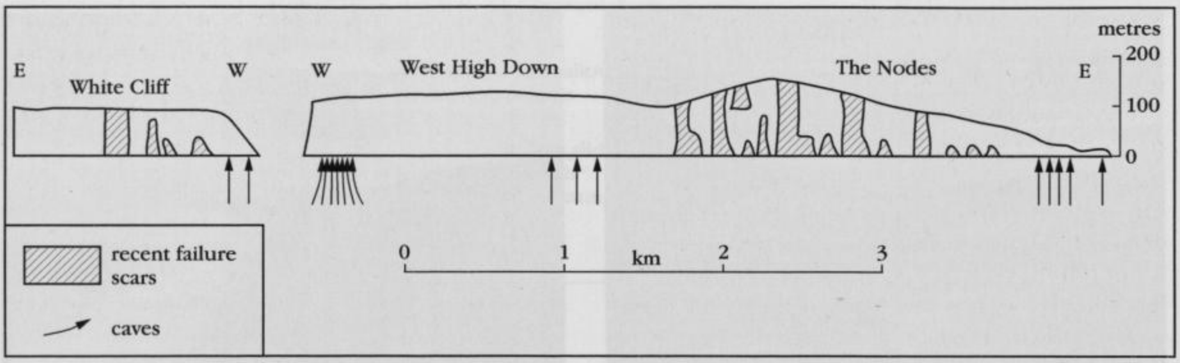


Figure 4.21 Cliff-face failures west of Freshwater Bay. (Based on British Gas aerial survey, February 1996.)

Elsewhere, the beach is minimal or is mixed with shingle and larger material derived from the Lower Greensand. From Compton Down, chalk pebbles indicate a transport direction towards the south-east, but are virtually absent 1 km downdrift from the cliff. Most beaches along the Wealden coastline are sandy, but contain varying amounts of shingle and clay depending on their relationship to the chines and landslides. Most beach material appears to be locally derived and recently produced. East of Atherfield Point, however, the beach is formed of flint shingle. There has been no detailed investigation of the sedimentological characteristics of this anomalous beach. Possible sediment sources to the south-east, but longshore transport has normally been described as being from north-west to south-east. However, Davies (1997) has shown that under south-westerly waves there are three sediment-transport cells with little exchange between them. In contrast, under easterly waves, there is net movement alongshore towards the west (Figure 4.17). The bulk of the material entering the beaches is fine-grained sand or clay, and much is transported away from the beach in suspension. There is a marked lack of shingle to the west of Atherfield Point, which acts as a groyne to westerly movement. Alternatively, this beach may represent part of a former larger beach system that extended throughout Brighstone Bay at an unkown distance offshore. Hutchinson (1987) showed that the foot of the Undercliff at the eastern end of the site includes a former sea cliff and platform probably related to a period of relative sea-level still-stand about 7500 to 8000 BP. A period of active landsliding occurring about 4500 BP protected this feature. Of particular interest is the suggestion that the shoreline position at the eastern end of the site was not different from that of today, but with sea level perhaps as much as 7 m lower. The western Yar was already open to the sea, having been cut to a depth of at least −13.4 OD (Nicholls, 1987) during the Pleistocene Epoch.

The south-western coastline of the Isle of Wight stands apart from the other south-west-facing beaches of the English Channel in the rapidity of its retreat (Figure 4.17). Although within broadly the same wave conditions as the Seven Sisters in East Sussex, both the mechanisms and the coastal plan of the south-west Isle of Wight differ as a result of the variety rock types and their different responses to sub-aerial and marine processes. Another key difference is that whereas the Seven Sisters display a more-or-less uniform rate of retreat over the 100 year timescale, the south-west Isle of Wight cliffline has retreated at varying rates that have accentuated coastal crenulations rather than reducing them. Finally, the Isle of Wight site can be regarded as the type area for chines in sands and clays, for they are well-developed common features about which a considerable amount is known.

This site is the best example in Britain of a coastline that cuts across an anticline in relatively weak geological materials. Erosion follows the core of the Brighstone anticline, but the variations in rock strength exposed in the cliff and foreshore have produced considerable differential erosion. The importance of the site lies mainly in the range of responses to erosion in different lithologies within the larger scenario of a shoreline that is strongly controlled in its general outline by the dominant south-west wave regimes. In contrast to the coastline of east Dorset, which is either clearly longitudinal (around Lulworth) or has a strong headland–bay pattern (the transverse coast around Swanage), this coastline is one where headland–bay topography is slight, but retains similar amplitudes as it retreats at comparable rates throughout its length.

The relationship between the old landslides at the Undercliff and former shorelines gives this site another distinctive feature. The resistance to erosion of the exposed southern side of Tennyson Down contrasts strongly with the much more sheltered northern side of the headland and demonstrates very well the importance of both structure and lithology. This also deserves more detailed investigation, because of its relationship to sediment supply and the potential for catastrophic change to the southern cliff.

The lack of large-scale anthropogenic interference with the coastal processes makes this site particularly important for investigation of the links between cliff retreat and beach development, especially since the different lithologies of the retreating cliffs provide natural markers for examination of longshore transport processes.

Conclusions

The south-west coastline of the Isle of Wight is dominated by cliff and beach features related to the south-westerly wave climate of the English Channel, but also demonstrates well the effects of differential erosion both where rock-types change and where coastal retreat outstrips the erosional ability of coastal streams. The site includes the Needles and extends from the Chalk of Tennyson Down in the west to the Lower Greensand cliffs of Blackgang Chine in the east. There are rapidly retreating cliffs, well-developed cliff-foot beaches and steep-sided valleys (the chines). This is the type area for chine formation. Differential erosion in relatively weak rocks is affected by more resistant bands, except at the extremities of the site where the Undercliff overlies an older shoreline in the east and the stacks of the Needles and the high cliffs of Tennyson Down resist erosion. Although not as well-recognized internationally as the very active landslide coast east of Lyme Regis, this coast contains examples of all the soft rapidly retreating coastal types that occur in Britain and parts such as the Undercliff are renowned internationally. It is one of the best examples of a coastline that cuts across a major anticline in generally weak materials.

KINGSDOWN TO DOVER, KENT (TR 382 472–TR 374 450 AND TR 368 443–TR 340 422)

V.J. May

Introduction

The cliffs between Kingsdown and Dover (see Figure 4.1 for general location) show an excellent example of structural controls on coastal cliff-form. These cliffs, broken only by the deep valley and bay at St Margaret's, rise to between 30 m and 110 m OD. Retreat of the cliffs has been about 0.2 m a^{-1}, but this takes place mainly as large slides affecting the whole cliff face. A well-developed platform extends to below low-tide level. Beaches are formed mainly of clasts of rounded chalk and a mixture of rounded and angular/unrounded flint. Little evidence now remains of a former fringing beach that extended from Dover to Kingsdown. The present beaches depend upon the contemporary erosion of cliffs and platforms. When major cliff-falls occur, boulder-sized debris usually forms a protecting rampart with the smaller chalk cobbles and flints being added to the beaches (Figure 4.22).

Research on the Kingsdown to Dover site has focused on the nature and processes of cliff retreat (May, 1964; May and Heeps, 1985; Hutchinson, 1980, 1983; Birch, 1990; Leddra and Jones, 1990) and the relationship between cliff-form and major structures in the Chalk (Middlemiss, 1983). Like many such cliff sites, it is referred to by Steers (1946a) and Bird (1984). Comparable surveys have been made of other Chalk cliff sites in England and Wales (see GCR site reports for Flamborough Head, Joss Bay, Ballard Down and Peveril Point to Furzy Cliff) and on the Normandy coast (Precheur, 1960).

Description

The vertical cliffs between Dover and Kingsdown are currently undergoing the most active change in England and Wales. They are cut through the Upper Chalk of the *Micraster cortestudinarium* and *Micraster coranguinum* biozones. Unlike the high Chalk cliffs at Beachy Head, for example, they are generally a simple near-vertical face up to 110 m in height. Erosion rates have increased in recent decades. Cut across the eastern end of the North Downs, their height reflects mainly the gradual slope of the Chalk landscape towards the north-east. Thus, between Dover and St Margaret's Bay the cliffs reach heights of 110 m, although at the Dover end of the site they also have lower faces where the cliffs are cut into coombs such as that at Langdon Bay. North of St Margaret's Bay, the alignment of the cliffs is closer to that of the strike and so they reflect more closely the dip of the Chalk surface, falling gradually to a height of about 30 m at Kingsdown.

Middlemiss (1983) describes the relationship between the structure of the Chalk and the failures of the cliffs. Between Kingsdown and the windmill at South Foreland, 300 measured joints fall into four main groups.

1. Striking at about 300°: major strike joints.
2. Striking at about 205° to 210°, dominantly vertical or very steeply dipping: tensional dip joints complementary to the first group.
3. Striking at 205° to 210° with dip angles between 50° to 70°, and
4. Striking at about 280°.

Middlemiss demonstrated that cliff-form corresponds both in plan and profile with the attitude of the jointing. Group (1) and (4) joints that are roughly perpendicular to the coastline in plan view are often important as the sites of caves and minor changes of the cliffline (e.g. Ness Point and White Fall). Almost every length of the cliffline is related to at least one group of joints, with groups (2) and (3) dominant (Figure 4.23).

To the south of South Foreland, there has also been a number of large falls in recent years, where the cliffs turn increasingly towards the west. The Chalk is greatly jointed but the cliff patterns have not been described in the same detail as those in Middlemiss's paper. Where

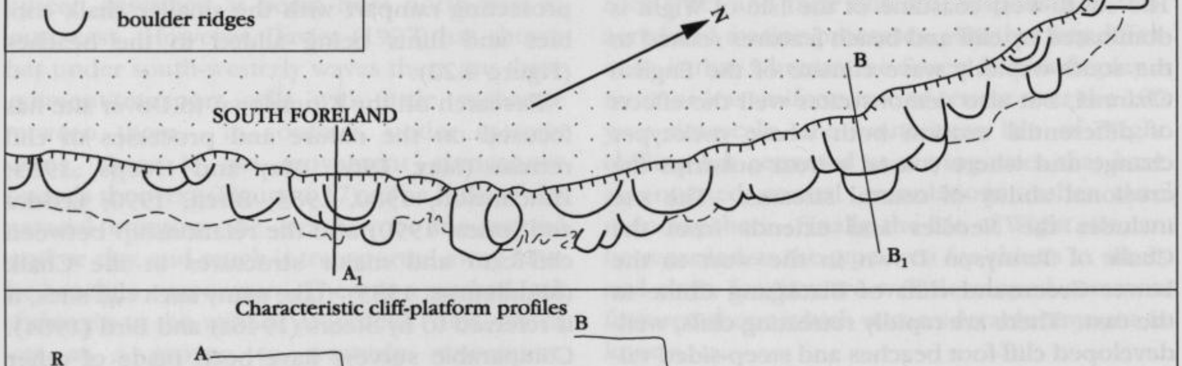


Figure 4.22 Sketch map of boulder ridges, South Foreland to St Margaret's Bay within the Kingsdown to Dover GCR site. Characteristic cliff-platform profiles through A–A_1 and B–B_1 are shown in the lower part of the diagram.

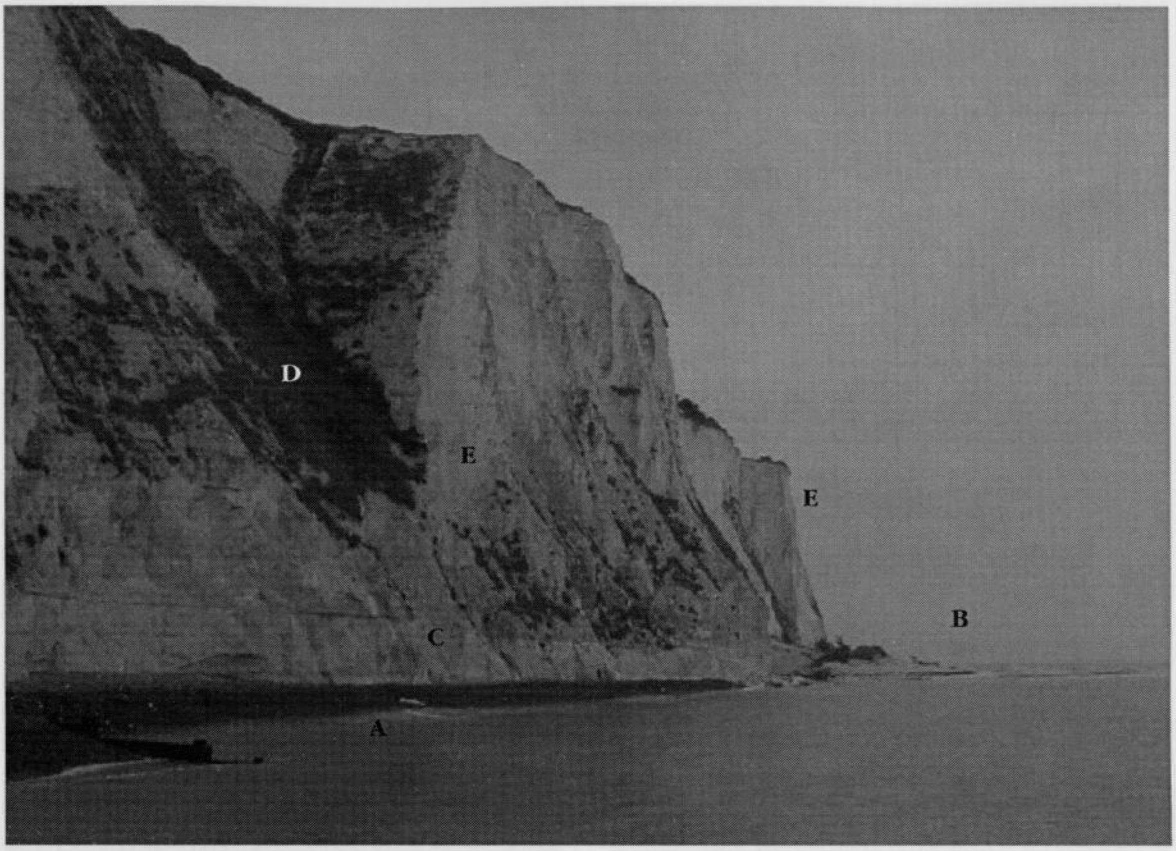


Figure 4.23 View looking north of St Margaret's Bay, Kingsdown to Dover GCR site. (A) Small, fringing beach of flint, mostly derived from recent cliff falls; movement alongshore is restricted by fall debris; (B) large toe of a slide extending beyond low-water mark; (C) cliff being eroded where previous rock fall has been completely removed; (D) vegetated slope that developed behind a former slide toe and debris; these features then protected cliff-foot bedrock from erosion; (E) typical upper cliff profile above debis slopes. (Photo: V.J. May.)

recent falls are absent, the cliff has a basal notch and a very steep profile (Figure 4.24). The platform in these areas is free of small chalk debris, but has small pockets of flint, both rounded and angular, the latter derived directly from the platform. Platform surfaces are generally of two types. The first of these is co-incident with tabular flint horizons in the Chalk and follows their dip so that flint forms the surface of the platform. The second type is steeper, lacks a flint surface and cuts directly into the Chalk. Both types of platform are dissected by sub-parallel channels up to 0.4 m in depth. There is considerable biological activity in the erosion of the platforms, with borers such as piddock *Pholas* spp. riddling the surface layer to depths of several centimetres. Substantial lengths of the site, in contrast, have platforms that are cloaked by debris. This is often boulder-sized and sufficiently stable to carry a cover of algae. Much of the large debris is derived from frequent rockfalls that affect this coastline.

Middlemiss (1983) identified four main areas north of South Foreland where falls have been particularly frequent:

1. South Foreland (TR 363 434) and the cliff immediately to the north-east. The structure of the cliff is determined by three sets of joints striking at 303°, 233° and 202°.
2. At Leathercote Point (TR 374 451) and for about 300 m northwards to The Cut (TR 375 454), where master joints striking at about 301° and 232° are the major factors.
3. At White Fall (TR 378 457), where two small faults, striking at about 301° with a throw to the north of about 1.5 m, are intersected by a major joint striking at 232° and dipping at 70°

to the south-east. Middlemiss suggested that the presence of about a 1.5 m thickness of calcareous downwash at the top of the cliff may be a contributory factor here.

4. East of Hope Farm (TR 376 462) and for 400 m northwards, where major joints determine the structure of the cliff. An additional set of joints striking at about 342° affect the outline of an embayment (TR 379 465). The valley bottom deposits of Hope Farm Valley, some 2–3 m of residual gravel and calcareous downwash, which not only cap the cliff but also fill several large solution pipes, may play a contributory role.

At the northern end of the site, joint-controlled channels cut into the platform are filled by angular flint and chalk mixed with rounded, oxidized, flint shingle together with shelly fragments in a chalky matrix. This is characteristic of the deposits occurring beneath chalk debris fans that preserve, albeit temporarily, the existing beach sediments beneath. The chalky matrix comprises the fine-grained materials at the base of the fall and may include fines that have washed through the debris above or have been derived by erosion of the overlying debris. These deposits are spatially associated with the remnants of a large talus fan at the cliff foot that has mostly been destroyed. Although the sub-debris sediments are normally ephemeral, their presence emphasizes the variability of sources for the beaches.

Interpretation

The rate of retreat of these cliffs is moderate, but in recent years retreat has accelerated. May (1966) reported the average cliff-top retreat over a period of 84 years from 1873 to 1957 as 6 m between St Margaret's and Kingsdown, and 16 m between St Margaret's and Dover. May (1971a) expressed cliff-top retreat at South Foreland as about 0.19 m a^{-1} between 1817 and 1962. Hutchinson (1972) compared chalk falls on the Kent coast in general between 1810 and 1970 with the number of days with air frost and effective rainfall. Falls tended to co-incide with, and to follow, periods of maxima of air frost and to follow periods of maximum water surplus. Bird and May (1976) stated that between Dover and Walmer there had been intermittent recession of the cliffs by rockfalls, which occur most frequently during the winter and are associated with periods of high average numbers of days with air frost. May (1964) described a state in which large falls produced extensive debris slopes that were sufficiently long-lived to develop a stable vegetation of chalkland grasses and coastal plants. The debris survived for several decades, sometimes in excess of 50 years. However, such longevity of debris no longer appears to be the case. Almost without exception the cliffs fall abruptly to a distinct junction with a platform, which is about 200 m in width. Where present, the beach is narrow and formed of rounded chalk and both rounded and angular flint. There is no evidence, apart from in the northernmost part of the site, of the once-continuous fringing rounded flint shingle beach described by Austen (1851). The construction of the harbours at Dover and Folkestone during the second half of the 19th century prevented any continuing supply from the south-west. Hutchinson *et al.* (1980) recorded the links between this interruption to the littoral drift and major changes at Folkestone Warren, but there has been no comparable record for the coastline east of Dover except at the northern end of the site. The effect has been less dramatic but no less important. Furthermore, the construction of groynes at St Margaret's and the former Royal Marines firing range at Kingsdown virtually prevent any supply of flint from the erosion of the present-day cliffs to reach the beaches at Walmer and Deal. The site is thus characterized by reduction in a protective lag deposit of flint shingle and depends for its basal protection entirely on the contemporary products of cliff-falls. These are now insufficient in volume to provide other than localized protection since much of the Chalk is dissipated by attrition. Residual boulder arcs reduce wave energy but do not provide the cliff foot protection that the 19th century beaches previously offered.

Two main processes promote the instability in these cliffs, namely wave action along the master joints, and the effects of percolating water within the joints. The latter effect is accentuated, according to Middlemiss, where residual gravel and calcareous downwash form the cliff top, as reservoirs for percolating water. The tendency for falls to follow periods of hard frost suggests a combination of mechanisms for the falls. Water freezing in these zones exerts pressure through its expansion. Alternatively, pressure is exerted by the ponding of ground-

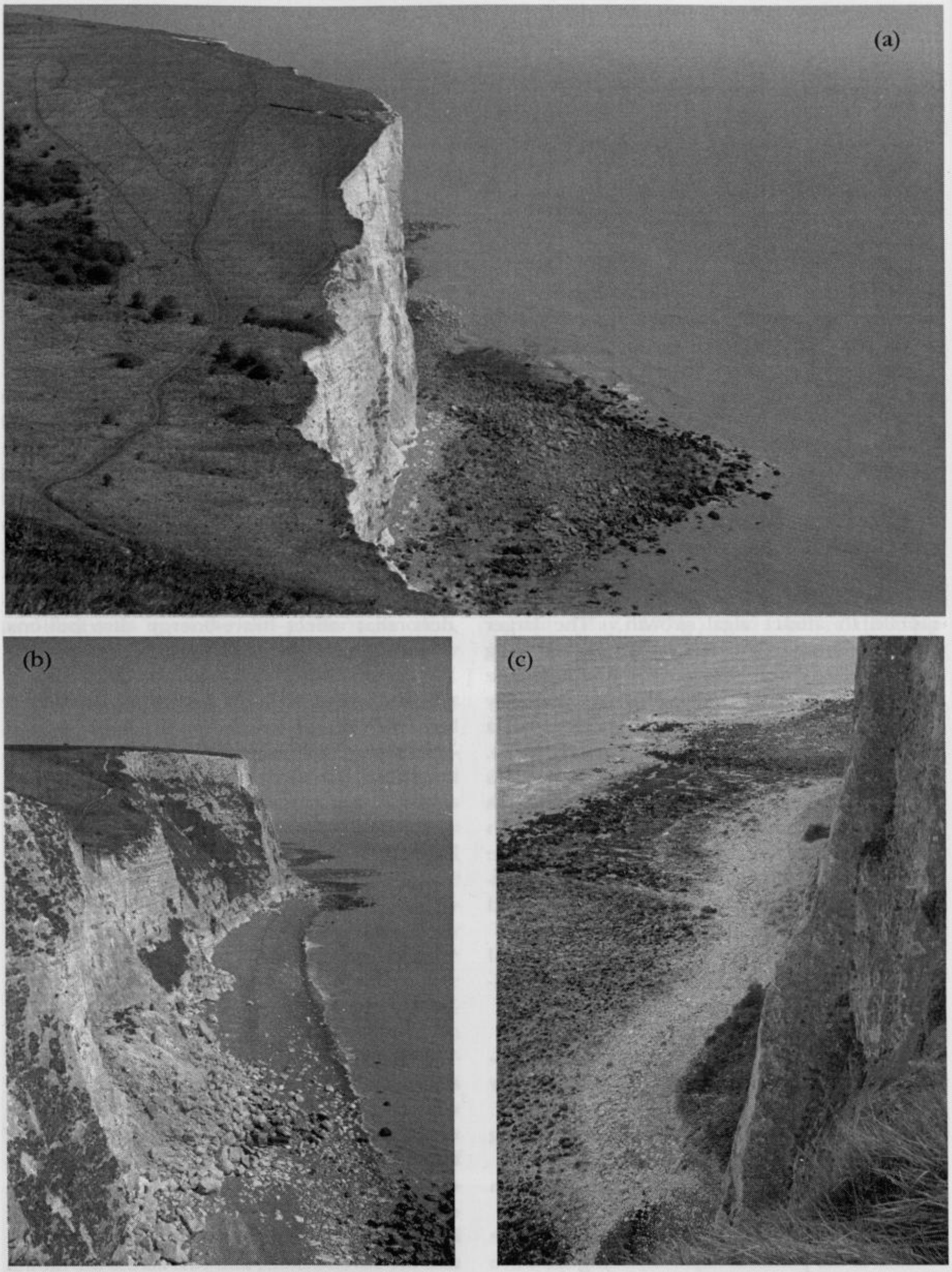


Figure 4.24 Langdon Bay. (a) Boulder rampart residue from earlier debris tongue; (b) in the foreground, talus from a clif failure is seen; in the background, residual boulder fields from flow-type failures are present; (c) parallel ridges bounding a large flow-failure that left the platform comparatively clear of large debris. (Photos: V.J. May.)

water in a joint behind a plug of ice.

Hutchinson (1980, 1983) showed that as cliff height and slide volume increase, a 'degree of flow' appears in the debris. In falls from the higher cliffs (70–150 m), a 'chalk flow' can occur, which may carry debris for distances in excess of four times the height of the cliff across the near-horizontal shore platforms. Hutchinson's working hypothesis was that these flow slides occur because high pore-water pressures were generated through the crushing impact of relatively weak blocks of high-porosity, near-saturated, chalk. Leddra and Jones (1990) show that steady-state flows can result from rapid or undrained loading of the Chalk, with the result that debris from high chalk cliffs can flow for considerable distances. The debris produced by cliff-falls, such as those described by Hutchinson, varies in size from fines to boulders over 1 m across. The fines are quickly dispersed by wave action and longshore currents. Shingle-sized debris is commonly rounded within a few days and is worn down to sand-sized fragments over a period of several months. It is often too mobile to attract algal growth. The larger material, however, remains *in situ* for very long periods of time and becomes colonized by algae and molluscs. While these boulders gradually diminish in size, the platform retains a substantial cover, commonly for many years. One fall in 1982 produced a fan of debris across the platform from which much fine debris was quickly removed; the main boulder pattern remains today. On one 1500 m length of the cliffs south of St Margaret's Bay, some 30 residual arcuate forms have been identified (Figure 4.24).

Kingsdown to Dover is an important coastal geomorphology GCR site because it demonstrates:

1. the role of structure in controlling cliff development in a site undergoing comparatively rapid erosion;
2. the significance of relict beaches in retarding recent cliff development;
3. the limited present-day sediment supply from the flint-rich Chalk;
4. the role of cliff-fall debris in modifying the form of the platform and controlling the wave refraction;
5. the role of structural features in affecting platform morphology and the role of flint layers;

Conclusions

At Kingsdown to Dover, vertical cliffs in the Chalk undergoing active erosion rise above well-developed intertidal platforms. Beaches are mainly contemporary in origin and depend upon frequent rockfalls. Boulder ridges occur on many platforms and mark the former extent of cliff-falls. The site is distinguished by the rapidity and nature of the changes within it, and by the relatively simple morphology of the cliffs and platforms. This is an important cliff site that demonstrates well the role of structures in controlling cliff development.

This geomorphologically active site is important for understanding the nature of cliff failure and its effects upon platform development, and unlike many similar cliffs it can be shown to have become much more active during the past 100 years as the supply of shingle from the west and the residual protection from the older beaches has diminished. Unlike other Chalk cliff–platform sites, it has a large and active sediment supply but much of the platform is cloaked by boulders that affect wave-energy distributions. Internationally, this is one of a very small number of near-vertical cliffs that have been investigated in some detail. It is also potentially very important for understanding the links between cliff erosion and the supply of sediment to adjacent beaches.

BEACHY HEAD TO SEAFORD HEAD, EAST SUSSEX (TV 490 980–TV 600 968)

V.J. May

Introduction

The Chalk of the South Downs reaches the sea between Brighton and Eastbourne in a series of cliffs that become generally higher towards the east and culminate in the 150 m-high cliffs of Beachy Head (see Figure 4.1 for general location). This site comprises a cliff–beach–platform system developed on the Chalk, includes the classic world-renowned cliffs of Beachy Head and the Seven Sisters, and cuts across the mouth of the Cuckmere Valley (Figure 4.25). The cliffs reach a maximum height of 156 m at Beachy Head (TV 588 956) and vary between 14 m and 79 m in height along the Seven Sisters. Retreat

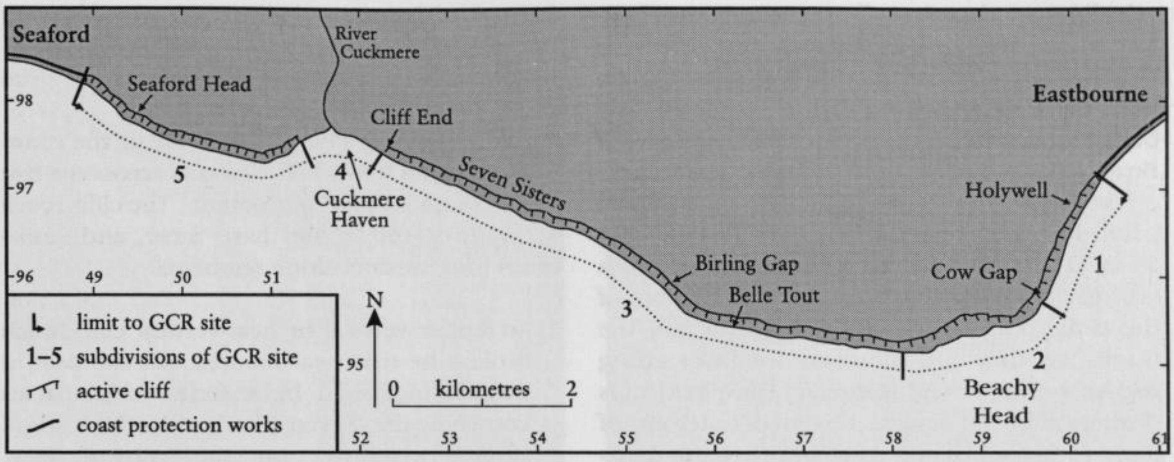


Figure 4.25 Sketch map of the Beachy Head to Seaford Head GCR site, showing the five subdivisions of the site as described in the text.

of the cliffs has been estimated at 0.42 m a^{-1}, reaching a maximum of 0.91 m a^{-1} at Birling Gap (May, 1971a). A narrow fringing beach of chalk and flint rests upon the cliff–platform junction, except where major falls, especially at Beachy Head, extend below low-tide level (Figure 4.26). Debris ramparts from cliff-falls are common at Beachy Head. The coastline plan is controlled primarily by dominant and prevailing wave energy from the south-west, with Seaford Head and Beachy Head acting as more resistant points between which a predominantly wave-energy controlled shoreline has developed. Structural variations seem to have had little effect upon the overall coastal plan, the cliff materials being sufficiently rapidly eroded to ensure control by wave action. However, in detail the cliffs are controlled by a rectilinear jointing pattern (see Figure 4.27). The beach is one of six major SW-facing beaches in southern England, all of which differ significantly in their geological characteristics. Most of the site faces south-west and is exposed to Atlantic waves. The fetch from the south-west is similar to that which affects all the major beaches in the English Channel. The cliff and beach of Seven Sisters in particular is unusual in having a very strong similarity in its alignment to such beaches as Chesil Beach and Dungeness. Of the beaches, Seven Sisters beach is the most rapidly and consistently fed by flint from cliff-falls. The most directly comparable cliffs also comprise Upper Chalk along the Normandy coast, but they lack the same aspect and degree of exposure.

Research here has been mainly restricted to understanding the nature and rates of cliff retreat (May, 1971a) and the relationship between the cliffs, platforms and the processes operating on them (Robinson and Jerwood, 1987a,b). They are nonetheless cited by a number of texts including Bird (1984), Holmes (1965), Small (1978), and Precheur (1960), the latter considering the contrasts with the similar Chalk coast of Normandy.

Description

The site comprises five sub-units (Figure 4.25):

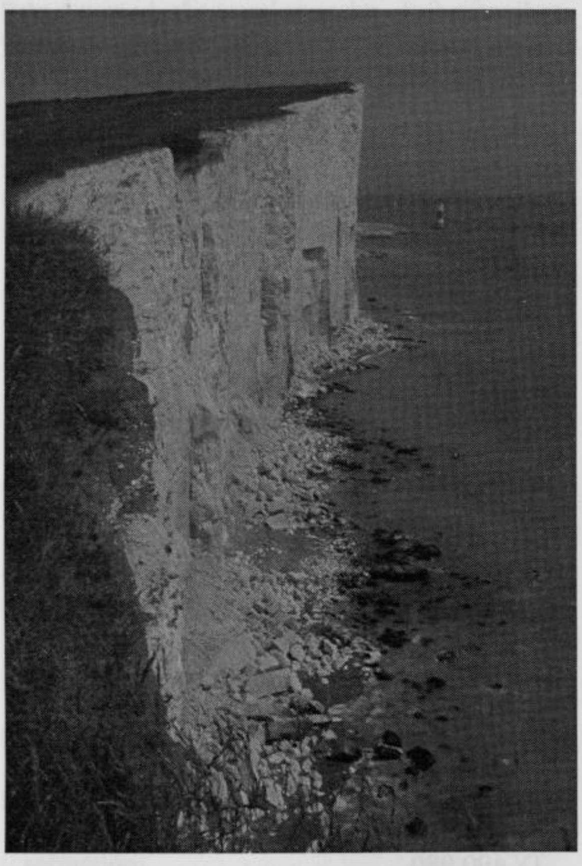
1. The Chalk cliffs and Greensand and Gault Clay platforms below Cow Gap and Whitebread Hole (TV 600 968 to TV 595 955).
2. The high complex cliffs of Beachy Head (TV 595 955 to TV 579 953).
3. The truncated dry valley mouths, cliffs and platforms of the Seven Sisters, including Birling Gap (TV 579 953 to TV 521 976).
4. The shingle beach and marine delta at Cuckmere Haven (TV 521 976 to TV 514 976).
5. The Chalk cliffs and platforms at Seaford Head and Hope Gap between TV 514 976 and TV 490 980.

Although most of the site is cut into the Upper Chalk, at Beachy Head the orientation of the coastline trends across the escarpment and virtually the whole of the Chalk from Lower to Upper Chalk is exposed (Figure 4.26). In addition, the Upper Greensand and the Gault Clay beneath crop out on the shore platform east of Beachy Head.

The easternmost part of the site is aligned south-west–north-east and has a cliff height of 24 m. The upper part of the cliff is formed by a staircase of narrow slipped blocks. At the foot of the cliffs, both the Upper Greensand and the Gault Clay crop out, failures in the latter giving rise to the upper cliff features. The platform is distinguished by several repeated outcrops of these rocks, which appear to be related to mass-movements that have penetrated below sea level. At the northern end of the site several springs flow from the top of the Plenus Marl and may affect the erosion of the cliffs. The beach is formed of flint and chalk rubble, and extends northwards towards Eastbourne where it is dominated by flint, the Chalk typically being worn down over a distance of about 1 km.

On the eastern side of Beachy Head, the coastline is aligned WSW–ENE and cuts across the line of the South Downs escarpment. The cliffs reach a height of 160 m and have three, and sometimes four, distinct slope segments.

1. An upper vertical or near-vertical cliff, much broken by tensional fissures. In the past, it was distinguished by a series of pinnacles known as the 'Seven Charleses', which stood about two-thirds up the vertical face. Although the pinnacles are said to have disappeared before the end of the 19th century (Castleden, 1982), similar forms continue to occur on this slope. Failures of the cliff carry



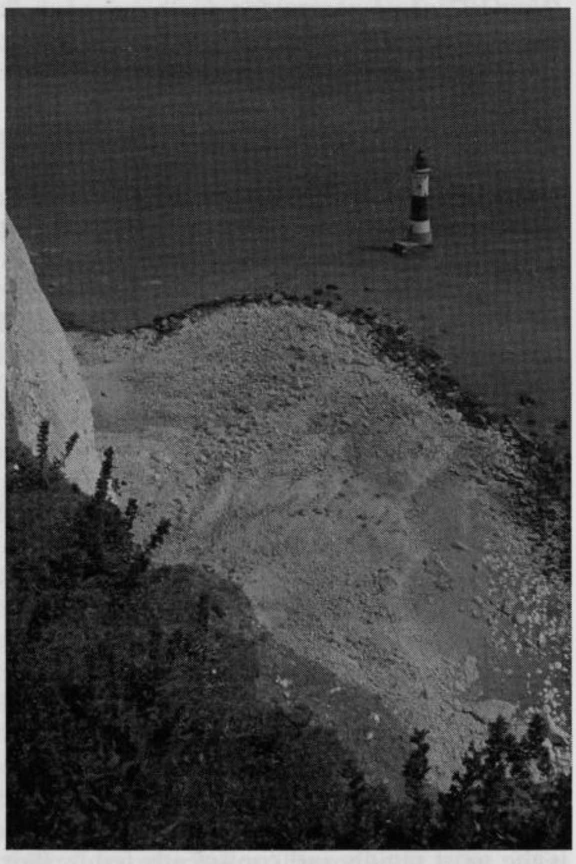


Figure 4.26 (a) Beachy Head, cliff top view looking east, the cliffs are characterized by slab failures in the lower cliff that gradually undermine the upper cliff. (b) Cliff collapse at Beachy Head, early 1999; the failure affected the whole cliff face and produced a very large debris area at the cliff foot. (Photos: V.J. May.)

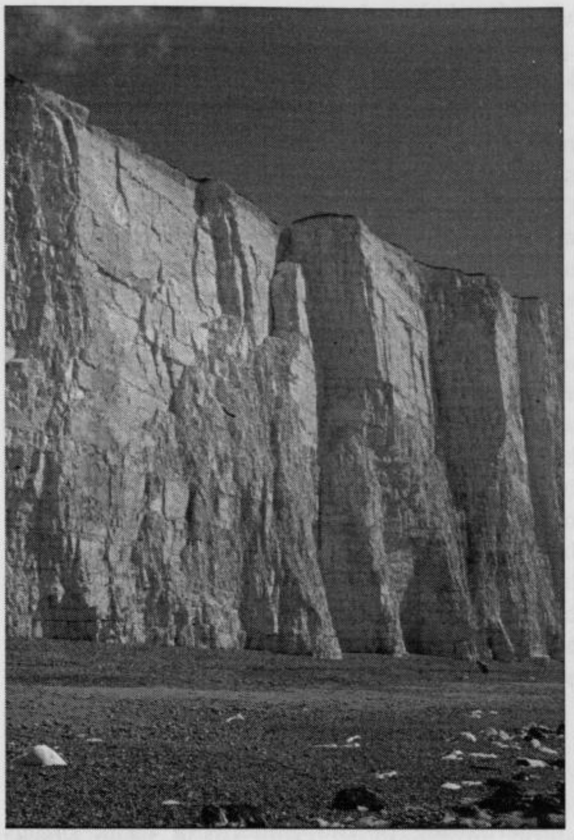


Figure 4.27 Relationships between joints, cliff morphology and retreat near Birling Gap. (Photo: V.J. May.)

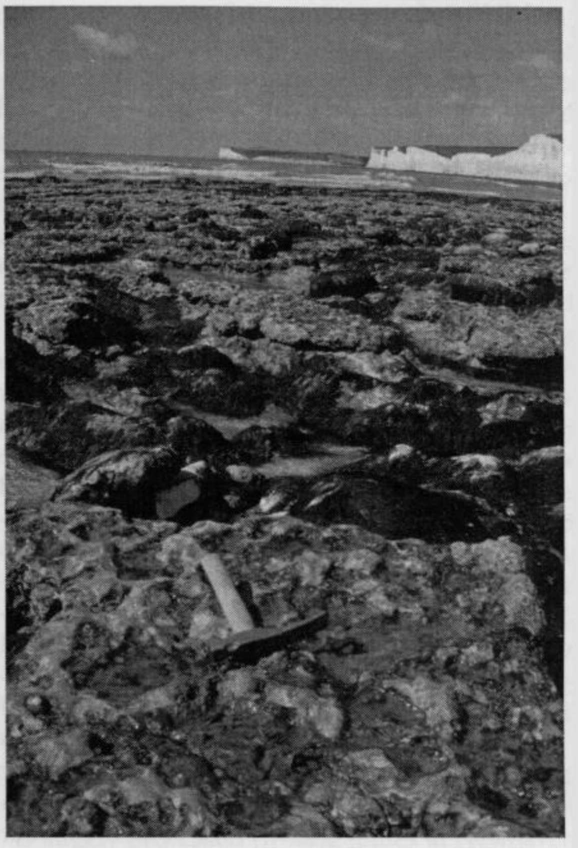


Figure 4.28 Detail of the chalk and flint platforms east of Birling Gap. (Photo: V.J. May.)

debris to its foot.

2. A middle vegetated segment, which has angles around 60°. The length of the slope varies considerably, sometimes forming the majority of the cliff. At some points, it is almost totally bare of vegetation and appears to be a shear plane along which failure has occurred.
3. A lower steep bare rock cliff, which is currently attacked by wave action, but may have been exhumed from beneath a debris fan. Wave energy at the foot of the cliff is much-modified by the alternation of debris with cliffed embayments.
4. A debris slope formed of material that has fallen from the upper cliffs.

Generally having angles of about 30°, these debris slopes often extend from below low-water mark, sometimes joining the middle slope segment. They provide considerable protection to the foot of the cliff. Older debris has often left a residual cover of boulders on the platform. At the western side of Beachy Head, these act as a natural groyne reducing the transport of shingle eastwards from the Seven Sisters. Pocket beaches of flint and chalk rubble occur between the debris fans.

The Chalk shore platform extends beyond low-water mark, providing the foundations for the Beachy Head Lighthouse. The water around this part of the site is characterized even during gentle seas by greatly increased turbidity because chalk fines are commonly in suspension.

Between the western side of Beachy Head (TV 579 953) and Birling Gap, the cliffs are similar to those of the Seven Sisters. In contrast to the Seven Sisters, however, these cliffs produce large debris fans and many residual boulders form curved low ridges on the platform, a pattern noted along the coastline east of Dover. Beachy Head itself is distinguished by many small high-frequency rockfalls, but there are also infrequent very large events, the most recent occurring on 11 January 1999. A mass-movement event affected the whole height of the cliff over 200 m in length. The debris from the slide extended seawards to the base of the lighthouse and was marked by a seaward boundary of very large boulders (in excess of 3 m in diameter). Similar events are recorded on maps dating from the earlier part of the 20th century (Figure 4.26b).

The Seven Sisters have been cut across the dip of the Chalk and the cliffline truncates seven dry valleys (Figure 2.9). The cliffs rise to over 72 m in height, but their lowest points occur at the valley mouths (heights of 18 m at Crowlink and 12 m at Birling Gap). The dry valleys are underlain by Coombe Rock, and the Chalk has also been affected by periglacial heaving and shattering. At both Crowlink and Birling Gap, this sub-valley weaker material passes below sea level and the platform is cut lower here than elsewhere as a result. At Birling Gap, the rate of retreat has been higher than on the other cliffs (Table 4.2). The cliffs are vertical, with a narrow platform upon which rests an intermittent beach of chalk and flint shingle. Much of this sediment is derived from the erosion of the cliffs.

May (1971a) showed that between 1950 and 1962 cliff-top retreat at Birling Gap varied substantially both from year to year and between winter and summer. Of cliff-top land-loss, 87% occurred during winter. Most retreat took the form of long narrow strips or small lens-shaped areas. Over the timescale of this survey the cliff-top retreat was close to parallel, whereas over the seasonal scale it was much more spasmodic in time and location. Very large falls, such as at Baily's Brow in 1925, estimated at half a million tonnes (Castleden, 1982), are less common. Along this cliff, marine erosion is very effective in removing the debris from cliff-falls of all sizes. The cliff is undercut and frequently collapses along the line of joints, which are at a slight angle to the cliff-face. The failures appear to have a toppling nature, responding to the slight seawards dip of the Chalk. The strong winter frequency of cliff retreat may also be attributed to the effects of frost, and increased pore pressures. Weathering of the cliffs and platform produce substantial quantities of smaller debris, which together with the debris from falls, provide the main input to the beaches. In contrast to the generally narrow and discontinuous beaches below the Seven Sisters, large beaches occur at Birling Gap (Figure 4.27) and below the western cliffs of Beachy Head. Like the others, they are predominantly composed of rounded chalk pebbles and angular flint. The beach at Birling Gap fills the slight embayment formed by the more rapid retreat of the cliffs and lowering of the platform. Its alignment is strongly related to the dominant and prevailing waves. As a result it tends to smooth the plan of the shoreline between the cliffs east and west of the beach. The platform is lower at Birling Gap partly as a result of the deep weathering of the Chalk associated with the dry valley and also the absence of flint layers within the platform (Figure 4.28). To both east and west, the beds dip slightly eastwards and flint bands form sloping surfaces that are truncated.

Although the platforms along this coast have been commonly described as erosional features, little account has been taken of the role of the flint bands in controlling the micro-relief. Thus although there is an accordance of heights along the platform, the platform is a series of gently sloping micro-cuestas (Figure 4.28), with scarps on their western side at a point where the undercutting of the underlying chalk brings about collapse of the flint cap.

At Cuckmere Haven, the lower River Cuckmere is now channelled artificially between two groynes. In the past however, the river was deflected to the east by a shingle spit to enter the sea below Cliff End. Both in the past and at the present, the river forms a series of frequently changing distributaries that produce a small delta. This is an unusual feature, both on the coast of south-east England and on a coast undergoing rapid erosion. It suggests an effective fluvial sediment supply to the beach as well as considerable reworking of beach sediments by the river distributaries. This is the only beach within the site that contains rolled oxidized flint shingle as the predominant constituent. Elsewhere, high proportions of the beach comprise rolled chalk and much angular and sub-angular flint recently derived from the cliffs and platform.

The westernmost part of the site is formed by Upper Chalk cliffs that rise to 85 m at Seaford Head. The cliffs east of Seaford Head itself are affected by a series of vertical joints and have a generally vertical form. At Short Cliff, the cliffs are less steep and include gentler facets. At Hope Gap, the cliffs truncate a dry valley exposing the weakened chalk beneath the valley floor to erosion both in the cliffs and in the platform. Parts of the Chalk are overlain by deposits of orange-brown sands, silts and clays that are well-exposed at Short Cliff. They have been described as Palaeogene beds modified during the early and mid-Pleistocene (Castleden, 1982) and appear to have played an important part in the development of pipes in the Chalk. The pipes can be seen in the cliff face, sometimes descending, as at Short Cliff, to high-water mark. On the platform, Castleden has noted up to a dozen circular holes up to 1 m in diameter which show that piping extended well below present sea level. Their rims sometimes stand several centimetres above the platform (see also GCR site report for South Haven Peninsula in Chapter 7). The platform is well-developed, and its micro-relief is strongly affected by differential erosion along joints that run at right angles to the shoreline. As much as 1 m in depth, these eroded joints act as drainage channels for the platform.

Interpretation

The cliffline of the Seven Sisters shows strong adjustment to the primary direction of wave approach from the south-west, the headlands at Seaford and Beachy Head acting as strongpoints between which it is aligned (see Figure 2.9). The mouth of the Cuckmere River also affects the coastal alignment. Nevertheless, this coast retreats more-or-less parallel and at a similar rate to shingle beaches that share the same wave climate, such as the southern side of Dungeness. The modern production of beach sediment is small and does not offer much protection to the cliffs. At Birling Gap, the beach should provide greater protection, but this is not the case. The role of the debris overlying the cliff foot and the platform may be considerable, both in supplying tools for abrasion and erosion and also in affecting water flow over the platform. There is little understanding of the sub-beach weathering of chalk platforms (but see GCR site report for The Dorset Coast: Peveril Point to Furzy Cliff in Chapter 11), in contrast to Robinson's (1977a–c) work on Lias platforms around Robin Hood's Bay. Robinson and Jerwood (1987a,b) have demonstrated the importance of subaerial weathering of the platforms during severe winters, when freezing and thawing produce considerable breakdown of the platform surface. This process releases both chalk and flint clasts, but as elsewhere on the Chalk coasts, only flint makes any long-term contribution to the beach sediment budget. The flint bands play a critical role in controlling the micro-relief of the platforms and so allow higher wave energy inputs to the cliff foot at lower points.

Erosion along this coast has been very active throughout its recent history, but despite the considerable activity at Beachy Head the Head itself has remained salient. The large debris fans provide a substantial degree of protection, with wave energy reduced slightly as the coastal alignment changes. Even so, the equilibrium between effective removal of debris and its retention is finely balanced. It appears to be strongly related to the size of debris produced by the rockfalls, for debris of small size is rapidly removed. Where a rockfall contains a large boulder element, it appears that the rate of boulder reduction (which is a function of boulder size) brings about greater roughness of the intertidal platform and thus more effective wave attenuation.

The longshore transport of beach sediment, particularly rounded flint shingle, from the west is largely prevented by long jetties at Newhaven and a long groyne at the eastern end of Seaford Beach. The older rounded and oxidized flint shingle, which forms beaches in West Sussex and to the east of this site at Pevensey, has been replaced almost exclusively in this site by recent subrounded and subangular flint and chalk clasts. The effects of longshore transport are such that only limited quantities of shingle derived from the falls at Beachy Head can travel to the west. As a result, this beach system now relies upon contemporary inputs of sediment. Both Seaford Head and Beachy Head act as headlands between which the less-protected more-active cliffs and beach of the Seven Sisters have adapted to the dominant and prevailing south-westerly waves. In this respect, these Chalk cliffs contrast strongly with all other chalk cliffs in England. The majority are more strongly controlled in their alignment by structural features (e.g. Kingsdown to Dover), the nature of the cuesta into which they are cut (e.g. south-west Isle of Wight) or have very complex shorelines resulting from structural weaknesses at high angles to the shoreline (e.g. Flamborough Head). The rapidity of erosion and the relatively sparse beach mean that much of the Seven Sisters coast acts in a similar way to major beaches in adjusting to the alignment of the dominant wave direction. Among British cliffed coasts, other than those in weak sands and clays, this is unusual. This site is a member of a suite of some six beach or beach–cliff English Channel sites that show a similar alignment towards the south-west and comparable adjustment to the wave energy input, even though they occur in different rocks or have variable supplies of beach sediment.

The geomorphological interest of this site is very high, even though, like most cliffed sites, it has not been thoroughly investigated. The potential for increasing our understanding the ways in which cliffs and platforms develop through studying this site is substantial.

The Beachy Head to Seaford Down GCR site is of particular importance to coastal geomorphology because of the following features:

1. the well-developed cliff–beach–platform sequence, in which platform development is directly related to cliff retreat and both processes depend upon, but also control, beach volume;
2. well-developed platforms, notably at The Mares and Birling Gap;
3. solution piping in the cliffs and platforms;
4. a marine delta at Cuckmere Haven;
5. truncated dry valleys in the Seven Sisters;
6. rapid cliff erosion associated with efficient removal of debris from falls and a limited supply of flint to the beaches;
7. very active high cliffs at Beachy Head supplying substantial quantities of sediment to the local beaches;
8. the development of a platform across slipped blocks of Gault Clay and Upper Greensand, an especially rare feature because it preserves several major mass-movement events.

Conclusion

The cliffed coast between Beachy Head and Seaford Head is a GCR site of worldwide landscape importance, and international importance to research into coastal geomorphology because of the links between cliff, beach and platform development, the alignment of the shoreline to the dominant wave conditions, the contemporary sediment supply to its beaches, the almost total lack of relict sediment ources, and its contrasts with other coastlines formed in the Chalk.

BALLARD DOWN, DORSET (SZ 041 825)

V.J. May

Introduction

Ballard Down (see Figure 4.1 for general location) forms a distinct promontory at the eastern end of the Isle of Purbeck where differential erosion of sands and clays to the north and south of the Chalk cuesta has produced Studland Bay and Swanage Bay respectively. Strahan (1898), Davies (1935) and Arkell (1947) described the stacks and cliffs around Old Harry Rocks, and Steers (1946a) described its main features. Precheur (1960) related the formation of the stacks to jointing in the Chalk. May and Heeps (1985) describe some of the changes that have taken place. Despite the comparative lack of research at this site, it is widely used as a textbook example of the cave–arch–stack–stump sequence (Figure 4.29).

Ballard Down is a key site for coastal geomorphology, and one of many GCR sites that collectively form the Dorset and East Devon Coast World Heritage site, which was declared on account of its Earth science features of interest. Ballard Down includes a series of predominantly Chalk cliffs, platforms and associated beaches, best known for the classic assemblage of stacks, arches and caves at Handfast Point (May and Heeps, in press). The site is also important for revealing not only the relationships between local tectonic structures and coastal form, but also the effects of different wave dynamics on the north and south sides of the peninsula. In terms of wave energy, Ballard Down is the most sheltered of the major Chalk cliff systems and forms a key element in the network of such sites.

Description

The Ballard Down GCR site lies to the north of Swanage and is cliffed throughout its length. The cliffs rise from about 30 m on the Wealden clays in Swanage Bay to 117 m at Ballard Point (SZ 040 813). They then fall to little more than 20 m at Handfast Point where they turn west and continue at a similar height to the northern end of the site towards Studland on the Reading Beds and London Clay in Studland Bay. These cliffs can be divided into six different sections.

First, the clay and sand cliffs that cut across the northward-dipping Wealden and Lower Greensand rocks at the northern end of Swanage Bay, and are marked by many small mass-movements as well as some larger slides that have brought about a scalloped outline to the plan form of the cliff top. These unstable cliffs collapse onto the predominantly shingle beach, and small lobes and fans of debris occasionally spread onto its upper surface. There are several springs within these cliffs that give rise to local gullying, as well as the larger surface movements.

Second, from SZ 040 810 to SZ 048 813 (Ballard Point), the cliffline cuts at a very acute angle across the south-facing Chalk scarp of Ballard Down. The Chalk dips northwards here at angles ranging from 60° to 90°. The slopes have vertical sections both near to the top and particularly towards Ballard Point, but much of the cliff is characterized by shallow slides, scree slopes and a cover of scrubby vegetation (Figure 4.30a,b). Marine action is only effective at the eastern end where these subaerial features become less dominant and the cliff-foot protection afforded by boulders and a shingle beach diminishes.

Third, from Ballard Point (SZ 048 813) to the southernmost of the Pinnacles (SZ 053 820) the cliffs are close to vertical and cut across the Chalk either side of the Ballard Down Fault. Despite the considerable changes in dip either side of the fault, there is no significant change in cliff-form. Throughout this section the cliffs fall directly into the sea. There is no intertidal platform, although there is occasionally a narrow beach of Chalk and flint shingle exposed at low tide. A submerged platform with a veneer of boulders extends seawards from the foot of the cliffs. The cliff foot is undercut in parts and there are several small caves, including one where the Ballard Down Fault reaches sea level.

Fourth, from the Pinnacles to Handfast Point, the coastal forms become increasingly more complex, with five small bays, several stacks, and many small caves and arches (Figure 4.31). The largest cave, Parson's Barn, is 12 m in height at its mouth. May and Heeps (1985) mapped the changes between 1887 and 1982, showing how the stacks at Handfast Point have developed (Figure 4.31). Precheur (1960) considered that the stacks developed where the sea has eroded a series of major vertical joints. These can be seen in the blocks that have not yet separated from the mainland. Small caves usually develop at sea level; arches cannot form, according to Precheur, because the Chalk forming the upper part of the cliffs is too weak to form permanent roofs. The stacks, in contrast, are relatively

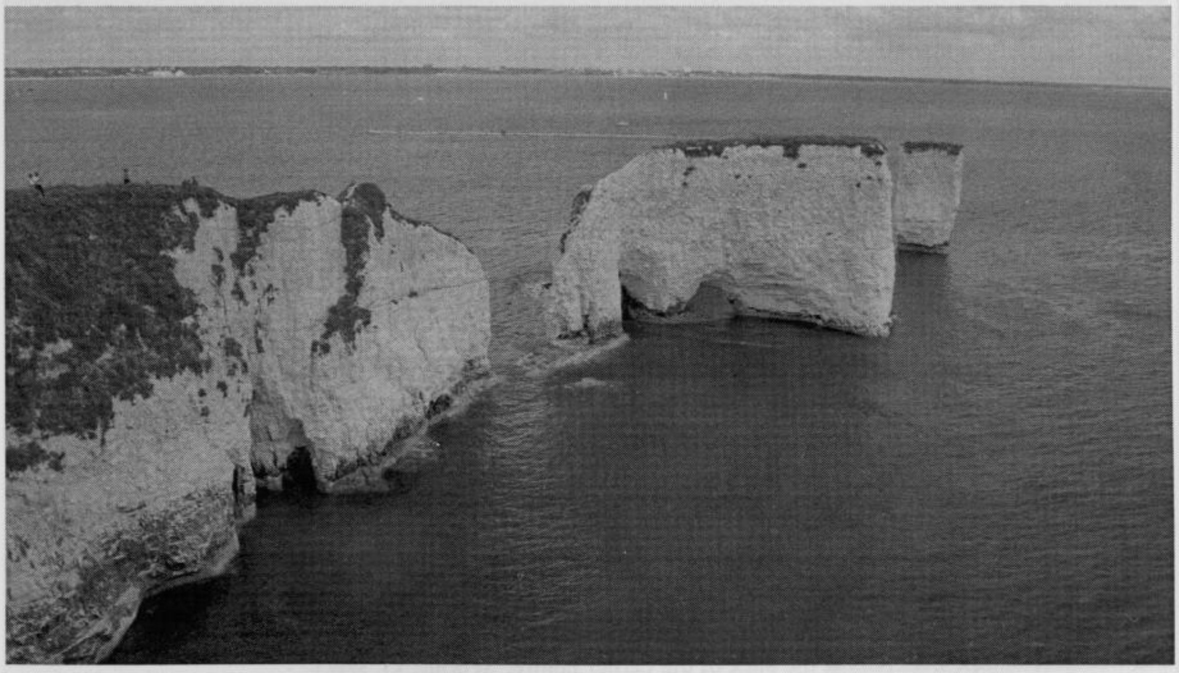


Figure 4.29 The cave–arch–stack sequence at Handfast Point, looking north-east, with Old Harry Rocks to the right. (Photo: V.J. May.)

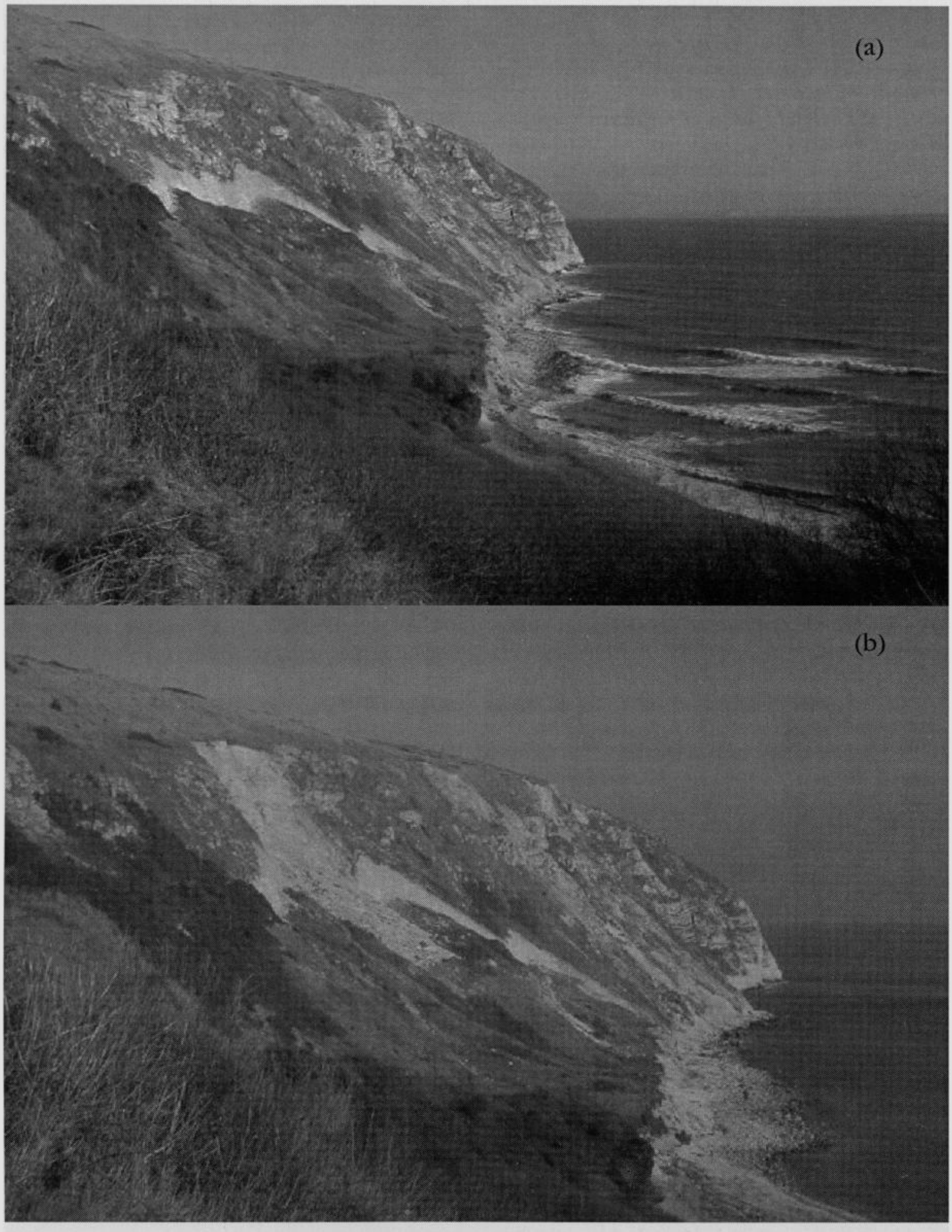


Figure 4.30 Ballard Down. Views looking east from SZ 038 810(a) taken on 12 January 2001 and (b) on 16 January 2001, showing the development of the landslip over four days. In (a) note the chalk scar formed by the failure of the slope. In (b), note the rectangular scar of the shallow rockslide that followed removal of bedrock and weathered slope materials at the back of the earlier failure. (Photo: V.J. May.)

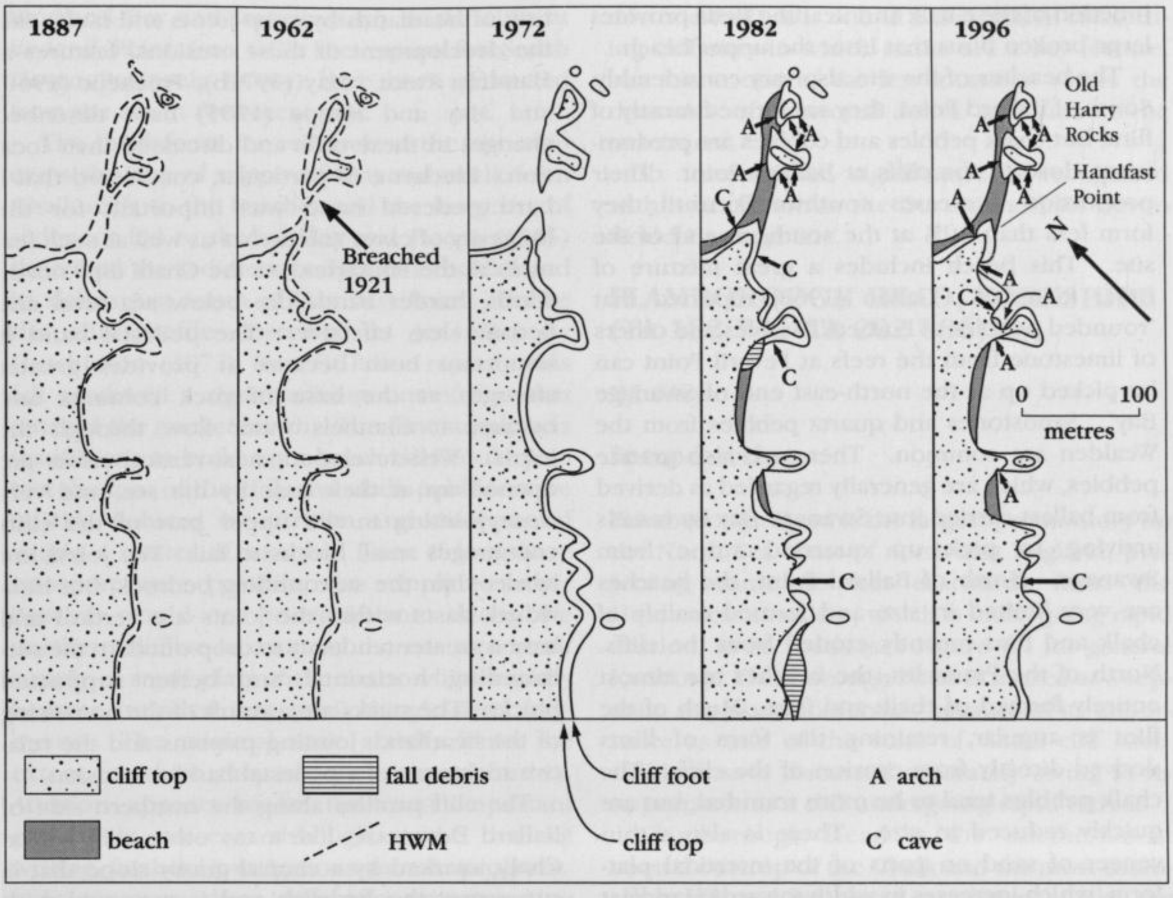


Figure 4.31 Cave–arch–stack development at Handfast Point 1887–1996. (Sources: 1887 Ordnance Survey and May and Heeps, 1985)

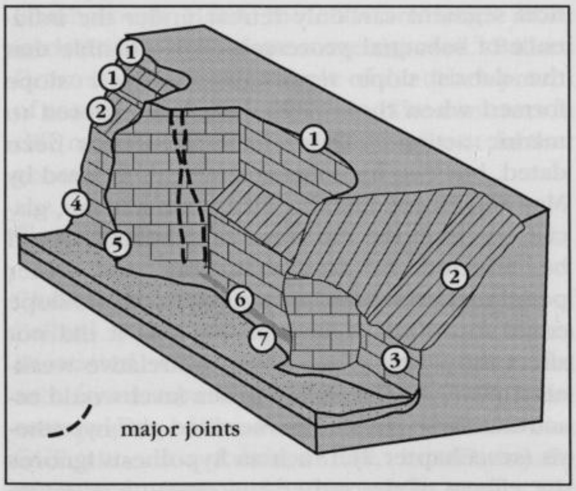


Figure 4.32 Multi-faceted northern cliffline west of Handfast Point towards Studland. 1. Vertical upper cliff; 2. vegetated debris slope; 3. lower vertical cliff; 4. smooth cliff-platform junction; 5. notch; 6. flint and chalk pocket beach; 7. chalk platform.

resistant to erosion as their foot is formed of harder Chalk. May (1971b) outlined the relationship of the erosional forms to the jointing pattern.

Fifth, the cliffs forming the northern sheltered side of Ballard Down, to the west of Handfast Point, appear to have a simple vertical form, but detailed surveys show that their form is made up of several facets (Figure 4.32). May and Heeps (1985) described the cliffs as affected only by rainwash, frost-action and gentle wave action. Notching and undercutting is rare. According to May and Heeps, many of the cliff profiles have a central truncated debris slope upon which further research is required.

Finally, at the western end of the Chalk cliffs towards Studland, the cliffs are cut in the Reading Beds and the London Clay and are affected by small slides and gullying, some of the latter associated with paths between the beach and the cliff top. Erosion of the lower cliff at the junction of the Chalk and Reading Beds provides large broken flints that litter the upper beach.

The beaches of the site also vary considerably. South of Ballard Point, they are formed mostly of flint, but chalk pebbles and cobbles are predominant close to the cliffs at Ballard Point. Their proportion decreases southwards until they form less than 10% at the southern end of the site. This beach includes a great mixture of other materials. Calkin (1968) reported that 'rounded pebbles of Purbeck Marbles and others of limestone from the reefs at Peveril Point can be picked up at the north-east end of Swanage Bay'. Sandstones and quartz pebbles from the Wealden are common. There are also granite pebbles, which are generally regarded as derived from ballast carried into Swanage Bay by vessels arriving to pick up quarried stone from Swanage. North of Ballard Point, the beaches are very limited in size and formed mainly of chalk and flint recently eroded from the cliffs. North of the Pinnacles, the beaches are almost entirely formed of chalk and flint. Much of the flint is angular, retaining the form of flints derived directly from erosion of the cliffs. The chalk pebbles tend to be more rounded, but are quickly reduced in size. There is also a thin veneer of sand on parts of the intertidal platform, which increases in width towards Handfast Point. West of Handfast Point, the beach and platform are narrow, but increasingly cloaked westwards by cobbles of chalk and flint. Below the cliffs of Reading Beds and London Clay, the beach includes more sand, although there are considerable spreads of chalk and flint cobbles as well.

Interpretation

Research at this site has focused on three issues:

1. the question of the development of the stack–arch–cave complex at Handfast Point, and its relationship to the strength and structures of the Chalk,
2. the nature of the cliff profiles along the northern side of Ballard Down,
3. the relationship between cliff erosion, beach development and protection of the cliff foot by beaches and debris.

Like several other Chalk sites, Ballard Down has a set of well-developed stacks, arches and caves associated with a headland. The penetration of headlands by cross-joints and faults aids the development of these erosional features at Handfast Point. May (1971b), Precheur (1960) and May and Heeps (1985) have described changes in these cliffs and discussed their location. Precheur, in particular, considered that a hard pedestal band was important for the longevity of caves and arches as well as such features as the Pinnacles. As the Chalk dips northwards, harder bands dip below sea level and become less effective. The pedestal band is important both because it provides greater strength at the base of rock columns and because it channels water flow through the joints. Well-developed, near-vertical joints are opened up at their base by the sea, and very close jointing in the upper part of the cliffs encourages small blocks to fail. The joints are harder than the surrounding bedrock, but individual clasts within the joints are vertical and have a greater tendency to drop out than the surrounding horizontal and better supported blocks. The stacks are a result of the narrowing of the headland, jointing patterns and the relative resistance of a pedestal band to erosion.

The cliff profiles along the northern side of Ballard Down are, like many other cliffs in the Chalk, marked by a central grassy slope that is cut across the bedrock and is veneered with chalk debris. The size of this debris slope tends to increase towards the western end of the cliffs. Marine undercutting of the lower cliff has been too slow to destroy this segment. The upper vertical segment can only retreat under the influence of subaerial processes. It is possible that the debris slope represents a former slope formed when these cliffs were less exposed to marine action. These forms have not been dated, but two hypotheses were put forward by May and Heeps (1985). First, with a lower, glacial, sea level the dip slope of the Chalk would be affected by frost-shattering and other periglacial processes. As a result, a debris slope could form, but it is surprising that it did not affect the whole slope given the relative weakness of the Chalk. A rise in sea level would re-activate these cliffs in the bevelled cliff hypothesis (see Chapter 2). Such an hypothesis ignores the effects of the rather late opening of Poole Bay. A second alternative is that these cliffs have been active during the period since sea level reached its present position, but were protected temporarily. This is a possibility since there have been very large accumulations of sand in

Studland Bay and features such as the cliffs at Redend Point (see GCR site report for South Haven Peninsula below) have been protected from the sea in the recent past.

The third focus for research at the site concerns the rate of supply of flint and chalk from Chalk cliffs to the beaches and the longevity of sediment fed to them. May and Heeps (1985) described the sediment budget of a rockfall and its debris just south of Handfast Point. Unlike the cliff profile described at Joss Bay by Hutchinson (1972) (see GCR site report), this fall produced a significant amount of flint that entered the pocket beach. The flint supply was insufficient to build up a beach that could protect the foot of the cliff, and chalk pebbles were quickly reduced by attrition and disappeared within a matter of months. Even if longshore transport were possible, the supply to other beaches would not be significant. Along the northern cliffline in contrast, there is a constant supply of small platy chalk clasts, which rapidly become rounded into small shingle-sized fragments. The minimal wave activity limits the extent to which they are then moved further. Attrition appears to be the most important process at present, although at the time of writing, further investigations were in progress.

In summary, these cliffs offer an interesting contrast to two other east-facing cliffed sites in the Upper Chalk, Joss Bay and Flamborough Head. At Joss Bay, there is less variation in dip and there are very wide platforms. At Flamborough Head, the cliffs are much more intricate in plan and are more exposed. Ballard Down is a textbook example of the development of coastal forms such as stacks. The contrasts in cliff morphology within the site give it further geomorphological importance.

Conclusions

Chalk cliffs and platforms in the northern part of Ballard Down are comparatively simple when contrasted with very complex stack, cave and arch forms around Old Harry Rocks. With the eastern part of the Furzy Cliff to Peveril Point GCR site, this forms a fine, internationally renowned, example of a transverse coast. The development of caves, arches, and stacks is a major feature of this site, but it is also an excellent example of the ways in which steep cliffs change as a result of both marine and subaerial processes. Unlike many such sites it is well-documented. It is one of a network of contrasting cliff sites in which stacks are a key feature, but this is one of the few locations where the dynamics of erosional forms continue to be monitored.

Its international significance is recognized with its inclusion in the Dorset and East Devon World Heritage Site.

FLAMBOROUGH HEAD, YORKSHIRE (TA 182 746–TA 202 686)

V.J. May

Introduction

Flamborough Head is the largest promontory on the North Sea coast of north-east England, projecting some 10 km eastwards from the Holderness coastline, which is undergoing rapid erosion, to its south (see Figure 4.1 for general location). Flamborough Head is treated as a separate site from Holderness because of its importance as one of the suite of Chalk cliff sites. Holderness is discussed separately owing to its importance as a cliff undergoing rapid retreat.

Flamborough Head is the northernmost coastal outcrop of the Chalk and the most extensively affected by glacial conditions. Like the Chalk cliffs of the North Downs in Kent, Ballard Down in Dorset and Tennyson Down in the Isle of Wight, the cliffline at Flamborough Head cuts across the Chalk cuesta and many different parts of the Chalk succession are exposed. This situation, combined with the effects of different levels of exposure to wave action, has brought about considerable variety of coastal forms within the site.

Flamborough Head forms part of the GCR network of Chalk coastlines and it lies within the zone of North Sea wave climate, unlike the majority of other GCR sites, which are partly or wholly affected by Atlantic swell and English Channel wave climates. Winds are generally offshore, but important secondary wind and wave directions are from the south, east and north-east, the latter being important in winter. The fetch for many waves generated in the southern North Sea is generally less than 700 km, whereas waves generated from a northerly sector may have a fetch extending into the Arctic area. As a result, much of the site is affected by long-refracted swell (Figure 4.33; see also GCR site reports for Holy Island, Chapter 11, and

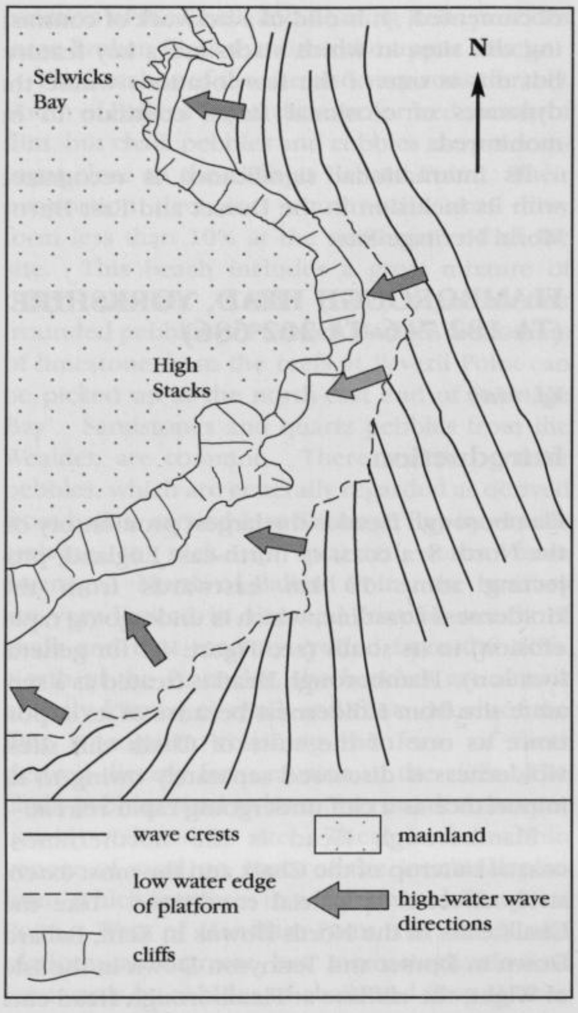


Figure 4.33 Wave refraction at Flamborough Head, showing variations in wave direction crossing the platform owing to wave refraction. See Figure 4.34 for location. (Based on aerial photographs in Pethick, 1984.)

Marsden Bay, Chapter 7). It is also the only GCR coastal geomorphology Chalk locality that is extensively overlain by glacial deposits. The northern cliffs are relatively simple, both in plan and profile (Figure 4.34); they feed small amounts of flint to their fringing beaches. The Chalk is extensively faulted, with some 1340 faults within one 6 km length (Peacock and Sanderson, 1993, 1994). Many excellent examples of caves, arches and stacks are associated with this faulting, and a number of blowholes have developed where the overlying till has collapsed into caves that intersected the Chalk–till junction. One contributing factor to the large numbers of caves has been the hardness of the Chalk. Secondary diagenetic deposition of calcium carbonate in the chalk pore spaces has produced chalk cliffs that are much more resistant to erosion than the Chalk of similar age in southern England. Shore platforms are well-developed both in this area and along the southern shoreline, where the beach is mainly sandy, and lacks flints. Marine processes vary from north to south: the southern cliffs are less active than those to the north.

As with many cliffed coastlines, there are more passing references to Flamborough Head in the literature than detailed studies of it. Nevertheless, the nature of both its cliffs and platforms has been commented upon in more general descriptions of the coast (Steers, 1946a; Straw and Clayton, 1979; Pethick, 1984) and discussions of platform morphology (for example, Trenhaile, 1974b).

Description

This site has three main subdivisions (Figure 4.34):

1. The northern cliffs between Bempton (TA 182 746) and Long Ness (TA 228 725), where the dip of the Chalk is to landward at about 20° (Figure 4.35b);
2. the complex coastline around Flamborough Head itself between Long Ness (TA 228 725) and Cattlemere Hole (TA 256 703; Figure 4.35a); and
3. the southern cliffs from TA 256 703 to the western boundary of the site at Sewerby, where the dip of the strata in the cliffs is to seaward (Figure 2.1b).

The northern cliffs, known as 'Bempton Cliffs', fall southwards from about 110 m at the northern edge of the site to about 65 m at Long Ness (TA 228 725). A narrow platform, Chalk and flint shingle beach and debris from rockfalls extend about 75 m from the foot of the cliff seawards to the low tide mark (Figure 4.35b). Both their plan and profile are simple. Straw and Clayton (1979) have suggested that wave erosion has been particularly severe on this coastline 'where, opposite a long northern fetch, the Bempton cliffs rise a sheer 130 m'. Steers (1946a) described the cliffs as being in greatly contorted flinty Chalk, but the contorted nature of the Chalk has not affected the cliff-form to any significant extent. At Staple Nook, there is a slight indentation of the coast associated with

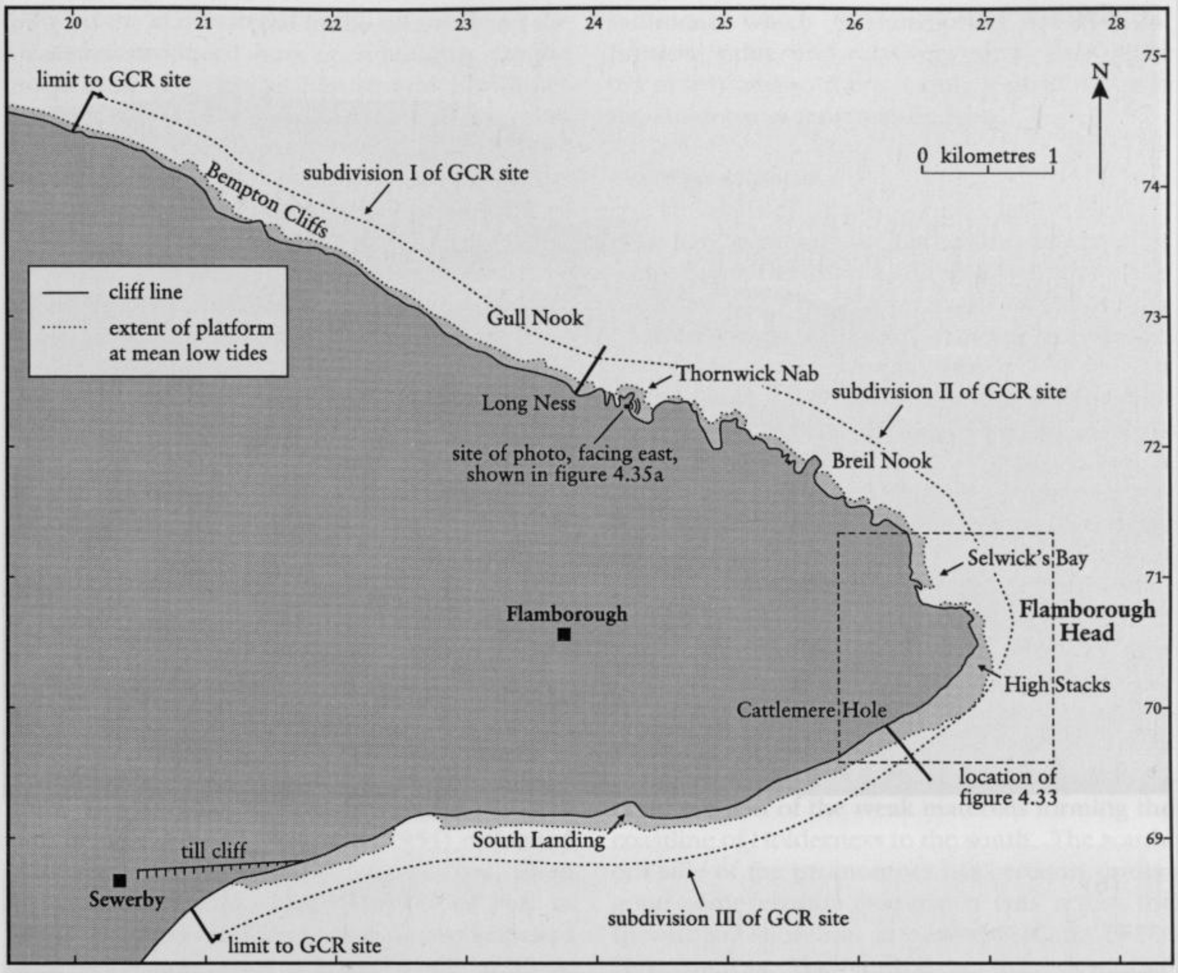


Figure 4.34 Sketch map of the Flamborough Head coastal geomorphology GCR site, showing the three main divisions of the locality.

weaker contorted Chalk.

The central cliffs are cut in the Middle and Upper Chalk (*Terebratulina lata*–*Micraster coranguinum* biozones) and are characterized by numerous caves, arches and stacks. There are well-developed, structurally controlled, platforms with many vertical joints and small faults exposed both in the surfaces of the platforms and in the cliffs (Figure 4.35a). Marine erosion along the joints and faults has been especially effective in developing a very large number of erosional forms. There are some 50 distinct inlets along this section of the coast. They vary in nature from caves and narrow steep-sided geo-like forms to small bays, over 55% of which are aligned towards the NNE and north-east and about 15% towards WNW. Devensian till cappings give the upper cliffs a complex profile that has been much affected by landslips. The lower part of the profile is steep, often with a tendency to overhang at its base. The plan of the cliffs is affected both by the erosion of the many structural weaknesses and by the form of the subglacial surface. Where former valleys have been truncated by the sea, and also where the dip of the Chalk brings the subglacial boundary closer to sea level, the sea has been able to erode inlets and bays more effectively. The dolomitized Chalk has also been affected by periglacial processes and much of it is deeply shattered, thus reducing its general resistance to present-day weathering and marine erosion.

There are several blowholes within large hollows in the till. These have developed where caves in the Chalk have grown upwards to the boundary between the Chalk and the till. Whereas the blowhole outlet would remain small if it were in the Chalk, the lower slope sta-

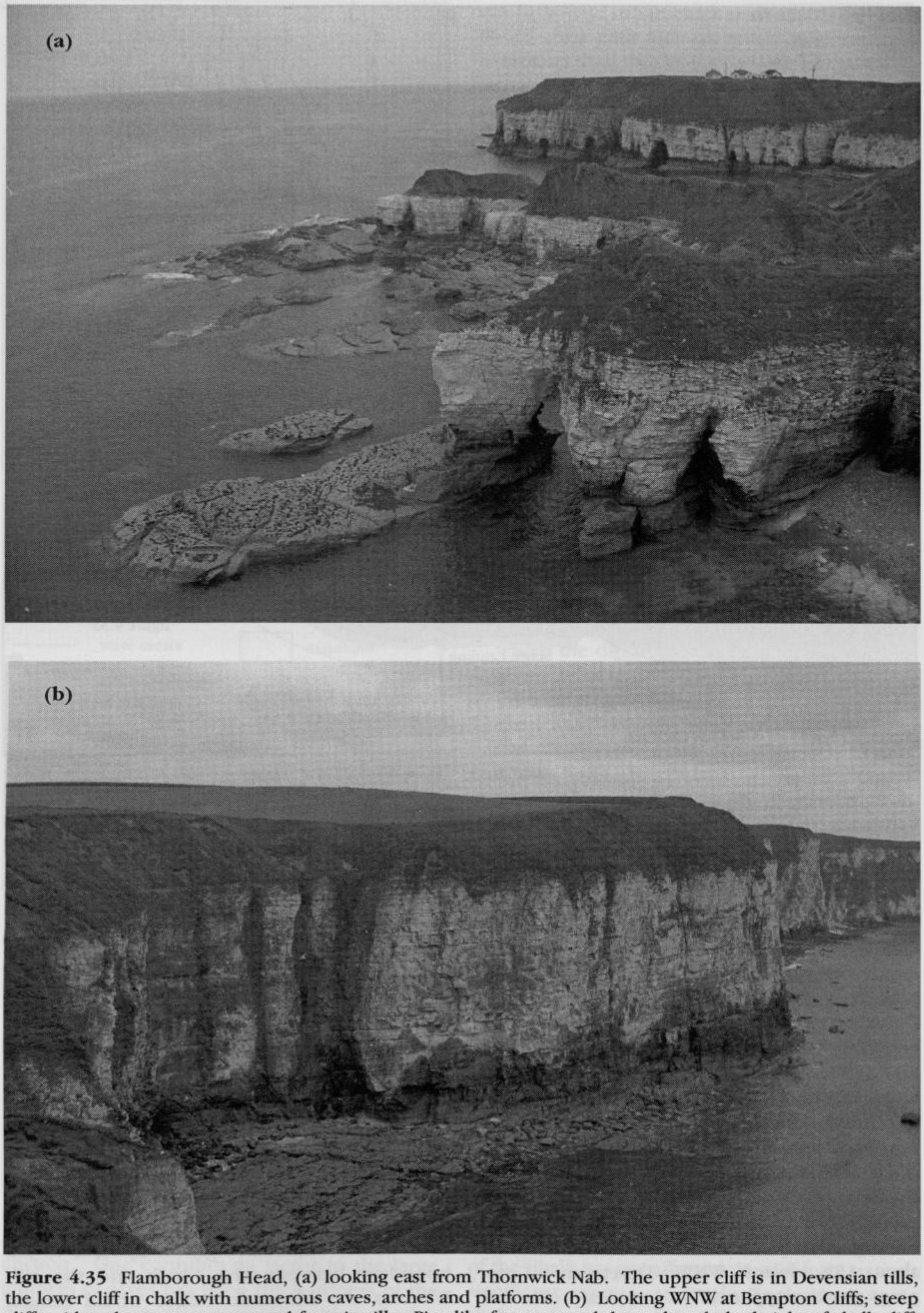


Figure 4.35 Flamborough Head, (a) looking east from Thornwick Nab. The upper cliff is in Devensian tills, the lower cliff in chalk with numerous caves, arches and platforms. (b) Looking WNW at Bempton Cliffs; steep cliffs with a short upper vegetated facet in tills. Pipe-like forms extend down the whole height of chalk cliff; the cliffs have a narrow platform with a cobble and boulder beach. (Photos: V.J. May.)

bility of the clay material in the till overlying the Chalk has produced more open hollows. On the north side of Selwicks Bay several blowholes appear to have merged and the intervening Chalk has collapsed to produce a complex inlet (Figure 4.36). Some of the caves are associated with gullies across the platform on the line of the joint or fault controlling the development of the cave. Other caves lack this relationship, their floors being formed by slightly dipping beds of more resistant Chalk standing above the general level of the platform.

The cliffs on the southern side of Flamborough Head are simple in plan and profile, but are less active than those to the north at Bempton (Figure 2.1b). Sheppard (1912) placed the coastline of Roman times 2000 years BP over 1.6 km offshore from Sewerby and close to the present shoreline south of Flamborough village. There is, however, no direct evidence to corroborate this, although farther south documentary evidence emphasizes the large landlosses since Roman times. Steers (1946a) noted that the rate of retreat was small because of the hardness of the Chalk forming the cliffs and platform and because the old pre-glacial cliff was still being exhumed. Valentin (1954) estimated that the cliffs at Sewerby retreated by 18 m between 1852 and 1952. The upper part of many of these southern cliffs is well-cloaked with vegetation, with a lower angle of slope reflecting the presence of the till above the very steep Chalk cliffs. There is a preponderance of small falls of Chalk, rather than the more substantial rockfalls of the northern cliffs. The platform is a true abrasion platform: it is not structurally controlled since it cuts uniformly across the strata (Figure 2.1b). Where backed by Chalk cliffs, the platform is cut into chalk, but is replaced by a till platform of the same gradient and width at Sewerby where the cliffs are in till. The beach has two elements, an upper narrow beach mainly of chalk pebbles, and patchy, but few, flints, and a thin, sandy veneer resting on the platform. Trenhaile (1974b) has shown that the gradients of the platforms around Flamborough Head are higher than at any other part of the north-east Yorkshire coastline and other Chalk coastlines in England. The dominance of waves from northerly directions means that most waves are refracted around the headland and approach these southern cliffs from the east (Figure 4.33). As a result, this part of the site tends to be swept clear of much of its surface sediment, which is transported southwards. Erosion rates are relatively slow (less than 0.3 m a^{-1}) and so there is only a small input to the Holderness sediment budget.

Interpretation

This site contains the largest assemblage of active coastal erosional forms anywhere in the English Chalk, coast protection works having removed most of the very complex features on the north coast of the Isle of Thanet at Birchington. The situation at Flamborough Head, like others on the English coast, presents a puzzling question concerning the apparent resistance of a promontory that is otherwise riddled with structural weaknesses. The many faults have given rise only to the large number of inlets because the Chalk is sufficiently hard to prevent collapse. It behaves more like a hard limestone coast than a weaker chalk coast. Thus despite the deep incision by caves and other inlets into the cliffs, it is the most prominent feature of the eastern coastline of England north of the Wash. In part its form is accentuated by the rapid erosion of the weak materials forming the coastline of Holderness to the south. The southern side of the promontory has certainly undergone some erosion because it cuts across the Ipswichian shoreline at Sewerby (Catt, 1977). Nevertheless, the central section described above does not appear to be undergoing rapid erosion. Comparison of the photograph of Selwicks Bay in Steers (1946a) with the present cliffs suggests that although there have been small changes, there have been no major changes. The dip of the Chalk here varies between 10° and 15° but the coastline is so complex that there is no simple relationship between the cliff-forms and the local dip. The platforms are complex with considerable variation in relief both towards the sea and along the platforms. The development of the cliffs cannot be considered without discussion of the platforms because they affect the distribution of wave energy over each tidal cycle, most particularly in reducing the energy available for marine erosion of the foot of the cliff and the removal of talus from its foot.

Trenhaile (1974b) demonstrated that the platform gradient here was higher than might be expected from consideration of both the geology and the morphogenic environment. Analysis of covariance shows that tidal range correlates

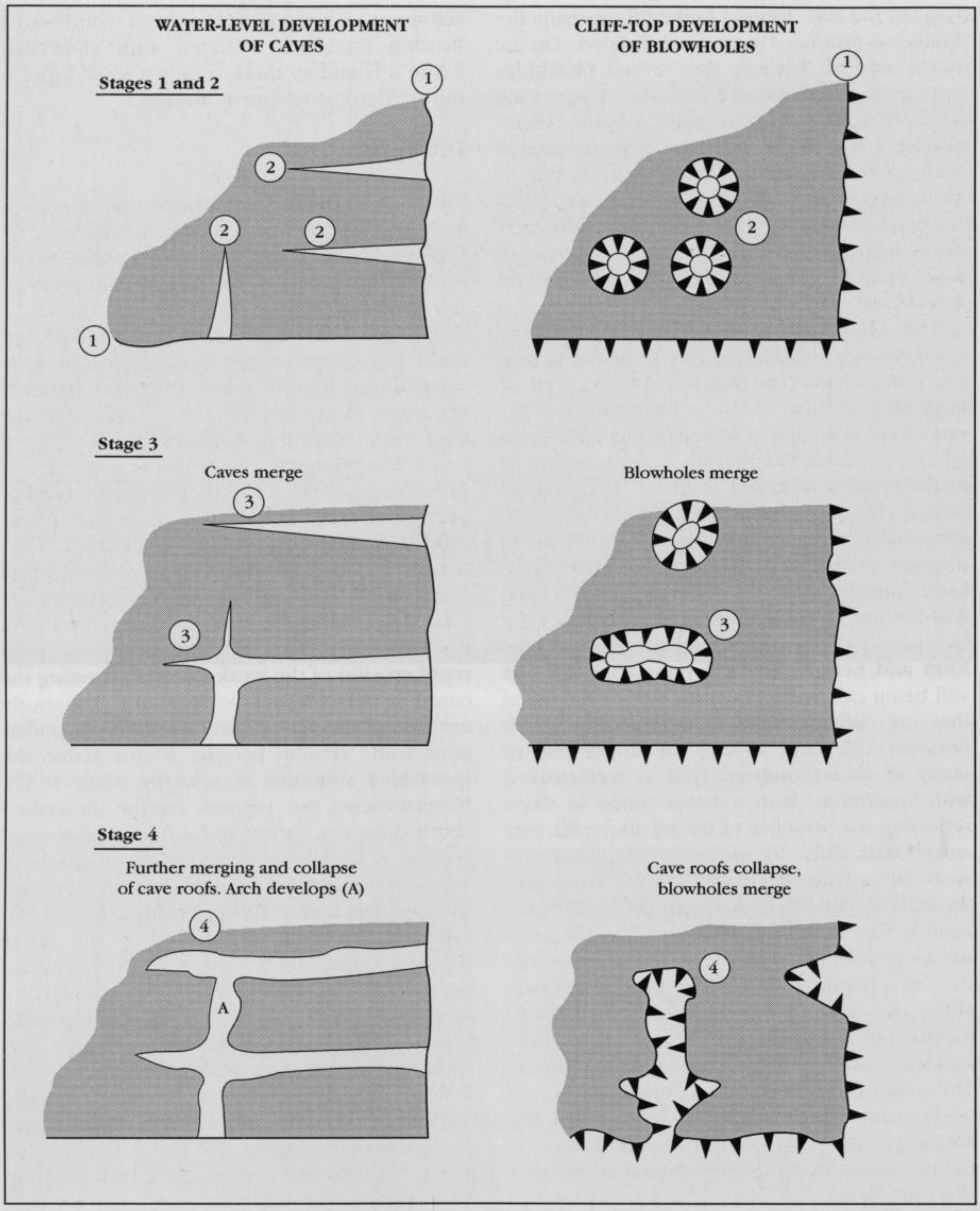


Figure 4.36 Cave and blowhole development at Flamborough Head, shown schematically in plan view. There are several stages in the development of blowholes here. Stage 1: caves develop along major joints or faults. Stage 2: caves extend upwards into the overlying till, which begins to collapse allowing hollows to appear in the till. Stage 3: caves merge and blowholes coalesce. Stage 4: Further merging of caves, cave rooves collapse, arches and/or geos develop. Subsequently, isolated blocks or stacks may develop.

strongly with platform gradient, but this correlation is not dependent upon rock type. For the same *Micraster coranguinum* Chalk biozone and a similar fetch and tidal range, the platforms at Flamborough Head have much greater gradients than those around the Isle of Thanet. This variation could be attributed in part, however, to differences in the lithology between geographically separate parts of the same biozone, an issue not discussed by Trenhaile. He has suggested that waves that approach with the least energy, owing to refraction, are most significant for platform development. This must, however, be modified by the roughness of the platform and surrounding intertidal areas. Much of the intertidal area in the central section of this site is distinguished by rocky outcrops that owe their features to the differential action of marine and sub-aerial processes upon them. There have been no detailed field surveys of these features, but the very rough nature of the surfaces has been observed to have the effect both of channelling water flow, particularly during backwash of waves and drainage on falling tides, and of dissipating much of the energy contained within waves crossing the intertidal area. The channelled flow of water along joints, into and out of inlets and caves, has a very localized effect.

When the sides of such channels are undercut sufficiently they may collapse, but the length of many of the channels and caves suggests that the penetration along them is carried out much more efficiently than widening of them. Most waves approaching Flamborough Head are strongly refracted. Their behaviour in crossing the intertidal area is very complex and, except during periods of storms, inefficient in attacking the innermost parts of the bays. As a result it could be argued that it is the very complexity of the coastline here that contributes to its relative resistance to recession.

In contrast, the platform along the southern shoreline of Flamborough Head westwards to Sewerby shows many of the features that have usually been associated with shore platforms. Its slope is not complicated by strong microrelief or debris accumulations. Most waves that affect it are strongly refracted around the headland and tend to approach from the south-east and east thus travelling at an angle across the platform rather than at a normal orientation to the cliffs. This area lacks flints in the Chalk and most of the sediment available to be used by the natural system as erosional tools is sand or chalk pebbles. This area thus raises important questions for the debate concerning platform development, which further modelling and observation should consider.

Conclusions

Flamborough Head is a very important site for the following reasons. First, it is the most complex cliffed Chalk coastline in England, with numerous caves and arches. Second, it is the largest such site that has been affected by glacial processes, which have not necessarily contributed directly to the coastal forms but may have affected the nature of the Chalk itself. The Chalk is overlain with Devensian tills, a combination that gives this site further interest because of the effects this has on the nature of the cliff-forms. Third, it exemplifies well the effects of different wave climate upon coastal forms. Fourth, it provides an excellent site for the study of coastal erosional processes and the linkage of cliff–beach–platforms processes that Pethick (1984) suggests is needed if platforms are to be placed in context and better understood. Finally, it is the only Chalk cliff GCR site that is affected solely by North Sea wave systems.

JOSS BAY, KENT (TR 383 716–TR 402 696)

V.J. May

Introduction

This site comprises the most extensive Chalk intertidal platform in England and is backed by near-vertical cliffs of Upper Chalk. It is one of the least-modified parts of the coastline on the Isle of Thanet between Margate and Broadstairs (see Figure 4.1 for general location). The cliffs have retreated at about 0.3 m a^{-1} in historical times, and the platform close to the cliffs has been lowered by about 0.03 m a^{-1}. Coastal retreat takes place by a combination of small rockfalls, shallow rock-slides and marine undercutting. The cliffs have two main orientations, which conform with joint patterns, the Chalk itself being well jointed and closely bedded with a northerly dip of about 1°. Beaches formed of small quantities of flint and chalk occasionally mask the cliff foot, whilst there is an accumulation of predominantly biogenic, shelly sand in

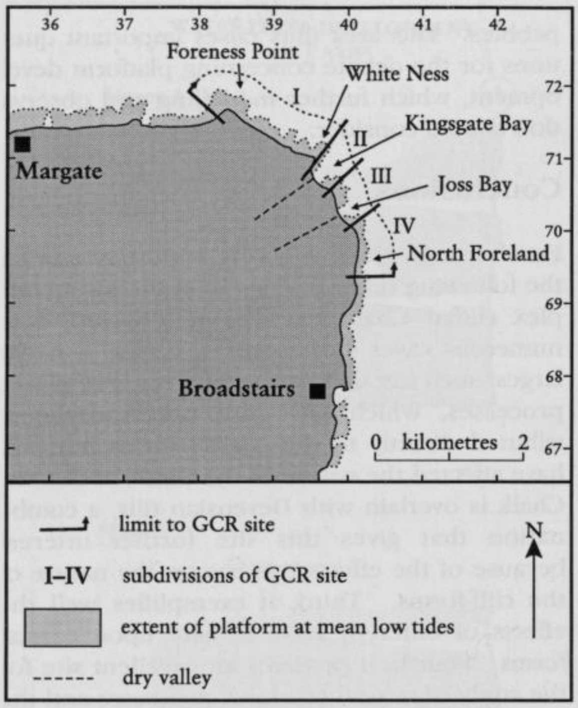


Figure 4.37 Sketch map of the Joss Bay coastal geomorphology GCR site.

the bays. In Botany Bay, a duniform ridge formed at the cliff foot in the early 1980s became sufficiently stable to be colonized by vegetation, but this is not characteristic of the site as a whole.

Although the geomorphology of the Chalk coast has attracted general attention (e.g. Steers, 1946a; Bird, 1984), there have been two groups of detailed studies, one focusing upon the platforms and their development (So, 1965; Wood, 1968; Trenhaile, 1974a,b), the other upon cliff-retreat processes (May, 1964; Hutchinson, 1972). There has been considerable engineering interest in this coastline in general because of the coast protection issues related to cliff retreat and in particular the penetration of caves beneath urban areas, such as at Broadstairs. In reality, cave development within this site is very restricted. The best examples were to the west of the site at Birchington (May, 1964; So, 1965) but they were destroyed as part of a coast protection scheme. Nevertheless, this site still contains good examples of cave–arch–stack development that can be traced in historical records for about 140 years.

Description

The site extends from Foreness Point (TR 383 716) to Hope Point (TR 402 696) south of North Foreland (Figure 4.37). The characteristic form is a vertical or near-vertical cliff about 20 m in height fronted by a sandy beach of varying width up to a maximum of about 180 m, and a well-developed Chalk intertidal platform up to 500 m wide. The plan form of the coast is marked by sharp changes in cliff orientation, which allow the site to be subdivided into four sections:

1. Foreness Point and Botany Bay, which includes several stacks,
2. Kingsgate Bay,
3. Joss Bay, and
4. the cliffs of North Foreland.

There has been some coast protection work, notably in Kingsgate Bay, to protect a cliff-top road and Kingsgate Castle, and in Joss Bay also to protect the cliff-top road. South of Joss Bay, very small segments of cliff have been bricked-up or walled-in in the past. Cave entrances have also been bricked over to prevent undermining of the cliff top and the further development of blowholes. At Foreness Point, sewage outfalls at the western boundary of the site cross the platform and appear to reduce sand transport westwards across the platform. As a result, it is possible to examine the contrasts in platform development with or without a significant sand veneer.

Although the whole of this site is cut into the Upper Chalk, there are differences between its northern and southern parts. Between Foreness Point and White Ness, the cliffs are cut mainly in the *Marsupites testudinarius* biozone above the *Uintacrinus socialis* biozone. Harder bands of the latter are associated with ledges on the platforms, thresholds at the foot of stacks and ramp-like cliff bases (So, 1965). South of White Ness, the coastal alignment is at right angles to the dip and the cliffs are formed mainly in the *Micraster coranguinum* biozone of the Chalk overlain by the *U. socialis* biozone. Within both Kingsgate Bay and Joss Bay, parts of the cliffs are cut across dry valleys that are underlain by periglacially modified chalk and slope wash. Hutchinson (1972) noted that the Chalk in the upper 3 m of the cliffs at Joss Bay appeared to have been frost-shattered, more or less *in situ*, as occurs

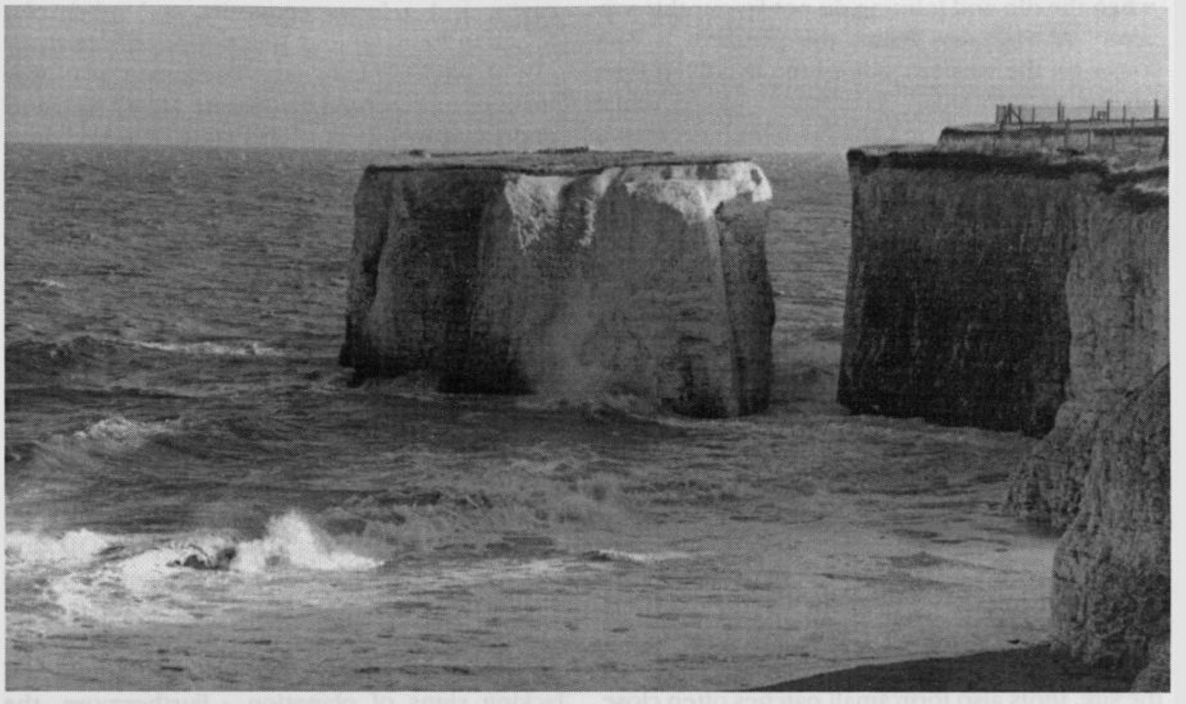


Figure 4.38 One of two stacks in Botany Bay. This stack was joined to the mainland in 1842 and became separated during the 19th century. (Photo: V.J. May.)

elsewhere in the site. Peake (1961) recognized two sets of major joints that are sub-vertical and generally lie within 10° of the main joint directions of 10° and 290°. The Chalk is closely but irregularly jointed between these major joints. Except in the *Micraster* Chalk, flints are uncommon in the cliffs. Their presence south of North Foreland affects the form of the platform, since they appear to provide a degree of armouring to its surface.

May (1964) described the coastal changes around the Isle of Thanet, and So (1965) examined the platforms in detail. They agree that the cliffs are generally retreating at about 0.3 m a^{-1} and the platform is being lowered at about 0.03 m a^{-1}. In detail, the changes are much more varied with many small cliff-falls taking place as well as localized lowering of the platform or accretion of sand. At Kingsgate, May (1964) noted that there had been little change since about 1870 when a brick facing- and buttress-wall was constructed below the castle. In the bay, however, the cliff-top road had been so undermined that it was supported on a concrete bed buttressed above the beach. Between White Ness and Foreness Point, the cliffs run parallel to the main direction of jointing, and rockfalls from the *U. socialis* biozone are frequent. South of White Ness, falls appear to be less frequent, but Hutchinson (1972) described one such fall in detail. This fall, in early 1966, cut the cliff top back by about 2.3 m along about a 20 m length. Hutchinson's analysis demonstrated that a notch of 0.5 m could produce such a failure given the shear strength of the Chalk. By February 1971, a notch 1 m deep was measured at the site of the fall. Thus not only had about 500 m^3 of rock been removed from the cliff, but the sea had also cleared this away and undercut the cliff once more. The average 0.3 m a^{-1} quoted above thus disguises some larger but less frequent events.

Despite their very exposed location, two stacks have formed at the eastern end of Botany Bay. Cartographic evidence shows that the larger of these separated from the mainland after the tithe survey of 1842 when it was joined by a neck of land about 22 m wide. The date of formation of the smaller stack is not known, but it is younger (Figure 4.38).

So (1965) showed that the platforms are gradually extended landwards by cliff recession. They show variable micro-relief often as a result of pitting, block-loosening and more resistant flint patches. Their height decreases from headlands to embayments, particularly at White Ness and Hackemdown Point, even (according to So) when the dip and jointing do not favour this pattern. At Foreness Point, the platform is also lower on the western side of the headland than on the eastern side. Irrespective of the initial height of the platforms, the gradient is greater in the embayments than at headlands. Profiles are characterized by a concave upper and a convex lower section, but are also steeper at Foreness on its eastern side. Wood (1968) showed that this platform steepened markedly seawards. The 120 m closest to the cliffs was very gently-sloping, with an average gradient of about 1 in 400, but below the +0.3 m OD contour it steepened to 1 in 70. At White Ness and Hackemdown Point, low cliffs also occur at the outer edge of the platform. Recession of these low-tide cliffs is also less rapid than the high-water cliffs (So, 1965).

There is often a sandy veneer on the platform, much of it composed of shelly fragments, some from reworking of the Chalk and some from present-day molluscs. In the southern part of the site, flints also form small patches often close to the foot of the cliff. Wave direction tends to keep the platform south of Hackemdown Point swept clear of sand, apart from small patches infilling hollows in the platform. In Botany Bay, however, considerable quantities of sand can accumulate and during the early 1980s an unusual cliff-foot dune built up and became temporarily stabilized by vegetation. This protected the cliff foot from erosion, although subaerial processes of rainwash and frost-shattering continued. As a result a series of small debris-slopes grew on top of the dunes, which themselves rested on the cliff–platform junction and beach.

Interpretation

This site represents very well the relationship between cliffs and platforms on the English coast, especially because the rates of change in both have been documented for a longer period of time than elsewhere. Cliffline crenulation is present but was much better represented in the past by the cliffs at Birchington in north-west Thanet, where a comprehensive set of caves, geos and blowholes had developed. These were mostly destroyed during coast protection works in the late 1960s. As a result some upper parts of the platform described by So (1965) have been destroyed. Because So showed that the platforms on Thanet had a generally upper concavity, and a lower convexity, and other platforms in England and Wales appear to lack this (Trenhaile, 1974a,b), the remaining platforms that are represented by this site are all the more important members of this suite of active shore platforms.

So (1965) argued that the coastal platforms of Thanet were the result of storm waves, both past and present. As water-levels change with the tides, so the zone of effective wave attack and of marine planation also shift vertically. The height at which the water-level associated with storm-wave action remains longest is within the mean neap tidal range. It was argued by So that wave attack would be most frequently focused at mean tide-level and storm-wave platforms would rise up to 1 m above this height; platforms within the site range in altitude between OD and +0.91 m OD, corresponding to a mean tide level of +0.17 m OD. Platforms around the Thanet coast, however, extend below low tide levels, decreasing in height comparatively rapidly and lacking signs of planation. Furthermore, the low-tide cliffs have not receded as rapidly as the rate of cliff recession. These platforms, So concluded, must relate to a lower sea level, but So did not explain their co-incidence with low tide levels. Debate elsewhere (Trenhaile and Layzell, 1981; Carr and Graaf, 1982) concerning the duration of wave attack related to the tidal duration curve may throw light on this issue in general, but has not been considered in relation to this site. Similarly, since waves lose energy in crossing the platform, a rising sea level is required to ensure that past platform-widening continues. Wood (1968) considered that the notch at the foot of the cliffs marked the 'true level of present day erosion' and that the platform close to cliffs had been cut with the sea near its present level. The greater retreat of the bays was attributed to the occurrence of sand and the potential for abrasion, whereas the headlands, lacking such aids to abrasion, would erode less rapidly. The width and steepening of the platforms may have resulted from a rise in sea level of as much as 6 m since *c.* 2700 years BP, according to Wood (1968).

Neither Wood (1968) nor So (1965) considered the origins of the bays. The eastern end of Botany Bay, Kingsgate Bay and Joss Bay are each associated with the truncated mouths of dry valleys that are underlain by frost-shattered chalk and slope wash. It is possible that not only were the bays already related to the drainage pattern of eastern Thanet, but also that the more weakened Chalk would aid retreat in the bays. South from White Ness the platforms have an extensive cover predominantly of flint, much of which is *in situ*. The extent to which this provides an armouring to the chalk surface has not been investigated. Between 50 m and 75 m from the main cliff foot there are, however, some small landward-facing micro-cliffs (up to 0.3 m in height) that are capped by this flint layer, which in places co-incides in its slope with flint layers in the main cliffs. These flinty layers are uncommon in the bays. South of North Foreland the micro-cliff is close to the position of the main cliff of about 100 years ago. The presence of these higher sections of platform poses a question about the way in which the platforms have developed, since it is evident from the above that the platform is a simple result of cliff retreat (see also GCR site report for Beachy Head to Seaford Head in the present chapter). Other processes appear to be important in the greater lowering close to the cliff foot. One possibility is that waves reaching this area from the north-east, despite refraction across the platform, travel strongly along the foot of the cliff rather than approaching it from seaward. Additional scouring in this position could accelerate platform lowering. The site thus provides continuing opportunities to investigate further the mechanisms by which platforms develop. Most models treat platforms two-dimensionally, concentrating upon the profile of the platform, and thus ignore the three-dimensional form and the behaviour of waves crossing it. In addition, the roughness of the surface itself affects the erosional efficacy of waves crossing it (see GCR site reports for Flamborough Head, and Kingsdown to Dover in the present chapter). The lack of boulders at Thanet means, for example, that platforms are given little protection from wave action, unlike some of these other platforms.

Like other active cliff and platform sites, Joss Bay has to be viewed as part of a network of such features in different tidal and wave environments. It is one of the few sites where there have been both detailed surveys of the platforms and geotechnical investigation of the cliffs. In common with the other sites, its importance also lies in its contribution to understanding of the complex relationships between cliffs, platforms and beaches, especially since this site lacks the considerable shingle cover found on other sites along the English Channel coast.

Conclusions

As the most extensive Chalk intertidal platform in England and Wales, Joss Bay provides several insights into the links between platform width, wave energy and platform extension. First, it is very wide and, according to some early literature, at the maximum limit of platform extension. Second, there have been a number of investigations of both the detailed morphology of the platform and of the geotechnical qualities of the cliffs. The rates of retreat of the cliffs and of lowering of the platforms may be causally linked. Third, it has a very restricted sediment veneer. Taken together, the investigations of form and process of the platform and cliff demonstrate the influence of the detailed lithological variations across the platform and the role of platform morphology in affecting the direction and nature of wave attack upon cliffs. Because of the detailed studies, this site provides a reference site against which other platforms can be compared.

PORTH NEIGWL, GWYNEDD (SH 270 274)

V.J. May

Introduction

The coastline of Llŷn (the Lleyn Peninsula, north-west Wales) is characterized by both hard rock and weaker till cliffs, and a number of distinctive beaches. Between the mouth of the Afon Glaslyn and the Menai Strait, there are some 18 sand, shingle and cobble beaches that are bounded by rocky headlands. Those along the south-eastern coast are the best-developed set of zeta-curve beaches associated with strong wave refraction on the coastline of England and Wales, but almost all are affected by coastal protection works. Aberdaron Bay (about 6 km to the west) and Porth Neigwl (Hell's Mouth) are more symmetrical in form than the others, Porth Neigwl in particular facing almost directly into the dominant south-westerly Atlantic swell (see Figure 4.1 for general location and Figure 4.39). It is a rare example of a cliff–beach system on the coast of Great Britain confined by long headlands where waves and swell are little affected by refraction (Guilcher, 1958). As a result, the predominantly till cliffs have developed a plan-form

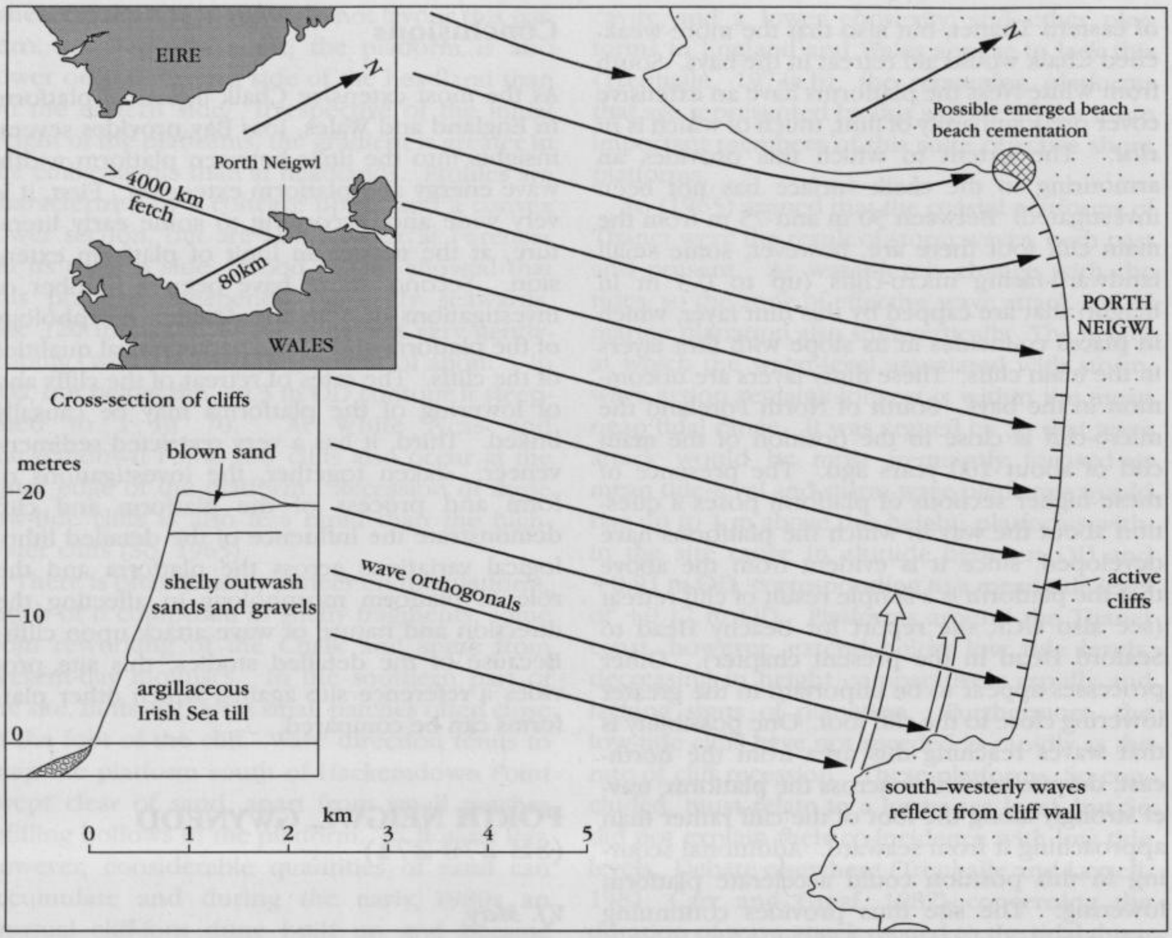


Figure 4.39 Wave refraction and reflection in Porth Neigwl. Wave orthogonals show the direction of travel of waves and are drawn at right angles to the wave crest. Open arrows are also orthogonals for reflected waves.

that is controlled strongly by the dynamic relationship between south-westerly swell and waves, and the strength of the till (Figure 4.39). The narrow beach is usually subdivided into a lower beach, formed mainly of sand, and an upper beach dominated by cobbles and boulders. A common feature of the beach is a series of bars aligned at an acute angle to the beach itself. Beach cusps are also a characteristic feature. The beach is unusual amongst British west-coast beaches in having no associated dunes (Steers, 1946a). Some controversy surrounds a possible emerged ('raised') beach at the western end of the locality (Whittow, 1957, 1960, 1965; West, 1972; Campbell and Bowen, 1989), where there may be present-day cementation of the beach (West, 1972).

Description

The Porth Neigwl (or 'Hell's Mouth') coastline is about 11 km in length and comprises three main elements; (a) a narrow beach, below (b) cliffs of glacial sediments, which lie between (c) cliffs of Cambrian and Ordovician bedrock.

The western side of the bay is formed by cliffs up to 60 m in height, cut partially into sandstones and partially into glacial sediments that rest upon the bedrock slope. The cliff runs SW–NE; this area is the most sheltered part of the bay. There is a narrow cobble and boulder beach. The main beach faces southwards at its western end but gradually curves to face south-west at its eastern end. The cliffs are over 30 m in height at its western end, but are more usually about 18 m high. Between SH 276 268 and

SH 283 263 they are only 10 m in height. The cliffs are cut mainly into thick blue-grey and brown Irish Sea till, but east of SH 283 263, there is a higher proportion of gravels in the cliff. Holocene peat and sands are also exposed in the cliffs (Campbell and Bowen, 1989).

Along the eastern side of the bay, the cliffs are cut mainly in Cambrian Hell's Mouth Grits, and attain a height of over 110 m. The lower parts of the cliffs are almost vertical, but, owing to the strata dipping at between 30° and 45° into the cliffs, only limited development of very narrow shore platforms has occurred. There is little evidence of active erosion in the cliffs of this part of the bay. Rockfalls are infrequent and small in magnitude. The till cliffs that form the central part of the bay are, by comparison, easily eroded and have retreated rapidly, undermining cliff-top tracks and fields.

The beach itself is formed by an upper berm composed mainly of cobbles derived from the erosion of the cliffs, and a lower finer-grained beach, which has a maximum width of about 100 m. Two regular features of the beach are well-developed cusps and small bars on the lower beach, which are aligned sub-parallel to the beach itself. They normally merge with the beach at their western end, and they disappear and reform over time depending upon the wave conditions.

Waves usually approach the beach from the south-west because of the effect of the restricting headlands, but the fetch varies between over 4000 km to the south-west to much shorter distances to the south and south-east (80 and 50 km respectively; Figure 4.39). Waves approaching from these directions are less strongly refracted than those of the long Atlantic swell, but there is some sheltering of the eastern corner of the bay under south-easterly conditions. The western corner of the bay, in contrast, is very exposed to the south–east waves and by refracted south-westerly waves. Despite these modifications of wave approach, wave energy appears to be often spread evenly along the whole beach and the similar plan of both the cliffs and the beach reflects this.

Interpretation

Guilcher (1958) described Llŷn, and Porth Neigwl in particular, as one of several examples where the coastline has become irregular as a result of the exhumation of the underlying rock surface from beneath a cover of drift. The broad outline of the bay results from the rapid retreat of the glacial infill between the two headlands to east and west, but there is no direct relationship between cliff height and cliff retreat along the glacial cliffs. The rapidity of erosion is such that cliff-top streams have been unable to keep pace with the rate of retreat and so hanging, truncated, valleys into which streams have incised their lower courses have developed (for example at SH 269 274). Similar features have been described elsewhere in the present volume (see South-west Isle of Wight and the Dorset Coast GCR site reports), and there is considerable debate about their origins (Flint, 1982). Unlike the truncated valleys in the area around Hartland Quay (see GCR site report), the valleys at Porth Neigwl are most akin to those of the south-west Isle of Wight and tesitify to the local rapidity of cliff retreat. This contrasts with the evidence discussed below concerning cementation of the beach.

The detail of the bay results mainly from the longshore movements of sediments within a *swash*-aligned system (see Chapter 5). Furthermore, water movements are strongly constrained by the confining headlands. Waves are little affected by refraction within the bay except along the foot of the two headlands, but reflection from the headland cliffs, especially to the east, may produce complex wave patterns.

The beach is notable for the very common occurrence of large beach cusps along its length. Cusp development has been attributed to edge waves, in which cusp spacing is related to interactions between the edge-waves and the incident waves (Darbyshire, 1982). The regularity of beach cusps has been described by many coastal scientists (see for example Komar, 1976; Pethick, 1984). Bowen and Inman (1969) suggested that the rhythmic beat of the incoming waves on the water of the near-shore zone creates a secondary set of waves at right angles to the incoming waves. The combination of incoming waves and edge waves produces a regular series of undulations in wave height along the beach. The resultant differences in wave-energy distribution produce the regularly-spaced cusps.

In Porth Neigwl, the lack of variation of the direction of wave approach means that cusps are likely to be broken down or change their wavelength mainly as a consequence of variations in the period of incoming waves rather than any directional change. They are, as a result, a common characteristic form on this high-energy beach. However, reflection from the eastern wall of the bay also produces waves that travel obliquely across the bay at regular intervals. Waves travel into Porth Neigwl from comparatively deep water, in contrast to many other similar beaches which are related to south-westerly swell (see, for example, GCR reports for Carmarthen Bay and the English Channel sites such as South-west Isle of Wight and Loe Bar). The site provides an excellent field-study site for future research into the effects of interference of reflected waves with incoming and edge waves. Because of the limited refraction and deep water close inshore, it also provides a good site for investigation of wave behaviour and beach and cliff responses to rapid sea-level rise.

Porth Neigwl contrasts with the other beaches of Cardigan Bay in lacking any significant development of cliff-top dunes. Some swash-aligned beach–cliff systems develop small cliff-top dunes that are maintained by wind transport from both the beach and the cliff-face. There is no evidence of this process here. The rate of cliff erosion and the narrowness of the beach inhibit intertidal drying and so wind action is insignificant. There is also no evidence of an offshore source of beach sediment. It is one of the best examples in England and Wales of a high-energy beach with local sediment feed. Although it has a similar wave regime to the south-west facing flint shingle beaches of the English Channel, it differs from them in having deep water close to the shore and in depending entirely on erosion of the cliffs for its sediment supply.

In one other aspect, this site is unusual. It is the site where cementation of beach materials was thought first to have occurred in an emerged beach situation (Whittow, 1960), but was later shown to be part of the present-day beach (West, 1972). Whittow (1957, 1960, 1965) described a shelly conglomerate as a postglacial (Holocene) emerged beach, although he recognized that a wave-cut notch could not be seen because of the masking effect of landslips in the till that formed the cliff above the site. He also noted that coastal shelly drifts terminated inland at a height of about 3 m against a steep rock cliff, which he suggested might represent the old sea cliff of the Great Interglacial (Hoxnian) emerged beach. West (1972) demonstrated that inorganic calcite had been deposited in the western part of the beach, but gave no evidence of it being a Holocene emerged beach. Campbell and Bowen (1989) accepted this interpretation. It is unusual to find present-day beach sediments cemented in this way, but there is evidence from elsewhere (for example, east of Dover) that it can take place beneath debris from cliff falls.

Whittow (1965) also suggested that the presence of the emerged beach indicated that the till cliffs could not have retreated more than about 800 m since the end of the transgression about 6000 years BP. There are, as yet, no ^{14}C or amino-acid dates for the cemented material. The presence of hanging and incised valleys indicates that the rate of retreat of the cliffs has been faster than the rate of down-cutting, but this does not provide evidence of either the rate of retreat or the magnitude and frequency of retreat events. West's (1972) re-interpretation of the cemented material as contemporary suggests that retreat has taken place at marked intervals, for sufficient time must have passed without disturbance of the beach to allow cementation to take place. In this respect, the site poses interesting and as yet unanswered questions about the nature, magnitude and frequency of retreat of the till cliffs in this very high-energy environment. There is no other site on the coastline of England and Wales where contemporary cementation has been reported in a comparable location below cliffs. For this reason alone, the site is of considerable scientific importance.

Conclusions

Porth Neigwl is a rare example of a cliff–beach system, confined by long headlands, in which waves and swell approach from deep water and are little affected by refraction. Porth Neigwl is one of the few beaches on the coastline of England and Wales where waves travel in deep water sufficiently close to the shoreline to be little affected by refraction.

The till cliffs are retreating rapidly, but despite ample supplies of coarse sediment, the beach remains very narrow. This locality is an excellent example of a very high-energy environment that lacks intertidal platforms (contrast with Nash Point, for example – see GCR site report in the present chapter). It is also of considerable interest because it is probably the only recorded site of possible contemporary cementation of a cliff-foot beach in England and Wales.

HOLDERNESS, EAST YORKSHIRE (TA 182 660–TA 142 190)
POTENTIAL GCR SITE

K.M. Clayton

Introduction

Cliffs cut into weak Quaternary rocks undergoing rapid erosion occur along the North Sea coast of Britain and locally around the Irish Sea. The Holderness Cliffs (see Figure 4.1 for general location) stretch from Bridlington in the north some 60 km to Kilnsea in the south, where the coast continues southwards as a spit to Spurn Head (Figure 4.40). Most of this line of cliffs remains undefended, though walls and groynes have been built along relatively short frontages at Bridlington, Skipsea, Hornsea and Withernsea, and more recently at Mappleton (south of Hornsea) and in front of the gas terminal site at Easington close to Kilnsea. The contemporary rate of erosion increases from north to south; from less than 0.5 m a^{-1} just south of Bridlington to as much as 3 m a^{-1} at Easington. A feature of this coast is the sectors with an unusually low beach profile; these are locally known as 'ords' and over time they migrate southwards down the coast. As the ords pass by, waves are able to erode the cliffs more effectively and the rate of erosion speeds up, to slow down again when a higher and wider beach replaces the ord (Figure 2.1c).

Description

The Holderness cliffs front an undulating till plain deposited during the last (Devensian) glaciation. The cliffs themselves cut through various till facies and related fluvio-glacial gravels. They begin in the north at the exposed Sewerby cliff of Ipswichian age, where the Chalk cliffs of Flamborough Head end, and continue southward for 61.5 km to Kilnsea at the northern end of the Spurn Head spit. The average height is

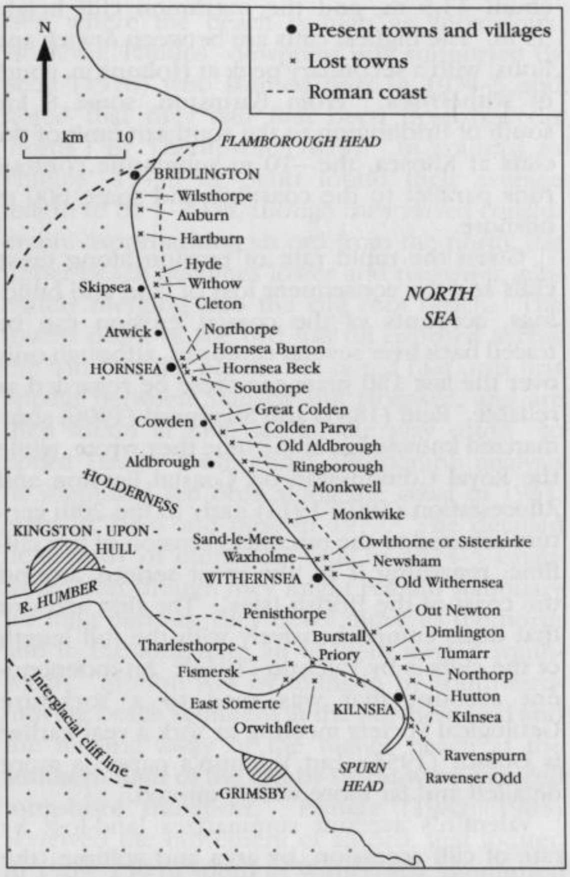


Figure 4.40 Lost villages of the Holderness coast. As the till has been easily eroded for hundreds of years at rates of 2 m a^{-1}, there has been substantial loss of agricultural land and villages. (After Hansom, 1988)

Table 4.4 Land-loss by natural sections of the Holderness coast, 1852–1952 (Valentin, 1954, 1971).

Section	Annual cliff recession (m)	Shore length (m)	Annual land-loss (m^2)	Average cliff height (m)	Annual loss in volume (m^3)
A. Sewerby to Earl's Dike	0.29	8100	2357	11.0	25 927
B. Earl's Dike to Hornsea	1.10	13 650	15 015	11.8	177 177
C. Hornsea to Withernsea	1.12	24 250	27 160	16.2	439 992
D. Withernsea to Kilnsea Warren	1.75	15 525	27 200	13.2	359 040
Entire coast (approx.)	1.20	61 500	72 000	14.0	1 000 000

about 13.5 m, and the maximum cliff height 35 m. The highest cliffs are between Atwick and Roos, with a secondary peak at Holmpton, south of Withernsea. From Barmston, some 8 km south of Bridlington to the southern limit of the cliffs at Kilnsea, the –10 m submarine contour runs parallel to the coastline and some 600 m offshore.

Given the rapid rate of erosion along these cliffs and the consequent loss of land and buildings, accounts of the coastal erosion can be traced back over several centuries, although only over the last 150 years can these be regarded as reliable. Reid (1885) and Sheppard (1906) summarized knowledge at the time they wrote, while the Royal Commission on Coastal Erosion and Afforestation (1907–1911) early in the 20th century referred to the relentless erosion of this cliffline, regarding it as 'the most serious around the coast of the British Isles'. The first account that deals comprehensively with the full length of the cliffs is by Valentin (1954). An independent account that was read to a Yorkshire Geological Society meeting in York a year earlier is Dossor (1955), but Valentin's paper is more detailed and far more widely quoted.

Valentin's account summarizes land-loss by rate of cliff recession, by area and volume (the last two on a parish basis). He divided the coast into four sections: Sewerby to Earl's Dike; Earl's Dike to Hornsea; Hornsea to Withernsea; and Withernsea to Kilnsea Warren. As Valentin's 1952 research post-dates the first edition of the six-inch map (1:10 560) by 100 years, he was able to summarize the pattern of erosion over a century (Table 4.4, Figure 4.41)

Valentin went on to discuss the reasons for the persistent cliff recession, concluding that wave attack was the dominant factor. Increasing exposure southwards (the northern sector being protected from the north by Flamborough Head) was thought to account for the steady increase in the rate of cliff recession from north to south.

Phillips (1962, 1964) described the ords and their relationship to coastal recession. The occurrence of these low beach sectors is of considerable importance in determining the local pattern of cliff recession, and their episodic migration down the coast eventually leads to their progression down the narrow spit at Spurn, threatening breaching as they pass southwards. More detailed studies of ord development and migration are to be found in Scott (1976).

The type of cliff failure varies with the lithology of the cliff materials, cliff height, the local water table, and rate of recession. These issues are addressed by Richards and Lorriman (1987), and from a soil mechanics standpoint in Robertson (1990), while the pattern in time and space is analysed by Pethick (1996). Most, though not all, authors link the passage of ords with increased rates of cliff recession.

Winkelmolen (1978) concluded from a study of lithological variations in samples collected from the cliffs, beach and offshore zone that the postulated north–south longshore drift of beach sediment could not be established, and concluded as a result that most erosion and sediment sorting was associated with easterly storms.

Short lengths of the cliffs in front of built-up areas have been protected for some 80 years, with groynes and sea-walls at Bridlington (4 km), Hornsea (2 km) and Withernsea (1.8 km) and as recently as 1992 a short length at Mappleton south of Hornsea was added. Many proposals have been put forward to increase the length of protection along this coast, including the construction of an offshore barrier utilizing colliery waste and a proposal for defended headlands separating eroding bays. To date the defences have remained restricted to the small coastal towns as a result of national policies on the funding of coast-protection structures that result in the limitation of protection to built-up areas through cost–benefit tests (see also Ramsay *et al.*, 1977).

A general account, setting the Holderness coast in its wider setting, is provided by Pethick and Leggett (1993).

Interpretation

There is widespread (though not universal) agreement on the major controls operating along this coast; the importance of the protection provided from the north by Flamborough Head (and the Smithic sandbank offshore), and the role of the beach (including the progression of ords) in controlling the rate of cliff recession. Recent studies have tended largely to confirm these features, while increasing the detail in which we understand the controlling coastal processes. However, the contribution from Winkelmolen (1978) shows that the field data are capable of alternative interpretations. His evidence does not preclude southerly littoral transport as surely as he claims – the effect of sporadic (in time and place) inputs of ill-sorted sediment derived from the rapid erosion associated with ords makes it unlikely that a north-south pattern of sediment size could develop. Pethick (1996) has provided a more detailed examination of the pattern in time and space of cliff recession, which is discussed below.

All authors agree that the recession along this coast has been occurring for a long period of time, no doubt moving landward rapidly during the earlier part of the Holocene transgression, and perhaps continuing at a relatively constant rate over the last 6000 years or so that sea level has stood close to its present elevation. Valentin utilized the recession rate for 1852–1952 to estimate that, 3000 years BP, the coast was some 7 km east of its present position at Dimlington, and perhaps half that distance at Skipsea. He also noted that the morainic ridge that forms the high ground at Dimlington declines westwards, and that while it reached 42 m on the 1852 map, the ridge top was at only 38 m at the cliff edge in 1952 and will be at only 30 m by 2052. Thus at the very least the present rate of erosion here is likely to continue and a much smaller volume of sediment will be contributed to the beach and offshore system in the future. Valentin notes that Sheppard (1912) regarded the Roman coastline (*c*. 2000 years BP) as lying 2.5 to 3.5 km east of the present-day cliffs, a view repeated by other authors since then.

The recognition of ords by Phillips (1962, 1964) has undoubtedly helped to explain variations in both the style and rate of cliff recession over time. Research on the Spurn Head spit showed the effects of an ord to be particularly noticeable. Similar features occurred in front of the cliffs farther north. Phillips reported their length as 45–55 m and that they were moved southwards by severe storms at an average rate of movement of about 1.6 km a^{-1}. She also noted that ords are unknown in Bridlington Bay (where a ridge and runnel beach occurs), but become common towards Hornsea, some 15 km south, explaining this by the southward increase in exposure to northerly waves. Phillips (1964) describes ords as a departure from a perceived normal beach form with a high upper berm and a lower beach ridge; where ords occur, the upper beach is missing.

It would seem equally legitimate, given the persistent erosion, to describe the low beach as the norm and the sectors with slower cliff recession where the beach is high as anomalous. However, Phillips' viewpoint was supported by Scott (1976) who studied ords in 1974–5 and noted that they had first been described (as 'hords') by Thompson (1824). In contrast to Phillips' 45–55 m, Scott found their average length to be 1–2 km, though they varied considerably. Approaching an ord from the north, the upper beach becomes lower and narrower, ultimately merging into the cliff foot beach. The lowest point of the ord has till exposed across the width of the beach. He noted that ords first appear between Skipsea and Hornsea, and are then found at intervals all the way south to Spurn Head. From aerial photograph analysis he identified ten ords along the coast in 1961, eight in 1966 and nine in 1972. The detailed field study of individual ords in 1974–5 established that though they might remain stationary for long periods, they never move to the north and in the long-term all of them moved southwards. Motion was by filling-in by southward-moving beach sediment at the northern end and the moving away of the higher beach at the southern limit of the ord by storm-wave induced longshore transport. Pringle (1981, 1985) reviewed the movement of an ord, first located in 1969, 250 m south of Withernsea, monitored between 1973 and 1976 (Pringle, 1985), and surveyed every six months from April 1977 to April 1983; it moved between 68 and 668 m in six months (with an annual average of 496 m) to the south. Where the ord occurred, the beach level was on average 3.9 m lower than elsewhere, allowing even neap tides to reach the cliff at high water. Cliff-top erosion of 10 m a^{-1} was associated with the passage of the ord (with a maximum of 15 m a^{-1}) and the site of maximum cliff recession moved southward as the ord passed by. The total till volume eroded from within the lengths affected by the migrating ord averaged 254 000 m^3 a^{-1} and from the inter-ord areas, 55 600 m^3 a^{-1}, despite the fact that the total length of inter-ord cliffs was nearly three times the length affected by the ord.

Description of the style of cliff failure and its development into a model of recession with active basal erosion is provided by Richards and Lorriman (1987). This includes a section based on cliff recession in Holderness: the process involves (a) toe erosion by marine action which both undercuts and steepens intact clay and removes failure deposits; and (b) a range of mass movement mechanisms including relative-

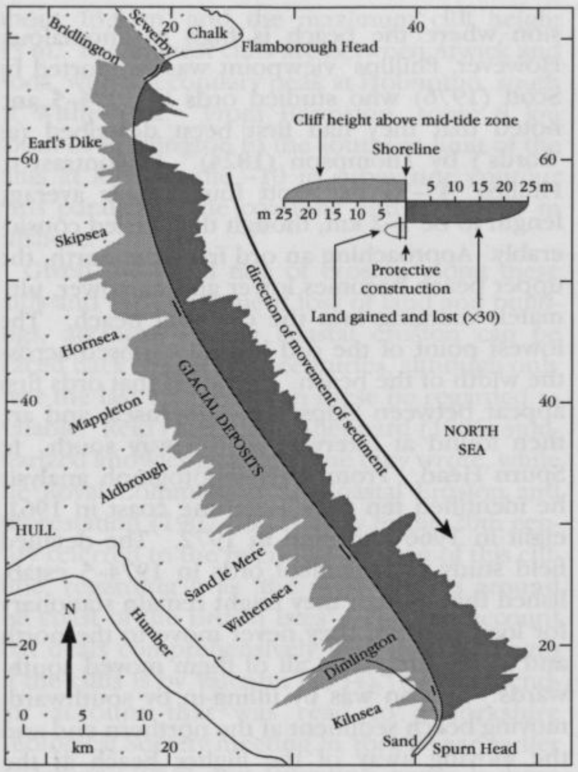


Figure 4.41 The relationship between cliff height and erosion along the Holderness coast. (After Valentin, 1971, in Steers, 1971a). For the cliff height profile, the vertical exaggeration is × 30.

ly deep-seated wedge and rotational failures, slumps, spalling and superficial mudflows. As in the case of the Norfolk cliffs (Cambers, 1976), there is a strong relationship between cliff recession rates and the frequency with which high tides reach the cliff base. The rate of recession is increased by the current rise in relative sea level, estimated as 2–3 mm a^{-1} (Suthons, 1963).

The changing nature of cliff recession as ords move along the coast was investigated by Robertson (1990). Although the cliffs of Holderness are appreciably lower than those of Norfolk, his description of the processes at work is very similar to the styles of recession observed in the Norfolk cliffs (Cambers, 1976). He found cliff height and beach volume to be the major controls on cliff failure, a relationship also identified by Valentin (1971; Figure 4.41). Cliff slope was generally 40–50°, because of the generally low pore-water pressures. The main method of recession is by deep-seated failure caused by weakening of the till by stress relief as a result of unloading and the removal of basal sediment by wave attack. Where the beach is high (between ords), recession is by mudslides and shallow slips. When a large landslip occurs, time is needed for it to be removed completely by wave action before further recession will occur at that point.

The changing nature of the beach fronting the Holderness cliffs was investigated by Mason and Hansom (1989). Using time-series surveys of a small stretch of coast at Atwick the occurrence and disappearance of areas of beach stripped of sediment (ords) was used to predict beach behaviour over different wave conditions and seasons. Using the Holderness beaches, they demonstrated that a Markov model was capable of describing and predicting transitions between beach types and different time periods.

Valentin's approximation of the sediment eroded from the Holderness cliffs as 1 000 000 $m^3\ a^{-1}$ has been refined and developed by later studies. Pringle (1985) noted that the average proportion of coarser sediment (sand and gravel) for the three tills present near Withernsea was 31.3%. A detailed field study of a 4 km length between Skipsea and Atwick by Mason and Hansom (1988) identified beach areas stripped of sediment and quantified changes in beach volume as well as inputs from cliff erosion over one year. They estimated an annual output (1850–1968) of 1 340 000 $m^3\ a^{-1}$, and an input to the beach of 462 000 $m^3\ a^{-1}$ from the cliffs on the assumption that 33% of the eroded till was sand and gravel. Southward sediment movement by longshore drift in their sectors averaged 28 000 $m^3\ a^{-1}$ to the south. Offshore transfer from the two central beach sectors, each 1875 m long, averaged over 50 000 $m^3\ a^{-1}$, an offshore proportion of two-thirds.

One outcome of Pethick's (1996) study was his estimate of 340 000 $m^3\ a^{-1}$ for the net annual potential longshore transport to the south. He estimated the non-cohesive sediment input at 280 000 $m^3\ a^{-1}$, giving an excess potential longshore rate at the southern end of the system. He concluded that the orientation of the Holderness coast provides the maximum possible potential longshore sediment transport, and an excess of potential over actual that increases steadily to the north. He estimated the total sediment store in the Holderness beaches as about 2 000 000 m^3, the equivalent of only eight years of input from cliff recession.

An informative analysis of the variation of coastal cliff recession in time and space was provided by Cambers (1976) based on her work on the Norfolk cliffs. Pethick reached similar conclusions in his 1996 study, using the recession data collected by the local councils from the 'erosion posts' located every 500 m along this coast. Though installed in 1951, annual measurements run from 1957 and the database available to Pethick (1996) was thus 45 years. Given the limitations of this database he initiated the collection of more detailed measurements from 1993. Pethick concludes that apparent variations in cliff recession rates are better explained by the spacing of the measurements in time and space than by the progression of ords. While accepting that ords are linked to more rapid recession, he does not believe they explain the 5–8 year periodicity he found and that relatively small landslips produce a pattern of migrating embayments separated by inclined promontories, and that the southward migration of these embayments leads to the observed periodicity. At any one site, 2.7 cliff failures each leading to average cliff-top recession of 0.68 m yields the overall average recession of 1.82 m a^{-1}.

Conclusions

Holderness is the longest and least-defended length of rapidly eroding cliffs cut into weak sediments in Britain. It has been studied intermittently over the past 150 years or more and although in general the relationships between wave energy, beach volume and recession are understood, and the style of cliff failure has been related to the strength and pore-water pressures of the Quaternary sediments, there is no doubt much still to be learnt from such a natural and extensive site. In addition, little is so far known of the fate of the eroded sediment, or the processes which, by deepening the adjacent sea floor, have allowed recession to continue over a distance of as much as 10 km over the last 5000 years.

The short defended lengths of this coast produce sectors where little or no erosion has occurred since construction of the defences. However, immediately to the south of each defended section, accelerated erosion occurs where the beach is depleted because of the retention of sediment by groynes to the north and the lack of cliff input behind sea-walls. These limited interruptions to an almost continuous length of eroding cliffs totalling almost 60 km do not detract from the value of this site; the comparable cliffs of Norfolk are defended for all but a few kilometres. The largely rural nature of Holderness has made it difficult to justify the expenditure of public money on coastal defences and this is likely to remain the case for the foreseeable future. Further, the erosion of the cliffs provides the sediment that maintains the Spurn Head GCR site, and in addition are the likely source for sand arriving on the prograding North Norfolk Coast GCR site.