Coastal Geomorphology of Great Britain

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Chapter 3

Hard-rock cliffs – GCR site reports

INTRODUCTION

J.D. Hansom

The selected hard-rock cliff GCR sites described in this chapter are formed in a wide range of rock types, from granites to sandstones, and, as described in Chapter 1, may be classified by overall rock resistance to denudation according to lithology and structure (see Figure 1.3). Strong lithological control and cliff development is seen where harder rocks form headlands and softer rocks form intervening bays, but rock structure and hinterland topography can be equally important. How far rocks at the coast depart from their overall mean position is a function of the importance of factors such as degree of rock jointing (which affects overall rock resistance to wave erosion) and/or the effectiveness of weathering processes, which may weaken the rock. Jointing and related structural controls are often involved in the development of headlands and bays, and over time lead to the isolation of headlands into islands, arches or stacks (see Figure 2.8). When stacks eventually collapse, their bases often survive for a time as reefs or skerries until these too merge into the developing coastal platform. In general, features such as arches and stacks are often found on actively eroding lengths of coast and on well-jointed rocks (see Chapter 2), but their absence is not necessarily an indication of slow coastal retreat. At a smaller scale, a wide range of features such as crevices, caves, clefts, and blowholes can form and even smaller-scale features such as tafoni and similar weathering forms also occur. Similarly, shore platforms have a range of features, from larger forms (ridges, scarps, runnels) related to structural controls to minor forms linked to abrasion or scouring (e.g. potholes and rock pools), those formed by weathering such as tafoni and solution basins on sandstones or limestones, and by bio-erosion, including the home scars and hollows of grazing molluscs.

The pattern of strata cropping out in cliffs affects their form (see Figure 2.7). In addition, the direction of the dip of rocks in relation to the coastline will affect cliff form. As occurs on inland slopes, steeper cliffs form where the strata are more of less horizontal; seaward dips result in a tendency to dip-slip rock failure and lower cliff angles. Unlike inland, these structural controls also affect the shore platform (the erosional stump left by a receding cliff), and study of the combined landforms over a wide range of rocks and structures should lead to a better understanding of the relationships involved. Intensely folded strata, as at Hartland Quay (north Devon) and on parts of the Pembrokeshire coast (see GCR site reports in the present chapter), can be eroded into complex forms that can be very different from the characteristic shore platforms and cliffs found nearby in the same strata without the folding. Some rock types develop characteristic cliff forms, such as the granite at the Bullers of Buchan or the sandstones of the Orkney Islands.

Just as local topography can fundamentally affect inland cliff form, the nature of the land adjacent to the coast affects coastal cliffs and rocky shores. Where coastal erosion has incised into former river valleys, a range of hanging valley features can occur, as at the Hartland Quay site in Devon. Submergence of previously glaciated landscapes creates a coastline of great diversity such as in the sea lochs of western Scotland or in the drowned, eroded glacial surfaces of Loch Maddy in the Western Isles.

The range of exposure to wave energy, the various geological strata involved, and the varying sea level history of these coasts, affected as they are by differential glacial unloading and different relative sea-level histories, form a good basis for future research work. Rates of cliff retreat and of platform lowering remain to be measured at almost all of these sites, though the existence of young features such as stacks imply that some coastal forms developed since the end of the last glaciation in spite of the host cliff coastline having been in existence for much longer and surviving several sea-level changes.

The conservation value of hard-rock cliff coasts

Unlike weaker-rock coasts, the pressure for coastal protection works is in general absent from hard-rock coasts and most sites will remain available for investigation without significant conservation activities. Nevertheless, it is also important to select a representative series of hard-rock cliff GCR sites to ensure that the Earth science conservation value, and geomorphological significance of such sites is recognized. Hard-cliff coasts are important to our understanding of the following processes:

Hard-rock cliffs

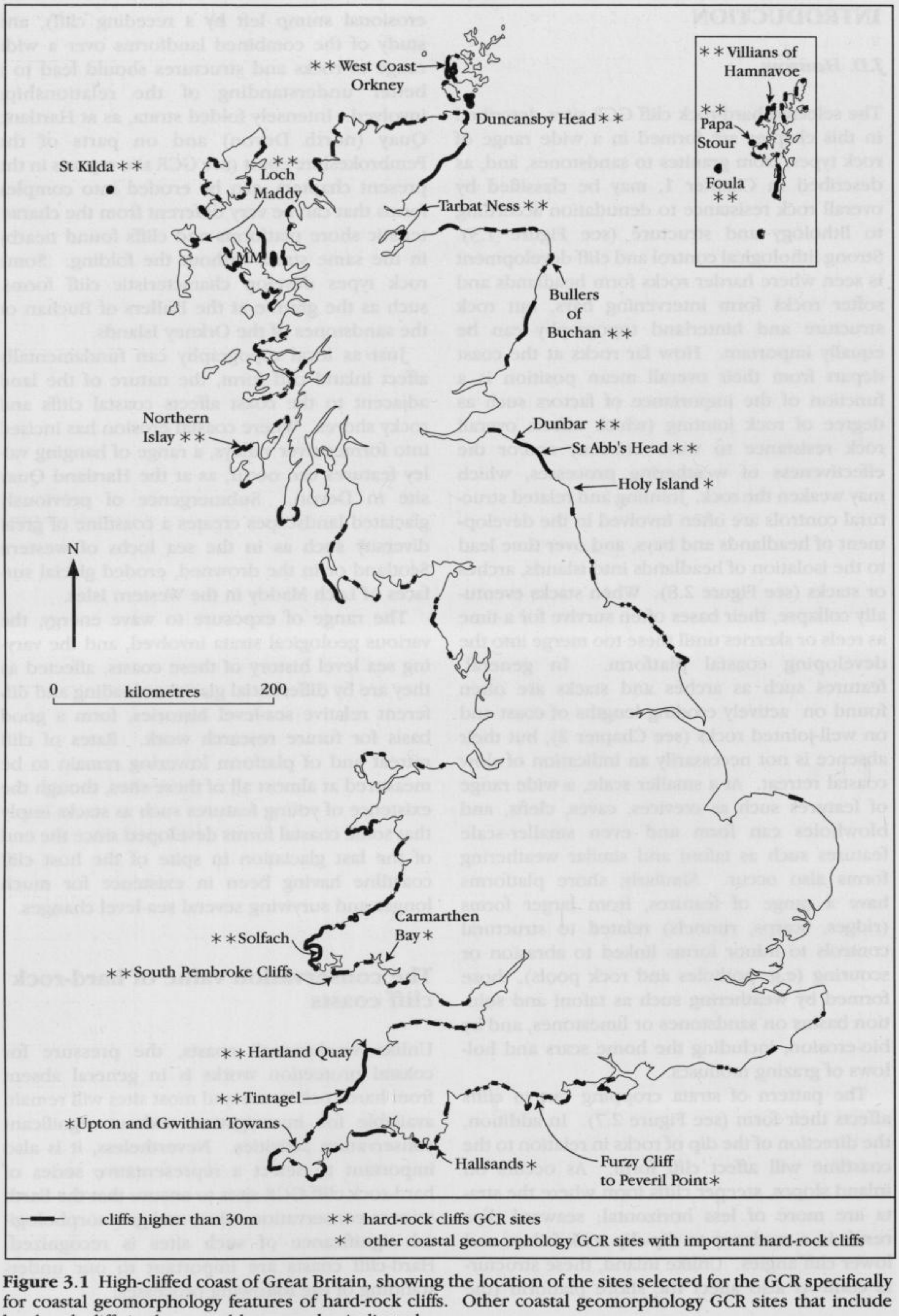

Figure 3.1 High-cliffed coast of Great Britain, showing the location of the sites selected for the GCR specifically for coastal geomorphology features of hard-rock cliffs. Other coastal geomorphology GCR sites that include hard-rock cliffs in the assemblage are also indicated.

Table 3.1 Hard-rock cliff GCR sites, including those sites described in other chapters of the present volume that include hard-rock cliffs in the assemblage.

Site*	Main features	Main geological materials	Tidal range (m)
St Kilda Archipelago, Western Isles	Plunging cliffs, submerged caves and platforms; structural controls	Igneous complex of granophyres, basalts and dolerites	3.0
Villians of Hamnavoe, Shetland	Structural controls, wave stripping, cliff-top boulder beaches	Devonian extrusive andesites and ignimbrites	1.5
Papa Stour, Shetland	Diversity of cliff forms, caves, stacks, arches; inherited cliffs	Devonian extrusive rhyolite and ignimbrite	1.5
Foula, Shetland	Higher cliffs, shore platforms, geos; exhumed cliffs stacks and geos	Devonian sandstones and Dalradian metamorphic rocks	1.5
West Coast of Orkney	Structural control of steep over-hanging cliffs; stacks arches; inherited cliffs; young individual features	Devonian Old Red Sandstone	3.0
Duncansby to Skirza Head, Caithness	Geos and stacks, shore platforms, blowhole	Devonian Old Red Sandstone	3.0
Tarbat Ness, Easter Ross	Weathering forms: tafoni and solution pits	Fault-controlled Devonian Old Red Sandstone	3.2
Loch Maddy–Sound of Harris coastline	Drowned surface of glacial erosion; rock basins, skerries and platform	Lewisian gneiss, faulted and crushed zones	3.5
Northern Islay, Argyll and Bute	Emerged shore platform and beach gravels	Precambrian quartzites and tillites; Dalradian Limestone	2.0
Bullers of Buchan, Aberdeenshire	Geos, caves, arches. stacks, platform, blowhole	Granite and dyke intrusions	3.5
Dunbar, East Lothian	Four shore platforms, some of which are glaciated	Devonian Old Red Sandstone, Carboniferous sandstone, igneous intrusions	4.5
St Abb's Head, Berwickshire	Steep cliffs, geos, fault-controlled inlets and headlands	Devonian extrusive felsites, tuffs, and grits; faulting	4.5
Tintagel, Cornwall	Longitudinal coast, structural control caves, arches, slope-over-wall cliff	Upper Devonian slates, siliceous sandstones, pillow lavas, tuffs and phyllites	6.5
South Pembroke cliffs	Structural controls, eroded karstic coast, stack, arch, cave, geo	Carboniferous limestones	6.0
Hartland Quay, Devon	Truncated valleys, waterfalls, slope-over-wall cliffs, shore platforms	Carboniferous interbedded fine-grained sandstones and shales	6.4
Solfach, Pembrokeshire	Ria, infilled ria	Cambrian and Ordovician flags and dolerites	5.9
Carmarthen Bay, Carmarthenshire	Ria, shore platforms	Old Red Sandstone and Carboniferous limestone	8.0
Furzy Cliff–Peveril Point, Dorset	Structural controls, longitudinal coast, slope-over-wall cliffs, truncated valleys	Portlandian and Purbeckian limestones and sandstones	1.9
Holy Island, Northumberland	Structural controls, shore platforms	Carboniferous sandstones and limestones	4.1
Upton and Gwithian Towans, Cornwall	Exhumed cliffs and stacks	Devonian slates	5.8
Hallsands, Devon	Emerged shore platform	Mica-schist and quartz-schist	4.4

*Sites described in the present chapter are in **bold** typeface

1. the processes of retreat in cliffs that are cut into rocks of varying resistance resulting from lithological and structural differences;
2. the effect of inheritance of cliffs and shore platforms from former sea levels
3. the controls on presence/absence of shore platforms and plunging cliffs
4. the detailed processes of wave quarrying, abrasion and weathering of rock surfaces at the coast
5. the processes of supply and transport of sediments from cliffs to beaches both below the cliffs and alongshore.

In the present chapter, the sites described represent a wide range of exposure to wave energy, a range of geological controls (structure and rock type) and varying sea-level histories. The order of the reports broadly reflects a reduction of wave energy and rock resistance, beginnign in the north and west, moving southwards into softer lithologies and lower wave energies

ST KILDA, WESTERN ISLES (NA 100 000)

J.D. Hansom

Introduction

The islands of the St Kilda archipelago rise out of the Atlantic Ocean 66 km WNW of Griminish Point on North Uist (see Figure 3.1 for general location). The four main islands of Hirta, Dùn, Soay and Boreray, together with their adjacent stacks of Stac an Armin, Stac Lee and Levenish have a coastline that is *c.* 35 km long in total. The coast is rugged and almost entirely cliff-bound, with Conachair (430 m) on the main island of Hirta forming the highest British sea cliff, and Stac an Armin (191 m) the highest stack. A variety of spectacular cliffs and cliff-related forms, including geos, arches, stacks, caves, blowholes and vertical cliffs characterize the coastline of the archipelago. Partly because of the dramatic sea cliffs, the entire archipelago was selected as Scotland's first natural World Heritage Site in 1987.

St Kilda is all that remains above sea level of a large ring volcano, thought to have been active about 60 million years BP (Steers, 1973; Miller, 1979; NCC, 1987). Although few fragments remain of the St Kilda volcanic complex, its geological history has been pieced together by comparing the precipitous remnants with the more complete and accessible igneous complexes of Mull and Ardnamurchan (Cockburn, 1935) and absolute dating based on the radioactive decay of minerals (Miller and Mohr, 1965). St Kilda is mainly composed of Tertiary intrusive igneous rocks, with coarse-grained gabbro in the south-west of Hirta and Dùn. Extensive exposures of igneous breccia intruded by dolerite occur on the north coast of Hirta, on Soay, Boreray and on the two large stacks (Figure 3.2). Granitic intrusions occur in the cliffs of Conachair and Oiseval. A late intrusive phase of sheets and dykes of dolerite and felsite has indirectly influenced the formation of arches, caves and ledges in the cliffs.

Unsheltered coasts in the western isles are exposed to high mean wind speeds and for 75% of the time, wind speeds exceed 4 m s^{-1} mainly from between west and south (BGS, 1977a) and so St Kilda experiences extreme weather conditions with high wave-energy levels that probably exceed any other site in the British Isles. The predicted 50-year wave height of 35 m for this area is significantly higher than for other parts of the UK (BGS, 1977a). Significant wave heights exceed 5 m and 1 m for 10% and 75% of the year respectively (UKDMAP, 1998) and although a maximum significant wave of 9 m was recorded 15 km west of South Uist (BGS, 1977a), individual storm waves regularly exceed this. For example, to the west of Shetland storm waves reached 15.13 m at 60°N, 4°W in January 1974 (Marex, 1975), and 24.4 m at 59°N, 19°W (Draper and Squire, 1967). Since the seabed around St Kilda lies at about 120 m depth and the islands rise from a plateau at a depth of about 40 m, the coastline is very exposed to large, high-energy Atlantic waves and this has resulted in some of the most dramatic and spectacular coastal geomorphology in the British Isles. In keeping with its oceanic location, spring tidal range at St Kilda is limited to 3 m and maximum tidal streams on spring tides are low at 0.25 m s^{-1} (BGS, 1977a).

The archipelago's present isolation dates from the end of the Devensian glaciation when sea levels rose to flood the intervening land surface. As a result of this isolation, little research has been carried out on forms and processes operating on St Kilda. To date, only descriptive works of the coastal geomorphology of St Kilda are available (e.g. Mathieson, 1928; Steers, 1973; Miller, 1979), although more exists concerning the Quaternary history of the islands (e.g.

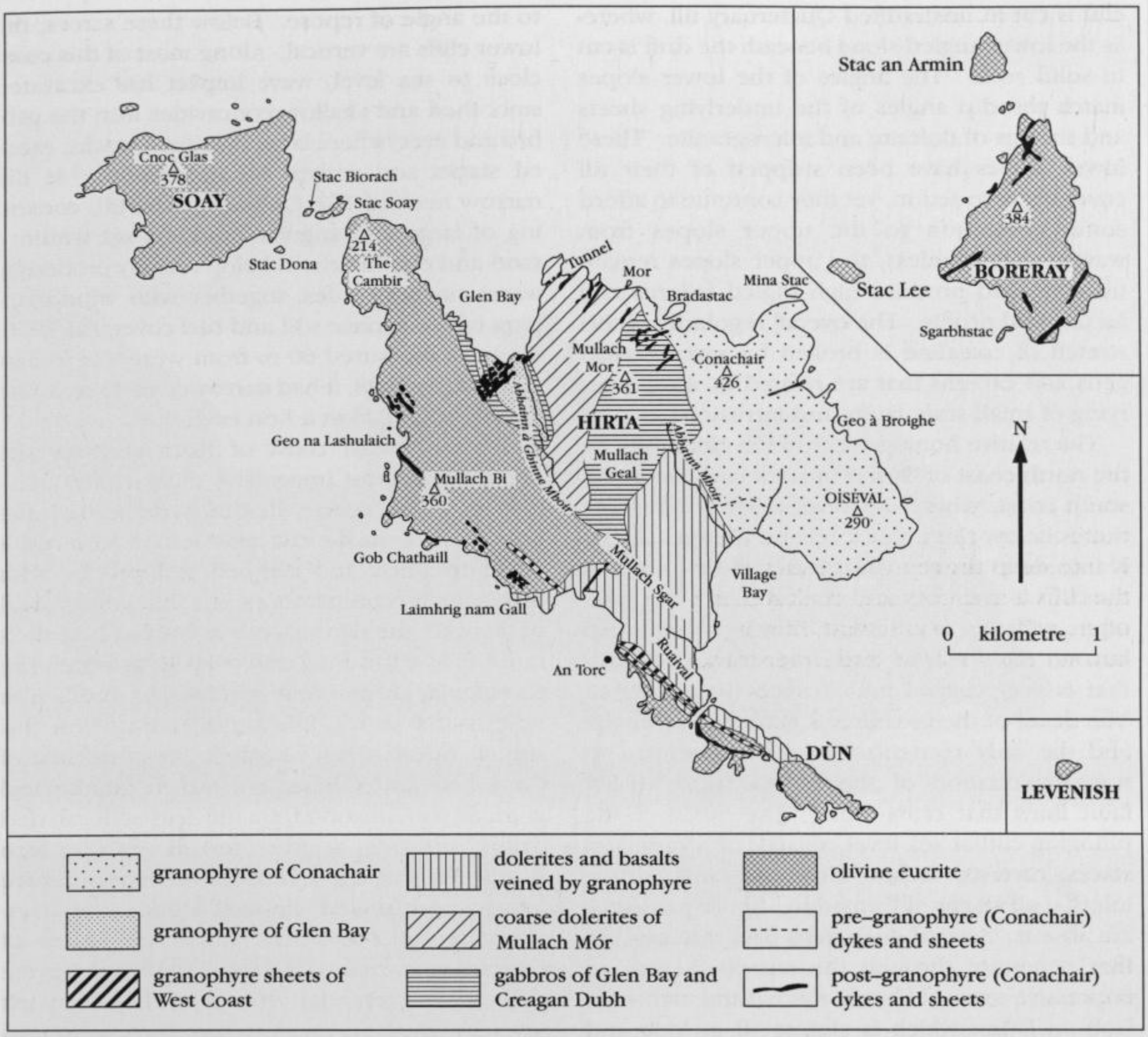

Figure 3.2 Geological sketch map of the St Kilda archipelago showing the dominantly volcanic nature of the bedrock geology and the controlling effect of the granophyre sheets of the west in producing an approximately linear coastline. For relative geographical positions of the component islands of the archipelago, see Figures 3.1 and 3.4. (After Nature Conservancy Council, 1987.)

Sutherland, 1984; Sutherland *et al.*, 1984; Peacock *et al.*, 1992).

Description

The complex and varied coastal outline of the St Kilda archipelago (Figure 3.2) is composed of a variety of cliffs, caves and geos, arches, tunnels, stacks and blowholes; since it would be over-exhaustive to describe the entire 35 km coastline in detail, the following account focuses on those features that are especially significant in the selection of this site for the GCR. Geos are deep inlets of the sea, often narrow with steep precipitous sides and often excavated along the line of a structural fault or less-resistant lithology. 'Geo' is derived from the Norse *gja*, meaning a crack or cleft, and so the name mainly occurs in those areas where Norse influence was most marked in the past, such as in the Northern and Western Isles and in the north of Scotland.

The southern coast of Hirta (from Village Bay to Caolas an Dun), together with the north coast of Dùn, comprises low cliffs that are characterized by a profile that is relatively unusual in the British Isles. The steeper upper section of the cliff is cut in unstratified Quaternary till, whereas the lower-angled slope beneath the drift is cut in solid rock. The angles of the lower slopes match the dip angles of the underlying sheets and shelves of dolerite and microgranite. These lower slopes have been stripped of their till cover by wave action, yet they continue to afford some protection to the upper slopes from waves. Nevertheless, the upper slopes remain unstable and produce high-angled failures and an unusual profile. The overall regularity of this stretch of coastline is broken by several small geos and caverns that are related to wave-quarrying of small-scale faults and intrusions.

The relative homogeneity of the cliff forms on the north coast of Dùn is in stark contrast to the south coast, where the vertical lower face continues below the water level and plunges directly into deep water. The characteristic profile of the cliffs is a smooth and vertical face at the base, often with an overhang. This is surmounted beyond the reach of wave impact by a 70° face that is very rugged and broken (Figure 3.3a). The detail of the coastline is extremely irregular and the only recognizable trend is related to wave-exploitation of the three major NE–SW fault lines that cross Dùn. The detail of the plunging cliff at sea level consists of a variety of stacks, caverns, arches, blowholes and narrow inlets at all stages of formation. Shore platforms are absent. Several deep geos pass into caverns that penetrate through the narrow island, an impressive example being the natural arch near Gob an Dùin, which is almost 50 m long and 24 m high. These caves and geos have generally been eroded along the line of dykes or thin, inclined, sheet intrusions where they crop out at sea level.

The south-west coast of Hirta (from Ruaival to The Cambir) displays local variants of the forms found on the south coast of Dùn, according to geological differentiation and differences in altitude. On the southern stretch of this coastline, the Mullach Sgar complex crops out and the many dykes and sheets of microdolerite and granite result in irregular notched and stepped cliff profiles, with remarkable colour contrasts. Farther north, towards The Cambir, the cliffs reach higher altitudes (up to 350 m at Mullach Bi) and are generally more uniform, although at water level the diversity of wave erosional forms resemble those of the south coast of Dùn. Free faces have developed in the high cliffs with massive scree deposits or block fields beneath, close to the angle of repose. Below these screes, the lower cliffs are vertical. Along most of this coast close to sea level, wave impact has excavated smoothed and shallow concavities into the gabbro and everywhere large columnar stacks, eroded stacks and arches are prominent. At the narrow neck of The Cambir, glacial till, consisting of large and angular boulders set within a sand and clay matrix, is being actively eroded by waves on both sides, together with wind-stripping of the surface soil and turf cover. In 1970, the neck measured 60 m from west scar to east scar but, by 1998, it had narrowed to 45 m, a rate of retreat of 0.26 m a^{-1} on each side.

The north-east coast of Hirta contains the highest and most impressive cliffs in the archipelago. The coarse dolerites cropping out between Gob na h-Airde and Mullach Mór, result in an irregular and stepped cliff profile, with many small protuberances. At the western end of this cliff, the natural arch at Gob na h-Airde is more than 91 m long and over 30 m high. The rectangular shape of the geo leading to this arch reflects the strong lithological control on this stretch of coastline. Farther east, the cliffs of Conachair and Oiseval are cut in granite and granophyre, intruded by dolerite sheets and dykes, creating a characteristic profile with short, near-vertical, free faces interspersed with longer, high-angled, grassed slopes and occasional screes. In places, horizontal sheets of dolerite have created pronounced ledges in the cliffs and preferential erosion of dykes has left several high altitude pinnacles. The continuous and very steep cliff of Conachair, the highest sea cliff in Britain, reaches a height of 430 m. This entire north-east coast is characterized by numerous stacks, caves, and overhangs with small horizontal cliff ledges at a variety of altitudes that appear to be related mainly to structure. Stripping of soil and turf by high winds occurs at a variety of altitudes east of Gob an h-Airde and reaches 400 m OD at Conachair.

The island of Soay to the north-west of Hirta is best defined as a complex and large stack (Steers, 1973) with no level ground. The coastline of Soay displays a similar sequence of features to the adjacent coast of Hirta, with the cliffs of north Soay reaching heights of 305 m. The arch in Soay Stac, together with the dog-tooth profile of Stac Biorach, in the narrow sound between Hirta and Soay, represent successive phases of coastal erosion. The island of Boreray, north-east of Hirta, has also been described by

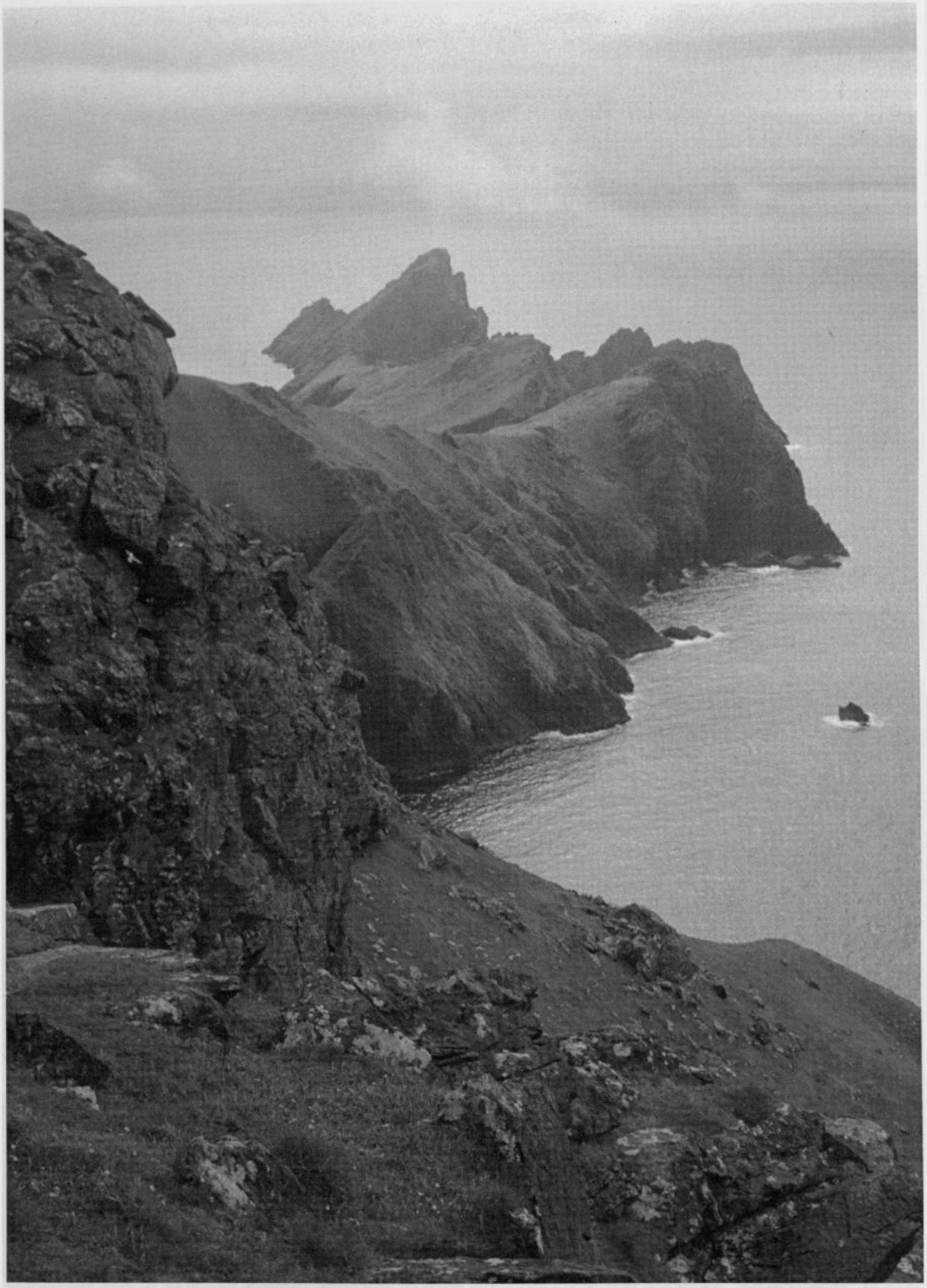

Figure 3.3a The west coast of Hirta, the main island of St Kilda, looking towards Dùn, is characterized by stepped cliffs that steepen downwards to plunge steeply to well below sea level. (Photo J.D. Hansom.)

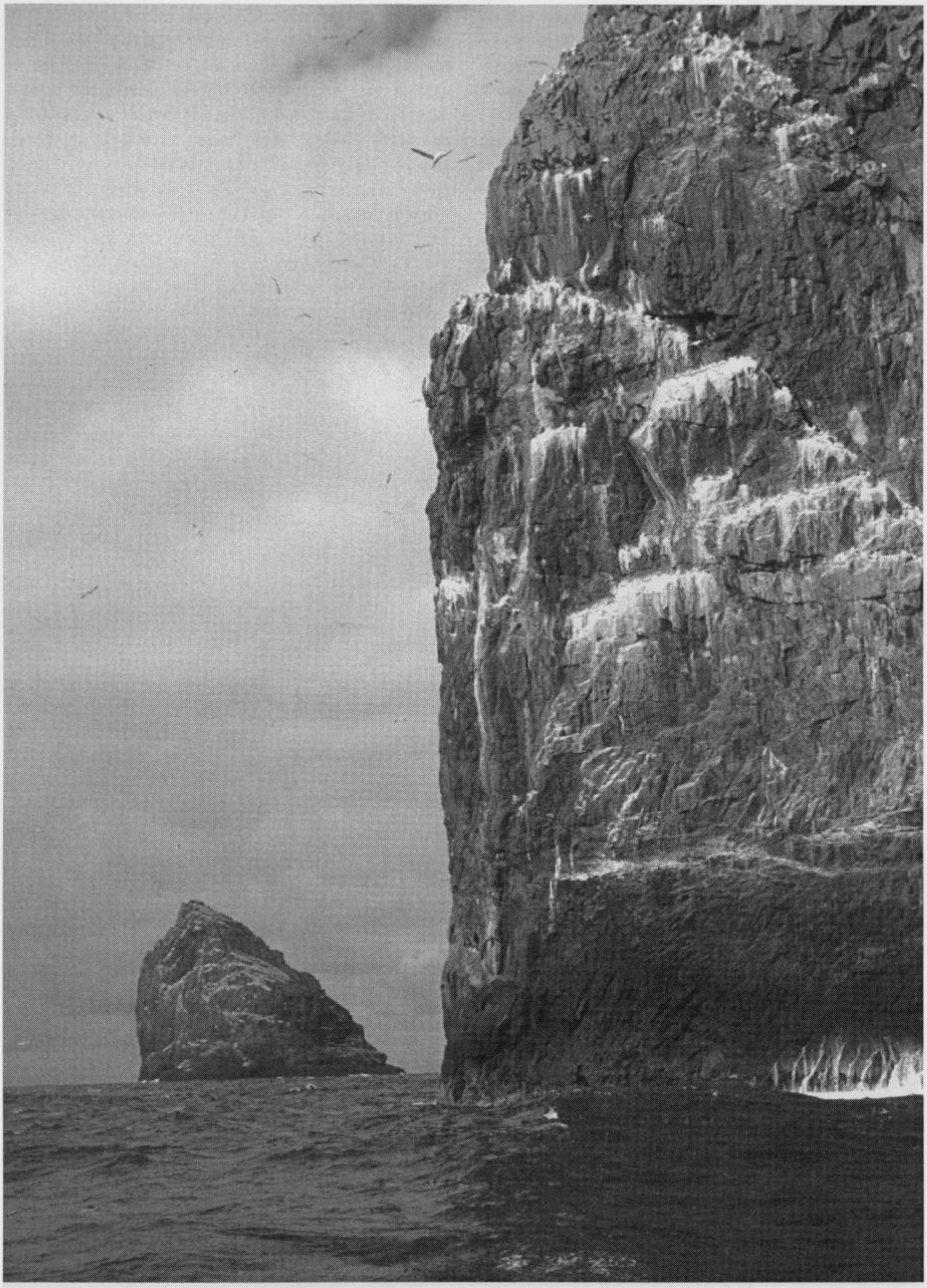

Figure 3.3b Stac an Armin, seen here with the vertical plunging cliffs of Boreray (the second-largest island of St Kilda) in the foreground. This is the highest sea stack in Great Britain. (Photo J.D. Hansom.)

Steers (1973) as a large stack, and the steeply cliffed coastline of the island is again honeycombed with caves and geos. The adjacent stacks of Stac an Armin and Stac Lee, tower 191 m and 166 m above sea level and are characterized by vertical faces plunging into deep water. The former is the highest stack in the British Isles (Figure 3.3b; Steers, 1973).

If the St Kildan landforms above sea level are impressive, then submerged beneath the waves is an equally spectacular suite of coastal landforms. Figure 3.4 reveals two relatively level sea-floor platforms, the largest of which lies to the west as a virtually horizontal bedrock surface at −120 to −125 m depth with only a patchy sediment cover (Sutherland, 1984). This platform is

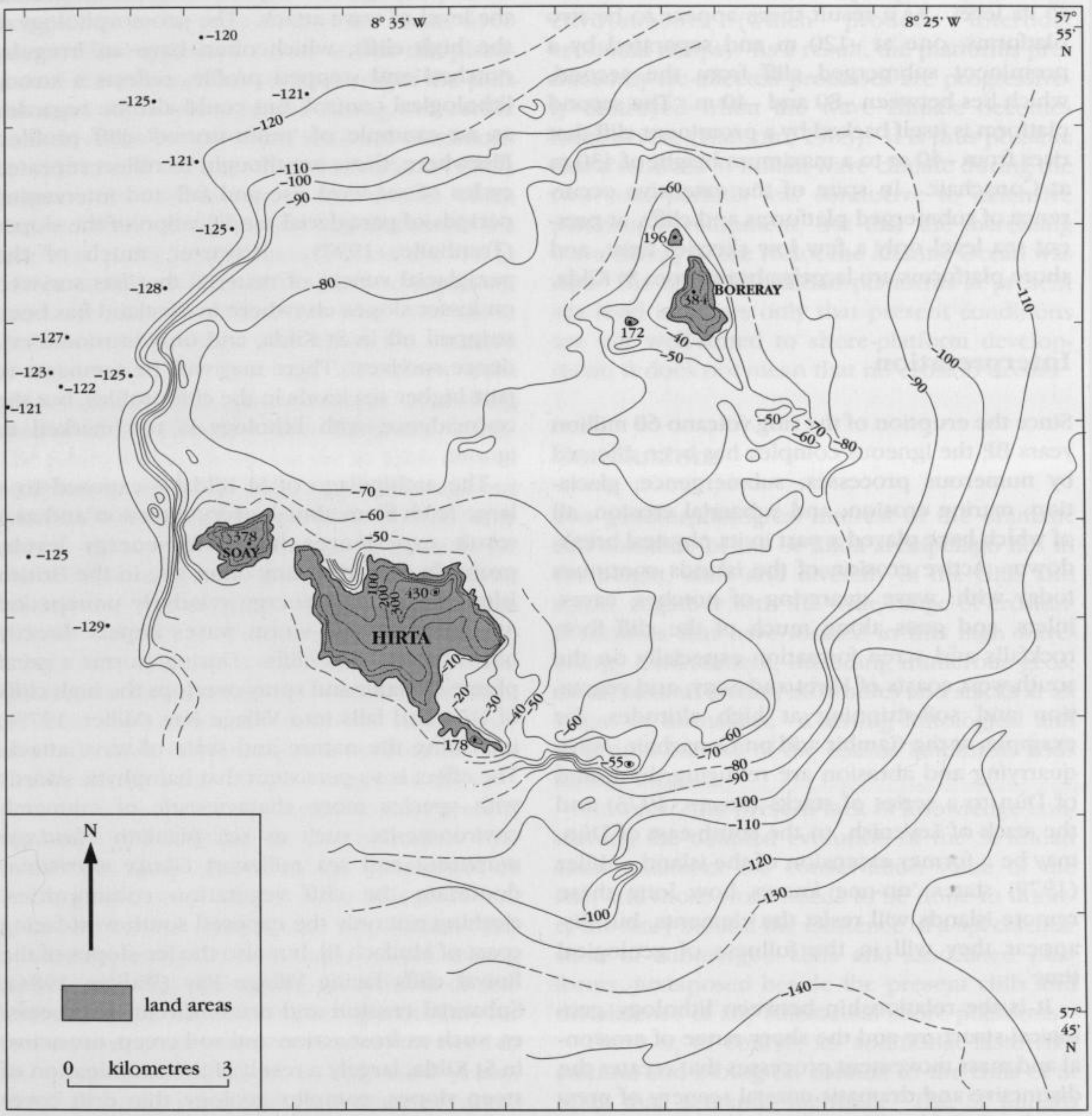

Figure 3.4 Bathymetric map of the St Kilda archipelago. Depths are given in metres. Note the prominent break of slope where the roughly circular igneous complex stands proud of the otherwise low-gradient seabed. The seabed lies at *c.* −120 m and abruptly gives way to steep submarine cliffs that rise to a *c.* −60 m surface. In turn this surface abruptly gives way to submarine cliffs that may rise above sea level. Bathymetry is in metres below OD. (After Sutherland, 1984.)

backed by a 40 m-high submerged cliff in the west and a series of 20–30 m-high benches in the south-east that separate the –120 m surface from a low-angled surface, which rises very gently from about –80 m in the north-west to –60 m in the south-east, although there is a fairly ubiquitous step in the profile at –70 m on most sides. The islands and sea stacks of the archipelago that rise steeply above sea level directly from this surface do so from a common depth of –40 m and the two valleys on Hirta can be traced down to its level. As a result there appear to be two platforms, one at –120 m and separated by a prominent submerged cliff from the second, which lies between –80 and –40 m. The second platform is itself backed by a prominent cliff that rises from –40 m to a maximum height of 430 m at Conachair. In spite of the extensive occurrence of submerged platforms and cliffs, at present sea level only a few low skerries exist, and shore platforms are largely absent from St Kilda.

Interpretation

Since the eruption of the ring volcano 60 million years BP, the igneous complex has been affected by numerous processes: submergence; glaciation; marine erosion; and subaerial erosion, all of which have played a part in its physical breakdown. Active erosion of the islands continues today with: wave quarrying of notches, caves, inlets, and geos along much of the cliff foot; rockfalls and scree formation especially on the south-west coasts of Hirta and Soay; and vegetation and soil-stripping at high altitudes, for example, at the Cambir and on Conachair. Wave quarrying and abrasion are reducing the island of Dùn to a series of stacks (Steers, 1973) and the stack of Levenish, to the south-east of Dùn, may be a former extension of the island. Miller (1979) states 'no-one knows how long these remote islands will resist the elements, but disappear they will in the fullness of geological time'.

It is the relationship between lithology, geological structure and the sheer range of erosional and mass movement processes that creates the distinctive and dramatic coastal scenery of present day St Kilda. The volcanic formation of the St Kilda igneous complex, the subsequent cauldron subsidence and the various intrusive stages that followed (see Miller (1979) for a fuller discussion) imparted a unique and complex geological structure. The gabbro that forms much of the islands has been injected with numerous sheets and dykes of basalt, dolerite and granophyres, many of which were further shattered, faulted and altered during each intrusive stage. Erosion of the gabbros, distinguished by their very coarse grain and dark colour, is responsible for the most jagged cliffs and stacks of St Kilda (Miller, 1979), while the numerous sheets and dykes provide weaknesses for preferential erosion, creating the complex of caves and geos at the level of wave attack. The geomorphology of the high cliffs, which often have an irregular notched and stepped profile, reflects a strong lithological control, but could also be regarded as an example of 'multi-storied' cliff profiles. Elsewhere, these are thought to reflect repeated cycles of sea-level rise and fall and intervening periods of paraglacial modification of the slopes (Trenhaile, 1997). However, much of the paraglacial veneer of material that has survived on lesser slopes elsewhere in Scotland has been stripped off in St Kilda, and only erosional evidence survives. There may well be remnants of past higher sea levels in the cliff profiles, but the co-incidence with lithology is too marked to ignore.

The archipelago of St Kilda is exposed to a large fetch from almost every direction and as a result experiences high wave-energy levels, probably exceeding any other site in the British Isles. Large, high-energy, relatively unimpeded Atlantic swell and storm waves impact directly onto the exposed cliffs. During storms a great plume of water and spray overtops the high cliffs of Dùn and falls into Village Bay (Miller, 1979), indicating the nature and scale of wave attack. The effect is so persistent that halophytic swards with species more characteristic of saltmarsh environments, such as sea plantain *Plantago maritima* and sea milkwort *Glaux maritima*, dominate the cliff vegetation communities, clothing not only the exposed south-west-facing coast of Mullach Bi, but also the lee-slopes of the Ruival cliffs facing Village Bay (Walker, 1984). Subaerial erosion and mass-movement processes, such as frost action and soil creep, are active in St Kilda, largely a result of the combination of steep slopes, complex geology, thin drift cover and extreme weather conditions. The operation of these highly active erosional processes upon structure and lithology creates much of the site's scientific interest and coastal geomorphology.

However, in spite of the apparently high-energy St Kildan wave climate, the presence of extensive platforms at –120 m and –80 to –40 m, both backed by precipitous cliffs the upper one represented by islands and stacks abruptly rising from –40 m, represents something of a paradox. A highly erosional system might be expected to produce a marked platform at, or close to, present sea level on the more gentle slopes, yet the final 40 m of Holocene sea-level rise seems to have accomplished relatively little by way of platform erosion (Sutherland, 1984), in spite of being close to its present level for about 6500 years. The suggestion clearly is that the planation of the two bedrock surfaces and of the cliffs that back them was achieved during two earlier periods of lower and stable sea-level conditions at –120 m and –80 to –40 m. Sutherland (1984) suggests the –120 m surface and its cliff, which rises to –80 m, to represent a Late Devensian sea level (i.e. about 18 000 years BP) and the –80 to –40 m surface and its cliff behind to represent the Loch Lomond Stadial sea level (i.e. about 11 000 to 10 000 years BP). There is a measure of agreement for these age allocations from glacio-eustatic and glacio-isostatic modelling studies of the Hebrides area (Lambeck, 1992). The predicted sea levels for the St Kilda area at 18 000 years BP lie at –120 m and, although not specifically modelled by Lambeck (1992), a figure of –80 to –40 m appears to be realistic for the St Kilda area at 10 000 years BP. However, whereas it is likely that the –120 m platform was indeed modified as recently as 18 000 years BP, it may date from glacial periods earlier in the Quaternary Period when sea levels were at similar lows. As a result, the shallower surface may also have been initiated much earlier than the 11 000–10 000 years BP date suggested above.

Since there are no shore platforms at present sea level in St Kilda, the interpretation that relates the development of the submerged St Kildan platforms to 18 000 years BP and 11 000 years BP carries with it the implication that erosional conditions were more severe during these times than during the final 40 m of sea-level rise of the Holocene Epoch (particularly for the Loch Lomond Stadial, because of the need to cut a substantial platform in only 1000 years). However, it may be that the severe erosional conditions experienced in these cold periods were more the result of ice-related processes than of wave-related processes. During both cold periods, low sea-temperatures, floating ice, and intertidal frost-shattering would have resulted in very efficient shore-platform development, similar to that experienced today on high-latitude shores (Hansom and Kirk, 1989) and also thought to have caused rapid shore-platform erosion in the Inner Hebrides during the Loch Lomond Stadial (Dawson, 1984). Research in high latitudes indicates that although such ice-affected shore platforms develop rapidly, the conditions for frost-shattering (which require standing water and low-gradient intertidal surfaces) are not favoured by high wave-energy environments (which produce intertidal erosional ramps). As a result, the platforms produced by ice-affected processes are progressively destroyed when the wave climate becomes more severe (Hansom, 1983). It is thus possible that a reduced St Kildan wave climate during the two cold periods was conducive to extensive platform development, but that the increasing wave energy of the Holocene Atlantic Ocean was not. The lack of St Kildan platforms at present sea level indicates only that present conditions are not well-suited to shore-platform development; it does not mean that no erosion occurs.

Conclusions

The geomorphological interest of the dramatic cliff coastline of the St Kilda archipelago lies in the height, scale and diversity of the cliffs and stacks, together with the wide range of erosional features that have formed in this high wave-energy environment, including numerous geos, caves, natural arches, blowholes and stacks at all stages of formation. A strong lithological and structural control of the coastal landforms adds further interest.

However, the present lack of knowledge concerning the detailed evolution of the St Kildan coast enhances the conservation value of the site, and more work needs to be done to unravel the story behind the existence of a spectacular suite of submerged cliffs and associated platforms, juxtaposed beside the present cliffs and the absence of any substantial shore platforms.

There is, of course, an additional historical, cultural and biological context to the cliffs of St Kilda that demands mention. The St Kildans maintained a 'hunting and gathering' economy on the islands up until the early 20th century, scaling the high cliffs to obtain seabirds for food. Cleits (store huts) still remain at various levels on the steep cliffs, such as Carn Mór and Aird

Uachdarachd. However since the 1930s, this inhospitable, but geomorphologically spectacular, environment has been uninhabited and is managed by the National Trust for Scotland. The cliffs are also of great ornithological significance and St Kilda is recognized as one of the most important seabird sanctuaries in the North Atlantic Ocean. This assemblage of cliff geomorphology, seabirds and cultural and historical contexts set within a land-ownership and management environment of high standard led to the designation of St Kilda as Scotland's first natural World Heritage site.

VILLIANS OF HAMNAVOE, SHETLAND (HU 240 810–HU 242 840)

J.D. Hansom

Introduction

The Villians of Hamnavoe, north-west Shetland, consist of over 3 km of almost vertical cliffs that rise from a height of 12 m OD at Whal Wick in the south to 45 m OD in the north. The coast is fully exposed to the west and north-west and receives the full violence and power of Atlantic storm waves. As a result, a range of cliff erosion features have developed along this stretch of coastline. The cliffs are cut in Devonian extrusive rocks, largely andesitic tuffs overlain by andesite lavas. In places the lavas, which are less resistant than the underlying tuffs, have been eroded to form a second cliffline fronted by a wide terrace up to 20 m above sea level, and yet remains so affected by storm waves that large blocks and slabs have accumulated to form a storm beach at the junction of the tuffs and lavas. In addition, differential erosion of the lava and tuff beds has led to a stepped cliff profile and marine exploitation of numerous cracks and fissures has resulted in the erosion of several geos and a large blowhole. Other parts of the site are characterized by large areas of wave-

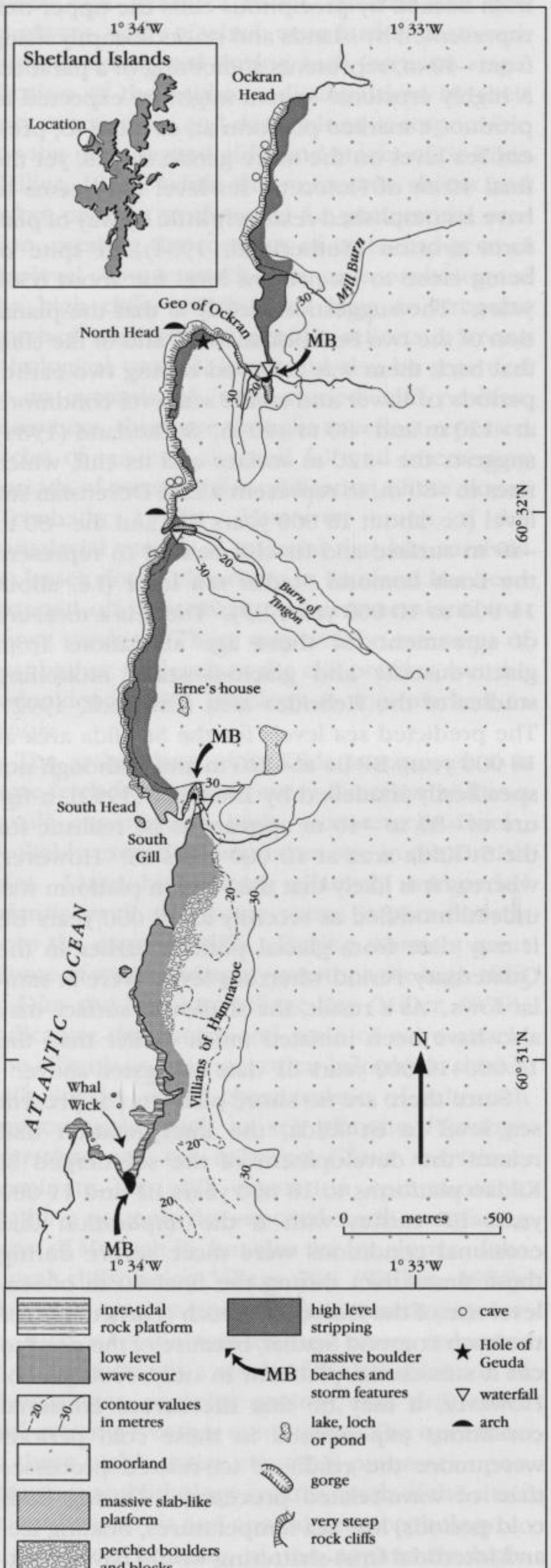

Figure 3.5▸ Geomorphological sketch map of the Villians of Hamnavoe showing extensive surfaces affected by both low-level wave-stripping in the south, and high-level wave-stripping in the north. For general location see Figure 3.1. (Modified from unpublished work by W. Ritchie.)

scoured bedrock that extend to altitude, together with individual wave-moved boulders, clusters of boulders and boulder beach ridges, all of which exist at altitudes well above those normally associated with wave processes (Figure 3.5).

The most characteristic feature of the Shetland climate is the frequency of strong winds. The mean wind speed is 6.5–7.5 m s^{-1} and gales occur on average for 58 days per year. Although not quite as exposed and windy as St Kilda, for 75% of the time the hourly mean wind speed exceeds 4 m s^{-1} with the most frequent strong winds from the south-west (BGS 1977a). Along the western coast of Shetland, a combination of exposure to prevailing winds and deep water close inshore produces a high-energy wave climate at the shore. For example, at the Villians of Hamnavoe, the sea floor falls steeply to depths of –50 m within 500–700 m of the shore.

The Holocene evolution of the Shetlands is dominated by submergence (Hoppe, 1965; Flinn, 1964, 1974; Mykura, 1976; Birnie, 1981), and numerous examples of intertidal and subtidal peats support this. As a result, the cliffs of Shetland are not characterized by features such as emerged ('raised') shore platforms or notches. The Villians of Hamnavoe was selected for the GCR because it vividly demonstrates the effects of high-energy storm-wave conditions on a low cliff coast. The high altitude abrasion and scour features, associated wave-shifted slabs and boulders and high-altitude contemporary storm beaches are of outstanding geomorphological significance. Even so, as with much of the hard-rock coast of Scotland, remarkably little geomorphological research has been carried out on these distinctive and outstanding examples of high-energy landforms.

Description

The near-vertical cliffs of the Villians of Hamnavoe, north-west Shetland, rise from a height of 12 m at Whal Wick in the south to 45 m in the north. South Gill (a boulder-filled geo)

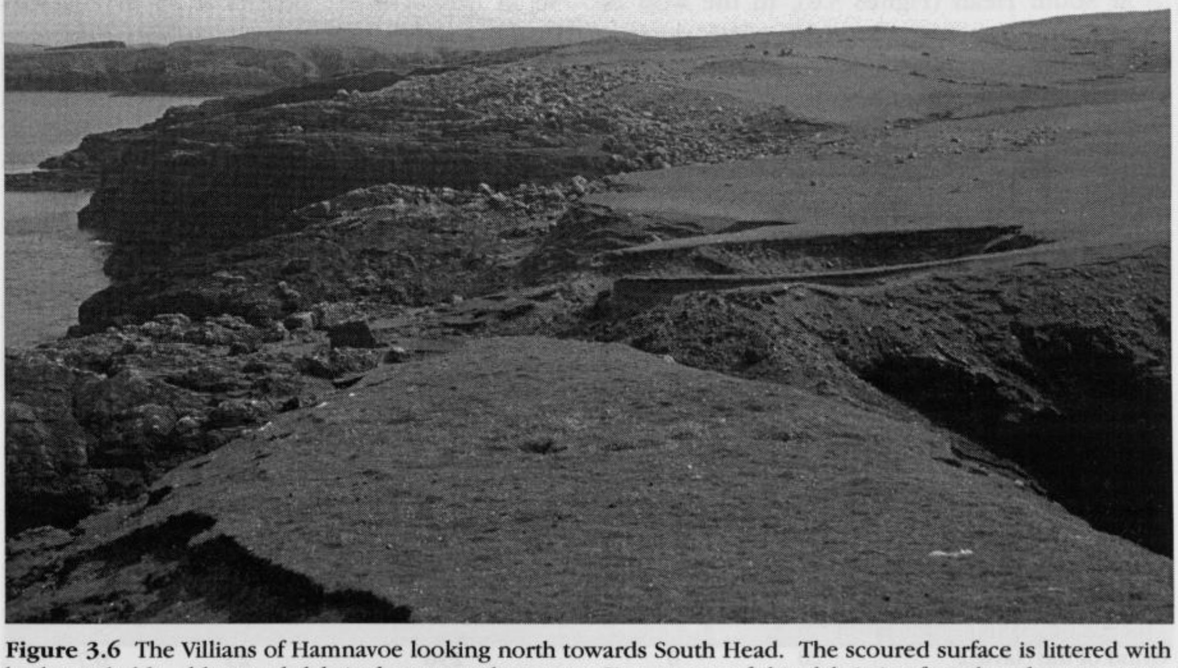

Figure 3.6 The Villians of Hamnavoe looking north towards South Head. The scoured surface is littered with both eroded boulders and debris thrown up by waves. Since some of this debris is of modern human origin (plastic fishing floats etc.) the waves that sweep the surface and emplace the debris and boulders are likely to be recent. (Photo J.D. Hansom.)

marks the boundary between the higher (*c.* 20–45 m OD), steeper and sometimes overhanging cliffs, with a narrow basal intertidal platform to the north and the generally lower (*c.* 10–18 m OD) coastal rock platforms to the south that are adorned with wave-shifted slabs and boulders that comprise the contemporary storm beaches.

In the northern part, the Burn of Tingon cuts through the plateau in a ravine-like valley, which falls to sea level as a stepped waterfall, a dramatic illustration of the influence of geological structure on coastal erosion and fluvial forms. Additionally, along this section of cliff coast, there are numerous examples of caves, natural arches and a blowhole (the Hole of Geuda) whose roughly circular vent falls some 30 m from the cliff-top plateau. However, the most distinctive feature of these cliffs is the extent and height of contemporary cliff-top surface stripping. Stripping of turf and scouring of bedrock occurs up to 30 m inland of cliff edges that are themselves some 30 m OD. The exposed rock surfaces and the cliff edges are remarkably rough and irregular, reflecting variations in rock hardness and structure. In places on the cliff top, vesicles in the bedrock have been exploited by the high-level spray to produce micro-forms that seasonal frost action and solution have exploited.

At South Head (Figure 3.6), to the west of South Gill, an unusually wide, gently-sloping, smooth and slab-like platform, is backed by a vertical cliffline set back some 50 m from the coast. This 30 m-wide sloping terrace co-incides with the junction of lavas that overlie tuffs. Although the terrace is around 18 m OD, it is affected by storm waves, and large blocks and slabs of up to 2 m in diameter form a contemporary storm beach at the base of the cliffline. To the south of South Gill, the bare rock coastal edge is more ramp-like in appearance, reaching 20 m some 200 m inland, but is heavily scoured with surface vegetation having been stripped. However, the scoured rock surface is strewn with excellent examples of shifted rock fragments in the form of both individual boulders and imbricate clusters of boulders, as well as perched slabs at heights of up to 20 m OD and, where lower heights occur, up to 100 m inland. In all the above cases, the imbricate clusters demonstrate common orientations that are consistent with the general orientation of the host coastline, although minor local variations in boulder cluster orientation and dip reflect intricacies of the cliff top and cliff-edge gradient (Table 3.2). In several cases the boulder clusters incorporate modern human debris, such as fishing floats and timber spars wedged between, behind and underneath the boulders (Hansom *et al.*, in press).

To the south of the Villians of Hamnavoe, at Eshaness, Hansom (2001) has described the boulder deposits on the cliff tops. The most spectacular of these, at the Grind of the Navir, reach almost 20 m OD and are situated some 50 m inland at the rear of a 15 m OD sub-horizontal rock platform, which is itself fronted by 15 m-high vertical cliffs. Three boulder ridges have been formed, the seawardmost of which reaches 3.5 m high and is composed of angular boulders of local ignimbrite that reach up to

Table 3.2. Altitude and orientation of some cliff-top boulder deposits in Shetland (after Hansom *et al.*, in press).

Location	Altitude (m)	Coastal orientation (degrees)	Mean orientation of boulder long axis (degrees)	Number of boulders	Mean long axis (m)
Virda Field, Papa Stour	35	5	300	15	0.7
South Head, Villians of Hamnavoe	25	0	315	25	1.1
Grind of the Navir 1 (beach ridge)	19	0	314	20	1.2
Grind of the Navir 2 (boulder clusters)	20	0	290	25	0.7
Esha Ness	35	20	275	15	1.0

2.1 m in length (Figure 3.7). Fresh scars of these dimensions occur in the cliff edge and on the sub-horizontal surface of the cliff top.

Interpretation

The Villians of Hamnavoe demonstrate the dramatic effects of high-energy storm waves on hard-rock cliffs, the relationship between geological structure and the high-energy process environment resulting in a distinctive and, in the British Isles, unique coastal geomorphology. The staircase cliff profiles, natural arches, caves and geos reflect a strong lithological and structural control, yet the resultant concentration of wave energy and power in geos and coastal valleys and the extensive wave run-up slopes on seawards-dipping rock platforms provide dramatic evidence of the extreme wave conditions experienced on these cliffs and shore platforms. The landforms that have developed in this high-energy wave environment are of great geomorphological significance and include: high altitude abrasion and scour features; contemporary storm beaches at the junction between the andesite tuffs and lavas; and the wave shifted slabs and boulders at high altitude.

In the north the stepped stairway inlet, together with the vertical blowhole of the Hole of Geuda, is a dramatic feature, particularly during storm conditions. The wave-quarried excavation of the inlet has proceeded inland along faults in the bedrock structure and intersected a fault or failure plane in the vertical dimension to result in the collapse of the cave roof to form the blowhole. To the south, the lower elevation of the cliffs, together with the low angle and exposure of the rock surface, facilitates wave run-up inland to remarkable distances and heights and this has resulted in wave-stripping of vegetation, together with wave-movement of boulders and gravels. Stripping by wind is also likely to play an important part in propagation of the stripping limit inland during storms. Turf edges at 40 m OD on South Head may mark the limit of wave wash of a major storm that occurred in

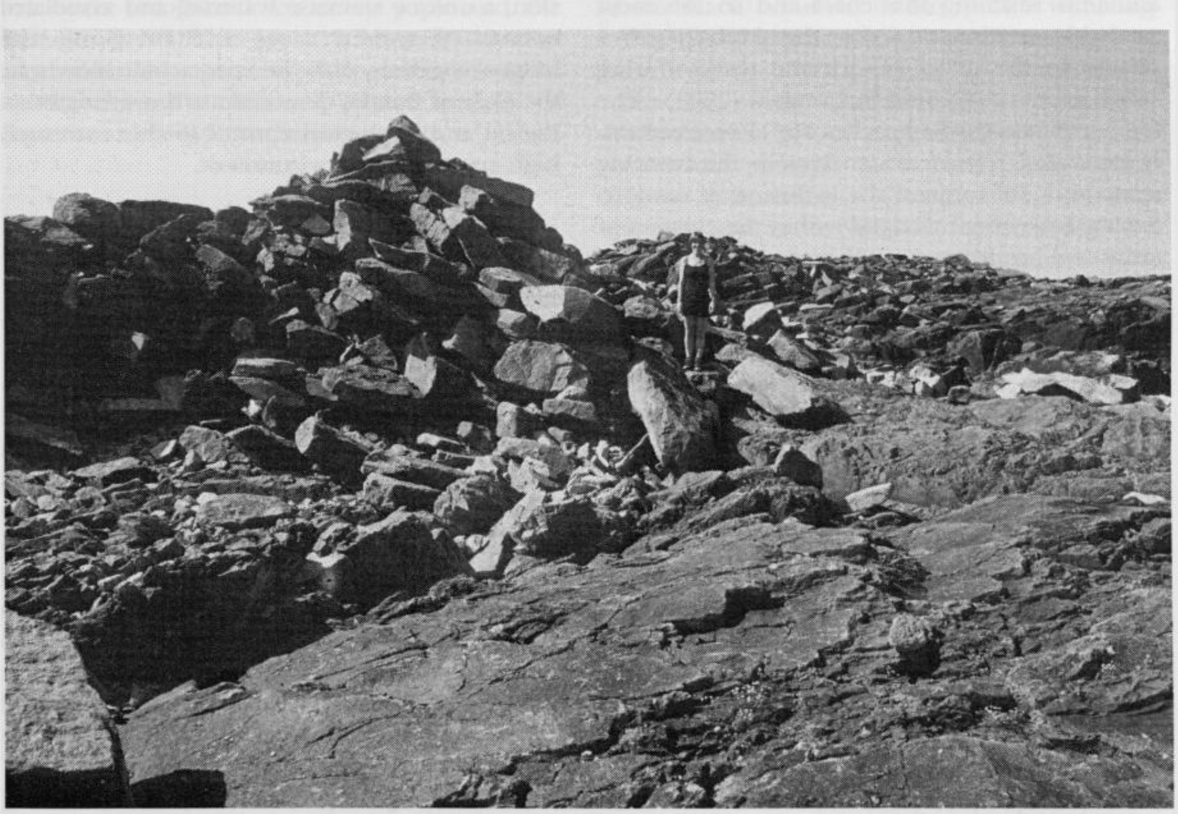

Figure 3.7 The largest of three wave-emplaced boulder ridges that occur on top of a 15 m-high cliff some 50 m inland of the cliff edge at the Grind of the Navir, to the south of the Villians of Hamnavoe. Note 1.8 m-high figure for scale. (Photo J.D. Hansom.)

1991/2, gravel thrown through the air during the same storm occurring up to 100 m inland of the upper limit of wave wash.

However, Hansom *et al.* (in press) show that the limits of scoured bedrock, and the clusters of imbricate boulders, closely follow the indentations of the cliff edge and are thus likely to be mainly related to extreme wave processes. Detailed wave-refraction modelling at The Grind of the Navir also indicates that deep-water offshore waves of between 15 and 20 m in height undergo enough nearshore refraction only to reach breaking at the cliff face itself and so they achieve maximum erosive power at this point. The implication is that 20 m-high, deep-water storm waves fairly regularly impact on the 15–20 m-high cliffs along this coast and are capable of constructing boulder beaches above 15 m OD and 50 m distance from the cliff edge (Hansom, 2001). Since the Holocene evolution of the Shetlands is dominated by submergence (Birnie, 1981), the boulder beaches are not emerged features. Other than the 7000 years BP tsunami produced by the Storegga slide (Smith, 1997), there is no convincing evidence of other tsunamis reaching this coast and so the most probable explanation for the high beaches relates to the effect of extreme waves during storm events suggested by Hansom (2001). The fresher blocks in the beaches are almost certainly excavated from fresh sockets in the fronting ramp and cliff top and the inclusion of modern fishing equipment wedged within the clusters of imbricate boulders strongly suggests a modern date. The distribution of larger, older blocks above and landward of the fresher blocks, suggests that storms of greater intensity have affected the coast of Shetland over the last 3000 years. Sands from underneath these boulders have yielded an Optically Stimulated Luminescence date of 1605 AD, and so may have been emplaced during the stormy conditions of the Little Ice Age (Sommerville *et al.*, in press).

Other than the very recent research noted above, there has been no other geomorphological work published for this outstanding environment, in spite of the geological and geomorphological importance of the site having been highlighted in the past (NCC, 1976). There remains great scope for research of international significance at the Villians of Hamnavoe, including: identification and measurement of the range and rates of processes operating on hard-rock coasts in extreme high-energy conditions; and assessment of the frequency of extreme storms and their effect on the rate of cliff retreat, denudation of the scoured rock surface, and transport of large fragments of rock.

Conclusions

One of the most exposed coastal sites in Mainland Shetland, the Villians of Hamnavoe provide some the best examples of the power of high-energy storm waves. Well-developed, high-altitude scour features occur at a range of heights above 15 m OD and up to 100 m inland, with associated wave-shifted slabs and boulders. Similar high energies occur during major storms on St Kilda, but the overall height of the cliffs reduces the amount of potential wave run-up and washover and so may reduce erosion since the waves reach the cliff unbroken. At the Villians of Hamnavoe, nearshore water depths are sufficient to allow breaking on the cliff and a higher net erosion rate. The products of erosion are evident in the accumulation of high-altitude contemporary beaches constructed out of large boulders at distance from the cliff edge. In addition, a unique staircase waterfall and associated system of arches, caves and overhung cliff ledges, together with the spectacular blowhole, the Hole of Geuda, demonstrate the strong lithological and geological control in this extremely high-energy wave environment.

PAPA STOUR, SHETLAND (HU 170 600)

J.D. Hansom

Introduction

The small island of Papa Stour (3.5 × 3 km), separated from the western Mainland of Shetland by the narrow Sound of Papa, contains a remarkable assemblage of hard-rock coastal forms of national importance (NCC, 1976). In many ways the coastal landforms of Papa Stour represents in microcosm the coastal landforms of the Shetland Isles and most of the distinctive features of the Shetland coastline are represented. Cliffs of various types, geos, stacks, skerries, subterranean passages, caverns, caves, natural arches and blowholes are all found within this relatively small, but highly scenic, area. Papa Stour and its surrounding seabed also displays many of the features of a submerged dissected plateau, which, on a rising relative sea level, has been actively and selectively eroded by a wide range of wave-energy environments.

Although Papa Stour is not quite as exposed and windy as St Kilda, it shares a wind and wave climate similar to the Villians of Hamnavoe and Foula. For 75% of the time the hourly mean wind speed exceeds 4 m s^{-1} with the most frequent strong winds from the south-west (BGS 1977a). At Papa Stour, a combination of exposure to prevailing winds and deep water close inshore produces a relatively high-energy wave climate at the shore and significant wave heights are about 3 m for 10% of the year and are less than 1.5 m for 75% respectively (Draper, 1991). However, storm waves at sea reach heights well in excess of this. The sea floor falls steeply away from the island to 50 m at about 1 km offshore but there are numerous skerries and stacks in the nearshore that serve to reduce wave energy. Wave energies are further reduced by the North Shoals and Ve Skerries that lie at 20–30 m depths to the west and south-west of Papa Stour.

Although the scientific interest of Papa Stour has been recognized for many years and the research potential is great, it has not attracted any detailed geomorphological research. Nevertheless, the cliffs and related features of Papa Stour warrant further investigation.

Description

The island of Papa Stour is composed almost entirely of Devonian extrusive igneous rocks, mostly rhyolites and ignimbrites, with smaller outcrops of basalts, tuffs and agglomerates. Locally, there are numerous small-scale changes in structural alignment and lithology. Small faults and fissures abound, facilitating differential erosion and differing levels of rock breakdown.

Although the entire coastline of Papa Stour is of geomorphological interest, an 8 km stretch of the western part of the island contains an impressive assemblage of hard-rock coastal landforms. The description that follows concentrates on this dramatic stretch of coast from Wilma Skerry (a low gradient wave-scoured promontory) on the south-west coast, clockwise round to Lamba Ness on the north coast (Figure 3.8).

At Wilma Skerry and around the offshore skerry of Swarta, the wave-scoured rock surfaces above the high tide line give way to sloping intertidal shore platforms, although why this should be the only development of sizeable shore platforms on the west coast of Papa Stour is unknown. North of Wilma Skerry, the cliffs are up to 20 m high and indented with caves, natural arches and geos. The three Galti Stacks, protrude prominently from the sea at the mouth of a narrow geo, all four features corresponding to exploitation of a distinctive fault line. Selective erosion of the many vertical joints in the rocks makes caves a common feature along this stretch of coast. North of the Galti Stacks, the relatively wide Brei Geo indents the coastline with steep, almost vertical, sides that increase in height to almost 35 m at the head of the inlet.

The coastline between Brei Geo and North Lunga Geo is highly indented, with alternating small geos and promontories. North Lunga Geo widens inland and has an isolated rock pillar (over 10 m high) in the centre of the inner geo. The backwall of the geo reaches *c.* 35 m high some 70 m from the outer coast and a gravel storm beach occurs at its base. This widening-inland characteristic is common to many geos on Papa Stour.

To the north, Christie's Hole provides a dramatic example of a geo inlet with a subterranean passage and collapsed cavern (Figure 3.8, inset). Complex relationships between marine erosional features and the structurally controlled pattern of shallow lochs on the plateau are clearly demonstrated at Christie's Hole. Marine erosion along a structural line of weakness has cut geos, caverns and subterranean passages that underlie depressions on the surface. The collapse of the roof of one of these subterranean passages resulted in the instantaneous drainage of one of the flooded depressions and the loss of an inland loch.

Farther north, two geos indent the coastline to the south of Aesha Head. Binnie Geo is a smaller version of North Lunga Geo and Hirdie Geo, with its extensive blocky scree slopes and basal boulder accumulations; it lies along a major fault-line. North-west of the fault the control of rock type on general coastal shape and evolution is perfectly demonstrated in the bay south of Aesha Head, where erosion of the basalt has produced a gently sloping and wide valley in the plateau and low-angled cliffs sloping inland. At low tide, a wide boulder beach extends

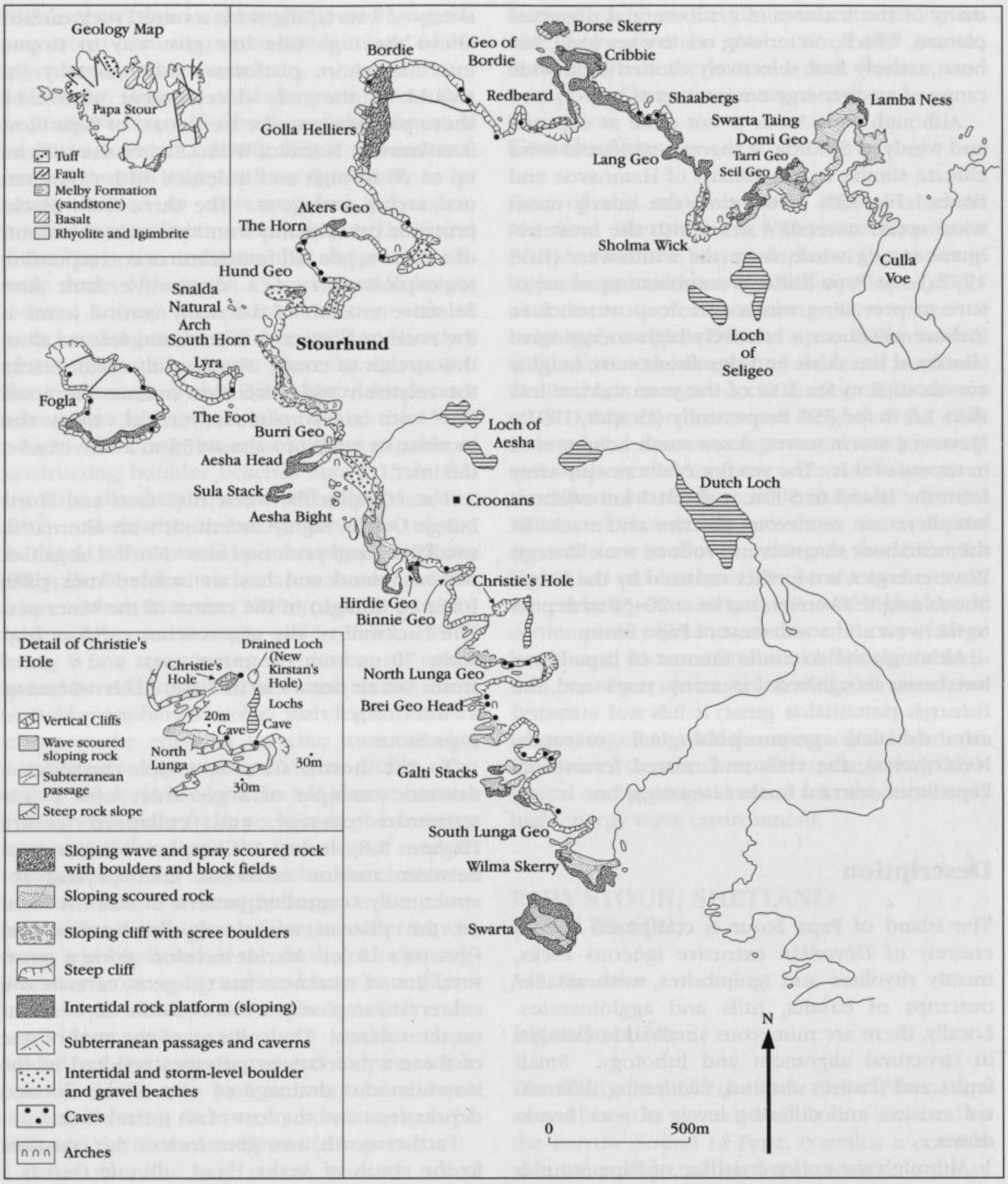

Figure 3.8 Geomorphological sketch map of Papa Stour showing extensive wave-scoured cliff-top surfaces, together with stacks, caves, arches and geos. For general location, see Figure 3.1. (Modified from unpublished work by W. Ritchie.)

almost as far as the low offshore rocky skerries where the two irregular-shaped stacks of Aesha and Sula protrude from the sea beyond. Aesha Head itself is a distinctive narrow promontory composed of rhyolite. A spectacular natural arch spanning the narrow neck of the promontory marks the rhyolite–basalt junction.

Northwards from Aesha Head the land rises steeply to over 50 m OD at Stourhund, with its horn-like point. The view from here to the caves, arches and cliffs of Lyra Skerry and, the larger, Fogla Skerry to the west, provides striking and dramatic coastal scenery. These islands contain numerous subterranean passages. The north headland of Fogla Skerry contains a magnificent series of buttresses, arches and interlinked caves and many of the cliffs are much steeper than those on the adjacent mainland.

The steep, almost vertical, cliffs north and east of Stourhund are over 50 m high, with no shore platform or basal apron of boulders. Offshore there are spectacular narrow rock pinnacles and stacks, including an impressive natural arch at Snalda. The high basalt cliffs are indented with the spectacular geos of Hund Geo and Akers Geo, whose high, vertical rock walls extend far inland, again corresponding to erosion along faults. Access to the inner part of Akers Geo is restricted by a rock promontory lying transverse to the long axis of the geo and which is pierced by a natural arch. Even so, powerful waves rush into the geo, creating an extensive, wide, boulder beach at the base of the 40 m-high inner wall.

A 400 m-long subterranean passage extends through the outer cliffs close to the headland of Bordie that marks the north point of the island. East of this headland is the Geo of Bordie, not a geo in the true sense, but a compound north-facing bay. The distinctive and narrow promontory of Redbeard subdivides the bay of Bordie into two unequal parts. High, vertical, and often overhanging, cliffs, of uniform basalt lithology extend for over 500 m at the western side of the bay of Bordie, declining in elevation to the east. East of the precipitous cliffs of Redbeard, the bay is wider and lower and has a cobble beach. Here the free face of the rock cliff is masked with recent rock falls and screes and occurs up to 100 m from the beach. This represents the subaerial recession of the basalt cliff top by failure and rock fall rather than by marine undercutting, such that the debris delivered to the cliff foot is reworked into beach deposits.

The low peninsula of Cribbie, to the east of the Geo of Brodie, is wave-scoured, with highly dissected sloping rock surfaces. Shore platforms are virtually absent. Indeed, the outer peninsula is almost detached as marine erosion has carved a narrow, deep geo on the east side, which terminates in a distinctive blowhole (the Kiln) in the plateau surface. Near the Kiln, there is a block field 15–20 m above sea level on the south side of the narrow geo. There is also a spectacular natural arch at Cribbie.

The relatively low rocky coastline from Cribbie to Lamba Ness is highly indented and irregular, with numerous small inlets, geos, reefs, low stack-like pinnacles and wave-scoured rock surfaces with only small fragments of shore platform in evidence on the east side of Sholma Wick. A boulder beach is present on the west side of the inlet of Sholma Wick. The low, rough, bare rock headland of Lamba Ness is severely wave-scoured for almost 100 m inland and to over 12 m OD. Wave action from the north-west is clearly an extremely effective erosional process in this exposed location and numerous stacks have been created by erosion, commonly along fault lines (Figure 3.9).

Interpretation

Erosion of the mainly basaltic rocks of the island of Papa Stour has produced an impressive series of geos, stacks, blowholes, cliffs and sea caves (NCC, 1976). This site provides textbook examples of almost all of the main hard-rock coastal landforms and the juxtaposition of these and the wide range of landforms found on Papa Stour without doubt justify its inclusion in the GCR.

The coastal landforms of Papa Stour represent a microcosm of the Shetland archipelago and display many of the distinctive features of the Shetland coastline. The origin and evolution of the Shetland coast has been much debated (e.g. Flinn, 1964, 1969, 1974; Steers, 1973). Flinn (1964) highlights the absence of modern shore platforms at the foot of the cliffs of Shetland, echo-sounding showing that the cliffs descend below present sea level often to considerable depths. The sea floor around the archipelago is stepped or terraced with common occurrences of nearly horizontal surfaces commonly at depths of 24 m, 46 m and 82 m below present sea level (Flinn, 1964). These terraces are regarded as indicating erosional surfaces produced by earlier sea levels before submergence took place (Flinn, 1964). The lack of shore platforms at present sea level with the steep cliffs plunging directly into deep water to submerged platforms also implies that conditions are no longer suitable for the planation of platforms, either because sea level has been too mobile or that the processes of planation have changed as was suggested in the St Kilda GCR site report.

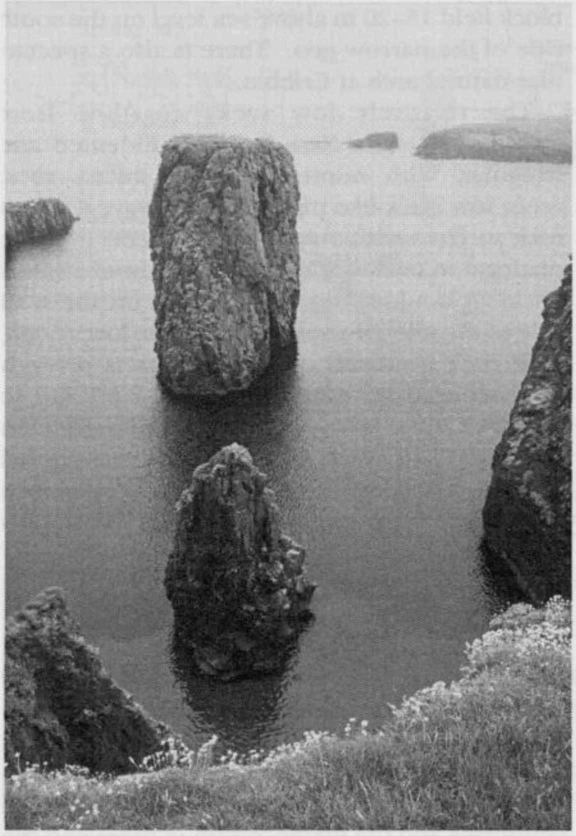

Figure 3.9 Fault-controlled stacks at Lamba Ness, Papa Stour. (Photo J.D. Hansom.)

The surfaces at 46 m and 82 m below sea level have parallels with those at St Kilda but not the surface at 24 m and this may reflect a divergence of the relative sea-level histories of the two locations in late Quaternary times. Flinn (1974) regards Shetland as an erosional remnant standing above the North Sea floor with sea-level rise gradually drowning the valleys and re-activating the relict cliffs of former sea levels. Certainly, the cliffs are likely to be inherited features of earlier higher sea levels, an argument put forward in the GCR site report for St Kilda.

The erosional features of Papa Stour have great potential for research into the ways in which lithology and structure control the geomorphology of hard-rock coasts. Well-developed geos on Papa Stour often co-incide with the axes of major faults (e.g. Hund Geo and Akers Geo), while wave erosion differentially exploits the small-scale faults and fissures, local changes in lithology, alignment and bedding planes to produce geomorphological diversity. This, combined with the variations in exposure to wave energy of Papa Stour, produces a spectacular range of structural and erosional situations.

Conclusions

Papa Stour is of national geomorphological importance owing to the juxtaposition of a diverse range of excellent examples of almost all of the main hard-rock coastal landforms; ranging from low wave-washed skerries to impressive near-vertical cliffs. Within an 8 km stretch of coastline, the western part of Papa Stour contains a spectacular range of coastal forms, with: cliffs of a range of altitudes, some of which are wave-scoured, some with well-developed scree formations; geos and inlets of varying size and orientation, some with inlet head beaches and others with sheer cliffs; subterranean passages, some over 400 m long; caverns; caves; natural arches; blow-holes; offshore islands; skerries and stacks. This dramatic pattern of diversity has its roots in differences in wave exposure, the presence of major and minor faults and subtle changes in lithology, alignment and bedding planes that are unmatched elsewhere in Britain (NCC, 1976).

FOULA, SHETLAND (HT 940 400)

J.D. Hansom

Introduction

The island of Foula (13 km^2) lies 22.5 km west of the Shetland Mainland and is the most westerly of the Shetland Isles. The island's dramatic profile is dominated by the summit of The Kame (376 m), Britain's second-highest sea cliff. The entire coastline is exposed to the extremes of wind and wave energy as it shelves steeply into deep water (greater than 60 m). The high cliffs and fragmented cliff-foot shore platforms along the west and south-west coasts are exposed to the frequent and high-energy Atlantic storm and swell waves.

The island is primarily composed of Middle Devonian sandstones, which rest unconformably on, and are faulted against, a narrow strip of Dalradian metamorphic rocks along the east coast (Blackbourn and Russell, 1981; Blackbourn, 1985). The metamorphic rocks are cut by a series of microgranitic intrusions, the topographic expression of which adds protrusions to the coastal outline of the island. Erosion and faulting of the sandstone has led to the development of a series of approximately east–west-trending gentle south-facing dip slopes and steep north-facing escarpments (Flinn, 1978; Blackbourn, 1985) that form ridges and valleys that dominate the skyline and control the form of the dramatic cliffs along the north, south and west coasts of the island. Flinn (1978) concluded that Foula had been completely overridden by ice during the last glaciation, with ice flow from the south-east that had been deflected to the north and north-west by the higher land of Hamnafield and The Sneug. Localized ice deflection to the west around The Noup influenced the glacial erosion of the Daal valley.

Although Foula may not be quite as exposed and windy as St Kilda, it shares a wind and wave climate similar to Papa Stour. At Foula, a combination of exposure to prevailing winds and deep water close inshore produces a relatively high-energy wave climate at the shore and significant wave heights are about 3 m for 10% of the year and less than 1.5 m for 75% respectively (Draper, 1991). However, storm waves at sea reach heights well in excess of this. There are few skerries and shoals offshore and since the sea floor falls steeply away from the island to –80 m depth, onshore wave energies are high.

Description

The Foula coast is almost entirely cliffed with heights of 150 m at Wester Hœvdi (HT 937 388), 210 m at Soberlie (HT 951 410), 248 m at The Noup (HT 953 375) and 376 m at The Kame (HT 940 400). However, the crest of the cliffline lowers dramatically along the east coast where it ranges from 50 m to below 10 m in height. Local variations in cliff form are related to the slope of the inland topography, itself controlled by the structure of the bedrock geology and, to a lesser degree, past glacial erosion. Cliff-foot shore platforms are found along some sections of the coastline, although they vary greatly in extent and are partly a function of structural control. Classic examples of caves, arches, tunnels, stacks, reefs and skerries are also present around the coast. It is convenient to subdivide the coast into seven sections on the basis of the bedrock geology and/or surface topography (Figure 3.10, after Pirkis, 1963).

In section one the area of Dalradian metasediments and microgranite intrusions between Wurr Wick and Shoabill is geologically distinct from the sandstone bedrock that dominates the rest of the island. The two inlets of Wurr Wick and Shoabill have been cut along the line of the faulted contact between the sandstones and Dalradian metasediments and the cliffs are lower than elsewhere at no more than 50 m high. Inland limits of weathering and surface stripping associated with wave spray are variable and dependent upon the geology and inland topography. On the northern side of Strem Ness a tunnel has formed along the line of minor fault plane between Wurr Wick and Scarf geo. The nature of the cliffs around Strem Ness changes at the Head o'Ruscar, where a microgranite sill has been intruded into the host rock and is characterized by a gentle, seaward-sloping bedrock ramp, which facilitates rapid wave run-up during storms and erosion of the bedrock surface. Deep geos occur at Kubbi a'Skeld and Sloag of Ruscar, and to the south towards Ruyhedlar Head, a near-vertical cliff of granulite rises to 50 m. The coastline becomes indented by intersecting geos with many excellent examples of rock-coast landform development such as caves, arches stacks and stumps. South of Swaa Head, the altitude of the mica-schist cliff averages 20 m in height. The rocks are significantly less resistant to weathering and erosion than the psammites to the north and the coastal edge is a low, gently sloping platform, locally dissected by narrow geos cut along the boundaries of microgranite intrusions and scour and stripping of vegetation is evident up to 20 m above sea level and 50 m inland. Hedd o'da Baa, to the south of Ham Voe, comprises a low, flat, coastal edge up to 10 m high composed of peat resting upon glacial till, but to the south the altitude of the coast rises towards the large and complex geos of Ham Little, Selchie Puddle and Shoabill.

The second coastal section from Shoabill to Hellabrick's Wick (Figure 3.10) and inland has some of the lowest and flattest land on the island. The surface falls from 40 m at Heddicliff to 20 m at South Ness reflecting the gentle southerly dip of the underlying sandstone. The cliffs south from Shoabill to North Hœvdi are mainly composed of sandstones and shales capped by glacial deposits that feed debris to the cliff-foot boulder beach, known as 'South Wick', via extensive and unstable scree slopes. South of this, the coast is composed of harder sandstones capped by a thin layer of glacial till

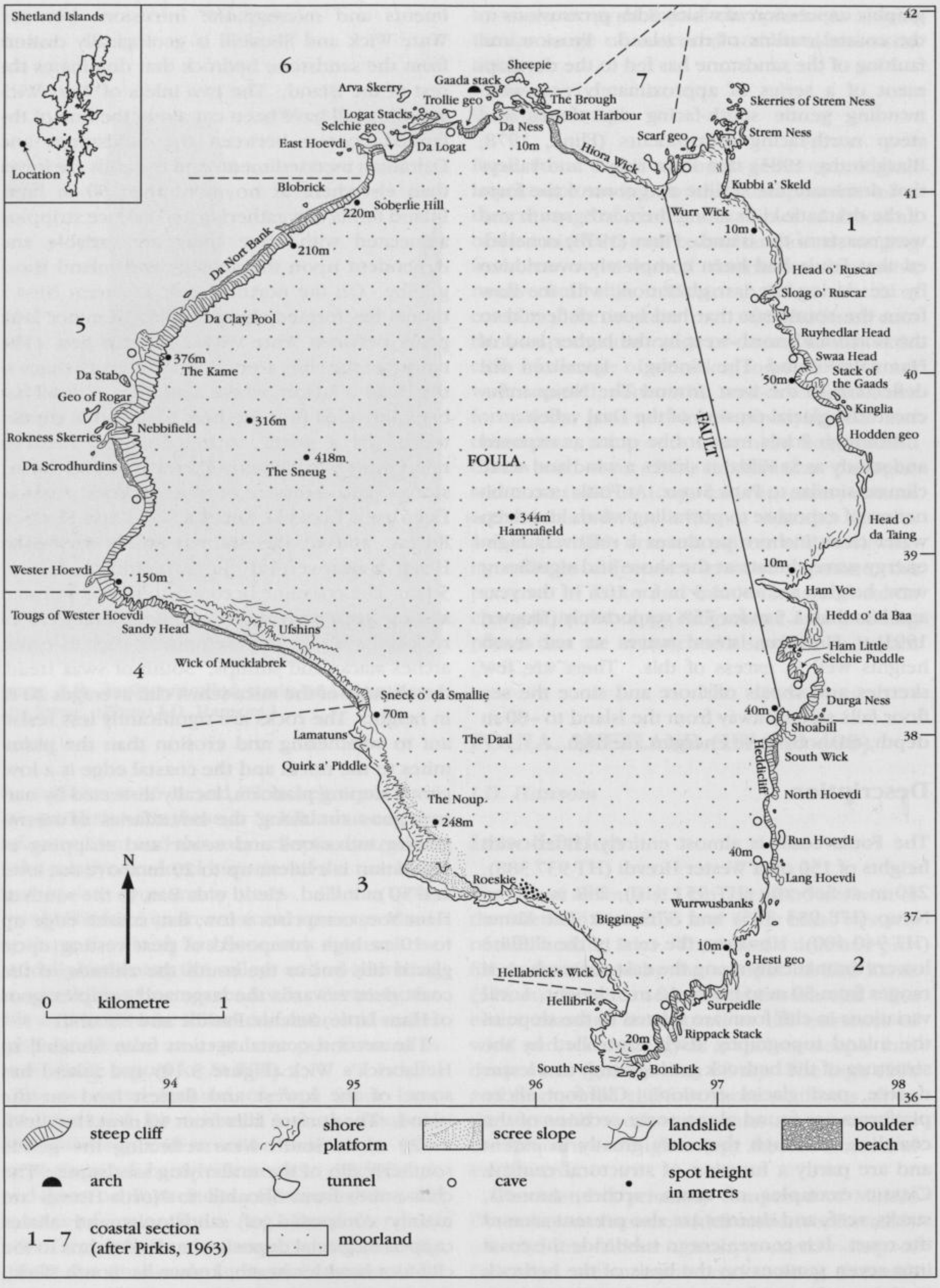

Figure 3.10 Coastal geomorphology of Foula. Sections 1–7 refer to descriptions in the text. The highest and most spectacular of these are Section 3 and Section 5 where the cliffs rise to 248 m at the Noup, and 376 m at the Kame respectively. See Figure 3.1 for general location. (After Pirkis, 1963.)

(Pirkis, 1963) and the cliffs are low, but sheer, and are deeply indented by geos with stacks offshore. The northern part of the third coastal section from Hellabrick's Wick to Smallie is mainly composed of the Noup Sandstone, the form and height of the cliff mirroring that of the topography inland and rises to The Noup at 248 m. The cliffs are stepped and formed of a series of landslided sandstone blocks and associated scree slopes. Steeply sloping (25°) cliff-foot platforms lead up to the base of the landslides. To the north the cliff edge drops to around 70 m where the Daal, a glaciated trough, intersects the coast. Large cliff failures are currently active at the western end and several large tilted slip blocks of sandstone appear to have failed along the upper junction of the intertidal ramp of the shore platform. One of the most impressive and distinctive is the Sneck o'da Smallie, a 60 m-deep and 1 m-wide cleft that extends for 50 m.

The fourth section of coast between Smallie and Wester Hœvdi is one of the most exposed parts of the Foula coastline and contains excellent examples of cliffs influenced by structural dip (Pirkis, 1963). The cliff profile shows a series of steps up to 250 m high, comprising at least one major rock slide. The southerly dip of the sandstone has produced a ramp-type shore platform along this section of coast that is narrow and structurally controlled. It is poorly developed and locally obscured by slabby boulder beaches and scree deposits. Just north of the Smallie, a large rock failure known as 'Ufshins' has slid at least 40 m down a section of cliff face defined by faults in both the east and west.

The fifth section of coast between the 150 m-high Wester Hœvdi and the 220 m Soberlie is composed of sandstone and has by far the most spectacular cliffs on Foula. The sheer face of The Kame at 376 m, is the second highest sea cliff in Britain (Figure 3.10). The cliffs at Wester Hœvdi are also sheer with numerous caves but no shore platforms. To the north, short lengths of sloping intertidal shore platform occur with skerries offshore. Beyond The Kame, the cliff crest drops rapidly to Soberlie Hill, its base indented with caves and headlands. Along the Da Nort Bank, localized accumulations of cliff-foot boulder beaches occur sourced from the joint controlled collapse of the upper cliff face. There is a general absence of shore platforms along this stretch of the coast.

The sixth part of the coast between Soberlie and Da Ness is composed of glacial till-covered sandstone into which have been eroded an abundance of caves, arches, tunnels, stacks and reefs. To the east of Da Logat, the Logat Stacks are well-developed examples of triangular stacks with rocks dipping steeply (around 45°) southwards. The stacks at Gaada, Sheepie and The Brough are similarly dip-controlled, Gaada stack being dissected by two arches the upper surfaces of which are capped by eroded and loosened boulders. The lower part of the uppermost bed remains unweathered towards the base of the landward face and protrudes as a low ridge, preventing downslope slippage of weathered material from above.

The final section of the coast to Wurr Wick is unique as it is both low-lying below 10 m and depositional being composed of a storm ridge composed of local sandstone, igneous and metamorphic *c*. 1 m-long boulders. During storms such boulders are thrown several tens of metres inland (Pirkis, 1963), for example at Boat Harbour.

Interpretation

Early work by Walton (1959) on cliff coasts along the east coast of Scotland suggested that many seemingly active cliff landforms are inherited features from earlier sea levels, buried by glacial till during the Quaternary Period, and subsequently exhumed and subject to further wave erosion over Lateglacial and Holocene times. Where conditions were favourable for preservation, even some fragile features such as stacks and arches were re-occupied and numerous examples of till-adorned stacks and till-choked emerged ('raised') stacks are known from the Scottish coast, for example at Tarbat Ness and Cullen in the Moray Firth. In Foula, cliffs with till caps and till plugs inside the heads of geos occur widely along the north and east coast and are a powerful argument in favour of the inheritance of cliffs from earlier times. This is supported by more recent analysis from a wide range of coastal settings including Antarctica, where fragile stacks have emerged as ice caps have retreated (Hansom, 1983), St Kilda (Sutherland, 1984) and Canada (Trenhaile, 1997). In spite of this, some of the more fragile features such as stacks and arches can also be shown to have developed, and in some cases were subsequently destroyed, entirely within the Holocene Epoch as marine quarrying and abrasion has progressed, for example the Old Man of Hoy in Orkney (Hansom and Evans, 1995). On Foula, The Brough stack supported an arch carrying a Bronze Age broch (fort) on its upper surface until the arch collapsed during a severe storm in 1965. This implies that whilst the overall form of a cliff coast may well be inherited from former conditions and reoccupied by present processes, the detailed form, development and change can be a relatively rapid process.

In Foula, the occurrence of inherited cliff features, especially along the north and east coasts, may be explained in terms of differential erosion rates leading to preservation. It is probably reasonable to assume the highest energies in Foula occur on the west and south coasts since these are fully exposed to waves from the dominant westerly and south-westerly directions. In comparison, wave energies may be relatively lower along the east and, possibly, north coasts. It follows that there is a greater likelihood of preferential preservation on the north and east coast and this broadly appears to hold. Foula would therefore provide an interesting site for a more detailed examination of the relative age of cliff coastlines in Scotland.

As with St Kilda, although shore platforms exist, the lack of extensive and well-developed shore platforms in such a high-energy environment as Foula, remains problematic and invokes similar arguments to those used for St Kilda. Pirkis (1963) argued that the absence of boulder beaches at the foot of the cliffs showed that erosion rates along the coast of Foula were low. However, beaches require a surface on which to develop and their absence here is probably related to the lack of an extensive and widespread cliff-foot shore platform, an absence itself related to unsuitable conditions for platform development. In Foula, where geological structures permit, limited shore platforms have developed, such as at Ufshins in the south-west. However, nowhere is there a shallow surface close to sea level from which these platforms, stacks and stumps commonly rise. Most of the cliffs of Foula plunge into deep water, and although minor erosional notching at present sea level exists, nowhere is it extensive or substantial.

In spite of the relative lack of shore platforms, several features of rock coast forms are well-represented and display good relationships with geological structure. For example, on the northern side of Strem Ness, a tunnel has been excavated headwards from two caves, one on either side of the Ness, to eventually coalesce along the line of minor fault plane between Wurr Wick and Scarf geo. At South Ness, some of the geos have deep and actively eroding caves at their head, suggesting that some geos form through cave formation and roof collapse along the lines of weakness in the sandstone. During south-easterly storms, wave action is intense within these geos, and cave formation is still active. The presence of large landslide-blocks along the west coast indicates that large-scale failure of the cliffs, which occurred in the past, probably continues as a result of failure along bedding planes in the sandstones and nowhere is this more dramatically displayed than at the Sneck o'da Smallie. Where shore platforms do exist in Foula, they tend to be structurally controlled. At the Noup, and to the north of here, the dip of the sandstone have been exploited by storm waves to produce a cliff-foot, ramp-type shore platform that is narrow and structurally controlled. This enhances wave run-up and has resulted in failure and slippage of the cliff-foot sandstone blocks.

With deep water offshore and adjacent steep cliffs, the boulders that comprise Hiora Wick beach are unlikely to be supplied with large quantities of fresh materials, and the boulders and gravels are likely be recycled. Pirkis (1963) used the distribution of clasts of different lithologies along the beach to infer that grey sandstone clasts eroded from Da Ness are fed southwards and alongshore to dominate most of Hiora Wick, whereas in the extreme south-east, igneous and metamorphic rocks sourced from outcrops in the south-east are found.

Conclusions

The island of Foula is outstanding for its assemblage of hard-rock coastal landforms, which include the second-highest sea cliff in Britain. With the exception of well-developed shore platforms, examples of most of the features and stages of coastal landform development in rock are found. The island experiences relatively high wave-energy levels and the west and south coasts are fully exposed to swell and storm waves generated in the Atlantic Ocean. These conditions have facilitated the development of a fine assemblage of sheer-faced and composite cliff forms, geos, sea caves, tunnels, arches, stacks and stumps, many of which show clear relationships with geological structure.

WEST COAST OF ORKNEY (NY 229 188–NY 222 094 AND NY 237 054–ND 173 991)

J.D. Hansom

Introduction

High-cliff coastlines are a feature of much of the Atlantic coast of the Orkney Islands. The 20 km stretch of cliffs between Rora Head, at the south-west tip of the island of Hoy, and the Hole o'Row, mid-way along the exposed west coast of the Mainland (see Figure 3.1 for general location and Figure 3.11), provide some of the best examples in Europe of Old Red Sandstone cliffs and associated features. Lithology and structure are major geomorphological controls and the cliffs and associated forms of west Orkney are good examples of the control exerted by geology on coastal landforms. The rich variety of cliff and cliff-related forms along this coast include steep and overhung profiles; sea-stacks; arches; caves; geos and shore platforms, all reflecting the dominant geological control of horizontally bedded, fractured and faulted, sandstone and flagstone.

The most characteristic feature of the Orkney climate is the frequency of strong winds. The prevailing winds are from between west and south-east for 60% of the year. Winds greater than 8 m s^{-1} occur for over 30% of the year and gales occur on average for 29 days per year. Along the south-west coast of Hoy, a combination of deep open water and exposure to prevailing winds produces a high-energy wave climate. Within Hoy Sound, conditions are more sheltered, especially from the north and south-west but on the outer coast of Mainland and Hoy during westerly and northerly storms, wave conditions are more severe. Because the sea floor falls steeply away from the west to 60 m, the coast is exposed to relatively high wave energies. Spring tidal range in the western Orkney Islands is 3 m (UKDMAP, 1998).

As with much of the hard rock upland coast of Britain, there have been few detailed geomorphological studies of the Orkney coastline. Nevertheless, the nature of the cliffs and associated features have been described in more general terms (Steers, 1973; NCC, 1978) and Hansom and Evans (1995) have examined the nature and development of the famous sea stack called the 'Old Man of Hoy'.

Description

The GCR site has three main sub-units (Figure 3.11):

1. The west coast of Hoy, from Rora Head to Kame of Hoy.
2. The north-west coast of Hoy, from Kame of Hoy to The Pow.
3. The west coast of Mainland, from Breck Ness to Hole o'Row.

The cliffs from Rora Head to Kame of Hoy are high, steep, and in places, vertical. The highest cliffs occur in the north at St John's Head, but no part is less than 50 m high. A narrow (40–70 m-wide) intertidal shore platform, with a cover of fallen boulders, is a common feature along much of this stretch of coast. The Old Man of Hoy, one of the tallest and most spectacular sea stacks in Britain (Figure 3.12) towers 137 m above the sea surface yet is only a few metres wide at the top. Its sides are composed of vertical or overhanging walls that fall sheer on all sides. The pinnacle itself is separated from the adjacent cliffs by a 60 m-wide chasm whose base is strewn with debris, which presumably has fallen from a collapsed arch (Hansom and Evans, 1995).

To the north of the Old Man, the cliffs of St John's Head rise vertically to 335 m. The rock is composed of alternating beds of relatively soft, sandy and pebbly sandstone with occasional beds of harder grey flagstone, bestowing upon the cliffs a slab-like, notched and often overhung profile. These variations in hardness, the near-horizontal bedding, combined with the multiple joints, cracks and faults common in sandstones and flagstones are important factors explaining the spectacular vertical cliffs, caves and stacks of this coastline. The cliff forms are dominated by blocky shapes and cut by deep steep-sided geos and ravines that often bisect headlands. Weathering has etched out vertical chasms in the cliffs along joint planes and near Kame of Hoy the coastline is extremely rugged with many minor sea stacks and inlets. Near the Old Man, a few near-horizontal platforms have been cut into the sandstone, but elsewhere the shore platforms are gently sloping at 10–20°.

The north-west coast of Hoy between Kame of Hoy and The Pow is a transitional coastline, between the high cliffs at Kame of Hoy and the lower, north-facing cliffs with platforms at the

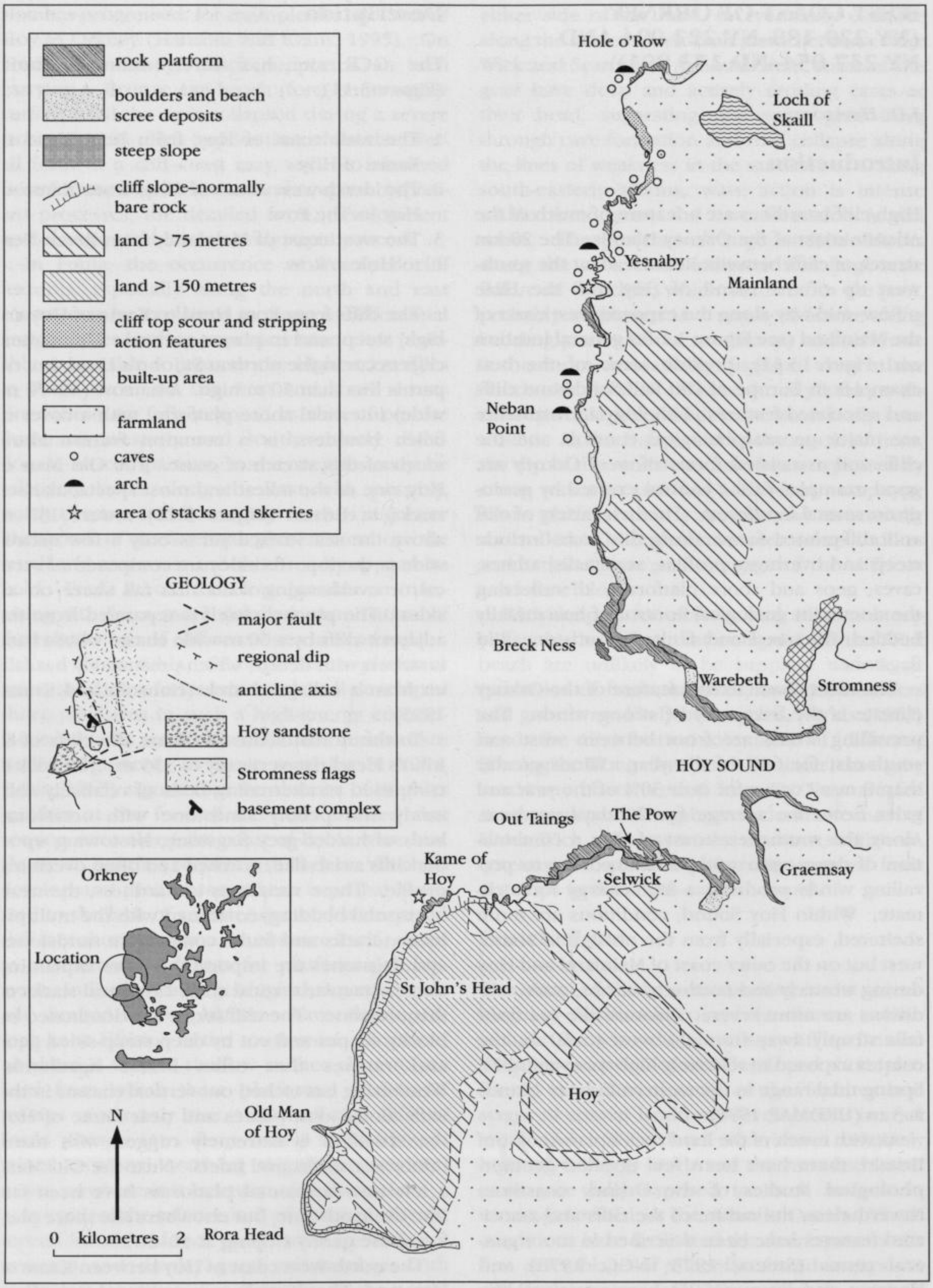

Figure 3.11 Coastal features of the West Coast of Orkney. Erosion of the Hoy Sandstone and Stromness flags (inset) has produced an impressive coast of steep cliffs, caves and stacks. (Modified from unpublished work by W. Ritchie.)

north-east of the island. The 1.1 km stretch east of the Kame contains some of the steepest coastal slopes in Orkney and there are excellent examples of high plunging cliffs with no shore platforms. This zone also marks the junction between the Old Red Sandstones to the south and the grey Caithness Flagstone Group to the north. These flagstones consist of rhythmic sequences of thinly bedded siltstones, shales and finely laminated sandstones and so, apart from the stretch of high cliffs east of the Kame, most of the remaining coastline towards The Pow consists of low cliffs, degraded terraces ranging from *c.* 5–10 m high, and some well-developed shore platforms, particularly at the Taing of Selwick. At Selwick, the rocks dip to the west, imparting to the 60 m-wide shore platform a well-defined ribbed appearance where the eroded fronts of the beds run north towards the water's edge. Numerous small-scale intertidal fissures and cracks have been excavated by the waves, some have been abraded by boulders and many of these have become lodged in fissures in the shore platform. The lower-lying areas of shore platform have become buried by accumulations of sand and gravel, for example at The Pow.

The west coast of Mainland between Breck Ness and Hole o'Row consists of a dramatic series of almost vertical cliffs reaching up to 60 m in height, within which the effects of erosion are well developed, with a great variety of geos, caves, arches, stacks and cliff forms. The underlying geology is the Caithness Flagstone Group but some basement granitic and gneissic rocks outcrop as inliers, the largest of which lies to the south of Yesnaby. This stretch of coast is typical of Orcadian cliffed coastline, in detail highly irregular but, in general, lacking substantial embayments. The cliff tops are lower than on Hoy at between 20–60 m, but occasionally reach 100 m above sea level, particularly in the north where the coastline intersects the generally rising relief of the landward plateau. The cliffs are mainly vertical or overhanging with a distinctive notch at wave level where the flagstones have been quarried by waves. The notch is best-developed where narrow sloping platforms front the cliffs and allow broken waves to impact on the cliff foot, such as at Alga Bar and Brough of Bigging. On the lower cliff tops, wave spray erosion is well developed and many cliff top areas have been stripped of their soil and drift cover up to 40 m inland. Gravel is rare along this stretch of coast, except occasionally within the heads of geos and at Billia Croo, where a small gravel beach occurs.

In general the shore platforms are steeply dipping and narrow, tending to occur as projections from the cliff foot rather than as a continuous fringe along the coast. In detail the platforms are controlled by intertidal outcrops of relatively more resistant flagstone beds. In the steeply dipping strata, these present coherent intertidal ramps (30°) over which waves surge to finally break on the cliff. The intertidal shore platforms have smooth seaward ramp surfaces whereas the landward surfaces are stepped and crenulated. Excavation of these landward steps is often well-advanced enough to have resulted in separation from the original platform to form offshore skerries. In some places deep water extends to the foot of vertical plunging cliffs, for example at Black Craig.

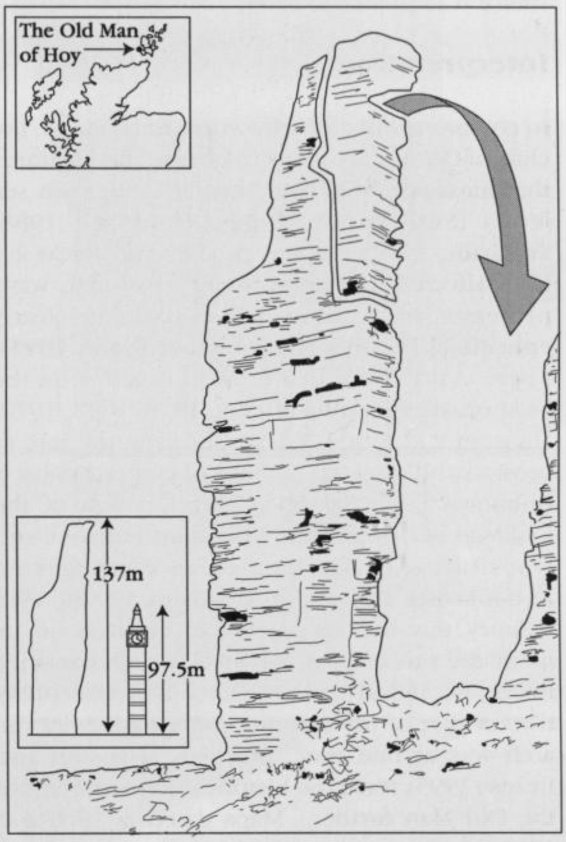

Figure 3.12 The Old Man of Hoy, West Coast of Orkney, showing incipient failure cracks. London's 'Big Ben' is shown for scale in the inset. (After Hansom and Evans, 1995.)

The variety of geos, caves, arches and stacks that occur along this coastline tend to be triangular or rectangular in form, rather than slot-shaped, reflecting the cross-cutting joint and faulting pattern of the flagstones. The stacks and arches at the Castles of Yesnaby and Qui Ayre are rectangular in plan and are known locally as 'castles' (Figure 3.13). Both narrow towards the base where arches have been eroded. At Qui Ayre, the arch is so large that the roof appears unstable. Variations in lithology and geological structure again are major controls on the coastal landforms and the resultant differential erosion and exploitation of weaker strata, joints, fissures or dykes are responsible for much of the meso- and micro-topography. To the south of the Hole o'Row wave and spray erosion is both active and effective (Steers, 1973) on the cliff face and the base of the cliffs and spray and wind erosion is important at the top of the cliffs. In summary, this is an actively evolving cliff coastline that encompasses, in a relatively small area, a consistent suite of cliff-type features developed in a uniform sequence of sedimentary rock.

Interpretation

In common with cliffs elsewhere in Scotland, the cliffs of Orkney are likely to be inherited features that have persisted over several changes in sea level (Sutherland, 1984; Hansom, 1988; Trenhaile, 1997). However, cliffs and stacks are also affected by present-day erosional wave processes, and features such as stacks are clearly ephemeral features (Hansom and Evans, 1995). There is no doubt that erosion is active on the west coast of Orkney (Steers, 1973; NCC, 1978; Hansom and Evans, 1995), however, the rate of erosion and thus the amount of cliff recession is unknown. The historical development of the Old Man of Hoy gives an insight into the rate and type of active erosional processes affecting these ancient cliffs. As late as the early part of the 19th century this famous stack had an arch on its landward side (Steers, 1973). The arch has since been lost and all that remains is a perceptibly thicker part of the column indicating where the arch was at one time attached. Hansom and Evans (1995) trace the historical development of the Old Man further. Maps dated *c.* 1600 and 1750 do not portray the Old Man as a stack but as a headland. However, by 1819, the headland had been eroded into a stack and arch with the twin legs that gave the 'Old Man' its name. Early in the 19th century, a severe storm washed away one of the legs (Miller, 1976) creating the free-standing stack. This pattern of ongoing erosion continues today and in 1992 a 40 m-long crack had opened up in the top of the south face leaving a large overhanging block that will eventually collapse. From the above it is apparent that the Old Man is a relatively young feature (less than 250 years old) and in geological terms a mere infant. It seems reasonable to assume that many stacks may have similar development patterns but variable life spans depending on exposure, structure and lithology. Certainly the dynamic nature of the processes that have shaped the Old Man will also lead to its eventual demise (Hansom and Evans, 1995). However, as erosion proceeds, other sea stacks will undoubtedly be eroded from the cliff face. Indeed, Steers (1973) noted a high pillar at Bre Brough, which had almost separated from the cliffs. In spite of this detail it remains difficult to estimate a rate of cliff recession from such intermittent activity.

It is recognized that active erosional processes, combined with variations in lithology and geological structure, have produced a unique variety of cliff and cliff-related landforms on the west coast of Orkney (Steers, 1973; NCC, 1978). For example, the coastline of Hoy is dominated by beds of red and yellow Hoy Old Red Sandstone that rise vertically above a pedestal of dark basalt lava (Kellock, 1969). Ritchie (1984) describes the lower Hoy beds as being soft and friable and the overlying beds to be harder forming prominent outcrops. Undercutting of such beds leads to sequential failure of beds above and the development of a vertical profile. The large stacks at the Castles of Yesnaby and Qui Ayre are rectangular in plan but both narrow downwards and have arches eroded through their base, an indication of marine erosion being more active than subaerial failure. Indeed the arch at Qui Ayre is now so large that it will soon fail and result in complete separation of the stack from the host cliff.

Variations in lithology and geological structure are major controls on the cliffs of Orkney and the resultant differential erosion and exploitation of weaker strata, joints, fissures or dykes are responsible for much of the meso- and micro-topography. Much of the detail depends directly upon marine erosion of joints, bedding planes, faults and dykes of igneous rock intruded into the sedimentary strata. The rock in con-

Figure 3.13 The spectacular arch at Qui Ayre, Yesnaby, West Coast of Orkney, is one of several arches and columnar stacks in the area in various stages of development. (Photo J.D. Hansom.)

tact with such dykes is often removed fairly easily, leaving impressive features such as the natural arch at the Hole o'Row. The diversity of caves, arches, stacks, geos and vertical cliffs along this short stretch of coast provide an excellent field site to study the development of erosional features and further our current understanding of coastal processes and forms on hard upland coasts. Although, to date, little research has been carried out on Orkney cliffs, the research potential is immense and the range, size and physical attributes of this spectacular coastline, together with its high wave-energy, justify its inclusion here.

Conclusions

The exposed Atlantic coastline of the west coast of Orkney is of national geomorphological importance. The 20 km stretch of coast includes some of the most spectacular and dramatic cliff forms in the British Isles, with numerous geos, inlets, caves, arches, stacks and excellent examples of the relatively rare phenomenon of clifftop scouring. Although sea stacks are familiar features of many hard rock coastlines in Scotland, few are more spectacular or famous than the towering monolith of sandstone, the Old Man of Hoy, which reaches a height of 137 m. The scientific importance of this site lies in the range of spectacular cliff forms displayed over such a short stretch of coastline and the clear influence that geological structure plays upon their form. The evidence of contemporary coastal retreat is also very clear and there are opportunities in Orkney to establish the retreat rate of these sandstone cliffs.

DUNCANSBY TO SKIRZA HEAD, CAITHNESS (SD 398 710)

J.D. Hansom

Introduction

One of the finest stretches of cliff coastline in mainland Britain extends southwards for 6 km from Duncansby Head on the north-east extremity of the Scottish mainland (Steers, 1973). The spectacular cliffs and related forms provide excellent examples of the characteristic cliff forms of the Old Red Sandstones of north-east Scotland and show clear relationships between geological structure and coastal morphology. The cliffs, caves, geos, arches and stacks provide a dramatic coastline and the famous Stacks of Duncansby are cited frequently in the international literature (e.g. Trenhaile, 1987). In spite of this, there has been no detailed geomorphological research on these spectacular cliffs, although numerous descriptive accounts exist (e.g. Steers, 1973) and the geological memoir provides an account of the relationships between geological structure and coastal form (Crampton and Carruthers, 1914).

Similar in many ways to Orkney, the most characteristic feature of the Caithness climate is the frequency of strong winds. The prevailing winds are from between west and south-east for 60% of the year. Winds greater than 8 m s^{-1} occur for over 30% of the year and gales occur on average for 29 days per year. However, the exposure of this east-facing coast is less than that of the west and north and for much of the time the winds blow off the land and so help reduce wave energies. The sea floor falls away from the mainland to 60 m depth by about 5–10 km offshore. Along the eastern coast, shelter is afforded by the mainland and the Orkney Islands, and so the wave climate is not as severe as in the north or west and significant wave heights off Duncansby Head are 2 m for 10% of the year and about 0.5 m for 75% of the year (Draper, 1991).

Description

The coastal geomorphology is dominated by horizontal beds of Old Red Sandstone that are classified locally into a block of resistant Thurso flagstones cropping out between Skippie Geo and Fast Geo and the more variable, but generally weaker, John o'Groats Sandstone Series to the north and south. The coastline is best described using four geologically defined sections from south to north (Figure 3.14):

1. Skirza Head to Skippie Geo: a *c.* 1 km stretch of cliffs and deep geos cut in the John o'Groats Sandstones in the south.
2. Skippie Geo to Fast Geo: a *c.* 1 km stretch of Thurso Flagstones.
3. Fast Geo to Gibbs Craig: a *c.* 3 km stretch of cliffs in the John o'Groats Sandstones, with magnificent stacks.
4. Gibbs Craig to Duncansby Head: a *c.* 1 km stretch of cliffs and geos of the horizontally bedded Thurso Flagstones in the north.

From Skirza Head to Skippie Geo, the compact, fissile, near-horizontal flagstones produce a coastal scenery dominated by 40 m-high cliffs, and an abrasion-ramp shore platform that extends more or less continuously for almost 1 km northwards from Skirza Head in the south to Sailor's Head. Four deep, near-vertical geos indent this stretch of coastline. Long Geo is the largest; farther north two shorter and rock-floored geos occur, one with a scree and boulder beach. Skippie Geo is an inlet part of which is raised *c.* 20 m above sea level. Flat skerries and an extensive intertidal shore platform are exposed below the caves, overhangs and slab-like walls of Skippie Geo.

Between Skippie Geo and Fast Geo the cliff height increases from 40 m to 55 m and the vertical cliffs are cut by Wife Geo, a 250 m inlet where an association of caves, arches, plunging vertical cliffs, rock pinnacles and buttresses have resulted in one of the finest compound geo features in Scotland.

Between Fast Geo and Gibbs Craig, the John o'Groats Sandstones form the famous high cliffs and stacks of Duncansby (Figure 3.15). The cliffs reach almost 80 m OD at Hill of Crogodale. In the south, between Girn and Hill of Crogodale, the steep cliffs rise from 55 m to 75 m and consist of vegetated slopes alternating with near-vertical rock buttresses. Low-gradient shore platforms form abrasion ramps of up to 100 m wide along much of this coastline, although north of Fast Geo and north of Crogodale, the shore platform is covered by extensive gravel and boulder beaches. Elsewhere the boulder beaches form a relatively narrow fringe at, or just above, the high-water mark. In the north, the impressive Stacks of Duncansby rise as pyramidal structures from the surrounding shore platform less than 100 m from the cliff base. The southernmost stack reaches in excess of 50 m and is higher than the adjacent cliff, on account of the landward slope of the mainland cliff edge. The stacks have distinctive outlines of almost square, castellated blocks of red sandstone.

The adjacent cliffs display considerable local variation in form and profile with steep buttress-type rock cliffs alternating with relatively low-angled vegetated slopes developed on a continuous cover of superficial materials. At the base of the extensive apron of slumped materials is a low rock cliff, succeeded by a low-angled shore platform with a variable cover of boulders and cobbles. Northwards, the cliffs gradually decline to *c.* 25 m OD at Gibbs Craig and the Duncansby fault boundary.

Between Gibbs Craig and Duncansby Head, the land rises to the north but the horizontally bedded flagstones display similar coastal forms to the flagstone area to the south (Section 2, Figure 3.14). The coastline is characterized by vertical, often overhanging, cliffs with irregular profiles formed as a result of differences in hardness and susceptibility to erosion of the flagstone beds. Pillar-like stacks occur close to the 35 m-high cliffs at Gibb's Craig and The Knee. The Geo of Sclaites, south of Duncansby Head Lighthouse, is a textbook example of this type of inlet with a natural arch at its entrance and a basal cave at its narrow head. Between the geo and Duncansby Head to the north, the vertical or overhanging cliffs display excellent examples of basal notches. Long Geo, north of the lighthouse on the north-facing coast of the headland, is long and steep sided with a distinctive overhanging profile. Farther west, at The Glupe, a large blowhole has developed, similar in form, although smaller, than The Pot at the Bullers of Buchan (see GCR site report).

Interpretation

The cliff coastline from Skirza Head to Duncansby Head is of high scientific and educational value for the following features:

1. The clear relationship displayed between coastal form and geological structure.
2. The spectacular and diverse range of plunging cliffs, stacks, arches, and caves.
3. The numerous deep, long, vertical-sided geos, some of which provide textbook examples (e.g. the Geo of Sclaites).
4. The erosional extension of the shore platform landwards into the cliff base.

Geological variations such as strike directions and dip angles at the coast, fault and joint patterns, differential hardness and resistance to erosion, and differential susceptibility to the processes of terrestrial and marine weathering and erosion all affect coastal form. At this site, the contrast between the fine-grained calcareous and argillaceous flagstones and the more-easily weathered, friable and varied sandstones appears to play a large part in determining

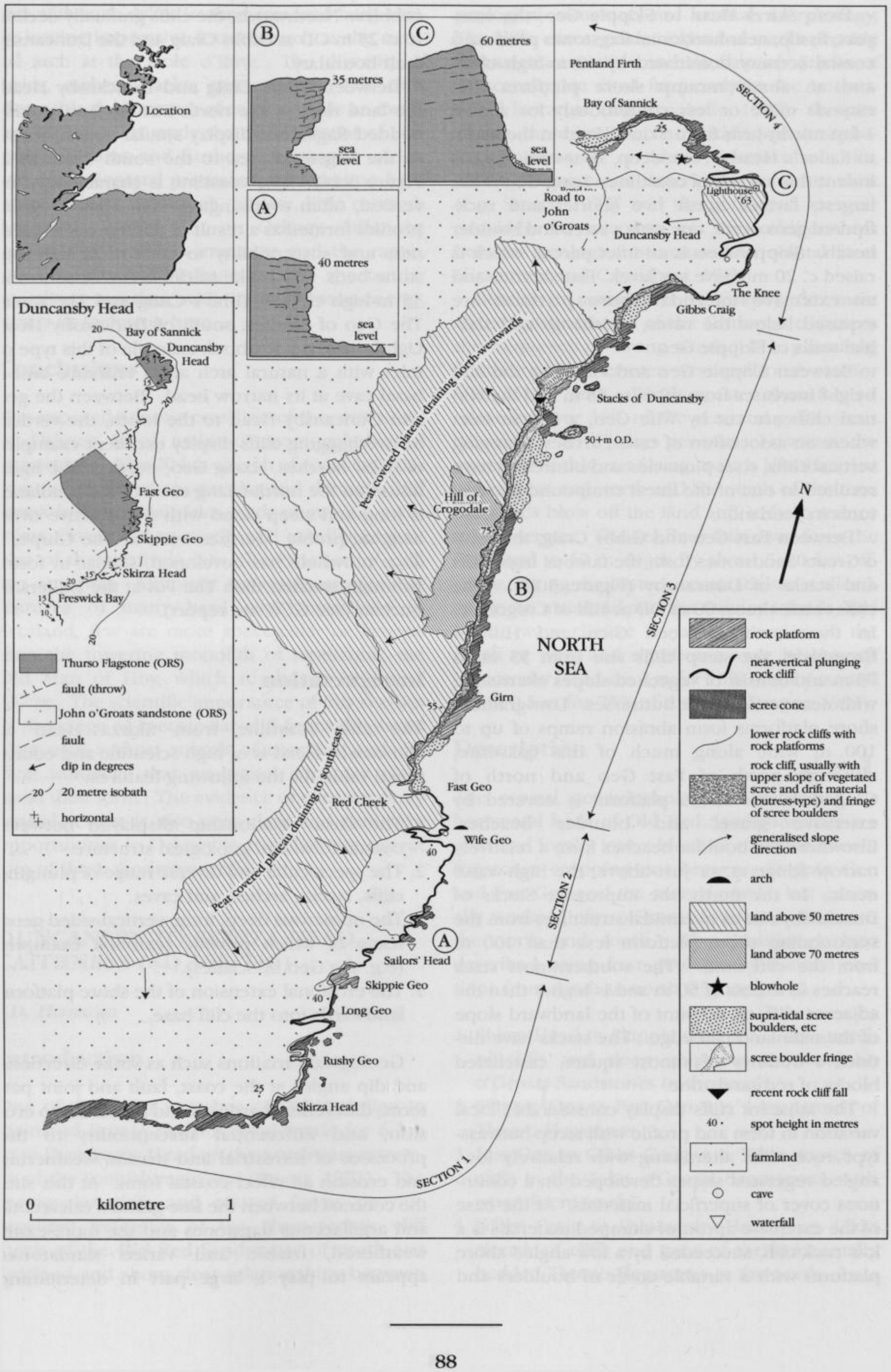
Location
B
35 metres
sea level
C
60 metres
sea level
A
40 metres
sea level
Duncansby Head
Bay of Sannick
Duncansby Head
Fast Geo
Skippie Geo
Skirza Head
Freswick Bay
Thurso Flagstone (ORS)
fault (throw)
John o'Groats sandstone (ORS)
fault
dip in degrees
20 metre isobath
horizontal
0 kilometre 1
Pentland Firth
Bay of Sannick
SECTION 4
Lighthouse 63
Road to John o'Groats
Duncansby Head
The Knee
Gibbs Craig
Peat covered plateau draining north-westwards
Stacks of Duncansby
50+m O.D.
Hill of Crogodale
N
SECTION 3
NORTH SEA
Girn
Fast Geo
Wife Geo
Red Cheek
Peat covered plateau draining to south-east
SECTION 2
Sailors' Head
Skippie Geo
Long Geo
Rushy Geo
Skirza Head
SECTION 1
rock platform
near-vertical plunging rock cliff
scree cone
lower rock cliffs with rock platforms
rock cliff, usually with upper slope of vegetated scree and drift material (buttress-type) and fringe of scree boulders
generalised slope direction
arch
land above 50 metres
land above 70 metres
blowhole
supra-tidal scree boulders, etc
scree boulder fringe
recent rock cliff fall
spot height in metres
farmland
cave
waterfall

Figure 3.15 The three large stacks of Duncansby stand in stark contrast to the otherwise bleak and smooth landscape of the north-east coast of Caithness. Looking north towards Duncansby Head and South Ronaldsay, Orkney, in the background. (Photo: courtesy of Ken Crossan.)

coastal form. For example, Crampton and Carruthers (1914) assert that the slight embayment that extends between the outcrops of Thurso flagstones at Gibbs Criag and Fast Geo, and includes the Stacks of Duncansby, is a result of the more rapid erosion of the intervening higher, but softer and more variable, John o'Groats sandstones. However, the rate of cliff retreat is unknown. The sandstone stretch (Section 3, Figure 3.14) appears to have retreated somewhat more than the flagstones to the north and south, probably due to lower resistance of the sandstone blocks allowing more effective wave erosion of the cliff base. Additionally, slope processes play an important part in the form of the sandstone cliffs, with frequent landslides and screes that alternate between rock buttresses, features that may have their origin in the pattern of master joints and other vertical lines of weakness. Erosion along bedding planes, in conjunction with the numerous vertical cracks and fissures, give rise to the often blocky and castellated appearance of the cliffs and stacks, best seen in the Stacks of Duncansby. The overall pyramidal shape of the stacks implies that subaerial weathering and the exploitation of joints and bedding planes higher up has been more effective than wave erosion of the base of the stack.

◂**Figure 3.14** Coastal geomorphology of north-east Caithness, Duncansby to Skirza Head GCR site. Descriptions of sections 1–4 and of representative profiles A–C are in the text. The geology of the area is predominantly composed of horizontally bedded Old Red Sandstones (ORS), which have been eroded into steep cliffs. (Modified from unpublished work by W. Ritchie.)

Large-scale structural weaknesses partly explain the formation of the numerous deep-set geos and rectangular stacks that are typical of the flagstone areas. The crush zones, rucks and strong vertical joints of the flagstones provide structural weaknesses that are exploited by marine action to form long geos, often with caves excavated in the backwall (e.g. at the Geo of Sclaites), although several geos have depositional beaches at their heads. Others have well-developed scree slopes indicating a local reduction in the efficiency of wave erosion and a relative dominance of subaerial slope processes. The irregular cliff profile characteristic of the flagstone cliffs again demonstrates the strong geological control on coastal geomorphology, the irregular stepped profile reflecting subtle differences in hardness and susceptibility to lateral weathering of the flagstone beds.

In both the sandstone and flagstone areas, shore platforms are relatively well-developed and in places are relatively shallow in angle, reaching 100 m wide. They appear to be best developed where the bedrock dips are low or horizontal in both lithologies and so their form is aided by structural control, in spite of extensive evidence of active abrasion of their surfaces. In the area between Fast Geo and Hill of Crogodale, the platforms appear to be actively extending the cliff base landwards, in spite of an intermittent covering of debris from above.

Conclusions

The cliffed coastline between Duncansby Head and Skirza Head is one of the finest and most spectacular stretches of cliff coast in mainland Britain. Lithological and structural control is important in determining cliff morphology. The flagstone cliffs cropping out in the north and central section are typically steep, near-vertical and sometimes overhanging, with irregular stepped profiles and numerous deep, long, vertical-sided geos. Although less steep, the cliffs of the John o'Groats sandstones are higher. The magnificent castle-like Stacks of Duncansby rise to above 50 m, but are less than 100 m from the base of the sandstone cliffs (Figure 3.15). Well-developed and actively evolving shore platforms extend along much of the cliff base.

This dramatic stretch of cliff coastline, with its complex of deep geos, caves, arches, stacks and shore platforms, provides textbook examples of many cliff forms and demonstrates the strong structural control on cliff morphology. It is also easily accessed via the road at Duncansby and so can be appreciated by most visitors. The scientific and geomorphological interest is very high, although, as with the majority of hard-rock coastal sites, it has not been thoroughly investigated. In this respect, the GCR site is of immense scientific importance, both in terms of its educational value and research potential.

TARBAT NESS, ROSS AND CROMARTY (NH 950 878)

J.D. Hansom

Introduction

Tarbat Ness forms the southern headland of the Dornoch Firth and juts out into the Moray Firth in a north-easterly direction (Figure 3.16). It is composed mainly of a peninsula of Upper Old Red Sandstone, separated from the underlying Middle Old Red Sandstone by a fault in the east and south. The cliff and shore platform features at Tarbat Ness are excellent examples of the operation of a range of pitting, saltspray and honeycomb weathering and tidally zoned biological processes that are relatively unusual in Scotland. The landward-dipping beds, occasional joints and minor faults in the Old Red Sandstone have been differentially eroded to provide a coastline of great variety, including some of the best examples of differential erosion processes on tilted sandstone strata in Scotland. In addition, the striking contrast between the coastal forms on the high-energy south-east and lower-energy north-west coast of the peninsula adds to the geomorphological interest. Emerged gravel beaches and platforms, together with a prominent emerged cliff are also found along the coastline of Tarbat Ness and emerged sea stacks are also well developed south of Wilkhaven pier on the south-east coast of the peninsula.

Hourly mean wind speeds in the inner Moray Firth at Tarbat Ness reach 3 m s^{-1} for 75% of the time and 18 m s^{-1} for 0.1% of the time but winds are mainly offshore. Onshore winds from the north-east (the longest fetch) account for only a small proportion of all winds, but winds from the south-east are almost as frequent as south-westerlies and have relatively long fetches of 25 km. Water depths off Tarbat Ness are relatively shallow, reaching 10 m depth at about 300 m offshore and 20 m at 5–10 km offshore (UKDMAP, 1998). The Ness is thus in a relatively sheltered location being subject to lengthy fetches only between north-east and south-east, with a maximum fetch to the north-west of 16 km. The north-west facing side is sheltered from the worst of the north-easterly storms that approach the ness obliquely and is mainly unaffected by easterly waves. Similarly, the south-east shore is also sheltered from the worst of the north-easterly storms but is more exposed to storm waves from the south-east.

The relict landforms of Tarbat Ness and the Dornoch Firth are of great significance for the interpretation of the glacial and sea-level history of the area. The Holocene development of the Dornoch Firth has been reconstructed based on these and other emerged marine features (Firth *et al.*, 1995; Hansom, 1991; Ogilvie, 1923; Smith, 1968; Smith and Mather, 1973). However, in spite of extensive research on the current processes of the coastline of the inner Dornoch Firth (Hansom and Leafe, 1990), there has been no geomorphological research on the active coastal forms and processes of Tarbat Ness itself.

Description

Tarbat Ness is composed mainly of a peninsula of Upper Old Red Sandstone, separated from the underlying Middle Old Red Sandstone that crop out in the east and south by a fault boundary to the south of the pier at Wilkhaven (P on Figure 3.16). There is a general decline in altitude of the headland from 17 m above sea level in the south and east to 10 m above sea level in the north and west. All of the features described below occur within the Upper Old Red Sandstone, which here is composed of a great variety of calcareous-rich layers, finer-grained red sandstone, grits and some conglomeratic beds. The beds individually range from a few centimetres to over one metre thick and some are fissile. The Ness itself is strike-aligned with a well-defined dip towards the WNW and mainland and this is reflected in the ridges and clefts in the shore platform that are angled obliquely to the coastline. Higher dips of 40° occur in the south and west, but these decline to 25° towards the north-east and the Ness itself. On the east coast south of the fault boundary at Wilkhaven Pier, there is greater variation in both strike and dip angles and a change in coastal morphology from the well-defined serrated shore platforms of Tarbat Ness to low and uneven platforms to the south.

The features of interest at Tarbat Ness centre on the development of distinctive shore platforms and on smaller-scale weathering features such as pitting and honeycombing. At the larger scale both the north-west and south-east sides of Tarbat Ness display excellent examples of serrated rock platforms that have been cut and weathered across dipping sandstone beds of varying resistances. On the north-west coast, differential and selective erosion of the steeply inclined sandstone beds of the shore platform has produced a staircase of steeply dipping parallel knife-edge ridges and narrow, linear clefts, typically no more than 2–3 m wide. At the upper levels of the platforms, the tops of the beds and protuberances are adorned with honeycomb weathering micro-forms and tafoni, while the clefts are occasionally partly filled with gravel deposits. The platforms on this coast reach 250 m wide at Camas Solais but taper to 50 m wide towards the north-east.

There is a greater variety of larger-scale rock forms on the more exposed south-east coast of the peninsula. To the north of the fault, the 12 m-high sandstone cliffs are in places overhanging due to active undercutting by waves. Farther north occur the remnants of higher shore platforms (e.g. Craig Ruadh) and several narrow inlets, one of which has a distinctive gravel beach at its head with steep rock cliffs on either side. Both contemporary and emerged shore platforms and the sides of the narrow inlets contain excellent examples of honeycomb, solution and abrasion micro-features. To the north, a series of seven sloping platforms, the upper surface of each representing the top of a more resistant bed of sandstone, have been cut into the receding cliffs producing a distinctive 'stepped' profile. These steps progressively lower and coalesce north-eastwards into a low angular broken shore platform that extends offshore as a series of dipping reefs towards Tarbat Ledge. To the south of the Wilkhaven fault a low, uneven and 300 m-wide rock platform is backed by an emerged platform covered by a grassy terrace of emerged gravels.

At a smaller scale there is a wide range of weathering micro-forms at Tarbat Ness, ranging from solution pits, saltspray tafoni and honeycomb features. The greatest variety of pitting features, ranging in size from millimetres to one or more centimetres in diameter, is found just above the high-water mark on both the north-west and south-east coast of the peninsula and

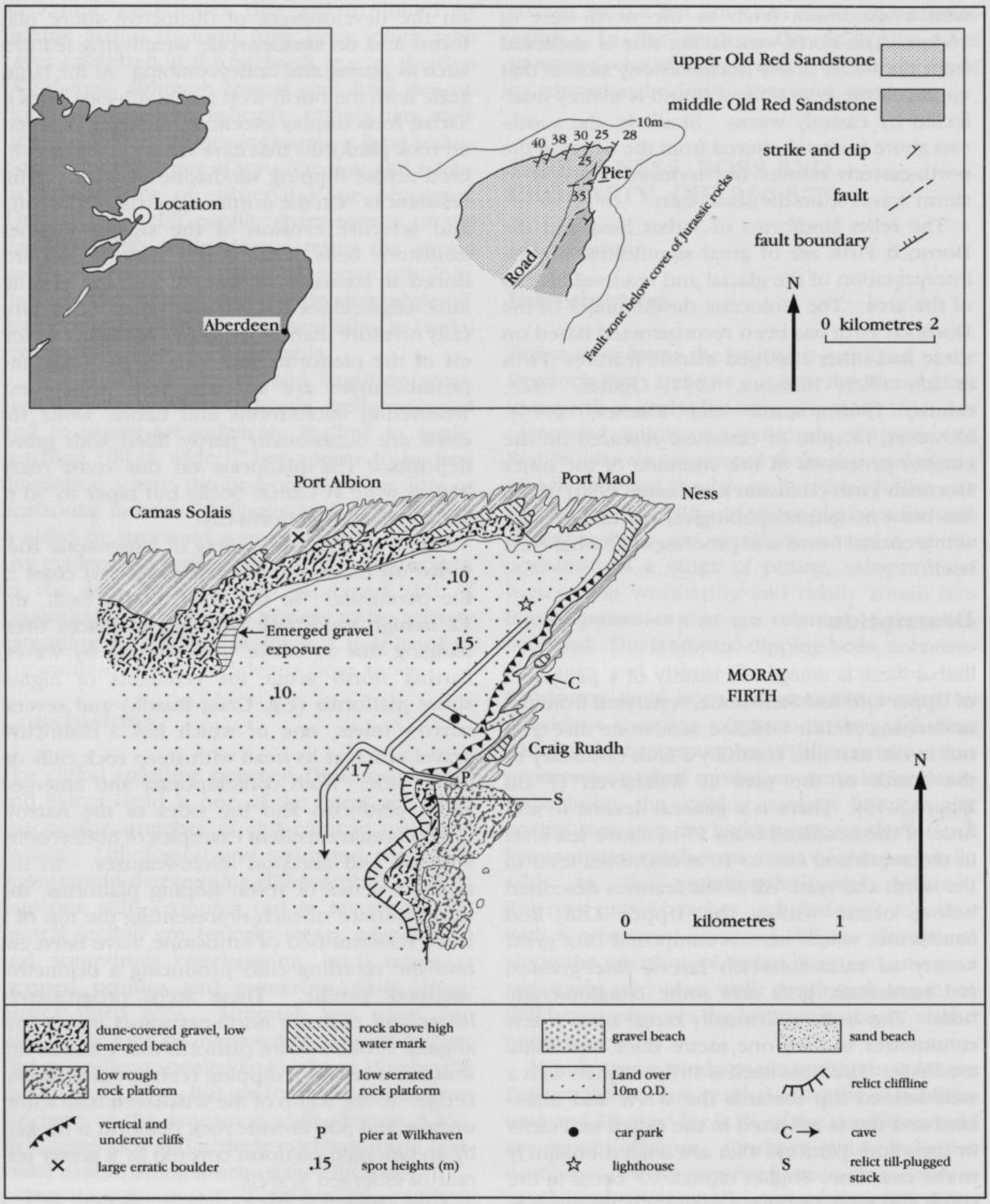

Figure 3.16 Geomorphological map and geological sketch map of Tarbat Ness, Ross and Cromarty, north-east Scotland. The eastern Moray Firth shore is fault-controlled and rocky with a prominent emerged cliffline. The northern Dornoch Firth shore has well-developed emerged gravel beach-ridges. At the Ness itself, the low rock shore platform is characterized by a range of well-developed weathering pits and tafoni that are rare on Scottish coasts. At 'S' an emerged till-plugged stack occurs in front of the relict cliff. (Modified from unpublished work by W. Ritchie.)

tend to develop selectively in certain strata. Larger pits and circular depressions are mainly found on the higher and flatter rock surfaces where they may become filled with stagnant water enriched by bird guano.

Interpretation

The rocky coastline of Tarbat Ness is dominated by varying amounts of the erosional processes of quarrying, abrasion, chemical weathering and biological weathering. However, none have been quantified or studied in any detail. As a result of the combination of exposure and dominant wave direction, there exists a fundamental contrast between the higher energy environment of the south-east facing coast and the more benign north-west coast. In addition, lithology and geological structure play an important role in determining coastal form. The landward-dipping beds, occasional joints and minor faults within the sandstones have been differentially exploited by erosion to produce a distinctive coastline, particularly on the exposed south-east coast. The variety of texture and composition of the tightly-bedded red and yellow sandstones, grits and conglomerate beds have responded differentially to coastal processes producing considerable local variation in form.

Differential and selective erosion of the calcareous sandstone beds has produced many of the larger-scale landforms such as the steeply dipping parallel platform ridges on the north-east coast and the 'stepped' platforms at the tip of the peninsula. Wave quarrying of small-scale faults or joints in the dipping beds has resulted in excavation along these joints to produce a series of characteristic knife-edge ridges and linear clefts. Geological structure, particularly the strike and dip of the strata, plays an important role in determining the morphology of the larger forms on each coast. A much more broken profile with large scarps and short dips characterizes the south-east coast, whereas the north-west coast has long, smooth-topped, dipping beds separated by small scarps. Except on the south-east coast, and where gravel is locally available, few platform surfaces show signs of fresh abrasion. The fresh scars that do exist have angular edges indicating that wave quarrying is important in places.

At Tarbat Ness, erosional micro-forms, such as small pitting features, are typically the product of karst-like solutional processes produced by spray action on the calcareous beds, although salt crystal growth is likely to account for the formation of the tafoni features. Wave-spray processes extend to greater altitudes on the south-east coast and at the Ness itself and, as a result, pits and tafoni are found at greater altitudes on these coasts. However, it is on the upper surfaces of the north-west coast platforms that several of the more delicate solutional features occur, principally because wave energy is less and the features have time to develop. Additionally, burrowing and boring by intertidal organisms plays an important role in the development of some micro-forms, particularly close to the water surface at the edges of rockpools where micro-notches have developed. Although unstudied, there is likely to be a biological zonation relationship between the types of organisms found, the morphology and altitude of the erosional forms produced, and the wave and spray processes operating. In addition, whereas some pits and circular depressions closely resemble karst-type solution hollows and cavities, some of the lower and larger pits and depressions now appear to be subject to mechanical abrasion from gravels within them. All of the lower altitude features are currently active although some, especially those at higher elevations, may be partially relict. There is great scope at Tarbat Ness for detailed research to determine the relationships between the factors responsible for the development of such micro-forms.

The relict cliff and emerged beaches that occur higher up on Tarbat Ness provide spectacular evidence of former relative sea-levels in Lateglacial and Holocene times. Although they are of great geomorphological interest in their own right (Hansom and Leafe, 1990; Hansom, 1991; Firth *et al.*, 1995), they are also of relevance to the sea-level context within which the platforms and micro-scale features of Tarbat Ness have developed. The southward extension of the active cliff at Craig Ruadh is represented by a relict cliff at Wilkhaven and comprises a rock cliff veneered with glacially derived tills and gravels that fill the gap between the cliff and a sea stack rising from the emerged shore platform. Thus it appears likely that the general morphology and association of cliffs and shore platforms at Tarbat Ness was largely in place before the last glaciation and as such is inherited. Tarbat Ness probably became ice free at about 14 000 years BP, and the glaciogenic sediments became trimmed by a high sea level at about 20 m OD. Gravel beaches were also constructed up to 20 m OD at this time (Hansom and Leafe, 1990). On the north-west side of Tarbat Ness, the high gravel beaches are cut by a prominent cliff whose base lies at 10 m OD. This cliff was probably first cut during the fall to a Lateglacial low sea level at about 10 500 years BP, but then reoccupied as the Holocene sea rose to 6 m OD at 6500 years BP. It is this last rise in relative sea level and the subsequent fall to present levels that has resulted in the erosional trimming of the present shore platform and the weathering of its surface. Present-day processes are thus likely to be engaged in the superficial trimming of an exhumed surface.

Conclusions

The principal geomorphological interest of Tarbat Ness GCR site lies in the range of active micro- and macro-cliff and platform forms. In addition, the juxtaposition of these actively evolving forms with the well-preserved emerged beaches and relict cliffs set back from the present coast adds to the scientific interest of this site.

The Upper Old Red Sandstone peninsula of Tarbat Ness displays a great variety of meso- and micro-scale forms on the cliff and shore platforms. The micro-forms in the rocks and platforms display excellent examples of pitting, salt-spray and honeycomb weathering and tidally zoned biological processes. Differential and selective erosion of dipping beds, occasional joints and minor faults in the sandstone have produced a coastline of great geomorphological variety. The 'stepped' profiles and parallel ridges of the shore platforms characteristic of this coast provide textbook examples of differential erosion processes on tilted sandstone strata. In addition, the contrast between the coastal forms on the high-energy south-east coast where abrasion is in evidence, and the low-energy north-west coast of the peninsula where weathering processes are more important adds to the geomorphological interest. The adjacent emerged gravel beaches and relict cliffs allow the development of both meso- and micro-forms at Tarbat Ness to be effectively placed into a temporal framework.

LOCH MADDY–SOUND OF HARRIS COASTLINE, NORTH UIST, WESTERN ISLES (NF 940 730)

J.D. Hansom

Introduction

At its maximum extent the GCR site of Loch Maddy is approximately 10 km wide and 10 km long, extending northwards from Loch Maddy (Loch nam Madadh) in North Uist to the south part of the Sound of Harris (see Figure 3.1 for general location). It covers slightly less than 100 km² in area of intricate and complex shoreline studded with innumerable islands, skerries and intertidal rock outcrops. The coastal geomorphology is both diverse and exceptional, with low cliffs, discontinuous shore platforms, sheltered sea-loch environments, intertidal sandflats, low rocky islands, reefs, skerries, isolated rock outcrops, rock pinnacles, intertidal rock and boulder pools (Figure 3.17). Almost all of these features are related to the submergence of rock surfaces close to sea level that have undergone intense glacial scouring in and around the main sea inlets of Loch Maddy, Loch Blashaval, Loch Aulasary and Loch Mhic Phàil. The coastal landscape produced is on a scale reminiscent of the Norwegian skjaergard or strandflat, and, with the possible exception of parts of western Ireland (Guilcher *et al.*, 1986), is not found elsewhere in the British Isles. The diversity of landforms within a general trend of Late Quaternary sea-level rise and land submergence is of particular geomorphological significance.

Unsheltered coasts in the Western Isles are exposed to high mean wind speeds, but the inner coast of the Minches is relatively more sheltered. The seabed offshore of Lochmaddy is shallow with numerous skerries and reefs. Spring tidal range at Lochmaddy is 3.5 m and maximum tidal streams are variable around 1 m s^{-1}, depending on location (UKDMAP, 1998). However, although the tides on the Atlantic side of the Sound of Harris are out of phase with those in the Minch, there are no strong currents flowing between the two. Along the east coast of the Western Isles, the irregular coastline produces a highly variable wave climate. Offshore of Lochmaddy, the outer coast of the Minch experiences moderate wave energies, particularly from the south and north-east, between Weaver's Point and Leac Na Hoe where the 20 m depth contour comes within 300 m of the shore. The inner parts of the shoreline are very sheltered and are subject only to small locally produced waves.

Description

Several types of coastline occur in this area but in essence all are the product of submergence of a glaciated rock platform close to sea level. To the east of the site lies a line of glacially scoured hills that correspond to the line of the Outer Hebridean Thrust zone (Figure 3.18). Beyond this the outer Minch coast is high and rugged, reaching 281 m at South Lee but reducing in height northwards to 154 m at Leac Na Hoe. To the west of the site a line of hills rises to 190 m OD. The intervening inner Minch coastline (i.e. within the sea lochs of Maddy, Blashaval, Mhic Phàil and Aulasary) rarely rises more than a few metres above present sea level. The geology of North Uist comprises an ancient basement of metamorphic Lewisian gneiss that was intruded by basaltic sills and dykes during Tertiary times. The Outer Hebridean Thrust Plane occurs high on the west facing slopes of the hills of eastern North Uist and divides the island into two distinctive geological provinces. To the west, the rocks are relatively uncrushed gneisses, whereas in the east the rocks are crushed gneisses and mylonites.

Loch Maddy, the largest sea loch of North Uist, reaches over 20 m deep and is described as a 'fjard' (Earll and Pagett, 1984). Unusual in Scotland, fjards are similar in origin to fjords but occur in areas of low-lying land that have been subject to extensive erosional scour by glacier ice and have intensely serrated shorelines, interrupted by many peninsulas and inlets (Earll and Pagett, 1984). The low and fragmented shoreline of Loch Maddy has numerous inlets and small rocky islands, while the intertidal area consists predominantly of gravel and boulders, with limited coarse sand patches and outcrops of scoured bedrock. Many of the irregular sea loch inlets link with inland freshwater and brackish lochs, particularly in the vicinity of the small town of Lochmaddy, allowing limited tidal exchange of water (Figure 3.17).

The outer Minch coastline to the north and south of the entrance to Loch Maddy consists of cliffs rarely more than 30 m high and with gradients of 20–50° that continue underwater. The term 'pseudo-cliff' has been coined to describe such features. The cliff slopes are highly irregular both in plan and profile, however there are no caves, arches or stacks and only limited cliff-foot accumulations of gravel or boulders. Shore platforms are absent. There are few, if any, scree slopes. The cliffs are 'clean' bare rock cliffs and contrast markedly with most cliff areas elsewhere in Scotland.

North-westward of Loch Maddy lies the highly irregular coastline and numerous large and small islands of Loch Blashaval. Here, the seabed is made up of a series of ridges and deep, rock-floored, narrow basins (Admiralty chart 2825). The scale, alignment and relief of this submarine topography mirrors that of the patterns of adjacent subaerial lochans and ridges. The trend is mirrored in the islands of Keallasay More, Keallasay Beg, the Cliasay group, and Flodday, and several of the minor inlets and small islets. The outline of the Sound of Harris coast is very irregular, although the north-west to south-east geological trend is evident in an extensive series of low, intertidal, shore platforms and skerries, known as 'the Rangas', which stretch towards the island of Torogay and the Sound of Berneray. Extensive banks of submerged sand are associated with these reefs, indeed, much of the floor of the shallow Sound of Harris is sand-covered. The larger islands in the Sound (Torogay, Sursay, Tahay, Opsay, Vaccasay and Hermetray) have a patchy cover of glacial deposits. Tahay is a conical, rocky island rising to over 65 m OD, whereas Vaccasay is low and irregular with extensive intertidal rock platforms at sea level. A complex and extensive group of shore platforms, reefs, skerries and islands lie close to Opsay where a series of extensive intertidal boulder shoals combine to form a complex small-scale archipelago, with enclosed tidal pools and uneven rocky intertidal surfaces.

Two large, but shallow and wide, sea lochs, Loch Mhic Phàil and Loch Aulasary, penetrate into the north coastline either side of the low 'island' of Stromay. Stromay is joined to the mainland for most of the tidal cycle. The low irregular coastline of Loch Mhic Phàil is characterized by a multitude of narrow interdigitations of land, sea and low rocky islets rarely rising more than a few metres above sea level, each thinly veneered by till and peat. Tidal ponds are a characteristic feature of this area. The ponds are basins whose centres lie below low tide and which remain partly flooded when the tide

Figure 3.17 The submerged landscape of North Uist looking north-west over Lochmaddy. Submergence of a low undulating rock surface has resulted in a landscape of low rock basins, platforms and skerries with a range of tidal and salinity conditions. (Photo: P. & A. Macdonald/SNH.)

recedes to reveal washed perimeters of boulders and rocks within the intertidal zone. The low, rocky and peat-veneered shoreline of Loch Aulasary is similarly irregular. At low tide Loch Aulasary is almost completely land-locked as a result of broken shore platforms in the north closing the gap between the island of Stromay and the long peninsula west of Leac na Hoe (Figure 3.18).

Interpretation

The essential character of this extensive and distinctive GCR site is a product of the submergence of a low-amplitude and intensely glaciated platform of ancient metamorphic rock. Accordingly, small-scale details of rock type and structure, patterns of previous glacial action and sea-level change, are all central to the explanation of the nature of any particular stretch of this intricate rocky coastal zone. To the west of the Outer Hebridean Thrust Plane the bedrock is composed of relatively uncrushed gniesses that are highly durable and resistant to erosion. As a result the relative durability of the underlying bedrock finds morphological expression in the orientation of the coastal rock skerries, headlands and reefs, all of which are strongly linked to the north-west to south-east regional foliation of the gneiss. For example, in the Lochs Blashaval and Siginish area, both subaerial and seabed topography is made up of a series of ridges and deep, rock-floored, narrow basins, the scale, alignment and relief of which mirrors the structural trend.

Several glaciations have moulded the rocky platform of North Uist into a complex of tightly packed linear depressions and ridges (Geikie, 1878; von Weymarn, 1974). The regional dispersion of ice during the last glaciation mirrored and enhanced the north-west to south-east geological trend (Gordon and Sutherland, 1993; Mactaggart, 1997a). The size, alignment and dimensions of the depression and ridges reflects both the direction of ice movement and the relative strength of the rocks. Since deglaciation of the Western Isles about 14 000–15 000 years BP, the dominant trend in the Outer Hebrides has been one of rising relative sea level, interrupted by temporary regressions (Sissons, 1967). Ritchie (1971) believes that the Holocene sea-level rise in the Uists was of the order of 80 m,

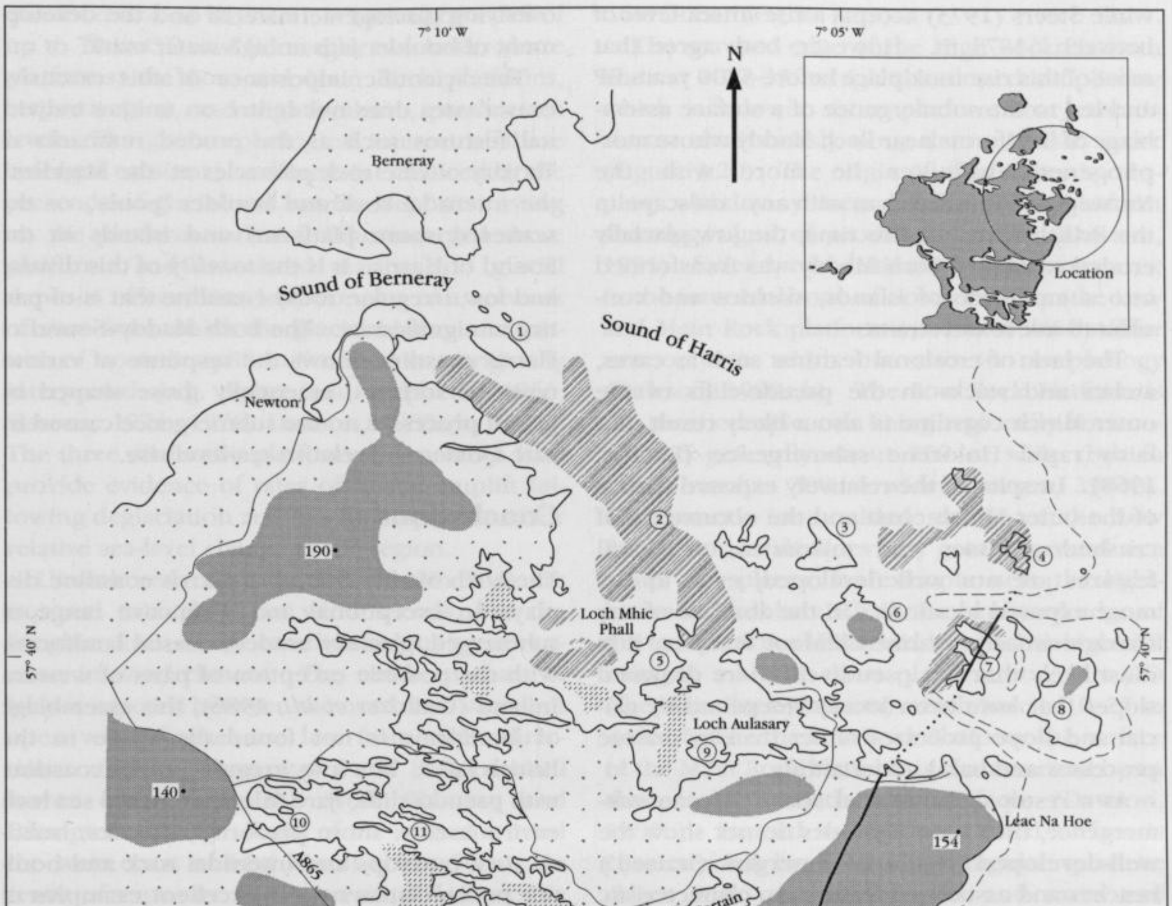

Figure 3.18 Coastal geomorphology of the Loch Maddy–Sound of Harris area, North Uist, showing the extensive areas of intertidal rock platform, small islets and skerries produced by submergence of a pre-existing low-lying rocky surface. The eastern coast is fault-controlled. (Modified from unpublished work by W. Ritchie.)

while Steers (1973) accepts a rise in sea level of between 61–73 m. However, both agree that most of this rise took place before 5700 years BP and led to the submergence of a surface assemblage of landforms near Loch Maddy whose morphogenetic affinities lie more with the Norwegian strandflat than with any landscape in the British Isles. At this time, the low glacially eroded terrain of Loch Maddy was transformed into a multitude of islands, skerries and convoluted inlets and straits.

The lack of erosional features such as caves, arches and stacks in the pseudo-cliffs of the outer Minch coastline is also a likely result of a fairly rapid Holocene submergence (Ritchie, 1968). In spite of the relatively exposed nature of the outer Minch coast and the occurrence of crushed gniesses and mylonites, erosional features are not well developed, even in the more exposed locations. In the absence of any characteristically marine cliff-foot features, it is most likely that the 'pseudo-cliffs' are drowned slopes that have been locally steepened by glacial and slope processes rather than by marine processes and basal undercutting.

As a result of Lateglacial and Holocene submergence, the Outer Hebrides do not show the well-developed suites of emerged ('raised') beaches and associated features so characteristic of much of the Inner Hebrides and Scottish mainland (Sissons, 1967; Ritchie, 1971; Steers, 1973). However, Godard (1965) recognized a number of shore platforms just above modern sea level (e.g. at 0.5 m above high-water mark on the south shore of Loch Maddy) which he suggested might indicate limited emergence. However, the platforms are undated and are more likely to be either interglacial in age, or glacial in origin and may be unrelated to marine processes. They may be simply rock surfaces that have been brought to their present altitude by subsequent submergence (Ritchie, 1968). Similarly, the rock platforms close to sea level in the northern part of the Loch Maddy area are also likely to be washed rock surfaces that now occur close to sea level, rather than shore platforms cut at this level by marine processes.

The inner bays of Loch Maddy are entirely sheltered from the storm and swell waves that sweep both the open Atlantic Ocean and the Minch. However, because the area experiences very strong winds, small but steep wind-generated waves are commonplace over short fetches and this results in very effective trimming of the overlying glaciogenic material and the development of boulder lags at high-water mark.

The scientific importance of this extensive coastal area does not centre on unique individual features such as the eroded remnants of Tertiary olivine rock pinnacles at 'the Maddies', the intertidal rock and boulder 'pools', or the scattered shore platforms and islands in the Sound of Harris. It is the *totality* of this diverse and low, irregular, rocky coastline that is of particular significance. The Loch Maddy–Sound of Harris coastline shows the response of various types of surfaces, essentially those shaped by glacial processes, to the submergence caused by Late Quaternary relative sea-level rise.

Conclusions

The Loch Maddy–Sound of Harris coastline displays an exceptional and distinctive range of submerged, glacially eroded, coastal landforms. With the possible exception of parts of western Ireland (Guilcher *et al.*, 1986), this assemblage of landforms is not found elsewhere in the British Isles. The low, irregular, rocky coastline with pseudo-cliffs, fjard inlets, sheltered sea loch environments, shore platforms, skerries, isolated rock outcrops and intertidal rock and boulder pools, displays many excellent examples of features produced by a marine transgression across a low glacially-scoured surface. It is this diversity of landforms, within a general trend of Late Quaternary submergence, that is of unique geomorphological and scientific significance in Britain.

NORTHERN ISLAY, ARGYLL AND BUTE (NR 363 766–NR 425 774)

POTENTIAL GCR SITE

J.D. Hansom

Introduction

The coastline of northern Islay in the Scottish Inner Hebrides is characterized by some of the finest examples of emerged shore platforms and emerged gravel beaches to be found anywhere in western Europe (see Figure 3.1 for general location). This coastline is the UK type locality for a feature that has come to be known in the literature as the 'High Rock Platform', a 650 m-wide shore platform formed during the Quaternary Period and now found at an elevation of *c.* 33 m OD. It is backed by a cliff of up to 70 m OD and fronted by two lower shore platforms, the Low and Main Rock platforms, respectively at, and slightly above, present sea level. The geomorphological interest of these emerged erosional landforms is enhanced by the presence of glacial and marine deposits resting on the platform surfaces. The emerged shore platforms and associated marine and glacial deposits of northern Islay are part of a network of sites from which the glacial history and pattern of isostatic uplift in Scotland was originally interpreted (e.g. Synge and Stephens, 1966; Sissons, 1974, 1976; Dawson, 1980a,b, 1991). The three distinctive platforms in northern Islay provide evidence of rates of isostatic uplift following deglaciation and this has implications for relative sea-level change in the region.

Unsheltered coasts in the Western Isles are exposed to high mean wind speeds, but the irregular form of the coastline causes great variation in wind climate. The northern coast of Islay is exposed between the north and west, but open water fetches are less from other directions. 68% of storm waves and 80% of swell waves come from the west (Ramsay and Brampton, 2000a). Much of the seabed around the west coast of Islay lies at about 50 m. In terms of exposure and open water fetches, the north-western coast is subject to high wave-energies whereas the eastern coast, south of Rubha a'Mhàil is much more sheltered.

Description

In northern Islay, a high shore-platform, eroded in quartzite rock, forms a continuous level feature between the headlands of Mala Bholsa and Rubha a'Mhàil (Dawson, 1993) (Figure 3.19). Along most of this coastline, the platform varies between 400 and 600 m in width and is backed by a cliff up to 70 m high. The height of the landward edge of the platform varies between 32 and 35 m OD, while the surface of the platform has a gentle seaward slope of *c.* 4° and is free of emerged stacks (Figure 3.20). In some areas, exposures reveal accumulations of till resting on the surface of the platform whereas in other areas the till is overlain by beach gravels. Elsewhere, accumulations of abandoned beach gravels rest directly on the high platform, but occur no higher than 27 m OD. Inland from Port a'Chotain, the platform is overlain by a prominent, arcuate end moraine at Coir Odhar (Figure 3.19).

The seaward edge of the High Rock Platform ends at a 20–35 m-high abandoned cliff, below which is a lower shore platform that extends almost continuously along the north Islay coast (Figure 3.20). The origin of this feature is complex, with many areas of the shore platform showing signs of moulding by ice (Dawson, 1991). Indeed, two distinct rock platforms exist in the intertidal zone of northern Islay (the Low and Main Rock platforms), both of which differ not only in width but also in morphology (Dawson, 1980a,b). The Low Rock Platform is the most conspicuous being regionally horizontal and generally about 100 m wide (but in places reaches 300 m wide; Dawson, 1980b). The smooth ice-moulded surface of the Low Rock Platform declines very gently seaward as a ramp. In places, for example near the lighthouse at Rhubha a'Mhàil, the landward edge of the low platform is marked by a 1–2 m-high cliff rising to a higher shore platform at *c.* 2 m OD (the Main Rock Platform) which here is 10–25 m wide. Unlike the Low Rock Platform, the surface of the Main Rock Platform is characterized by an absence of smooth rock surfaces (Dawson, 1980b). Instead its regionally tilted surface is characterized by protruding angular quartzite ridges with occasional stacks and caves and arches being cut into the backing cliff.

The abandoned quartzite cliffs that mark the landward edge of the Main Rock Platform and the seaward edge of the High Rock Platform, are typically crenulate and indented. The cliffs are adorned with emerged geos, stacks, natural arches and caves (e.g. Uamh Mhór near Port a'Chotain, and the complex cave network on the headland of Mala Bholsa). The floor of the emerged caves and much of the surface of the extensive Low and Main Rock platforms is mantled by gravel beach deposits. Between Mala Bholsa and Port a'Chotain gravel accumulations are locally banked against the cliff. Elsewhere the gravels occur as ridges, the most conspicuous ridge located in the Port a'Chotain embayment where it is succeeded landwards by the most extensive suite of Holocene beach sediments on the northern Islay coast (Figure 3.19).

Interpretation

Since the Low and Main Rock platforms occur at, and slightly above, present sea level, their ages are important in the debates surrounding the age of the present coastline and whether it has been cut during the Holocene Epoch, or whether it is an older feature simply re-occupied by modern sea level. The origin of the High Platform of northern Islay has long generated scientific debate (e.g. Johnson, 1919; Sissons, 1967). Early workers considered the High Rock Platform to have a warm interglacial origin (McCann, 1968; Dawson, 1979) whilst other opinion considered the platform to represent the product of periglacial shore erosion followed by glacio-isostatic uplift (Sissons, 1982). Similar debate surrounds the origins of the Main and Low Rock platforms (e.g. Wright, 1911; Dawson, 1980a,b, 1991). The regionally tilted Main Rock Platform can be traced throughout much of the Inner Hebrides and is now thought to have been produced largely during the severe cold conditions of the Loch Lomond Stadial some 11 000–10 000 years BP (Dawson, 1991), the tilt reflecting differential crustal recovery following deglaciation. The glaciated and regionally horizontal Low Rock Platform has been interpreted as interglacial in origin on account of its lack of isostatic recovery and tilt (Dawson, 1980a) and thus pre-dates the formation of the Main Rock Platform.

Debate surrounds the origins of the emerged shore platforms, beaches and end moraines. The High Rock Platform was described by Wright (1911) as representing 'a preglacial plain of marine denudation', and was interpreted as having formed prior to the only apparent general glaciation of the area. A later, more detailed discussion considered that the High Rock Platform was interglacial in origin and that the Coir Odhar end moraine was the product of a Lateglacial readvance (McCann, 1964). Synge and Stephens (1966) disagreed with this view, suggesting that the Coir Odhar Moraine was the product of ice-sheet decay, although they agree that the High Rock Platform formed prior to the last glaciation of the area. Sissons (1982) asserted that the High Rock Platform had been cut in periglacial conditions but Dawson (1993) calculated that to achieve this would take 28 000 years of relatively stable sea levels, a level of stability not shown by evidence elsewhere. Accumulations of till resting on the High Rock Platform also demonstrate that the platform must pre-date at least one period of glaciation (Dawson, 1991). Beach gravels, which overlie the till up to 27 m OD in places, indicate that a period of high sea level occurred after glaciation (Dawson, 1991). In northern Islay, these beaches are thought to have been formed during the Lateglacial period when sea levels reached 27 m OD (Dawson, 1991). As a result, only the seaward part of the High Rock Platform was exhumed from beneath the till cover and the inner edge of the High Rock Platform which lies at 32–35 m OD was left untouched. It is therefore most likely that the platform itself is the result of abrasion and quarrying during interglacial conditions and has been re-occupied several times since during periods of high relative sea level.

The Main Rock Platform identified in northern Islay is also well developed throughout much of the Inner Hebrides, cropping out along the coasts of Jura and Scarba (Dawson, 1980a) and can be traced intermittently to the Oban area, where it rises to maximum levels of 10–11 m OD (Dawson, 1991). Towards the west and south-west from Oban, the altitude of the platform decreases at a rate of between 0.13 and 0.16 m km^{-1}, until it passes below present sea level in northern Islay, Colonsay and western Mull (Dawson, 1991). The origin of this platform has also been hotly contested (e.g. McCann, 1964; Synge and Stephens, 1966; Gray, 1974, 1978; Dawson, 1980a,b, 1982, 1991). It is now generally considered that this feature, which exhibits no evidence of glaciation, is a relatively young feature that was formed by very rapid and efficient periglacial shore erosion during the Loch Lomond Stadial (Younger Dryas), some 11 000 to 10 000 years BP (Dawson, 1980a, 1991). This interpretation is supported by the rapid rates of erosion identified on similar platforms in modern polar environments (Hansom, 1983; Dawson *et al.*, 1987) and from cosmogenic dating of the Main Rock Platform on Lismore, which indicates that it was cut during the Lateglacial period (Stone *et al.*, 1996). A further suggestion in support of a periglacial origin is that the platforms are wide and well developed in sheltered locations. Such locations can be argued to disadvantage wave abrasion and quarrying and to favour periglacial conditions (Hansom, 1983).

It has been estimated that global sea level at this time was approximately 45–50 m below present, thus the present elevations of this tilted shoreline reflect a pattern of substantial, but differential, isostatic recovery in western Scotland over the 10 000 years since the platform was cut (Dawson, 1991). Isostatic uplift, following

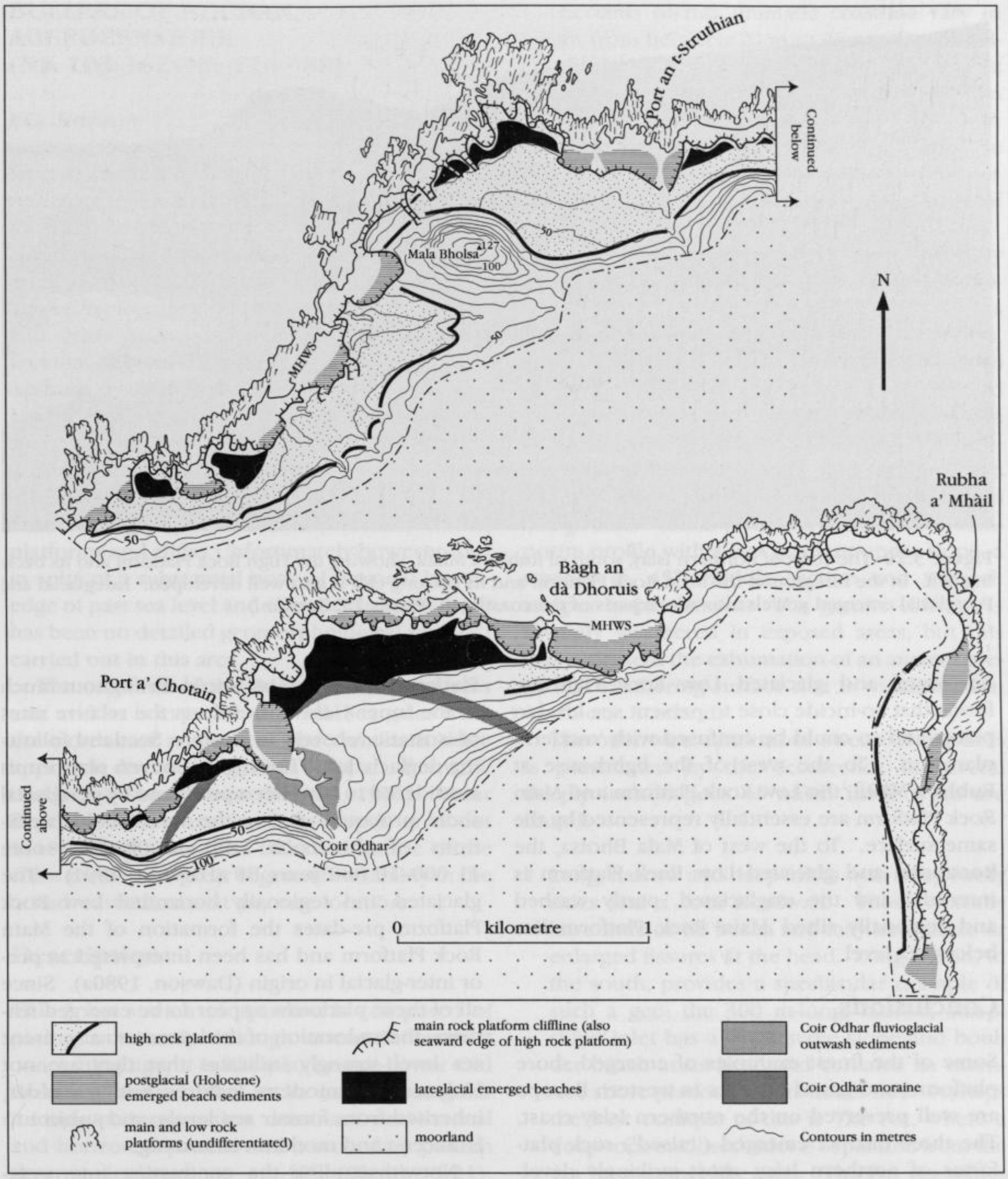

Figure 3.19 Geomorphological map of the coast of northern Islay between Mala Bholsa and Rubha a'Mhàil, northern Islay, showing a fine series of emerged rock platforms and beaches some of which have been capped by glacial moraines whose age informs the chronology for the platforms and beaches. MHWS = Mean High-Water Springs. For general location see Figure 3.1. (After Dawson, 1991.)

deglaciation, was greatest at the centre of the last (Late Devensian) ice sheet in Scotland and the tilt of the Main Lateglacial Shoreline (i.e. the Main Rock Platform and its emerged gravel beaches) reflects this pattern. Northern Islay is of particular geomorphological significance because it is the location where the regionally tilted Main Rock Platform crosses the regionally

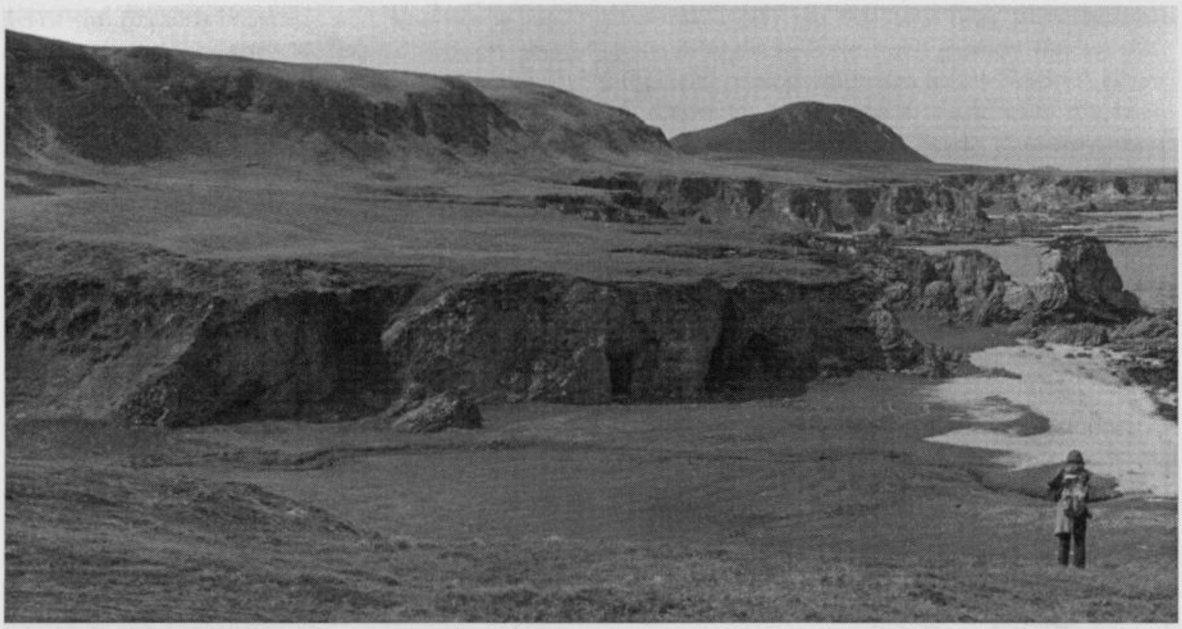

Figure 3.20 The coast of northern Islay, south of Rubha a'Mhàil, showing the High Rock Platform and its backing cliff. In the foreground the Main Rock Platform and its backing cliff is also well developed. Lateglacial and Postglacial emerged gravels also adorn parts of the coastline. (Photo: J.E.Gordon.)

horizontal and glaciated Low Rock Platform, forms that co-incide close to present sea level in places and so could be confused with 'modern' planation. To the west of the lighthouse at Rubha a'Mhàil, the Low Rock Platform and Main Rock Platform are essentially represented by the same surface. To the west of Mala Bholsa, the horizontal and glaciated Low Rock Platform is intertidal and the unglaciated, partly washed and regionally tilted Main Rock Platform lies below sea level.

Conclusions

Some of the finest examples of emerged shore platforms and gravel beaches in western Europe are well preserved on the northern Islay coast. The three distinct emerged ('raised') rock platforms of northern Islay, most strikingly developed between the headlands of Rubha a'Mhàil and Mala Bholsa, have provoked much scientific debate concerning their origin. This is the type locality in the UK for the High Rock Platform, here emerged to an elevation of *c.* 33 m OD. The High Rock Platform is mantled with till and marine deposits, demonstrating that the platform pre-dates at least one period of glaciation and a later period of high sea level (Dawson, 1991). The regional tilt of the Main Rock Platform, which can be traced throughout much of the Inner Hebrides, reflects the relative rates of isostatic recovery in western Scotland following deglaciation. The highly uneven platform is considered to have been produced by periglacial shore processes during the severe cold conditions of the Loch Lomond Stadial some 11 000–10 000 years BP (Dawson, 1991). The glaciated and regionally horizontal Low Rock Platform pre-dates the formation of the Main Rock Platform and has been interpreted as pre- or inter-glacial in origin (Dawson, 1980a). Since all of these platforms appear to be emerged features, the co-location of the lower two at present sea level strongly indicates that they are not Holocene or modern features but are older, inherited from former sea levels, and subject to Holocene and modern retrimming.

Notwithstanding the contrasting interpretations that surround the origin and age of these emerged marine features, the complete assemblage of well-preserved marine and glacial features in northern Islay is of outstanding geomorphological and scientific importance. The juxtaposition of the three platforms facilitates observation and study of cliff-slope evolution since abandonment, as well as rates of platform/cliff formation under varying process regimes.

BULLERS OF BUCHAN, ABERDEENSHIRE (NK 103 362–NK 116 388)

J.D. Hansom

Introduction

The granite cliffs at the Bullers of Buchan in north-east Scotland contain fine examples of many of the typical features of rocky coasts, such as the exploitation by erosion of joints, cracks and dykes in massive igneous rock. Selective erosion of lines of weakness in the otherwise uniform rock, such as intrusive dykes, and marine exploitation of minor differences in hardness and structure, has produced a wide variety of rock coastal landforms. The range of features is impressive at a variety of scales with numerous geos, inlets, caves, arches, stacks, platforms and cliffs. Unfortunately however, and in spite of a substantial body of regional knowledge of past sea level and climatic changes, there has been no detailed geomorphological research carried out in this area.

The coastline of the Bullers of Buchan faces east and so is exposed to North Sea gales from the north-east and east. The dominant wave approach directions on this coast are from the north-east to south-east (Buchan, 1976). Water depths offshore reach 60 m depth at about 5–10 km offshore. The indented nature of the coast results in a great degree of variability in the actual wave climate at any one location.

Description

This 3 km stretch of coastline is composed of pink granite and, although uncertainties exist concerning age, it is likely to be pre-Lower Old Red Sandstone. The rocks have rectangular jointing patterns with a dominant near-vertical and horizontal pattern and a secondary pattern that is inclined at *c.* 45° (Figure 3.21). Exploitation by marine and subaerial processes along these joints, fissures and cracks has resulted in angular, near-vertical and triangular cliff forms. In addition, later intrusion of igneous dykes has further weakened the host rock, leading to rapid erosion at such sites and a likely explanation for many of the geos and inlets (Steers, 1973). The coastal plateau is capped by a 1–3 m-thick cover of till and is subject to mass movement and failure at the coastal edge.

The cliffs of this dramatic coastline vary in height from between 20 m to 40 m OD. Bevelled cliff profiles occur over about 50% of the coastal length. The lower cliff is steep and cut in bedrock, while the upper part of the cliff is often composed of a more gently sloping till surface that has been subject to slumping and mass movement (Figure 3.21). The cliffs consist of two distinctive types.

The cliffs to the north of the island of Dunbuy are steep, although rarely vertical, with discontinuous intertidal or submerged shore platforms that are best-developed adjacent to the geos. The cliffs are capped by a relatively thin and sometimes absent till cover (e.g. on the exposed headland of Grey Mare the till cover has been stripped away for up to 100 m inland).

South of Dunbuy the cliffs are lower (*c.* 20 m OD) and have a more irregularly dissected plan and profile. These low cliffs often have a composite profile with a low gradient upper slope, a steeper (*c.* 45°) middle section and a much steeper basal element. The granite cliff top is severely weathered in exposed areas, but this may represent the exhumation of an ancient pre-glacial weathering surface that is widespread in north-east Scotland.

The otherwise continuous sweep of the cliffs is punctuated by the occurrence of several deeply incised geos of which three types are found:

1. Long, narrow and deep inlets with steep rocky sides and a rock headwall. These typically have little or no beach and may have caves or enlarged fissures at the head. Long Haven, in the south, provides a spectacular example of such a geo: the 300 m-long, narrow, steep-sided inlet has a small scree slope and boulder beach at its head and contains an extensive shore platform on its north side. Perhaps the best example of this is The Pot, where a deep rock-enclosed inlet is separated from the sea by a tunnel-like arch. The Pot resembles an enlarged blowhole and during storms this dramatic feature, which is *c.* 60 m deep and 15 m wide, is awash with a froth of white water as waves crash against the precipitous cliffs (Figure 3.22).
2. Wider more complex inlets (e.g. Robie's Haven, North Haven and Twa Havens) typically contain residual pinnacles, buttresses, skerries or stacks. Boulder beaches, till or scree slopes and slumped debris are often well

developed at the inlet heads. The boulder beach in North Haven extends to *c.* 6 m above present sea level. Dunbuy is a large till-capped stack with the same summit elevation as the adjacent mainland plateau surface 30 m away.

3 Numerous smaller irregular indentations in the cliffs also occur and usually have less steep walls and a more serrated and uneven surface (e.g. at Partans, south of Dunbuy).

The intertidal shore platforms are characterized by a jagged but gently sloping morphology. However, they are discontinuous and tend to occur in association with geos in the north and south of the area. The cliff coastline is characterized by so many geos, skerries, stacks, reefs, caves and arches that a detailed description of each is impossible. Perhaps the best example of a conical stack is the Temptin' at NK 110 384 on the north side of North Haven. Skerries at two distinct levels occur between here and the Grey Mare headland to the south. Jagged linear reefs are characteristic offshore from the narrow rocky headlands between Bowness Castle and Dunbuy. The caves of North and South Seals provide the best examples of caves, while spectacular natural arches can be found at Robie's Haven and Long Haven. However, the most dramatic example is the natural arch cut through the island of Dunbuy. Though now above high tide level, the Dunbuy arch may not be entirely an abandoned feature since the collapsed remains of part of the roof litter the base.

Where a supply of material has been available from above, boulder beaches have developed at the heads of the inlets and geos. Some of these are only accessed by waves in the severest of storms, such as the beach at North Haven, which lies at 6 m OD. Others are composed of well-sorted and rounded gravels such as at Twa Havens and Dunbuy.

Interpretation

The range of hard-rock coastal landforms found in the Bullers of Buchan area reflects an interplay between geological structure and exposure to wave activity. The rectangular joints of the mainly uniform granite, together with the presence of intruded dykes, have resulted in planes of weakness in the host rocks that are susceptible to differential marine quarrying and abrasion. The characteristic angularity of the cliff profiles appears to be the result of erosion along the main joint directions in the granite, a dominant near-vertical and horizontal pattern and a secondary pattern that is inclined at *c.* 45°. Steers (1973) states that some of the caves and inlets have been cut along dykes of dolerite, which are eroded more easily than the granite, specifically referring to the geo at Dunbuy as a good example. Buchan (1931) describes the exploitation of two porphyrite dykes at Robie's Haven and Lammylair. Although fully exposed to storm waves from the north-east to south-east (Buchan, 1976), the degree of development of particular erosional features is probably influenced more by detailed differences in structure than by differences in degree of exposure to waves. In addition, subaerial processes on the cliff faces, such as mass movements induced by cold and wet conditions or frost action, may also be of considerable importance.

A noticeable feature of this coast is the contrast between the higher cliffs in the north where a mantle of slumped till masks the upper section of the cliffs and the lower cliffs in the south where wave and spray action has removed most of this superficial layer. Cliff-top stripping occurs up to *c.* 30 m OD in Orkney and Shetland and where cliff heights are low and wave exposure is high at the Bullers of Buchan, it may not be unreasonable to expect stripping of cliff-edge till, at least on the cliffs in the south. Most of the tops of the narrow peninsulas and stack-tops are stripped of till cover but they are also occupied by nesting birds whose activities may accelerate the stripping process.

The presence of till on top of isolated islands, such as at Dunbuy, might be used to argue for an entirely Holocene age for the geos that now separate islands and stacks from the mainland. However, the glacial legacy in the north-east of Scotland is predominantly one of till deposition and of preservation of pre-glacial surfaces, rather than of glacial erosion. For example, Devensian glaciation failed to remove or substantially modify the Tertiary weathered bedrock surface and in places a substantial thickness of saprolite or superficial weathering material has been preserved (Hall, 1986). As a result, it is possible that pre-existing stacks, islands and geos may have been similarly preserved only to be re-occupied by the Holocene rise in sea level. Such an interpretation infers that the plugs of till that once filled and flanked such sites have subsequently been removed by Holocene processes and the

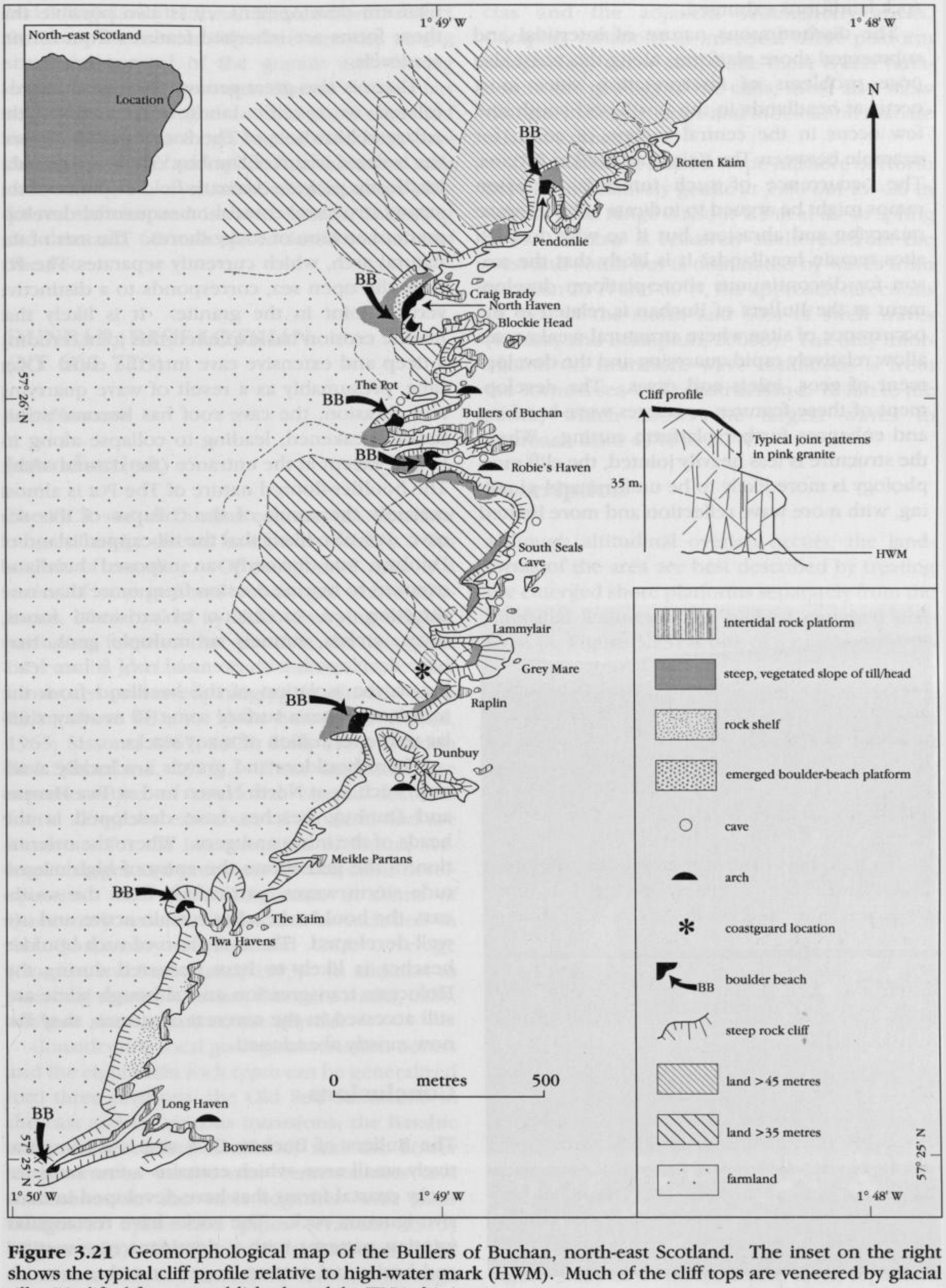

Figure 3.21 Geomorphological map of the Bullers of Buchan, north-east Scotland. The inset on the right shows the typical cliff profile relative to high-water mark (HWM). Much of the cliff tops are veneered by glacial till. (Modified from unpublished work by W. Ritchie.)

rock landforms exhumed.

The discontinuous nature of intertidal and submerged shore platforms along this coast also pose problems of interpretation since most occur at headlands in the north and south and few occur in the central section of coast, for example between The Kaim and Meikle Partans. The occurrence of such intertidal abrasion ramps might be argued to indicate efficient wave quarrying and abrasion, but if so why do such sites remain headlands? It is likely that the reason for discontinuous shore-platform development at the Bullers of Buchan is related to the occurrence of sites where structural weaknesses allow relatively rapid quarrying and the development of geos, inlets and caves. The development of these features promotes wave-breaking and enhances further platform cutting. Where the structure is less heavily jointed, the cliff morphology is more likely to be uniform and plunging, with more wave reflection and more limited platform development. It is also possible that these forms are inherited features from former sea levels.

Figure 3.22 The Pot, Bullers of Buchan is a 60 m-deep enlarged blowhole connected to the sea by a 15 m-wide tunnel-like arch. (Photo J.D. Hansom.)

There is also great geomorphological interest related to specific landforms, such as the enlarged blowhole of The Pot (Figure 3.22) and the isolated island of Dunbuy. These spectacular landforms provide dramatic field evidence of the strong structural control on sequential development of erosion of rocky shores. The axis of the natural arch, which currently separates The Pot from the open sea, corresponds to a distinctive vertical joint in the granite. It is likely that marine erosion has exploited this joint, eroding a deep and extensive cave into the cliffs. Over time, presumably as a result of wave quarrying and abrasion, the cave roof has become structurally weakened, leading to collapse along its length except at the entrance (the natural arch). The boulder-floored nature of The Pot is almost certainly the result of the collapse of this sea cave. It is also likely that the till-capped island of Dunbuy was formerly an exposed headland exposed to marine erosion from more than one direction. A succession of erosional forms, caves, arches, tunnels or multiple geos, may have developed, with eventual roof failure leading to the isolation of the headland from the mainland plateau surface some 30 m away, similar to the formation of many stacks.

Where boulders and gravels are locally available, such as at North Haven and at Twa Havens and Dunbuy, beaches have developed at the heads of the inlets and geos. Where the orientation of the geo allows the entry of high magnitude storm waves, particularly from the south-east, the boulder beaches remain active and are well developed. The inception of such boulder beaches is likely to have occurred during the Holocene transgression and although some are still accessed in the severest of storms, they are now mostly abandoned.

Conclusions

The Bullers of Buchan GCR site is a comparatively small area, which contains a fine range of rocky coastal forms that have developed in massive igneous rock. The rocks have rectangular jointing patterns with a dominant near-vertical and horizontal pattern, together with a secondary pattern inclined at *c.* 45°. Exploitation by marine and subaerial processes along these weaknesses has resulted in angular, near-vertical and triangular cliff forms. The landforms reflect the complex relationships between the strong structural control of the granite and varying degrees of wave exposure. Marine erosion has selectively eroded igneous dykes and exploited minor differences in geological structure, producing a complex and spectacular coastline with numerous geos, caves, arches, stacks, shore platforms, skerries and isolated islands, including the dramatic, 60 m-deep, enclosed sea inlet of The Pot.

DUNBAR, EAST LOTHIAN (NT 661 778)

J.D. Hansom

Introduction

The GCR site of Dunbar contains an excellent range of rocky coastal landforms within a 2 km stretch of coastline. Of exceptional note is a series of emerged and submerged shore platforms, often backed by cliffs of varying heights, including features that pre-date the last (Late Devensian) glaciation. Four distinct shore platforms are preserved, ranging in altitude from 25 m above OD, to 11 m below OD (Rhind, 1965; Sissons, 1967, 1976; Hall, 1989; Gordon and Sutherland, 1993). These landforms are representative of erosional coastal features found along the east coast of Scotland and are important for the interpretation of former sea-level changes and processes of rock coast development. The site is important in terms of Quaternary reconstruction and is included in the Quaternary of Scotland GCR coverage (Gordon and Sutherland, 1993). In addition to intertidal shore platforms, there are stacks, cliffs, offshore skerries and coarse gravels.

Considerable local geological variation occurs and the eight main rock types can be generalized into three divisions: the Old Red Sandstone in the east and its igneous intrusions; the basaltic tuffs of the central headland; and the Lower Carboniferous sandstones, cementstones and cornstones in the west together with their numerous dykes and pipes (Francis, 1975) (Figure 3.23). The foreshore is characterized by numerous volcanic intrusions that run through the fractured sandstone, mudstone and cementstone, as well as well-defined shatter zones at the junction between the bedded tuffs and breccias and the adjacent sedimentary rocks. Complex variations in intertidal shore platform morphology occur and, while there is less variation in the geology of the cliffs, these also show changes in height, slope and indentation that are related to rock type.

The nearshore seabed slope offshore of North Berwick is relatively gentle at 1:60 out to –20 m depth. Tidal range is about 4.5 m at mean spring tides. Dunbar is relatively sheltered from the west and south but is dominated by waves from between 20°N and 60°N, the approach directions of 35% of the storm and 60% of swell waves (Ramsay and Brampton, 2000b). The only information on nearshore wave conditions is from the Torness sea-wall construction *c.* 10 km to the south, which shows the largest waves to approach from 45°N to 90°N.

Description

Although altitudinal overlap occurs, the landforms of the area are best described by treating the emerged shore platforms separately from the intertidal features. The highest emerged platform (A, Figure 3.23) is one of a number of fragments that occur at 16 to 25 m OD between North Berwick and Berwick-upon-Tweed (Rhind, 1965; Hall, 1989). This emerged shore platform lies at an elevation of *c.* 20 m OD at Dunbar and its surface shows evidence of ice-moulding (Hall, 1989) and a thin cover of glacial till and of the drift tail of a crag-and-tail is preserved on its surface (Sissons, 1967, Hall, 1989).

A second platform (B, Figure 3.23) co-incides with the present intertidal zone and reaches a maximum width of more than 300 m west of Long Craigs, where it truncates the underlying sediments and agglomerates (Clough *et al.*, 1910, Francis, 1975). For about 1 km west of the Harbour, the platform is backed by a 20 m-high cliff composed of volcanic tuffs and sandstones and into which are cut several shallow caves. Several stacks protrude above the platform surface. Present-day gravel and boulder beaches mainly occur at the heads of the embayments in the cliffline.

Farther west, the backing cliff of the intertidal platform is degraded and fronted by Holocene beach deposits resting on a third platform (C, Figure 3.23) at an intermediate level, separated from the lower intertidal platform (B, Figure 3.23) by a rock step 1–2 m high (Gordon and Sutherland, 1993). Fragments of this platform, whose front edge lies between 2 and 4 m OD are found intermittently along much of the coastline between Aberlady and Torness (Hall, 1989). The relationships between the three platforms are best seen in section at NT 6633 7899 (Gordon and Sutherland, 1993). The lowest platform (D, Figure 3.23) occurs offshore at depths of between –11 and –13 m OD.

The intertidal landforms of the area vary depending on location and geology: the offshore skerries; the Old Red Sandstone in the east; the tuffs and agglomerates in the central section; and the Carboniferous sandstones with dykes in the west.

The 12 low skerries that lie approximately shore-parallel offshore from the Yetts to Long Craigs are part of a single Late Carboniferous quartz-dolerite dyke. They provide a degree of protection from wave processes at low tide but serve to widen the zone of wave breaking at high tide and consequently result in wave energy dissipation on the shore at high tide.

Between Victoria Harbour and the peninsula to the west of the bathing pool, most of the coast consists of an intertidal abrasion platform developed on tilted Upper Old Red Sandstone, although steep rugged cliffs cut in basanite occur at Castle Rocks near the harbour entrance and low irregular stacks occur to the south of the harbour. The surface of the intertidal platform is very uneven and is crossed by bedding and minor joint systems that have been selectively eroded. A patchy scattering of subangular boulders occurs on the surface. In the west, the distinctive conical stack of Dove Rock is a volcanic plug composed of basanite girdled by rings of tuff and breccia.

The intertidal zone of the central section comprises a series of wide seaward-dipping platforms cut in mixed tuffs and agglomerates and crossed by quartz-dolerite dykes, minor faults and distinctive rectangular fracture patterns that have produced numerous clefts and slot-like inlets. Isolated residual rock pinnacles and stacks of up to 8 m high interrupt the surface, for example, at Bath Rock and Pincod. A great variety of micro-morphological features occurs on the platform surface. Close to the platform surface potholes and sand- and gravel-filled pools occur whereas higher up pitting and honeycomb features are found. The platforms are backed by low but bold, near-vertical cliffs, with the cliff–platform junctions often masked by accumulations of boulders and gravel.

In the west, between the shatter zone and the sandy beach of Belhaven Bay, a bold north-west facing conglomerate cliff gives way along the line of shatter to a rock projection, which extends into Belhaven Bay. A fringing sand and gravel beach extends from the end of the cliff westward at the upper edge of the shore platform to merge at its western extremity with a low emerged ('raised') beach and dune area. Traversing the main rock platform, in a south-west to north-east direction, is a narrow, but prominent, quartz-dolerite dyke that rises from the adjacent surface as a rocky ridge.

Interpretation

A great variety of rock coastal forms exists within a small area at Dunbar. The juxtaposition of structural and lithological settings, together with changes in wave exposure and abrasion, have produced a broad range of cliff forms that show striking variations in plan and profile. At the micro-morphological scale, there exists a wealth of forms on the shore platform surface that are related to weathering processes, such as solution and pitting, and also a range of micro-forms related to abrasional processes. For example, on the intertidal platform to the north and west of the headland, narrow linear pools separated by densely spaced 30 cm-high ridges are partly structurally and lithologically controlled and partly the result of differential abrasion. To the north and west of the headland, the intertidal zone consists of lower shore platforms with many local differences in form according to rock type and structure. The low angle of dip of the strata (5–15°) produces a corrugated platform with changes in form and colour according to lithology.

At the larger scale, the shore platforms at Dunbar demonstrate the relationship between marine erosion, sea level and glaciation. Shore platforms occur at four main levels in this area (Rhind, 1965; Sissons, 1967, 1976; Hall, 1989; Gordon and Sutherland, 1993) although differentiation between levels is often problematic. The highest platform (A) is ice-moulded and has a till cover indicating that it pre-dates the Late Devensian glaciation, although its age is unknown (Hall, 1989). Similarly, the ages of the next two lower platforms (B) and (C) are unknown, although evidence from elsewhere suggests that they too pre-date the last ice sheet (Hall, 1989), with the lower of the two (B)

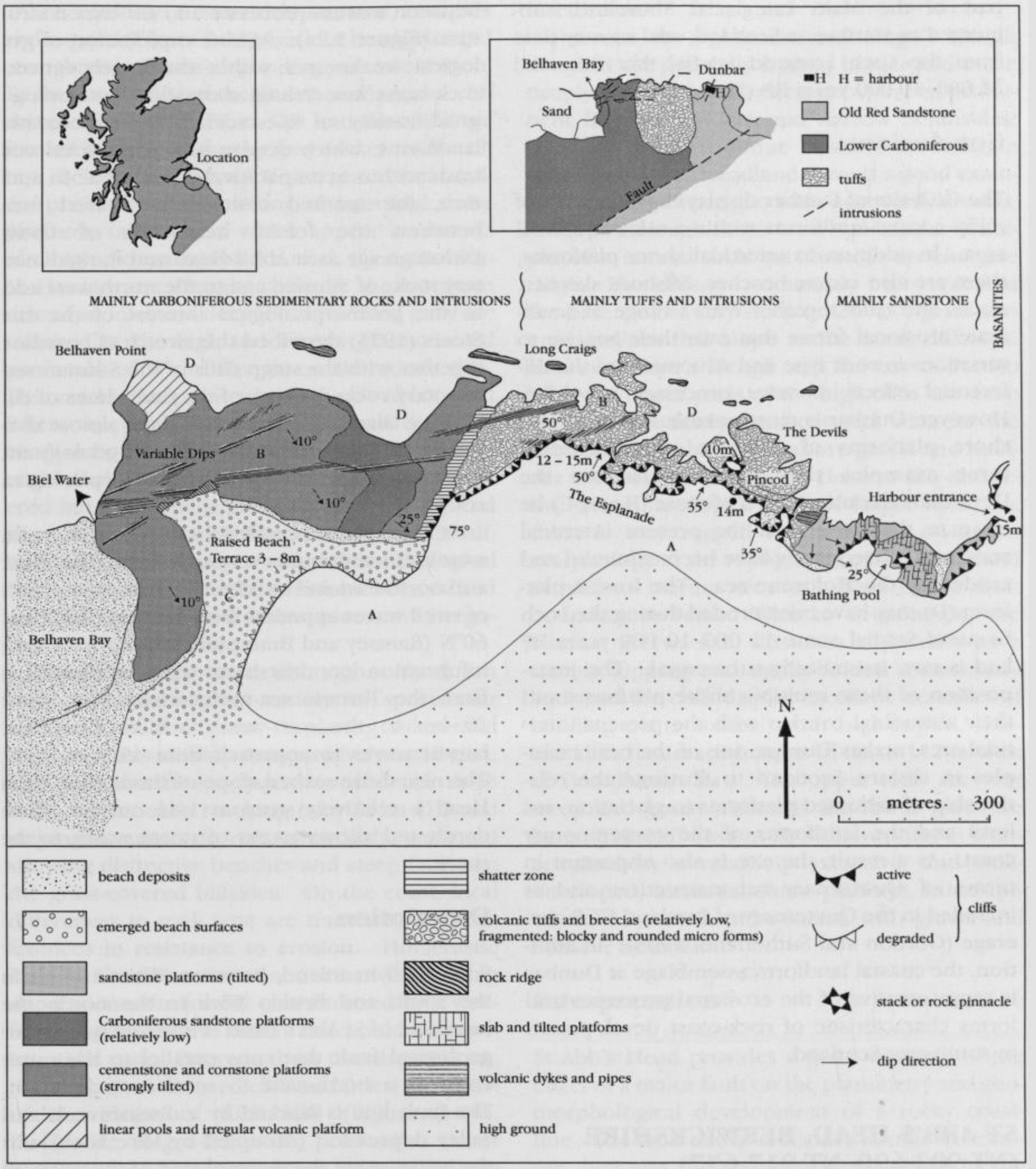

Figure 3.23 Geomorphological map and geological sketch map of the Dunbar GCR site showing a series of emerged rock shore platforms that have been eroded across a varied geology and are backed by cliffs of varying heights. Platform A lies at *c.* 20 m OD and is ice-moulded; Platform B is intertidal; Platform C underlies emerged Holocene beach deposits and Platform D is subtidal. (After Gordon and Sutherland, 1993.)

suffering partial stripping of its till cover and renewed marine erosion in the present intertidal zone during the Holocene Epoch. It is possible that both platforms form part of an intertidal platform equivalent to the Low Rock Platform of western Scotland (Dawson, 1980a). The offshore platform has been correlated with a buried gravel layer and platform farther west in the Firth of Forth and a submerged platform at Burnmouth farther south. As a result, it may be part of the Main Lateglacial Shoreline, submerged in south-east Scotland, and so may date from the Loch Lomond Stadial that occurred 11 000–10 000 years BP (Sissons, 1974).

Conclusions

The GCR site of Dunbar displays a wide range of rocky coastal landforms within a relatively small area. In addition to intertidal shore platforms, there are also coarse beaches, offshore skerries, stacks and cliffs together with a range of small-scale erosional forms that owe their genesis to variations in rock type and structure and the differential effects of wave processes on these. However, Dunbar is most notable for a series of shore platforms of different ages, including three examples that probably pre-date the Devensian glaciation. Two of these (B and C) lie close to the altitude of the present intertidal zone and consequently have been exhumed and eroded by the Holocene sea. The lowest platform (D) may have been eroded during the Loch Lomond Stadial some 11 000–10 000 years BP and is now isostatically submerged. The juxtaposition of these multiple shore platforms and their altitudinal overlap with the present intertidal area, makes Dunbar one of the best examples in eastern Scotland to illustrate the relationship of exhumed platforms to glaciation, sea level and the landforms of the contemporary coast. As a result, the site is also important in terms of Quaternary reconstruction and is included in the Quaternary of Scotland GCR coverage (Gordon and Sutherland, 1993). In addition, the coastal landform assemblage at Dunbar is representative of the erosional processes and forms characteristic of rock-coast development in south-east Scotland.

ST ABB'S HEAD, BERWICKSHIRE (NT 902 690–NT 917 677)

J.D. Hansom

Introduction

St Abb's Head, some 65 km east of Edinburgh, forms a coastline of magnificent rugged and precipitous cliffs cut by numerous clefts, gullies, geos, caves and coves with many offshore stacks, reefs and skerries. This serrated coastline demonstrates well the intricate relationship between marine processes and geological structure (Figure 3.24). Marine exploitation of geological weaknesses within the largely igneous rock mass has created a coastline containing a great variety of spectacular hard-rock coastal landforms, which display substantial local contrasts within a comparatively small area. In addition, the marked contrast in coastal form between the felsite headlands of Lower Devonian age at St Abb's Head and the sedimentary rocks of Silurian age to the north-west adds to the geomorphological interest of the site. Steers (1973) described this stretch of coastline, together with the steep cliffs of the Silurian sedimentary rocks, as 'one of the finest lines of cliff in these islands'. However, to date, almost all of the scientific literature concerns the geology and there has been little detailed geomorphological research.

St Abb's Head is relatively sheltered from the west and south but is very exposed to the north and north-east and so 35% of the storm and 60% of swell waves approach from between 20°N and 60°N (Ramsey and Brampton, 2000b). The only information on nearshore wave conditions is from the Torness sea-wall construction, some 18 km to the nort-westh, which shows the largest waves to approach from 45°N to 90°N. The nearshore seabed slope offshore of St Abb's Head is relatively steep at 1:45 out to –40 m depth and allows access of storm waves to the shore.

Description

Some 200 m inland, between White Heugh in the south and Pettico Wick in the north, the headland of St Abb's Head is bisected by a major geological fault that runs parallel to the outer coast in a north-west to south-east direction. The fault line is marked by a distinctive inland valley depression (occupied by Mire Loch) and the isolation on the seaward side of the valley of a series of volcanic ridges that reach over 75 m OD and meet the coast in a series of high cliffs. West of the fault boundary lie the Silurian sedimentary rocks, although in the south lies an area of Devonian conglomerates with inliers of Devonian–Carboniferous rocks and an area of Devonian intrusive rocks. East of the fault boundary are the Devonian extrusives of St Abb's Head, largely felsites with tuffs and grits. A series of minor faults run perpendicular to the major fault in a north-easterly direction.

The coastline is extremely serrated, complex and rugged (Figure 3.24), but can be subdivided into three sections depending on orientation. To the south-west of the fault boundary, the cliff altitude lies below 50 m OD and the cliffs are formed mainly of Silurian greywackes with a till cap. Below these lies a series of gravel and boulder pocket beaches masking an intertidal shore platform, outcrops of which appear landwards of a high elongate offshore stack (Craig Robin). At Hardencarrs Heugh, cliffs on the northern side of an inlet and deep, boulder-filled gully are matched by the high and narrow grass-covered peninsula of White Heugh on the south side. This marks the point where the St Abb's fault meets the coast. The complex and dissected headland of Wuddy Heugh lies to the north-west of the fault boundary. The cliff tops are till covered but the slope is generally steep, rocky and bare with no shore platform at the base. Small-scale structural features and minor lithological differences in the igneous rock have been etched out as numerous small indentations and irregularities at the cliff base.

The north-east coast, although only 2 km long, contains a great variety of spectacular rocky coastal landforms, displaying substantial local contrasts within a comparatively small area. The hinterland topography consists of three main ridges, each reaching over 75 m OD and sloping at various degrees towards the coast and showing distinctive benches and steep facets on the grass-covered hillsides. On the coast, local differences in rock type are translated into differences in resistance to erosion. Horsecastle Bay and Cauldron Cove are distinctive low-lying depressions, the former characterized by a well-formed gravel storm beach and boulder-strewn intertidal zone. Between these two depressions, the steep grass-covered cliffs and inlets form part of the slope of Kirk Hill (Figure 3.24). Distinctive finger-like rock peninsulas occur here (e.g. the long asymmetric ridge of Waimie Carr, vertical on its northern side and gently-sloping on its southern side), together with blocky scree slopes, finger-like shore platforms and high, vertical cliffs. North of Cauldron Cove, the 75 m OD 'lighthouse cliffs', consist of extensive and steep grass slopes punctuated by a series of grassy benches protruding as free faces. An intertidal shore platform occurs at the base of the cliffs, although in places this is replaced by near-vertical plunging cliffs. The offshore area is complex with numerous skerries and high, fractured stacks.

Between the lighthouse and Hope's Heugh the cliffs are generally higher, bolder and more deeply indented, with deep geos, inlets, prominent finger-like ridges and narrow peninsulas, some of which continue offshore as elongate ridges or stacks. Headland Cove is a good example of a long linear geo with near-vertical sides. At Hope's Heugh there is an spectacular example of a natural arch cut through an elongate ridge. The cliffs are commonly near-vertical at the base, below very steep (*c.* 20–25°) grass-covered inclines that slope to the main cliff tops. Between Hope's Heugh and the bay of Pettico Wick the upper parts of the high cliffs are steep and predominately grass-covered whereas the lower parts are bare rock above gravel and boulder beaches. In the south, close to the distinctive triangular-shaped stack of Staple Rock, the coast is very rugged and complex owing its morphology to the topography of the hinterland as well as marine erosion. West of the fault boundary at Pettico Wick to Broadhaven, the Silurian greywackes, siltstones and shales have steeply dipping and tightly folded sedimentary beds and the cliffs display excellent examples of bedding plane control, with high-angled, slab-like cliffs that reach heights of up to 152 m west of Broadhaven Bay. The upper cliffs are very steep and grassy although the lower parts are bare. The cliff base in Broadhaven Bay is characterized by a relatively extensive, and well-developed, intertidal shore platform, interrupted only by small embayments with gravel and boulder beaches.

Interpretation

St Abb's Head provides a good example of the effect of a major fault on the planimetry and geomorphological development of a rocky coastline. The fault marks a distinct change in lithology between the sedimentary province in the west and the St Abb's Head igneous province in the east. The hinterland topography of the headland consists of a north-west to south-east valley developed along the fault line and a series of high volcanic ridges composed of different lava flows running normal to the fault. This geological control has resulted in a serrated and intricate coast characterized by steep high cliffs that have grass-covered upper faces and bare lower faces. Marine exploitation of minor faults has produced a distinctive series of finger-like

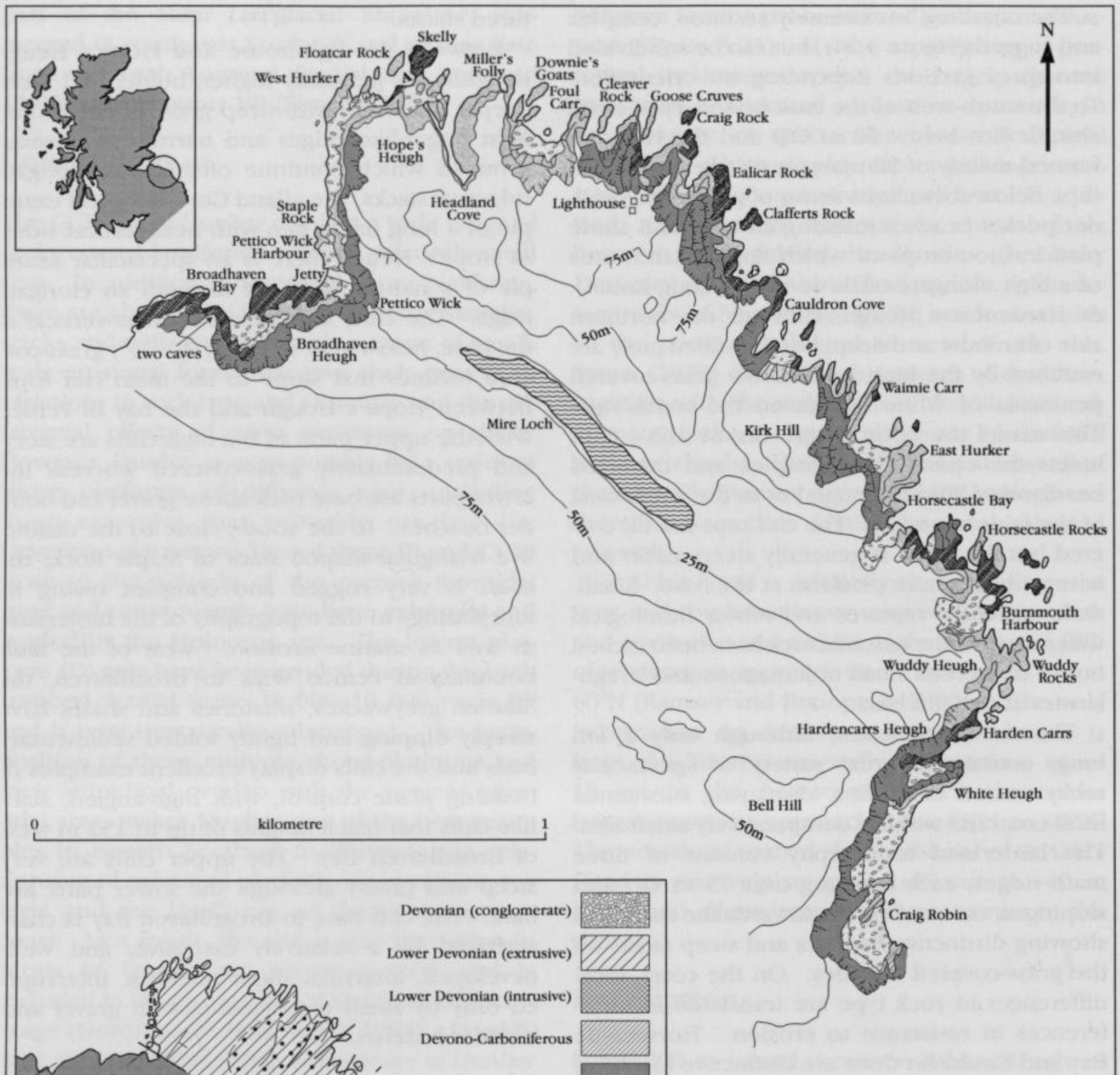

Figure 3.24 Geomorphological map and geological sketch map of St Abb's Head showing the heavily indented nature of the coast resulting from a strong structural control. (Modified from unpublished work by W. Ritchie.)

ridges, geos and inlets that trend normal to the axis of the main fault, producing a rugged coastline. In this respect, the coastline of St Abb's Head provides an exceptional example of the strong control of geological structure on coastal geomorphology.

There is a marked contrast of the cliff form on either side of the major fault. The abrupt geological transition from the felsite of the headland to the Silurian greywackes, siltstones and shales to the west of the fault is reflected dramatically in coastal form. The high-angled, slab-like cliffs cut in the sedimentary rocks strongly reflect the steeply dipping and tightly folded sedimentary beds, displaying excellent examples of bedding plane control. The unique contrast between these sedimentary cliffs and the rugged cliffs and associated forms of the igneous headland provide an excellent site for both research and educational purposes.

A complex interplay between geological structure, marine processes and subaerial processes is evident at St Abb's Head. Exposure to high-energy waves from the easterly quarter has resulted in very effective quarrying and abrasion processes that have exploited both major and minor lithological and structural differences in the igneous rock mass. Geos, caves, inlets, stacks, arches, rock peninsulas and ridges all reflect the differential resistance of the rock to marine processes. In addition, subaerial processes play a part in shaping this unique headland. The distinctive benched profile of the grassed upper coastal slopes at St Abb's Head, with numerous rock outcrops, reflects differential subaerial erosion of the sequence of lava flows that make up the volcanic headland. Free rock faces of lavas and grits often protrude from the grassy cliff slope, some of which are subject to active subaerial erosion, the rate of which is a function of minor differences in lithology and geological structure. The numerous scree slopes and boulder fields (e.g. the bay between Cleaver Rock and Foul Carr) are now largely inactive.

The origin of the shore platforms in this area is also worthy of note. Unlike at Dunbar, where four levels can be identified and approximately dated, only intermittent development of intertidal shore platforms occurs at St Abb's Head. The platforms appear to be best developed in both igneous and sedimentary rocks where the surface of a lava bed or bedding plane crops out in the intertidal zone. Irrespective of geology, all of the shore platforms are intertidal abrasion ramps. However, in spite of suitable structural conditions for the widespread development of platforms, the general distribution of platform remnants separated by embayments suggests that a once more extensive platform has undergone dissection. Some of these remain active under present conditions but, in common with many other east coast cliffs capped by till deposits, it is probable that both shore platforms and cliffs are exhumed features that have undergone modification by Holocene marine erosion.

In summary St Abb's Head is of high scientific importance for the following reasons:

1. The clear relationship between geological structure and coastal form.
2. The contrast between the coastal forms of sedimentary and igneous rocks indicating the strong relationship between lithology and coastal form.
3. The spectacular coastal forms produced in a large igneous rock mass.

Conclusions

The igneous mass of St Abb's head forms a spectacular rugged coastline with numerous clefts, gullies, geos, caves, stacks, reefs and skerries. Headland Cove provides a dramatic and textbook example of a near-vertical geo, the adjacent steeply benched coastal slopes rising to above 75 m. Of principal geomorphological importance is the clear relationship displayed between lithology, structure and coastal form. Marine erosion has exploited planes of weakness within the igneous rock (e.g. major and minor faults and local lithological differences) creating a complex, varied and highly indented coastline. The transition from the felsite of the headlands to the sedimentary rocks west of the fault boundary produces a dramatic and unique contrast in coastal form that enhances the geomorphological interest of the site.

TINTAGEL, CORNWALL (SX 043 858–SX 070 895)

V.J. May

Introduction

Much of the northern coastline of Devon and Cornwall is characterized by cliffs cut into relatively resistant rocks. Even on this resistant coastline, differences of rock strength are reflected in the development of a headland and bay topography. The rocky cliffed headland at Tintagel is one of the many locations where the coastal forms are strongly related to major structural features (see Figure 3.1 for general location). It is also one of the few locations where these relationships have been studied in an assemblage of coastal forms, including slope-over-wall cliffs, geos, caves, arches and stacks.

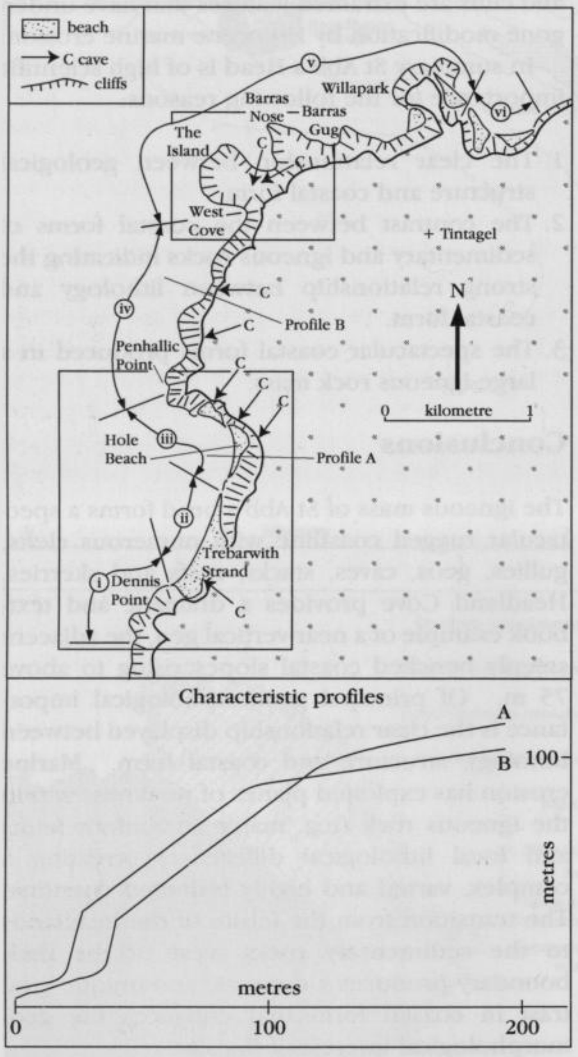

Figure 3.25 Main features of the Tintagel coast (i) Start Point to Dennis Point: vertical and slope-over-wall cliffs; (ii) Trebarwith Strand: sand beach backed by cliffs over 90 m high; (iii) Hole Beach: caves developed on line of faults and thrust planes; (iv) Penhallic Point to West Cove: slope-over-wall; (v) West Cove to Bossiney Haven: complex coast with peninsulas at different stages of separation from mainland; (vi) Bossiney Haven: geo and arch. The inset shows characteristic slope-over-wall forms between Trebarwith Strand and Tintagel Island.

Description

The site extends from Start Point in Backways Cove (SX 043 858) in the south to Bossiney Haven (SX 070 895) in the north. There are sandy beaches at Trebarwith Strand and Bossiney Haven, but much of the coast is formed by cliffs that drop over 100 m directly to below sea level. Some lower cliffs form the lower element of slope-over-wall features: some of these latter forms are bevelled, whereas others form hogbacks. The cliffs and rock platforms are cut in Upper Devonian and Lower Carboniferous rocks, the former much affected by metamorphism. Although there are major thrust faults, the cliff form is most influenced by several roughly parallel normal faults. South of Tintagel Island, some short stretches of cliffline are true fault-line cliffs. Elsewhere erosion has cut back the cliffs from their original fault-controlled position. North of the Island, the coastline is more complex, with many inlets and headlands. Erosion along normal faults, less-resistant beds and joint-planes has produced an intricate set of bays, headlands, stacks, blowholes and caves. Local variations of structure and rock strength are the major control on the landforms. Dewey (1909, 1914) and Owen (1934) described the structures of the area, and Steers (1946a) outlined the main coastal features. Cotton (1951) saw much of this coastline as having two cycles of development, placing particular emphasis on the differences in the cliff profiles. The most important work was carried out by Wilson (1951, 1952) who described the relationship between the coastal features and structures (Steers, 1971a).

This very indented cliffed coastline (Figure 3.25) can be subdivided on the basis of its present cliff and beach morphology into six subunits.

(i) Between Start Point and Dennis Point (SX 043 858 to SX 045 863), the cliffs vary in both height and form. At Backways Cove near-vertical cliffs are only 15 m high at the mouth of a hanging valley, whereas at Dennis Point the overall height of a well-developed slope-over-wall form exceeds 80 m. Gull Rock is an isolated stack about 500 m offshore.

(ii) Trebarwith Strand (SX 045 863 to SX 049 868) is a sandy beach, backed by cliffs that rise to over 90 m. Access to the beach is via a hanging valley with a floor at about 14 m OD whose seaward end has been much degraded by paths and steps.

(iii) At its northern end the beach gives way to a complex of boulders, eroded volcanic rocks including elongated pillow lavas. The coastline has a right-angle bend at Hole Beach where it is cut by a normal fault, to the east of which is a major thrust plane. The lower near-vertical rock-faces usually give way to an upper slope but occasionally extend almost to a bevelled surface at about 80 m.

(iv) From Penhallic Point (SX 046 877) to West Cove (SX 050 889) slope-over-wall forms are dominant and the plan is characterized by several straight sections aligned from north-east to south-west *en echelon* and separated by shorter north–south sections.

(v) Between West Cove, Tintagel and Bossiney Haven (SX 065 896), the coastline is very complex. Three promontories, The Island, Barras Nose and Willapark, each with a narrow neck, are in different stages of separation from the mainland. The cliffs are mainly slope-over-wall forms bevelled at about 80 m OD, but at Willapark there is an excellent example of a hogback cliff.

(vi) Bossiney Haven has a strongly joint-controlled geo as well as the well-known Elephant Rock where a high vertical arch has formed almost separating a narrow 'trunk' of rock from the mainland (Figure 3.26).

The main features of the site were described by Wilson (1952) and this account is based largely upon Wilson's interpretation of the geological features of the area. The coast is cut into Upper Devonian slates, siliceous sandstones, pillow lavas and tuffs and phyllites, which have been overthrust towards the NNW (Wilson, 1951). The overthrust strata were affected by approximately parallel normal faulting. The beds dip generally to the west and the normal faulting throws the thrust-slices down to the west or north-west. The faulting at Tintagel (Figures 3.27 and 3.28) is dominated by two important fault zones: the Castle Fault between West Cove and Smith's Cliff, and the Caves Fault Zone, which cuts through The Island across

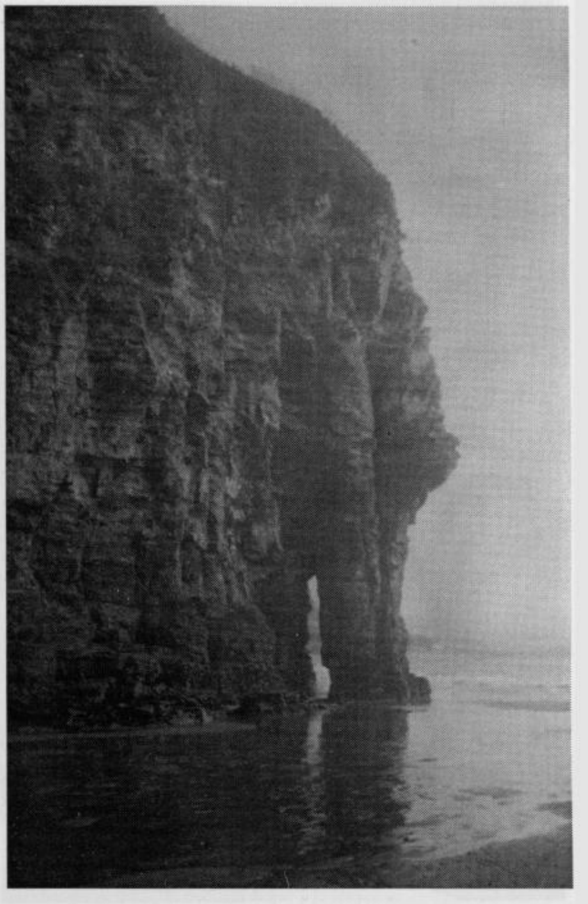

Figure 3.26 Elephant Rock, Bossiney, showing the relationship of cliff features to vertical jointing. (Photo: V.J. May.)

Tintagel Haven to Barras Gug. Similar fault zones affect the cliffs both north and south of Tintagel. The thrust planes lie at low angles, but the normal faults form sloping shear zones, which Wilson noted are easily worked on by marine erosion. Joints particularly with a general alignment towards 325–330° and north–south joints also play an important part in the coastal morphology of this site.

Much of the coastline is distinguished by narrow joint-controlled inlets (for example at Bossiney Haven), known locally as 'guts' or 'gugs', caves cut along fault zones, as well as landsliding on undercut seaward-dipping bedding planes and inclined fractures (Wilson, 1952). Marine erosion along such features has allowed the sea to reach relatively weaker materials, such as the slates, and to cut narrow inlets parallel to the coastline. Wilson compared the site with the coastline around Lulworth Cove. The development of caves is strongly associated

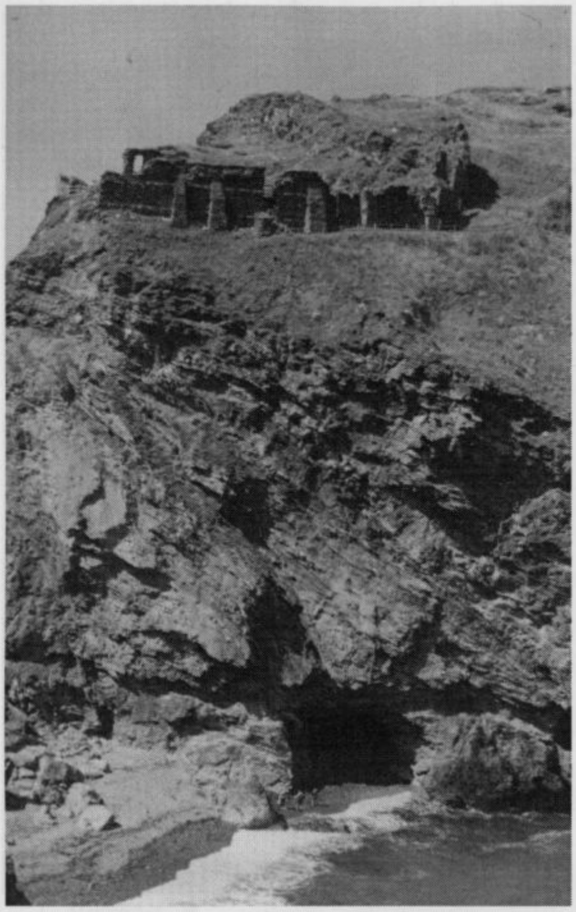

Figure 3.27 Major fault and thrust at Tintagel as the focus for marine erosion, cave and ultimately stack development. (Photo: V.J. May.)

with fault zones, but Wilson also considered that some inlets associated with faults had been the focus of more rapid erosion when they co-incided with former or present lines of drainage. South of The Island, the en-echelon form of the cliffline is strongly linked to faults and other weaknesses parallel to the general alignment of the coastline.

Interpretation

Wilson (1952) observed that active erosion took place along structurally controlled and preferred locations. Where structural weaknesses were flat or gently dipping, they only influenced the process of marine erosion if they occurred close to sea level. In contrast, steeply inclined lines or zones of weakness could control the direction of marine erosion over a large range of sea levels, for if the line of weakness continues through the cliffs both above and below sea level, any features associated with it can continue to develop whether sea level falls or rises. Normal faults appear to have been most important as they trend at an acute angle to the present-day coastline. Moreover, most of the faults on this coastline strike in a direction more or less parallel to the direction of maximum fetch. Once the sea had penetrated into these parallel fault-zones it began to cut back the cliffline by undercutting the harder rock bands between the inclined shatter zones (Figure 3.27). Since many of the faults dip seawards at about 45°, cliffs develop by removal of the material of the shatter zone material and the development of a structurally controlled sloping surface. The sea would subsequently cut a vertical wall in the lower part of the slope to produce the slope-over-wall form.

Wilson also considered the two-cycle model proposed by Cotton (1951) in which the structurally controlled slope was first eroded by the sea, but with a fall in sea level and the onset of periglacial conditions during the last glacial, the upper slope was affected by subaerial slope processes, a talus of debris accumulated to protect the former sea cliff. With a Holocene rise in sea level, the debris would be removed and the sea would exhume and retrim the former sea cliff. Wilson believed that Cotton's two-cycle origin for the cliffs explained many of the coastal features of the area. Unfortunately there is no evidence of relict talus or emerged ('raised') beach deposits within this site to corroborate it. Caves occur at or close to present sea level, but are absent at higher levels and there are no reports of submarine caves or the continuation of caves below sea level. Nevertheless, the alignment of 'guts' and coves with hanging valleys indicates that preferred lines of erosion were available to the sea. Along the foot of the cliffs, the debris of 'ancient rockfalls is still to a great extent protecting the base of the cliff from erosion' (Wilson, 1952, p. 39). Modern falls, however, have the same effect but, as elsewhere on the cliffed coasts of Britain, there has been no investigation of their longevity and their effectiveness in providing temporary armouring to the cliff foot. Between Penhallic Point and Tintagel the cliffs drop directly into the sea with only narrow steps forming the intertidal area. Elsewhere in the site, platforms occasionally reach 150 m in width and occur either at the foot of the cliffs or in the small bays where they underlie the sandy beaches. There has

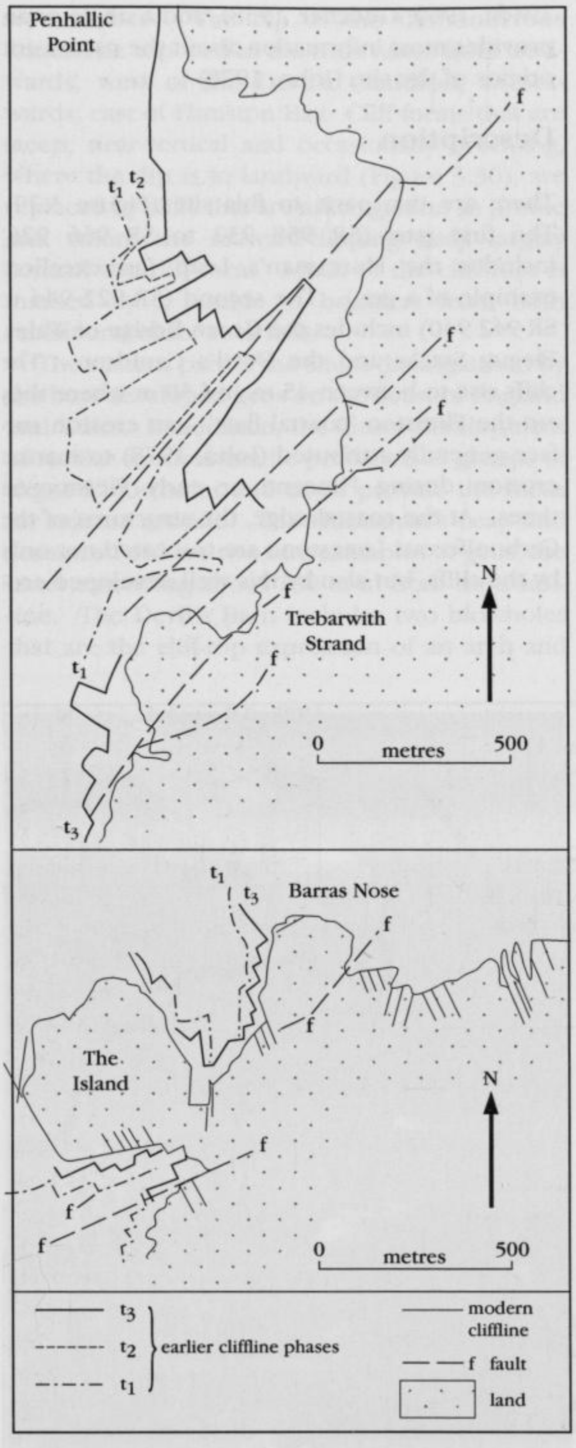

Figure 3.28 Examples of coastline development controlled by major faults, Penhallic Point and Barras Nose. See Figure 3.25 for general location. (After Wilson, 1952.)

been no detailed investigation of the shore platforms, but their form appears to reflect strongly the effects of rock strength and the detailed structures.

Wilson's (1952) paper remains unusual amongst the coastal literature in considering the detailed relationship between cliff development and rock structures on a hard-rock coast. There are comparable sites, for example, in south-west Wales and at Trearrdur Bay in south-west Anglesey, but no comparable work. Like Hartland Quay (see GCR site report) to the north, this site contains hanging valleys, waterfalls, hog's-back and bevelled cliffs. Unlike Hartland Quay, it also demonstrates very clearly the relationship of structure to cliff development. It is not generally regarded as a longitudinal coast, but in terms of the development outlined by Wilson (1952) it has similarities to the coastline around Lulworth Cove (see GCR site report for the Dorset coast in Chapter 11). Lulworth Cove is backed by relatively weak materials and so the effects of breaching of an outer resistant wall are followed much more strikingly by the development of bays than has occurred at Tintagel. Tintagel is thus important not only because of the links between structures and landforms, but also because it provides a contrasting example to Lulworth Cove.

Conclusions

Tintagel is one of the very few hard-rock sites where the relationships between major structural features and coastal development have been examined in detail. The landforms include geos, caves, stacks, arches and slope-over-wall cliffs. An excellent example of the way in which major structural features can control the development of coastal landforms, it is also a good example of a longitudinal coast, although not so strikingly obvious as the most commonly cited example at Lulworth Cove. Unlike the latter, it is predominantly in hard rocks and the rates of change are less.

SOUTH PEMBROKE CLIFFS, PEMBROKESHIRE (SR 958 932–SR 966 928; SR 922 944–SR 942 940)

V.J. May

Introduction

The coastline west of St Govan's Head contrasts with that of southern Gower because of its absence of emerged ('raised') shore platforms and the presence of steep active cliffs. The two sections of cliffed coastline that form this site (Figure 3.29) enclose some of the finest examples of coastal forms in England and Wales. Cut into massive limestones of Carboniferous age, the cliffs include exceptional examples of the development of geo, stack, cave and arch. Faults and other lines of weakness have been exploited by the sea to produce such well-known features as the Green Bridge of Wales, Elegug Stacks and the Huntsman's Leap. The importance of this site is greatly increased by the retreat of the coastline into an area of karstic landforms. Thus, the combined effects of solution, collapse and marine reworking of these landforms have produced an intricate and geomorphologically important assemblage of forms. Like a number of cliffed sites, the literature is limited (Steers, 1946a, 1969; Guilcher, 1958), and a single paper provides most information about the nature and origins of the site (John, 1978).

Description

There are two parts to this site (Figure 3.29). The first part (SR 958 932 to SR 966 928) includes the Huntsman's Leap (an excellent example of a geo). The second (SR 922 944 to SR 942 940) includes the Green Bridge of Wales, Elegug Stacks and the Devil's Cauldron. The cliffs rise to between 45 m and 50 m where they cut the Flimston 'coastal flats' – an erosion surface generally attributed (John, 1978) to marine erosion during Pliocene or early Pleistocene times. At the coastal edge, the structures of the Carboniferous Limestone are truncated not only by the cliffs, but also by this well-developed ero-

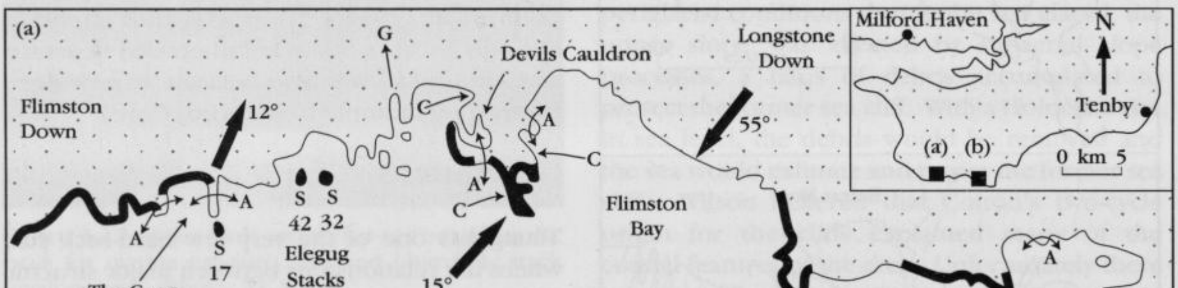

Figure 3.29 Erosional features of the south Pembrokeshire coast. (After John, 1978.)

sion surface. The dip of the Carboniferous Limestone exposed in the cliffs varies from landwards, west of the Devil's Cauldron, to seawards, east of Flimston Bay. Cliff forms that are steep, near-vertical and occasionally overhang, where the dip is to landward (Figure 3.30), are replaced by cliffs that are much gentler in profile and where the seaward-dipping beds largely control the cliff form. Much of the cliff foot is marked by a jumble of boulders from both recent and older rock falls.

The eastern part of the site is distinguished by the best-developed geos on the coast of England and Wales. In addition, the future development of similar features can be predicted as groups of aligned blowholes and caves provide the focus for marine erosion. The Huntsman's Leap and Stemmis Ford are two fine examples of geos, the latter extending about 180 m in from the coastline. The Devil's Barn includes two blowholes that are the cliff-top expression of an arch and marine erosion beneath them. At the Castle, there is a sequence of caves and arches as well as a blowhole. If their roofs collapsed much of this area would become separated from the mainland. They are probably solution forms that are being reworked by marine action.

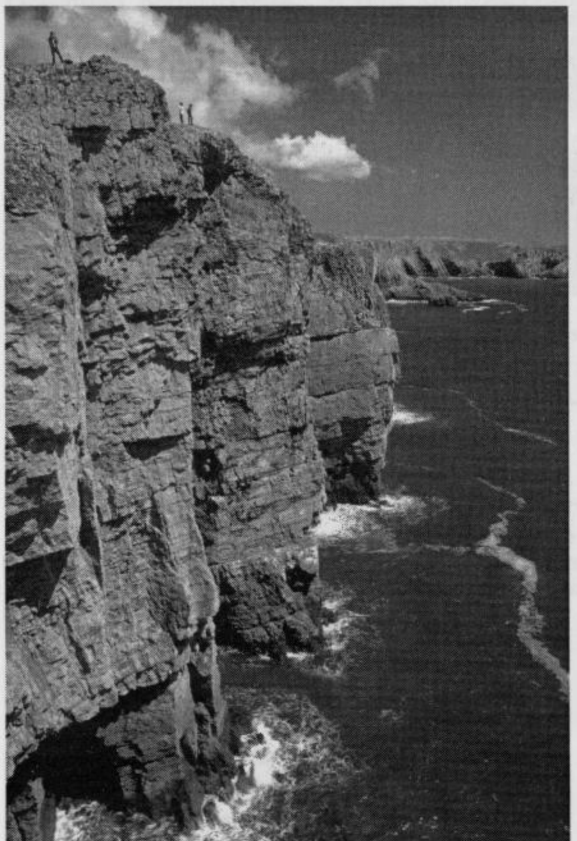

Figure 3.30 Cliff profiles, South Pembroke Cliffs GCR site. Cliffs are steep, near-vertical and occasionally overhang where the dip is to landward. (Photo: S. Campbell.)

The western part of the site includes some of the most unusual coastal forms of the coastline of England and Wales. The Green Bridge of Wales is an arch of about 24 m in height and it spans more than 20 m. Its upper surface slopes down from the cliff top. The outer limb of the arch rests on a broad pedestal-like base. Here the limestone dips inland. The Elegug Stacks, of which the higher reaches about 36 m, also rise from a broad, sloping pedestal. A fault runs through the eastern base of the larger of the two stacks. To the east of the Elegug Stacks, the sea has exploited a large number of faults and major shear planes, as well as deposits of gash breccia, to produce an intricate assemblage of caves, arches and geos (Figure 3.31). Of 52 faults and major shear planes recorded by John (1978), 22 co-incide with a cliff face, 11 form the axis of geos and 19 are associated with neither. Only four co-incide with a cave or arch. This pattern continues to the east in Flimston Bay. It is largely absent on Longstone Down where the Bullslaughter syncline produces seaward dips of up to 55°. From Moody Nose eastwards, the local control of erosion by faults and shear planes is also very evident.

At Flimston Castles, the coastline is extraordinarily complex and includes the Devil's Cauldron. Here a shaft, 45 m deep with a maximum diameter of 55 m, is open to the sea via an arch 18 m high and 21 m wide, a narrow fault-guided chasm connecting with the sea. John (1978) cites Thomas' estimate that some 113 000 m^3 of rock was removed to produce the Devil's Cauldron. Its considerable interest arises from the fact that much of this coastline truncates solution features of the limestone landscape. The Devil's Cauldron, like several other features on this coast, is probably a karstic form that has been exploited by the sea as the coastline has retreated. Similar eroded features occur at Flimston Castles and at the Devil's Barn and the Castle.

Interpretation

There is no comparable site in England and Wales, and, with a few exceptions, similar exam-

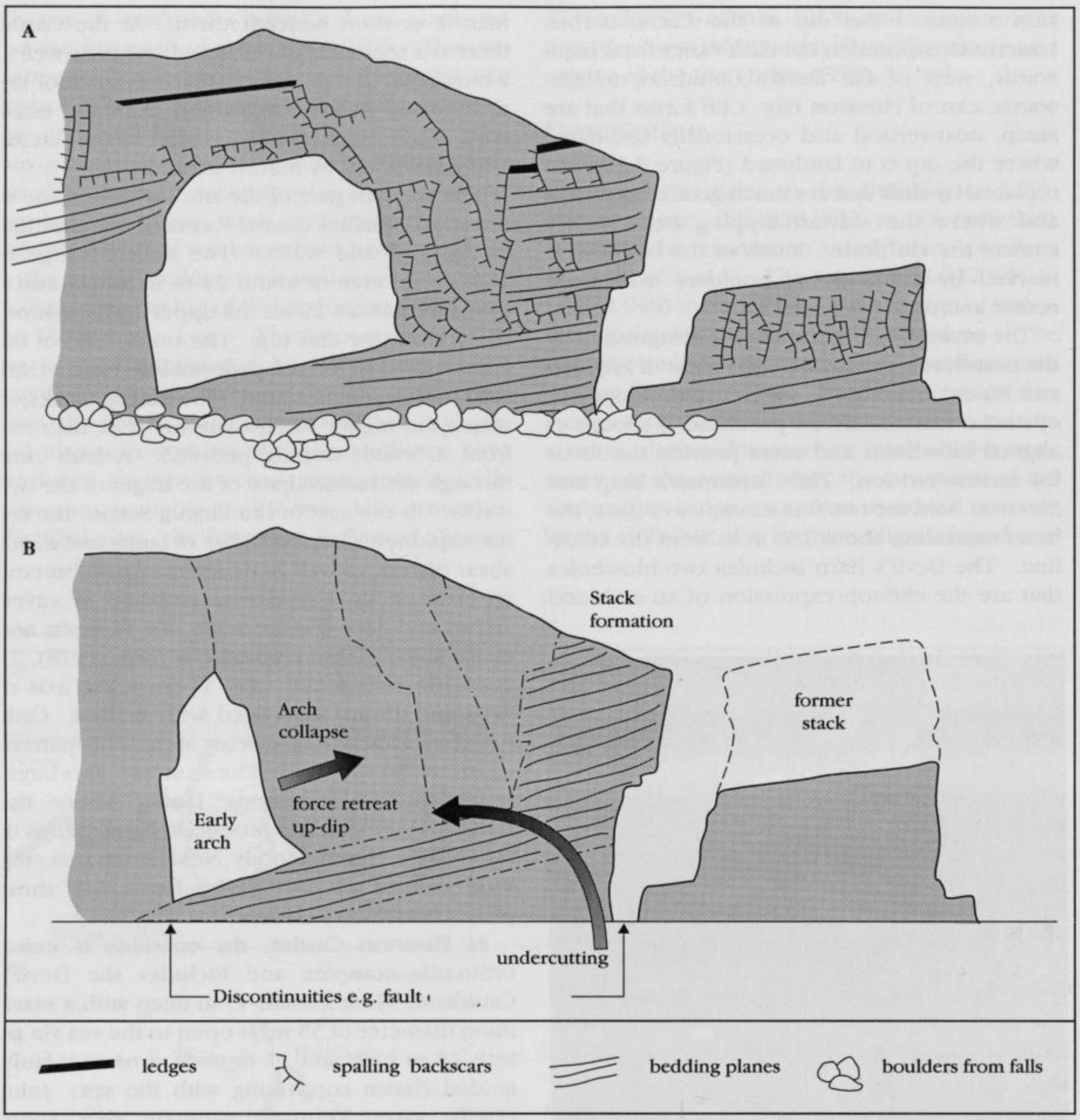

Figure 3.31 Arch and stack development. (A) Form of the arch and stack at The Green Bridge of Wales. (B) Interpretation of development of the feature. An initial arch develops on the line of a discontinuity, and extends up-dip by spalling and collapse of up-dip rock surfaces. The arch roof collapses and a new stack is isolated.

ples around the European coastline have rarely been described in detail. The only other similar site in Britain in which exhumation of erosional forms has been well described is the Bullers of Buchan in Scotland. There, however, the stacks and geos are often cloaked by, and infilled with, till and so their preglacial or interglacial origins can be accepted with little question. Here, the evidence is more circumstantial. A rock platform that may be reworking an earlier form is subject to erosion at present by both chemical and physical processes.

Marine erosion of karstic forms is common along the north-eastern Adriatic coast, and comparable features on the south coast of Gozo, Malta have been described briefly (May and Schwartz, 1981; Paskoff and Sanlaville, 1978). Although stacks and arches are well represented in Chalk, such cliffs generally lack the development of geos found here. Some features where karstic forms are truncated by marine erosion occur in Chalk north of Flamborough Head. The South Pembroke cliffs include a well-developed coastal landscape in Carboniferous Limestone and, unlike much of the Gower peninsula, is not characterized by emerged ('raised') beaches and platforms. Nevertheless, the coast both to the east and west provides evidence of considerable longevity. In West Angle Bay, pre-Devensian till may underlie Ipswichian emerged beach deposits and both lie above a rock platform, which could therefore be attributable to higher sea level during the last Ipswichian interglacial (Campbell and Bowen, 1989). Inland at Hoyles Mouth and Little Hoyle's Cave sediments have been interpreted as showing that the limit of the Late Devensian ice was close to this site. Furthermore these caves record the occupancy by humans in Upper Palaeolithic times (*c.* 18 000 years BP) and suggest that the area to the south must have been ice free. Similarly Marros Sands farther to the east preserves evidence of intense Devensian periglaciation. It thus appears that the South Pembroke coast was ice-free during Devensian time, was probably affected by intensive periglacial processes and that parts of the coast may have been reworked. However, although John (1978) has suggested that parts of the cliffs may be more than 5 million years old and that others may date from the last interglacial, there is no direct evidence that the south Pembroke cliffs preserve former features. For example, the present sea-level platform may not be entirely contemporary, but no evidence is available to support or reject the hypothesis that it is exhumed. There is similarly no evidence to date for the age of the karstic features into which the cliffs are currently being cut. Solution forms are well developed on some parts of the platform (Guilcher, 1958) and are generally regarded as being contemporary features. Any attempt to relate the levels of the platforms to past sea levels must take account of the rates at which solution takes place. There has been, however, little research here into the detailed evolution of these forms.

The present-day changes in features such as the Green Bridge of Wales as recorded by photographs show that most changes this century have occurred on the down-dip side of the arch wall. Undercutting and spalling have narrowed this part of the feature and provide an insight into both its future and more generally the development of stacks in this hard-rock context (Figure 3.31). The original break through the promontory from which the bridge formed probably occurred at the point where the pedestal rock occurs at the cliff foot. The seaward face of the cave and then the arch has retreated more rapidly. This face has retreated most rapidly at its base and in due course when the arch collapses the stack will stand on a pedestal several metres above sea level. The largest geos are characterized by a narrow neck and/or blowholes. They appear to have developed by widening and lengthening around these blowholes (which may co-incide with karstic features) rather than by progressive lengthening.

In summary, the regional evidence points towards a very long history for this coastline, but the local evidence supports a modern origin for the coastal features as the cliffline cut into the existing karstic landscape. There is little evidence in the cliff forms that the cliffs are anything other than modern surfaces resulting from the undercutting, toppling failures and rock falls of an older cliffline.

Conclusions

This is a rare assemblage of active coastal erosional features, whose origins are better documented than many other cliffed sites. Well-developed geos, stacks, arches and cliffs truncate a former karstic landscape. In addition, it forms part of a southern British suite of structurally controlled coastal landforms, which includes Tintagel as the least dynamic and Old Harry (see GCR site report for Ballard Down) as the most rapidly changing. The marine erosion of former karstic features to produce an intricate coastline of arches and stacks is not found on this scale elsewhere on the British coast.

HARTLAND QUAY, DEVON (SS 221 226–SS 230 278)

V.J. May

Introduction

The coastline of North Devon runs transversely across Devonian and Carboniferous strata, but at Hartland Point it changes direction abruptly towards the east (see Figure 3.1 for general location). Much of the coastline is cliffed, broken only by small valleys that have been eroded to present sea level (for example at Crackington Haven) or form hanging valleys (for example south of Hartland Quay). South of Hartland Point, the relationships between coastal valley systems and coastal retreat are of particular interest. This site contains fine examples of cliffs and shore platforms, and demonstrates clear relationships between cliff forms, platform development and lithological variations (Arber, 1911). Furthermore, it is also noted for a remarkable set of river valleys that have been truncated by the cliffline, so that their floors now lie well above present sea-level (Arber, 1911; Arber, 1949). Unlike similarly truncated streams in the south-west Isle of Wight (see GCR site report in Chapter 4), those in the Hartland Quay area have been unable to erode valleys to sea level and so many reach the shore via waterfalls (Arber, 1911). In some cases the streams have also cut gorges that include waterfalls. In common with other hard-rock coasts, Hartland Quay has been the attention of only limited research since the detailed monograph by Arber (1911). Keene (1986, 1996) and Goudie and Gardner (1985) have reviewed the development of the site in the light of more recent interpretations of Pleistocene geology in western Britain (Stephens and Synge, 1966; Kidson and Tooley, 1977).

Description

Described as 'perhaps the finest coastal scenery in the whole of England and Wales' (Steers, 1946a, p. 219), this site extends some 6 km from Longpeak Beach in the south (SS 221 226) to Hartland Point in the north (SS 230 278). Cliffs cut into Carboniferous interbedded fine-grained sandstones and shales vary in height between 25 m and 100 m. The structural features lie east–west, following the Variscan trend. Because the shales are eroded more easily than the sandstones, these structures are etched out both in the cliffs and the platforms. Caves have been cut in the weaker shales and mudstones, or along faults on the axial planes of the folds (Keene, 1996). Five valleys truncate the coastline and reach the sea via waterfalls. A platform, up to 300 m in width, dominates the intertidal zone. Its mean width is 160 m (based on 30 measurements at different localities), with headland platforms being on average 50 m wider than those in bays). Beach development is limited, being mainly confined to small bay-head accumulations of locally derived shingle and cobbles. There are also considerable areas of boulders resting both at the cliff foot and upon the platform. The cliffs are subject to much localized mass-movement, for example at Blagdon Cliff where there is a fault-controlled landslide. To the east of the site at Keivill's Wood (SS 352 237), the co-incidence of a large rotational slip scar and an almost flat boulder spit (The Gore) have been interpreted as the scar and lag deposit of a large landslide, which based on chart evidence pre-dates 1795 (Keene, 1996). The rate of retreat of the cliffs around Hartland Point has been estimated at between 20 and 40 mm a^{-1}. With sea level at or close to its present level for the past 6000 years, this suggests net retreat of up to 240 m, a distance close to the width of the platforms.

The cliffs at Hartland Point and Blagdon Cliff reach over 100 m, but decline to just over 30 m at the mouth of Tichberry Water (SS 228 267), which flows into the sea over the northernmost of the waterfalls that distinguish this stretch of the coastline. The narrow flat floor of its valley is continued southwards between a small hill known as 'Smoothlands' and the continuation of its southern valley side. A small stream fed from a spring flows along part of this hanging valley floor to enter the sea over a 22 m cliff on the northern side of Damehole Point (SS 226 265). Two streams, Blegberry Water and Abbey River, both flow onto Blegberry Beach via waterfalls, although of very different forms. At Blegberry Water the stream flows from about 35 m OD down a joint-controlled waterfall that Arber (1911) described as a 'primary sheer waterfall' (Figure 3.32). Abbey River in contrast has a flat floor that hangs some 12 m above beach level. The valley is underlain by solifluction debris, and the stream has cut (in Arber's terminology) a 'mature canyon'. Steep cliffs up to 100 m in height form the coastline to Hartland Quay.

Between Hartland Quay and Speke's Mill Mouth, the cliffs vary in height from below 30 m to over 70 m. Each of four small headlands (Hartland Quay, Screda Point, Screda Bay south-side, and St Catherine's Tor) slope inland to a flat-floored valley that hangs at about 30 m OD above each of the intervening bays. Wargery Water flows along part of the hanging valley to drop to the sea at Childspit Beach. To the south, Milford Water flows over a flat-floor until it plunges into the sea over 'the most spectacular' waterfall at Speke's Mill Mouth (Arber, 1911). To

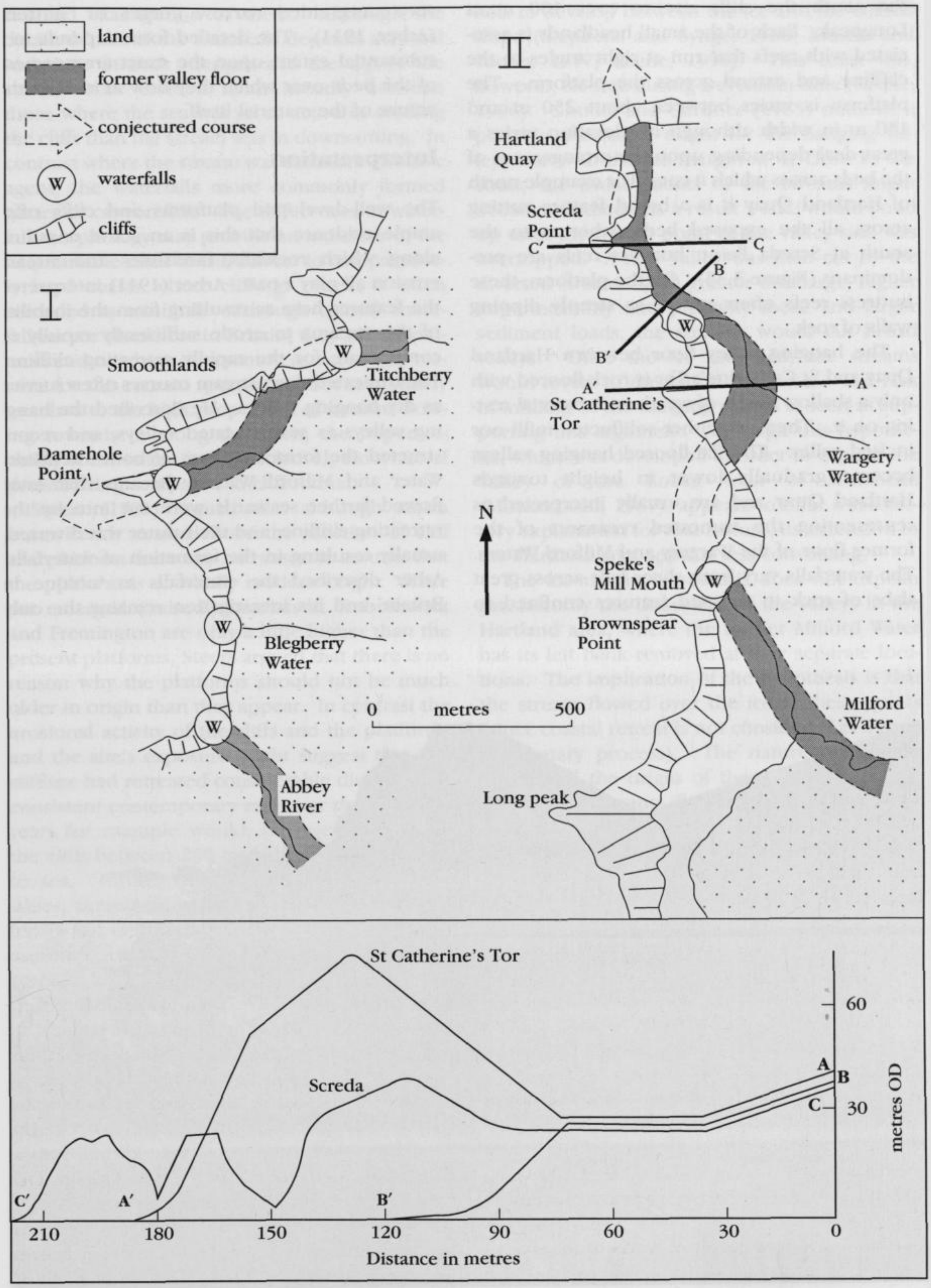

Figure 3.32 Hartland Quay GCR site – showing the pattern of truncated valleys. The profiles A–A′, B–B′, C–C′ are shown at the bottom of the figure. Section I lies to the north of Section II. (After Arber, 1911.)

the south the cliffs rise to over 100 m at Longpeak. Each of the small headlands is associated with reefs that run at right angles to the cliffline and extend across the platform. The platform is varies between about 250 m and 150 m in width although its elevation varies a great deal depending upon the arrangement of the beds across which it cuts. For example north of Hartland Quay it is a broad feature cutting across all the exposed beds, whereas to the south at Screda Point, buttress reefs are predominant (Figure 3.33). On the platform, these buttress reefs often appear as steeply dipping walls of rock.

The hanging valley floor between Hartland Quay and St Catherine's Tor is rock-floored with only a shallow depth of weathered material resting on it. There is neither soliflucted infill nor incised valley. The flat-floored hanging valleys become gradually lower in height towards Hartland Quay and are usually interpreted as representing the truncated remnants of the former floor of the Wargery and Milford Waters. The waterfalls vary from sheer falls across great slabs of rock to stepped features confined to very steep-sided narrow gorges or 'gutters' (Arber, 1911). The detailed form depends to a substantial extent upon the exact arrangement of the beds over which they flow as well as the nature of the material itself.

Interpretation

The well-developed platforms and cliffs offer ample evidence that this is an active coastline along which rockfalls, landslides and stream erosion all play a part. Arber (1911) interpreted the features here as resulting from the inability of the streams to erode sufficiently rapidly to compensate for the rapidly retreating cliffline. The truncated downstream courses often survive as dry hanging valleys. He described the hanging valleys as sea-truncated valleys, and reconstructed the former courses of both Titchberry Water and Milford Water. Streams that once flowed farther seawards were cut into by the retreating cliffline, and their water was diverted, usually resulting in the formation of waterfalls. Arber described the waterfalls as 'unique in Britain' and his investigation remains the only

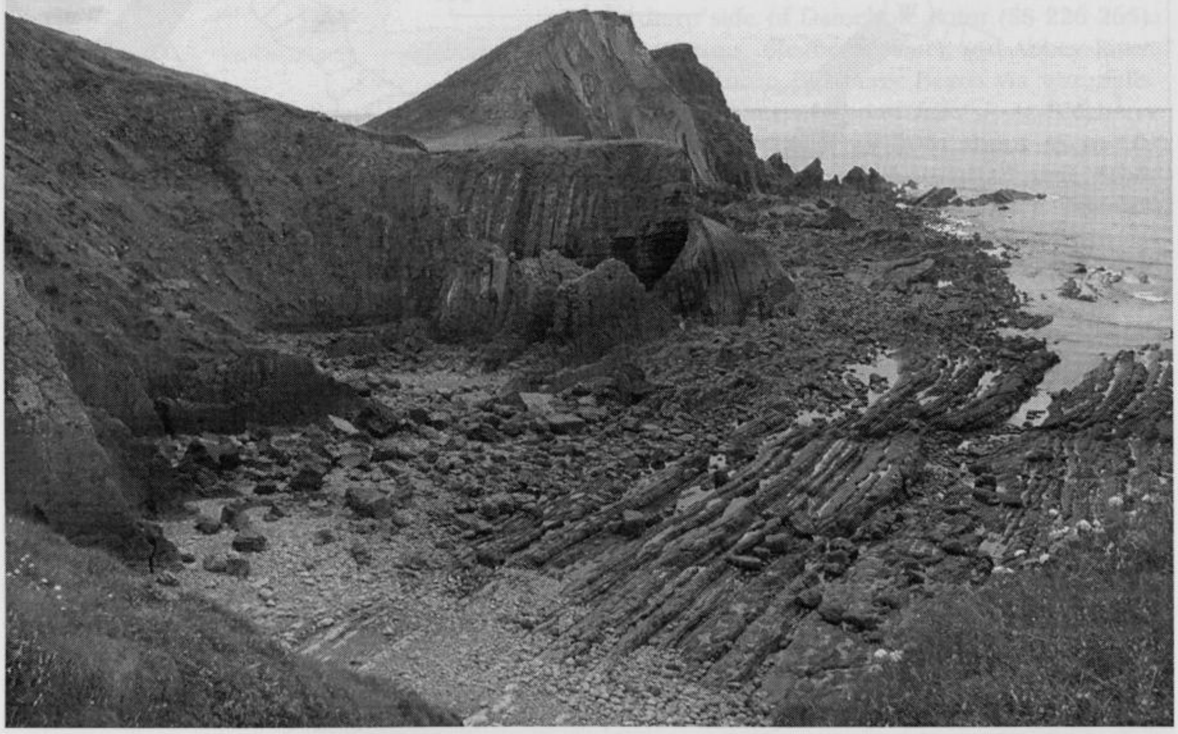

Figure 3.33 Cliffs, platform, beach and truncated valleys south of Hartland Quay. (Photo: Lou Johnson, www.walkingbritain.co.uk.)

detailed examination of them. Although the detailed form of the waterfalls depends on local variations in rock strength and the dip of the strata, Arber divided them broadly between those where the sea was more active in eroding the cliffs than the stream was in downcutting. In contrast where the stream was the more effective agent, the waterfalls more commonly formed gutter or canyon falls. The differences in waterfall morphology may provide an indicator of the very variable rates of cliff retreat in comparatively hard coasts where cliff-top retreat is often recorded as minimal. Although coastal waterfalls occur elsewhere in Britain, they are uncommon and nowhere as common as here. The reasons for this remain speculative, but seem likely to relate to the high proportion of streams flowing towards or along the coast, the impermeability of the strata, and the relatively slow rate of downcutting compared to cliff retreat.

Steers (1981) argued that although storm waves reach to and above the junction of cliff and platform there was no reason to assume that the platform is of wholly modern origin. Since the emerged ('raised') beaches at Trebetherick and Fremington are only a little higher than the present platforms, Steers argued that there is no reason why the platforms should not be much older in origin than they appear. In contrast the erosional activity of the cliffs and the platforms and the site's exposure might suggest that this cliffline had retreated considerable distances. A consistent contemporary rate over the last 6000 years for example would, however, only place the cliffs between 250 m and 120 m farther out to sea. Farther north on the south coast of Wales, there are well-preserved emerged platforms and beaches. The shales and sandstones around Hartland present a significantly different surface for erosive processes. Whereas the Carboniferous Limestone of Gower is comparatively free of discontinuities, the Carboniferous shales and sandstones of Hartland are very thinly bedded, much folded and faulted and provide numerous opportunities for erosion by both marine and slope processes.

An ice-margin explanation is proposed by Goudie and Gardner (1985) as an alternative to the coastal retreat explanation. If the Fremington tills are Anglian in age, then ice entered the nearby Taw–Torridge valley about 450 000 years BP. Irish Sea ice probably extended far enough south during the penultimate glacial period to allow marginal drainage channels to develop between the ice and the coastal slope (Stephens and Synge, 1966; Kidson and Tooley, 1977; Keene, 1996). This coast was, however, ice-free during Devensian time (Keene, 1996). Goudie and Gardner (1985) outlined a possible alternative origin for the hanging valleys, for with the ice margin at or close to the coast, the usual outlets of the streams might become blocked. As a result a lake would build up until the lowest point of the valley side was overtopped. A new valley was then cut by the diverted stream. With greater discharge, higher impermeability and probably more and larger sediment loads, the streams would cut broad valleys. Once the ice retreated, the streams would revert to their former courses. The lack of infilling of the hanging valleys is seen as supporting this argument. Although this hypothesis, which was developed in order to explain the Valley of the Rocks west of Minehead (Mottershead, 1967), appears to offer a satisfactory explanation for that feature, its extension to the Hartland area appears less convincing.

The ice-margin hypothesis does not explain satisfactorily the dissection of the valleys in the Hartland area, where the former Milford Water has its left bank removed at four separate locations. The implication of the hypothesis is that the stream flowed over the ice at these points (since coastal retreat is not considered as a complementary process). The nature of the evidence and the origin of these unusual coastal landforms warrants further detailed investigation. Keene (1996) points out that the valley of Milford Water upstream of the truncated supposed meltwater section is also flat and steep sided. Valleys such as Abbey River are, in contrast, infilled by soliflucted material, probably of Devensian age. Their rock floors lie much closer to present sea level. Unconsolidated angular material in a matrix of finer-grained materials is entirely local. Post-Devensian increases in stream activity account for the development of meander terraces in the soliflucted material (Keene, 1996). In both cases, subsequent retreat of the cliffs would have allowed truncation to have taken place leaving them hanging above the present beaches.

Farther south at Marsland Water and Welcombe Mouth, valleys are incised much nearer to present sea level and there is clear evidence that earlier valleys were filled by soliflucted debris (probably Devensian in age: Keene, 1996). This suggests that at least in that area pre-Devensian streams flowed to a similar local base-level to today, but does not necessarily confirm that the coast was near its present position. On balance, the ice-margin hypothesis is less likely unless either Devensian ice reached the area and was banked against the coast or the valleys preserve forms that derive from the Anglian glacial presence along this coast. The latter also seems unlikely given that there have been four major changes of sea level since the Anglian and that cliffs could retreat at least 200 m in each interglacial period. An intrinsic part of the debate arises from the anomalous relationship of the truncated valleys to the structures. The majority of valleys follow the strike of the rocks. The question to address therefore is whether the development of drainage in these patterns is anomalous. If not, then the simple explanation that the valleys result from truncation by coastal retreat would appear most likely.

Conclusions

This part of the north Devon coast displays excellent examples of cliffs, platforms and differential adjustment of stream systems to coastal retreat. The only site in Britain where the development of coastal waterfalls has been examined in detail, Hartland Quay is also important for the remarkable truncation of valleys running along, rather than towards, the cliffs. The shore platforms have been cut across the complex structures, but little research on them has been carried out.

This site has caused controversy in that the origins of one of its main features, Arber's 'sea-truncated valleys', remain open to discussion. It contains some of the best examples of coastal waterfalls in Britain, the cliffs are finely developed, and a series of hanging valleys give the site unusual characteristics. The platforms are also well developed, although, as Steers has pointed out, they may well owe their existence to more effective marine activity in the past. If the ice margin was sufficiently close to produce (or at least influence) the flat-floored valleys, there remains the possibility that sea-ice and later periglacial conditions may also have played a significant role in the development of this site. However, in the absence of clear evidence that Devensian ice was marginal to the coast, the ice-margin hypothesis for valley development is less convincing. These valleys differ from those along the south-west coast of the Isle of Wight where cliff retreat has cut across the upper courses of cliff-top valleys. On the western hard-rock coasts, similar beheaded valleys occur, for example at Dinas and Cemaes, north of Fishguard, but these have been explained as ice-marginal overflow channels (Steers, 1946a). The different forms of waterfall described by Arber (1911) add to the unusual nature of this site.

SOLFACH, PEMBROKESHIRE (SM 802 241)

V.J. May

Introduction

The small ria at Solfach (Solva) and its infilled counterpart, the Gwada valley, are the westernmost such features on the south coast of Wales, lying some 5 km east of St David's (see Figure 3.1 for general location). Rias (drowned river valleys) are common features of the coasts of the Bristol Channel, Devon and Cornwall. Many are large landforms such as Milford Haven, Pembrokeshire, and the Fowey River, Cornwall, but many more are small. Solfach is a good small-scale example of a ria. The site includes both the present ria of Solfach Harbour itself and the infilled ria called the 'Gwada Valley'. The proximity of the two features adds interest to the site, which has been little affected by human activity. Slope-over-wall cliff forms surround the present and former rias that have been cut into a near-horizontal surface at an altitude of about 60 m OD. There has been some infilling of the upper reaches of the present ria, whereas the Gwada Valley has been almost entirely infilled by alluvial sediments. Mentioned briefly by Steers (1946a), Solfach was described by Goudie and Gardner (1985).

Description

Solfach Harbour and the Gwada Valley are very good examples of two phases of the development of submerged rocky coastlines. Solfach is a good example of a ria: a former glacial meltwater channel that a subsequently became a river valley that was flooded by rising sea-level during Holocene times. The Gwada Valley is a comparable feature in origin, but sedimentation has filled almost all its length leaving a small bay with a sandy beach at its mouth. Solfach and the

Gwada Valley are cut into a near-horizontal surface (commonly regarded as a former marine erosion surface) at about 60 m OD. From this surface, the land slopes at between 20° and 35° before dropping abruptly into the sea at the seaward end of the valleys. Both valleys are thought to be 'curved' segments of subglacial meltwater channel.

Solfach is flooded at high tide, but gravel, sand and mud are exposed at low tide. These sediments that have been dumped here in a narrowly confined delta will gradually fill in the whole ria just as has happened to the Gwada Valley. In the lower part of the ria, the intertidal forms are more related to marine action as waves penetrate the estuary. Shore platforms of rock occur, particularly on the eastern side.

The Gwada Valley has much the same general form but its valley floor infill is extended almost to its seaward end. Flat-floored with only a small stream across it, this valley has a much-reduced fluvial input compared to Solfach, and its beach is predominantly sandy.

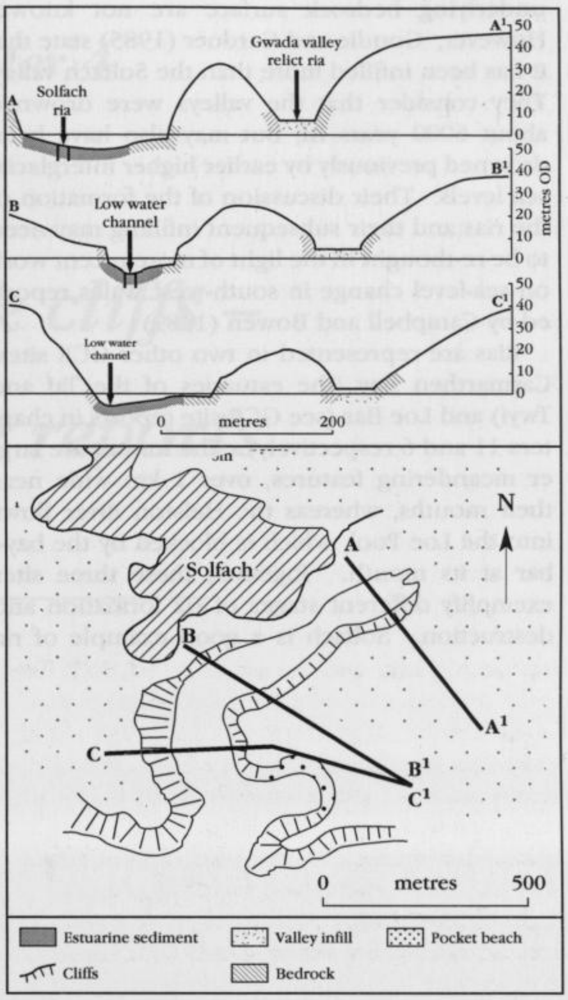

Figure 3.34 Cross profiles of Solfach and the Gwada Valley, showing the contrast between the ria of Solfach and the infilled former ria at Gwada.

Interpretation

The present-day features combine vertical cliffs in hard Cambrian and Ordovician rocks with sedimentation in a small marine delta at the head of Solfach Harbour. Steers (1946a) passes little comment on the site other than to note that it is a good example of a ria. The stream, though capable of carrying fine-grained sediments into the estuary, would require a long time to bring about the substantial erosion that was necessary to carve the steep-sided meandering valley. Similarly, present day marine action does not appear to be especially effective in eroding the shoreline. Several separate phases of development have to be invoked to explain the present assemblage of forms.

The first phase (Figure 3.34) appears to have been predominantly fluvial and produced the gentler upper slopes of the valleys. A second phase (Figure 3.34) then produced the steep sides of the lower valley, which in parts of the estuary extend well below sea level. If this phase was fluvial, it required much larger discharges than occur at present. The development of the forms to below present sea level suggests that they developed during a period of lower sea level, i.e. they derive from a glacial period. Much larger discharges at that time could help explain the incision. Alternatively, changed climatic conditions with higher rainfall and greater runoff during an interglacial could also generate the larger discharges needed. Goudie and Gardiner (1985) have suggested that an alternative explanation may be sought in the erosional vigour of sub-glacial streams that flowed beneath, or issued from, ice-sheets covering south-west Wales. If so, Solfach differs significantly in origin from the rias of southern Cornwall and Devon.

The differential infilling of the two valleys has not been explained. The stream carrying sediment into the Gwada valley appears to have been more active and been able to overcome the sorting and transporting action of the sea. The subsurface sediments and the depth of the underlying bedrock surface are not known. However, Goudie and Gardner (1985) state that it has been infilled more than the Solfach valley. They consider that the valleys were drowned about 6000 years BP, but may also have been drowned previously by earlier higher interglacial sea levels. Their discussion of the formation of the rias and their subsequent infilling may need to be re-thought in the light of more recent work on sea-level change in south-west Wales reported by Campbell and Bowen (1989)

Rias are represented in two other GCR sites, Carmarthen Bay (the estuaries of the Taf and Twyi) and Loe Bar (see GCR site reports in chapters 11 and 6 respectively). The former are larger meandering features, over 1 km wide near their mouths, whereas the Helston River flows into the Loe Pool, which is blocked by the bay–bar at its mouth. Together, these three sites exemplify different stages of ria formation and destruction. Solfach is a good example of ria development, but questions have been raised about its origins. The extent to which fluvial processes were associated with sub-glacial streams remains open to conjecture, nevertheless Solfach may represent a ria form that combines the effects of both glacial and fluvial environments. If so, it is a rare feature in Britain, and probably in Europe.

Conclusions

A small ria and its infilled neighbour form the site. Solfach and the Gwada Valley provide a distinct contrast in the development of coastal landforms, both being drowned water-worn valleys, but the Gwada Valley has been infilled in contrast to the tidal Solfach. Solfach is a distinctive example of a ria, not least because of the combined effects of glacial and fluvial processes in its formation.