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The role of sediment supply and sea-level changes on a submerging coast, past changes and future management implications.

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Abstract

Climate change is arguably one of the greatest threats that the World's population faces in the twenty first century. At the coast, which has been preferentially developed through history, sea level rise and storminess are components of climate change which will be increasingly hard felt in the coming decades. Also key to the control of the behaviour of soft coastlines is sediment supply since if it is plentiful, the effects of relative sea level rise can be minimised or reversed. Conversely, if sediment supply is limited, soft coastlines will retreat as inland sediment stores are consumed. The interaction of *sea level change*, storminess and *sediment supply* co-control the behaviour of coastal landforms during periods of submergence, albeit within the context of the underlying geological framework

To investigate the interaction of these three factors, a suite of coastal landforms has been identified which have undergone submergence, have reflected the changes within their geomorphology and have preserved the geomorphic record during the submergence. It is also important that the landforms have not been affected by human interference. The eastern coast of Sanday (Orkney Isles) has a suite of relict and active landforms that reflects the interaction of relative sea level rise and sediment supply variations, on an undulating geological surface. For this reason Sanday has been used as a test-site to investigate the interactions of these controlling factors.

Geomorphological, geophysical, archaeological and documentary investigations have been employed to establish the variation of sea level change, sediment supply and geological control from the Late-Holocene, through the Historical period to the Present day, in Sanday. Techniques such as Ground-Penetrating Radar and geomorphological surveying have identified a suite of gravel ridge recurves and placed them within their geomorphological context. The provisional regional sea level curve has been updated and clarified following the discovery and successful dating of a submerged forest. This sea level curve was then used to constrain the development of the coast of Sanday into separate time periods. A range of

archaeological and historical evidence also informed and corroborated the geomorphological evidence to allow the island's coastal development to be established over the last few thousand years towards the present day, where differential-GPS and sonar techniques allowed these long-term trends to be placed into their modern context. These Late-Holocene, Historical and Present day investigations have established that island-building occurred during Holocene submergence along with other radical changes to the shape and form of the coastline, all reflecting the changing dominance between the three controlling factors. The accepted outcome of submergence is transgression and fragmentation of islands rather than island building and this is wholly a result of a healthy sediment supply at the early stages. However, this sediment source has since begun to diminish and fragmentation, erosion and transgression may well be the outcome of the present trends in Sanday. This coastal change scenario has been projected forward, using climate change scenarios, to raise significant questions not only for Sanday and those regions which have historically experienced submergence, but also for those areas which previously experienced emergence and more recently are starting to be affected by relative sea level rise. The geomophological situation that such coasts now experience have important implications for the management of the coastal asset both now and in the future.

Declaration

Except where specific reference is made to other sources, the work presented here in this thesis is the original work of the author. It has not been submitted, in part or in whole, for any other degree.

Alistair F Rennie

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The GPR used in this investigation was loaned from the Natural Environmental Research Centre, geophysical equipment pool (NERC - GEP) in Edinburgh. Two applications were made (Loan 690&791), the first for a pilot study to test the suitability of the equipment and a second to more completely account for the distribution and internal architecture of the gravel ridges.

1 Introduction

1.1 Introduction and justification of investigation - Why look at sea level change and sediment supply?

Much of the World's population is located at or near the coast, and given the present and expected rises in global sea level (Figure 1.1), conflict between natural processes and human land-use is never far away. At a British level the pattern of coastal behaviour cannot wholly be attributed to relative sea level rise (Figure 1.2), therefore other factors must be responsible for the varied pattern of coastal change currently being experienced. Coastal sediment supply, changes in wave height and patterns in storminess, may play a part in the present behaviour of our soft shorelines, they are also likely be the key to their future management.

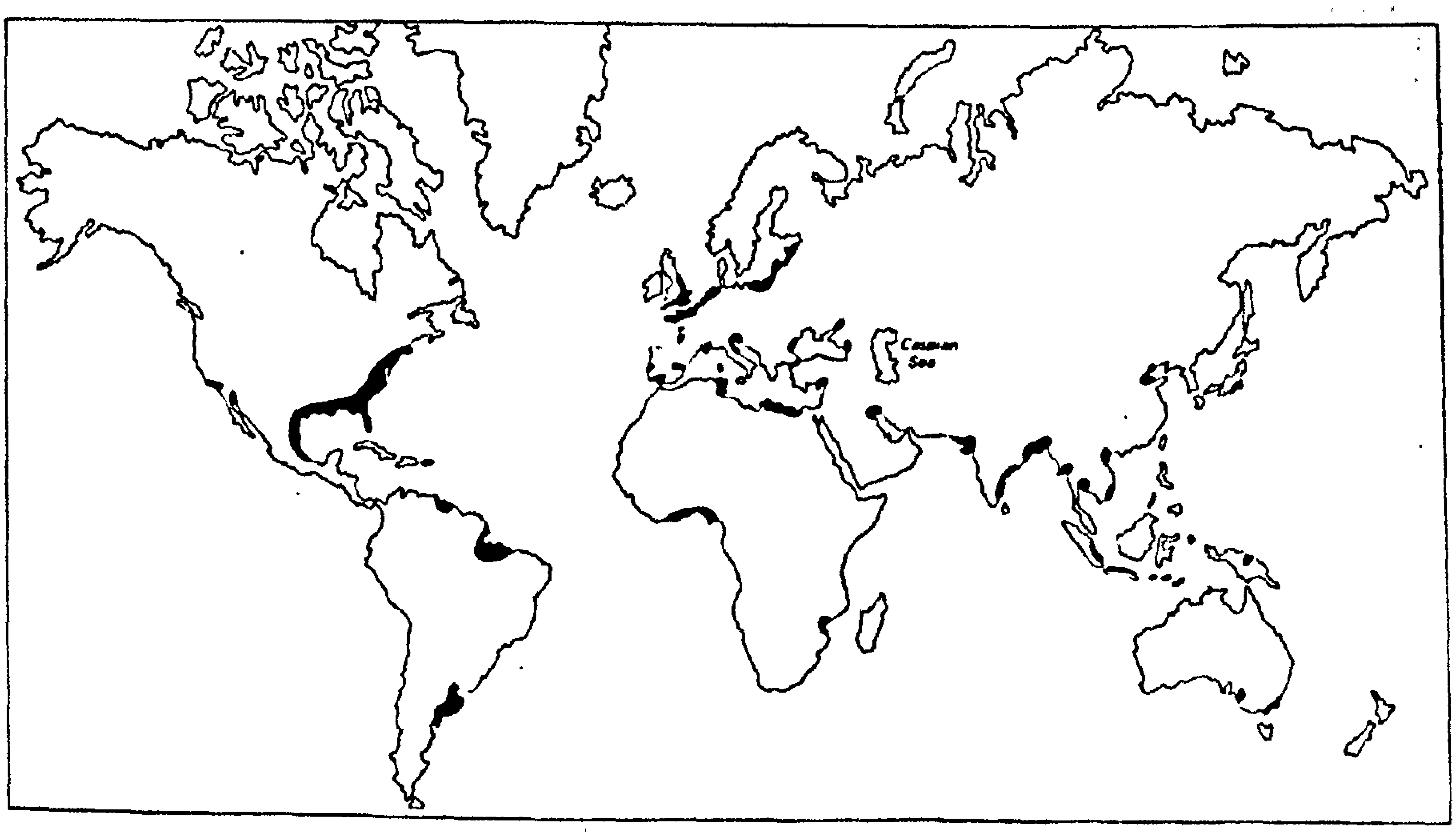


Figure 1.1 Areas of the world's coastline experiencing relative sea level rise (shaded stretches of coast). Bird (1993)

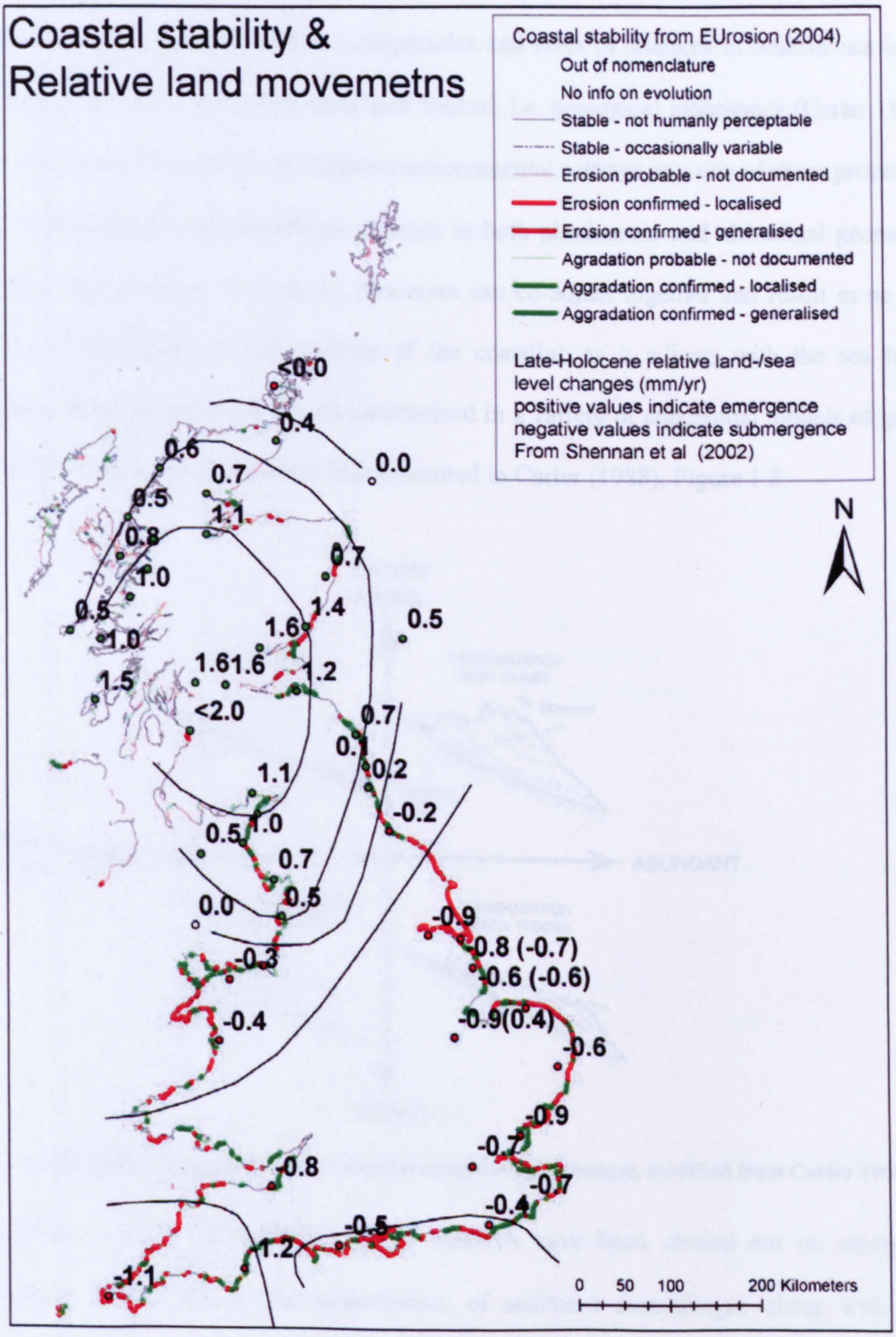


Figure 1.2 The behaviour of Britain's coastline (EUrosion 2004) superimposed on the present rates of relative sea level change (Shennan 2002) where positive values indicate Late-Holocene emergence and negative values indicate Late-Holocene submergence.

It is widely accepted that the large spatial and temporal scale behaviour of soft coasts depends upon the balance between magnitudes and rates of changes in relative sea level and sediment supply along with basement control, i.e. geological inheritance (Carter 1994, van der Molen, Bird 1988,). In different environmental settings any one of these processes can dominate producing significant changes to both planimetric and altitudinal geometry and shoreline position. Conversely, processes can co-adjust together and result in no net change in the geometry and position of the coastline as it adjusts with the sea level changes. These balances have been summarised in a variety of conceptual models of gross shoreline changes, exemplified by that presented in Carter (1988), Figure 1.3.

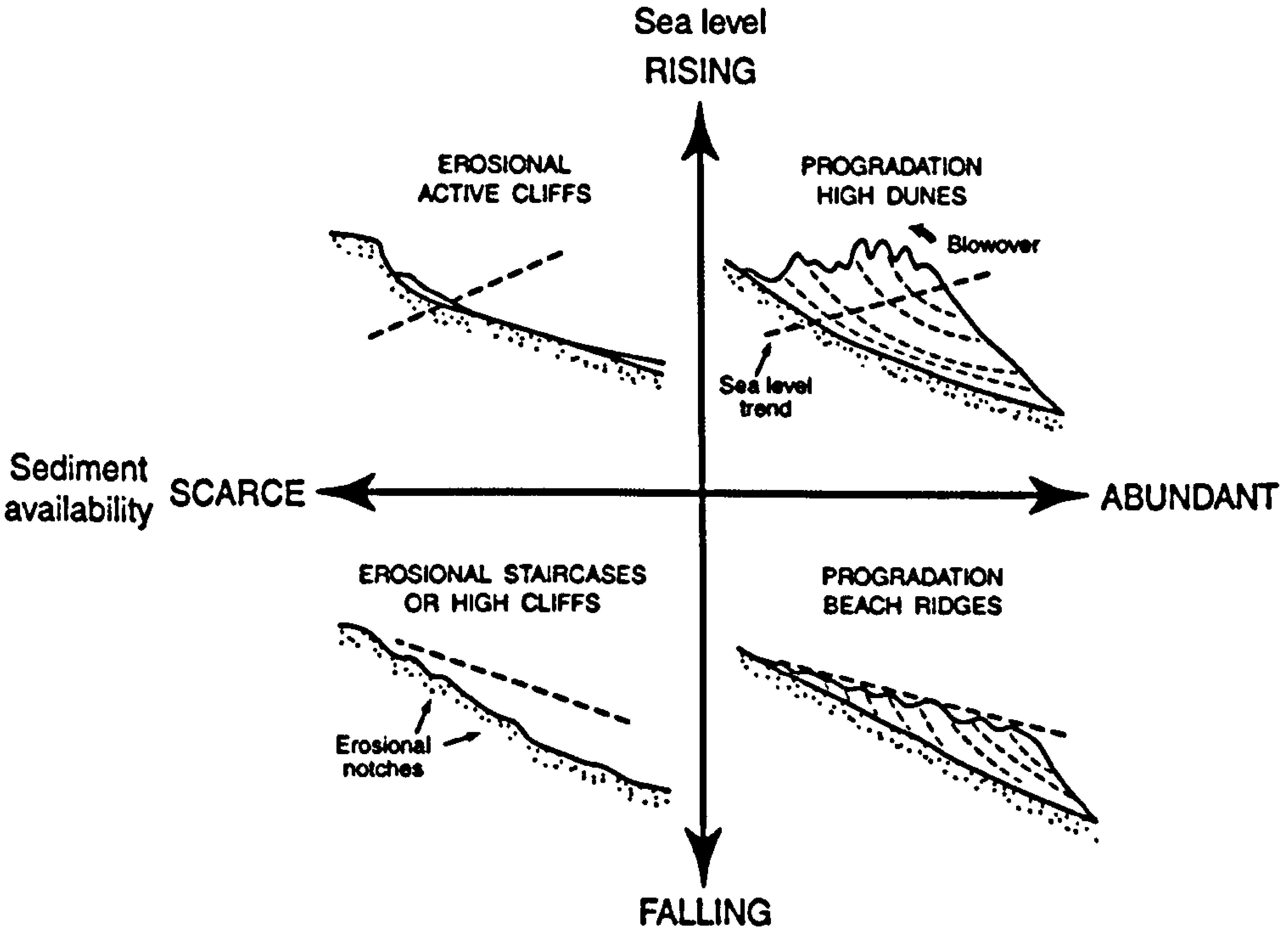


Figure 1.3 Coastline responses to sea level and sediment supply changes, modified from Carter 1988.

Substantial amounts of coastal evolution research have been carried out on emergent shorelines, mainly due to the preservation of sediment assemblages along with the information they contain. Much of the World is experiencing relative sea level rise and there is increasing concern about the implications of accelerations in the rate of sea level rise and any associated changes to sediment supply. In the Scottish context, much of the interest has been focused on emergent shorelines benefiting from isostatic readjustment contributions towards the centre of the country. However, since decreasing isostatic uplift through time is currently being progressively outpaced by sea level rise (Dawson *et al* 2000, Graph 1998) the areal extent of submergence across both Scotland and the rest of the UK is increasing (Figure 1.4). This has significant implications for coastal populations, infrastructure, land-use, our environment and many other interests.

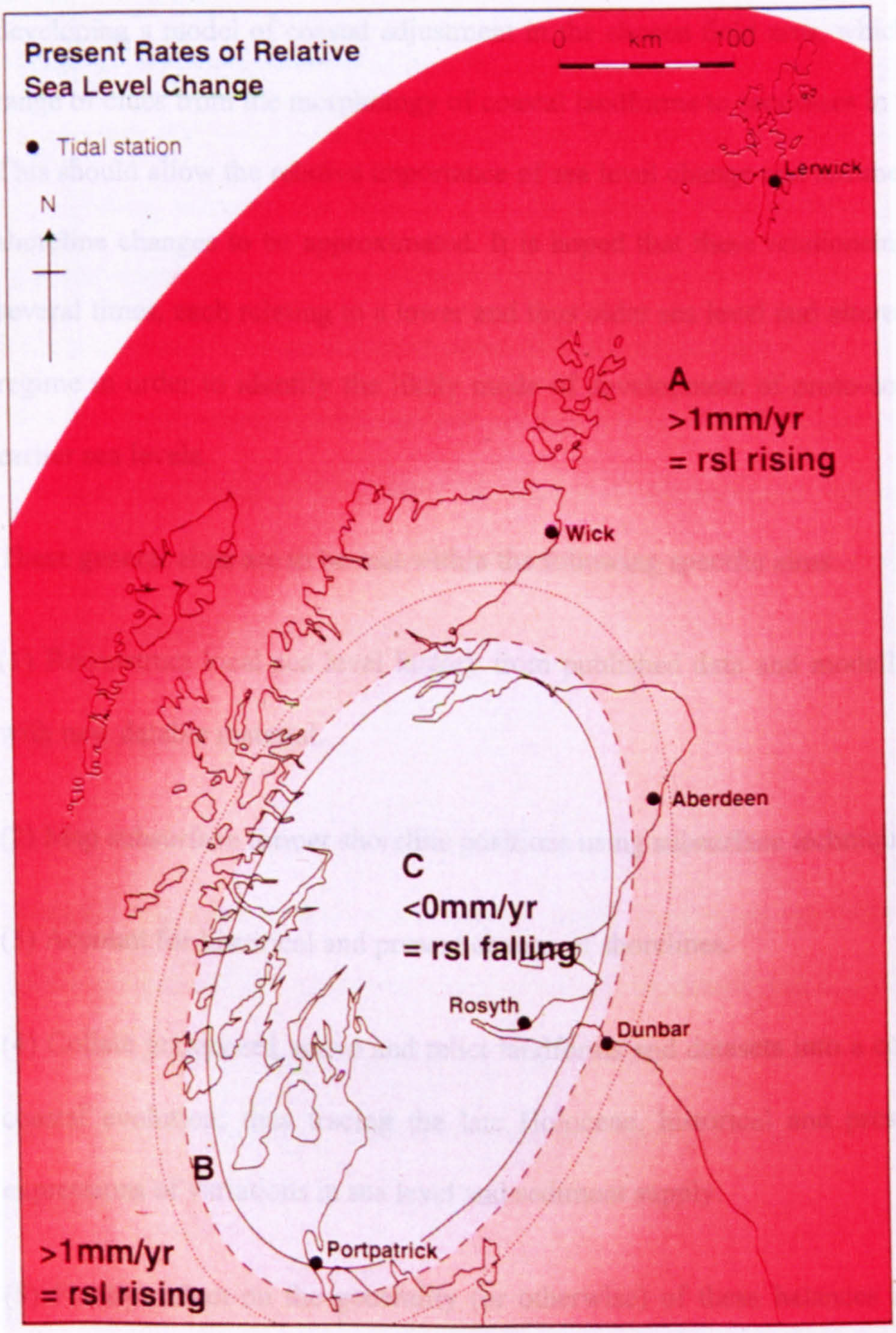


Figure 1.4 Generalised present sea level trends in the UK, after Dawson *et al* (2001).

1.2 Aims of the research

This project aims to establish shoreline response to changes in sediment supply and coastal submergence as a result of sea level rise. From the shape, size and orientation of existing coastal landforms in an area of Holocene coastal submergence, field data will be gathered to help clarify the main drivers behind this adjustment. This will provide the basis for developing a model of coastal adjustment in the chosen field area, which will interpret as range of clues from the morphology of coastal landforms to processes in the offshore zone. This should allow the relative importance of sea level change and sediment supply to these shoreline changes to be approximated. It is hoped that these relationships can be iterated several times, each relating to a lower and thus older sea level and altered sediment supply regime in order to identify the likely mode of development of proto-coastal landforms at earlier sea levels.

These general aims are to be met within the following specific aims:

(1) Reconstruct local sea level history from published data and modelling, supplemented with new datable material.

(2) Map subsurface former shoreline positions using subsurface techniques.

(3) Account for historical and present change of shorelines.

(4) Collate juxtaposed active and relict landforms and datasets into a conceptual model of coastal evolution; thus tracing the late Holocene, historical and present morphological expressions of variations in sea level and sediment supply.

(5) Finally reflect on the generality (or otherwise) of these balances and outcomes, and outline the main management implications.

1.3 Selection of field site

Given the aims of the research a field site was needed which was located in an area outwith the region of isostatic recovery and subject to more or less continuous submergence throughout the Holocene. The site must also contain a wide variety of landform evidence including geomorphic, vegetation/climatic and archaeological.

Mainland Scotland is dominated by a region of glaci-isostatic uplift (Figure 1.4), but much of the north and west coast including i.e. the Western and Northern Isles of Scotland[1] is experiencing submergence (Figure 1.4). In addition, since anthropogenic effects have modified much of the United Kingdom coast, the signal of natural coastal changes has become muted. However, the outer coast of Scotland, including the Western and Northern Isles are largely unmodified by human activity and thus fill the requirements of this study. The island of Sanday in the Orkney Islands has all the attributes required for this study: it is located on a submerging shoreline, contains a variety of coastal accretional units and is largely unmodified from human activity.

1.4 Outline of thesis

This thesis aims to investigate the coastal development of the field site by evaluating the changing role that sea level and sediment supply has had on the Holocene evolution of a submerging shoreline. Historical changes will be examined and related to changes in sea level and sediment supply over the last few hundred years. Modern-day processes will be established by assessing beach and nearshore profile changes over the three years of research.

[1] The Northern and Western Isles of Scotland, the north eastern tip of the Scottish mainland and the south west (Dumfries and Galloway) were located towards the periphery of the last ice sheet. These areas are referred in the remainder of the thesis as 'peripheral areas'.

These aims will be achieved by geomorphological, geophysical, archaeological and historical investigations and collated into a conceptual model of shoreline evolution, tracing the changes between the major driving mechanisms of sea level and sediment supply. This provides an understanding of the dominant processes and their changes throughout the Late Holocene, over the last few hundred years and presently. These changes implicate shoreline position, sediment budget, health, and wider environmental effects and so are essential for sustainable management of the area in the future.

1.5 Summary

This investigation aims to establish the interrelationship between sediment supply and rises in sea level on a submerging shoreline, (1) through the late Holocene, (2) through historical periods and (3) at the present time.

To achieve this:

- Chapter 1 has established the context within which the project lies, the approach to be taken and the structure of the thesis.
- Chapter 2 provides the literature and background to the study, introducing the concepts, reporting what is known and what is yet to be established.
- Chapter 3 outlines the methods undertaken to achieve the aims stated in Chapter 1.
- Chapter 4 reports the results of investigations undertaken. Outlining the changes in coastal configuration and form during the Late Holocene, historical times and to the Present-day.
- Chapter 5 discusses the implications of the results, with specific relevance to the literature.

- Chapter 6 outlines the management implications for submerging shorelines.

- Chapter 7 assimilates the research conclusions.

- Chapter 8 appraises the approaches undertaken, discusses what would be done differently if the project were repeated and highlights future research directions.

2 Coastal responses to submergence – a context

2.1 Introduction

This investigation sets out to understand changes to beaches that have been affected by submergence and varying sediment supply through time. It is necessary to understand the mechanisms and interactions of rising sea levels and varying rates of coastal sediment supply and the responses of the coast to these changes. This chapter will report relevant literature relating to these driving mechanisms and their geomorphological consequences, summarising current understanding and highlighting gaps that remain to be addressed.

Coastal evolution is driven by morphodynamics as a result of changes in conditions of controlling factors. Wright and Thom (1977) defined morphodynamics as the mutual adjustment of topography and fluid dynamics via sediment transport. Positive and negative feedbacks are common on the coastal zone introducing levels of complexity, which can be investigated using non-linear dynamics and chaos theory. However, the identification of mutual adjustment needs some sort of ground truthing and this information can be located in remnants of surface and buried landforms that reflect the balance of adjustment at different times of deposition. This investigation chooses to concentrate on this second level of behaviour in order to define the overall role of the main driving mechanisms. Thus from the catalogue of active and relict geomorphic landforms present, previous changes can be hypothesised. This investigation sets out to scale-up above the noise of morphodynamics, to identify the net changes within the landscape (and their driving mechanisms, namely sediment supply and sea level) for the modern day and place any identified trends within their historical and palaeo-context.

2.2 Sea level changes

2.2.1 Sea level changes ~ an introduction

Many factors affect sea level over various orders of magnitude of both space and time, ranging from edge waves (lasting for a few minutes and operating over a few tens of metres) to glacial cycles and crustal movements operating over large (10^3 km) spatial and temporal scales (10^3 yrs). The range of factors affecting sea level in space and time has been summarised by Pugh (2004) and is presented in Figure 2.1.

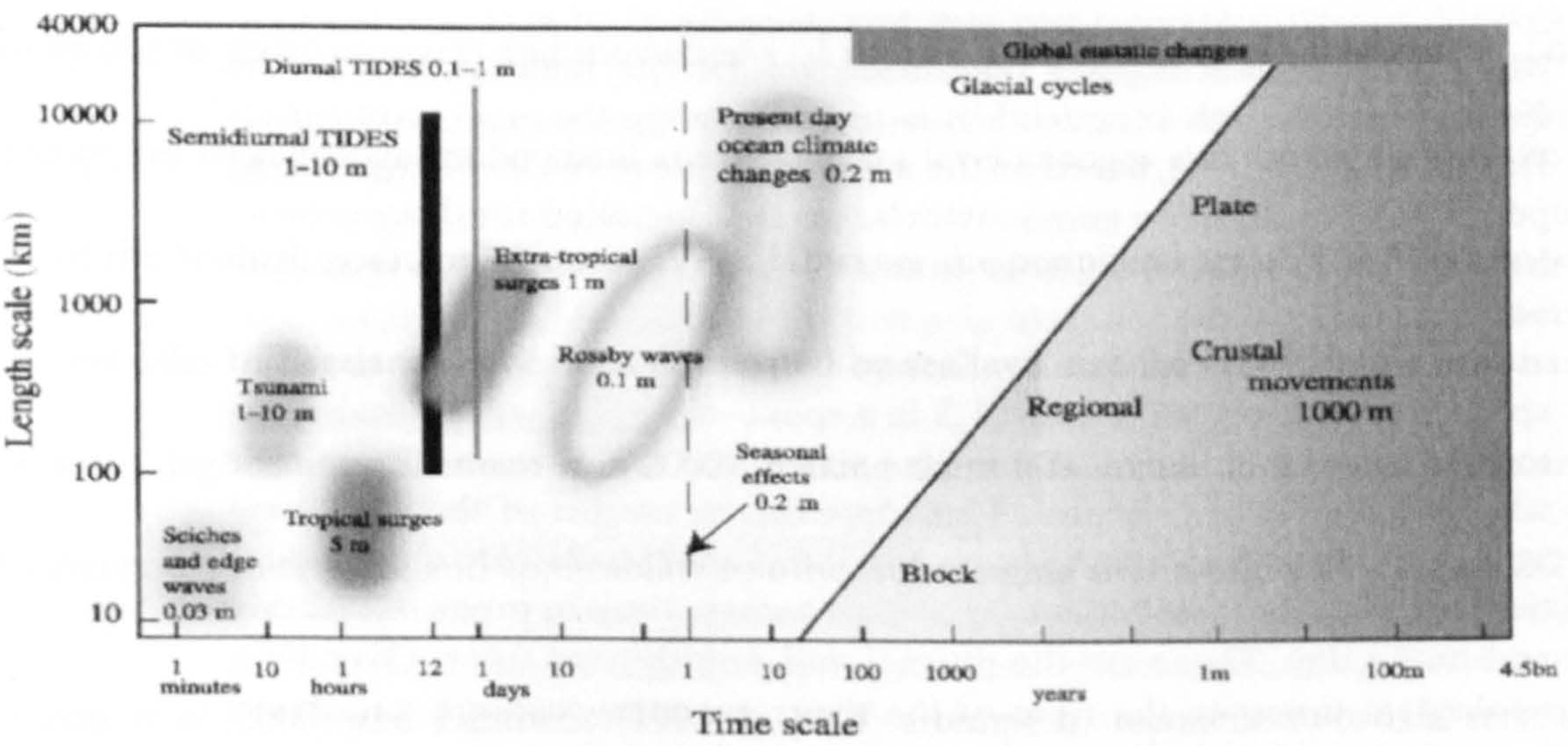


Figure 2.1 Factors that change sea level in space and time (Pugh 2004).

The scale of the present investigation focuses on the medium scale factors, namely the mechanisms of glacio-isostasy, glacio-eustasy and rheological factors and their impacts on the evolution of a submerging shoreline.

2.2.2 Sea level change over the Holocene

The glacial melting at the end of the Devensian glaciation contributed over 100m of eustatic sea level rise (sea level changes driven by adjustments to the volume of the worlds oceans), Gordon (1997). In addition, in areas that were previously covered and depressed by ice sheets, the land rose in response to the removal of the overburden (isostatic recovery), as well as local crustal rheology (elastic properties of the earth). Eustatic sea level rise and isostatic recovery occur more or less simultaneously, however the latter responds more slowly and proportionally to the weight of overburdening ice. This can result in a varied spatial and temporal pattern of both transgression in areas of relative sea level rise and regression in areas of relative sea level fall.

Lambeck (1993, 1995) and Shennan *et al* (2002) emphasise the utility of the British Isles in investigations into crustal loading and unloading and the coastal response to these changes. Smith goes further stating: "fundamental to an understanding of sea level changes and coastal responses in Scotland is the nature of the complex interplay between movements of the land (mainly due to glacio-isostacy) and movements of the sea (mainly due to glacio-eustacy). Thus in reality, sea level changes in Scotland are relative sea level changes and are highly specific to parts of the Scottish coastline" (Smith, 1997). However the peripheral areas (The Western and Northern Isles of Scotland) have been dominated by sea level rise for considerable lengths of time since deglaciation (Shennan *et al* 2002), making them less unique in a global sense and, thus increasing their value and applicability to other submerging sites world wide (Figure 2.2).

Shennan *et al* (2002) and Lambeck (1993 & 1995) attempt to reconcile two data sets: the physical evidence of former sea levels distributed across the region and an understanding of the rheological characteristics of the Earths' crust and its responses to loading and un-loading of glacial ice. Lambeck utilised the spatial distribution of all available data sets to constrain his models, where as Shennan has used more detailed coring studies, such as marine and freshwater sediments within isolation basins, to track detailed changes in relative sea level. Shennan *et al* (2002) considers the suitability of Britain to Glacial Isostatic Adjustment (GIA) investigations to be favoured by the availability of a large amount of data in temporal and spatial scales and the fact that the British ice sheet was small enough to produce radically different relative sea level changes across Britain. The balance between a relatively small ice sheet and the shallow Earth structure contrasts with that of the much larger scale

Fennoscandian and Laurentide ice sheets, where relative sea level changes are more sensitive to the deeper earth structure.

Since the mid 1990's the accuracy of GIA models has increased significantly and they are now capable of approximating general spatial and temporal patterns of sea level changes (Shennan *et al* 2002, Lambeck 1995). However, significant disagreements remain between GIA models. Current analyses are Lambeck (1995) and Shennan *et al* (2002) which, provide very good fits for the general patterns of relative sea level change between areas under the thickest ice at the Late Glacial Maximum (LGM) to those beyond the LGM limits, but none of these model solutions give predictions that agree with relative sea level observations at all sites. These variations are associated with different viscosity profiles and melt water contributions from far-field ice sheets used in the different GIA models. Further comparisons between these models are made in Section 5.1.1.

GIA models produce three behavioural zones: namely areas which have undergone submergence over the Holocene (in Scotland mainly located in the peripheries of the north and west), those areas which are isostatically stable over the Holocene (located close to the zero-isobase line, Figure 2.2 and those areas which have experienced emergence (located in mainland Scotland). Figure 2.2 (Shennan 2002) documents the modelled sea level curves across Scotland and the data which constrain the model. The trends in Shetland, Orkney and the northern mainland (Wick) show continual submergence for the last 10,000 years, relating to their peripheral location. Montrose shows +/- 5m fluctuations around current sea levels with isostatic recovery and eustatic sea level rise, generally in balance. Site 17 near Stirling, located towards the centre of the ice mass, has emerged as isostatic recovery has dominated, resulting in the emerged estuarine flats, known as carse, now currently well inland.

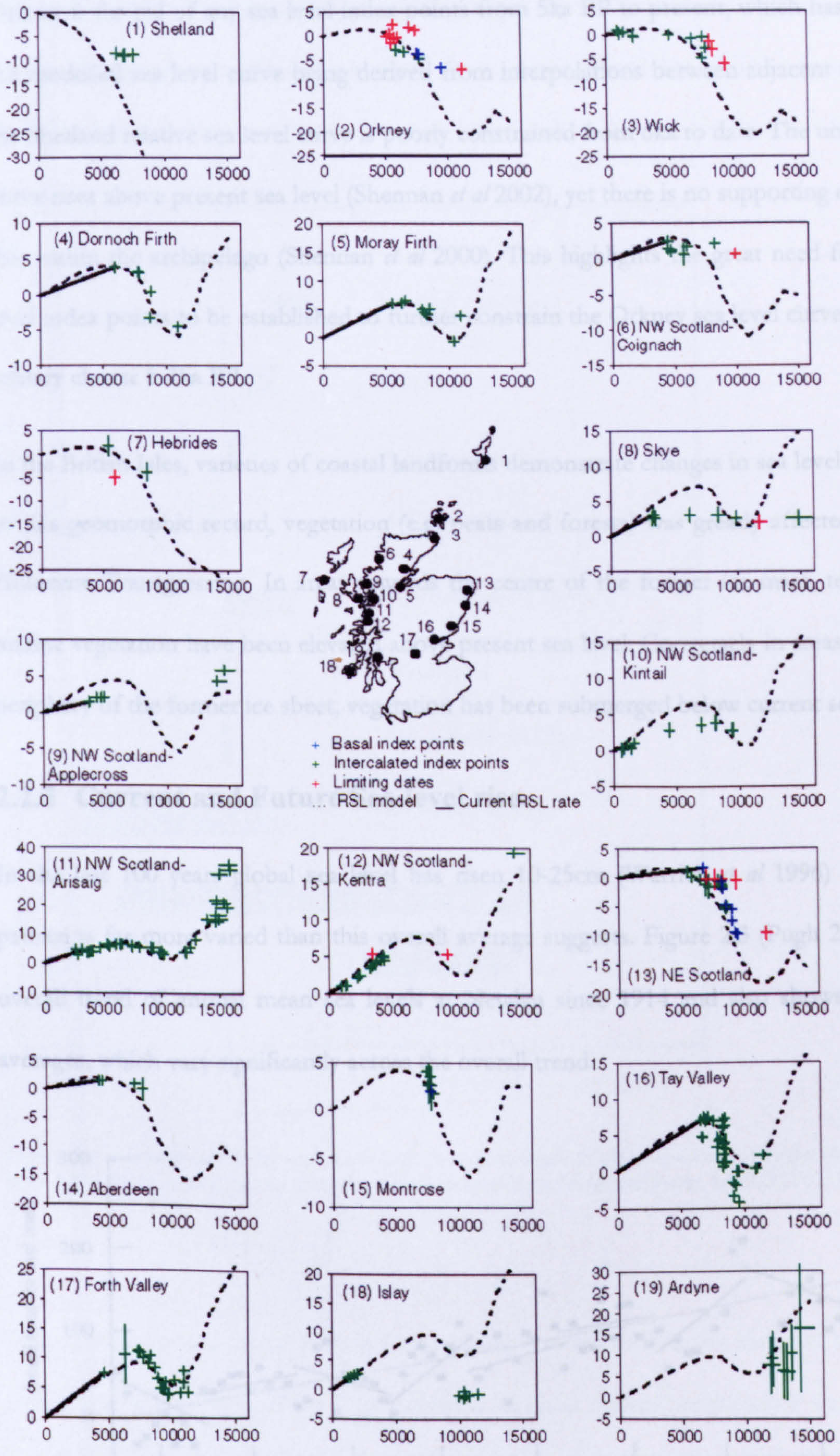


Figure 2.2 Sea level curves across Scotland (Shennan *et al* 2002) and the constraining data points.

Orkney is devoid of any sea level index points from 5ka BP to present, which has resulted in the modelled sea level curve being derived from interpolations between adjacent regions and the Shetland relative sea level curve is poorly constrained from 6ka to date. The unconstrained curve rises above present sea level (Shennan *et al* 2002), yet there is no supporting evidence for this within the archipelago (Shennan *et al* 2000). This highlights the great need for more sea level index points to be established to further constrain the Orkney sea level curve beyond the solitary cluster 5-7ka BP.

In the British Isles, varieties of coastal landforms demonstrate changes in sea level. In addition to this geomorphic record, vegetation (e.g. peats and forests) was greatly affected during the Holocene Transgression. In areas towards the centre of the former ice mass, terrestrial and marine vegetation have been elevated above present sea level. Conversely in areas towards the periphery of the former ice sheet, vegetation has been submerged below current sea level.

2.2.3 Current and Future Sea level rise

In the last 100 years global sea level has risen 10-25cm (Warrick *et al* 1996) however the pattern is far more varied than this overall average suggests. Figure 2.3 (Pugh 2004) displays overall trend of annual mean sea levels at Newlyn since 1914 and also shows the 10 year averages, which vary significantly across the overall trend.

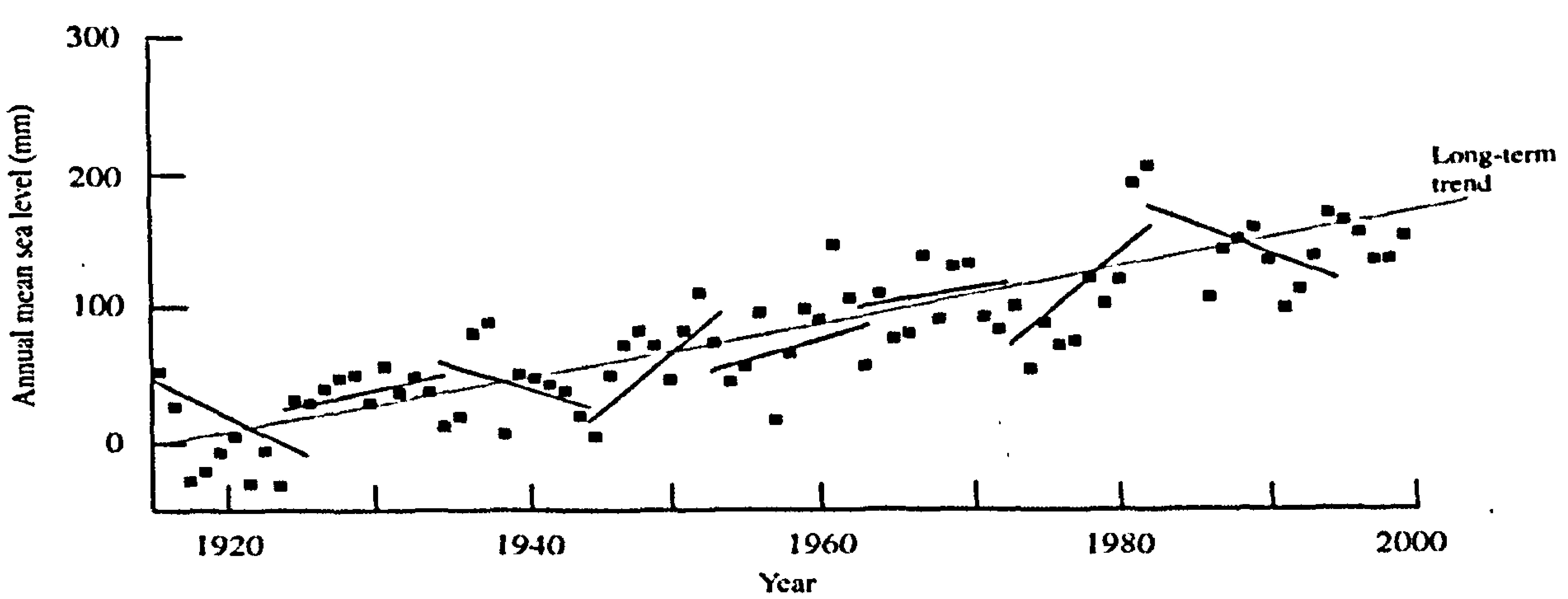


Figure 2.3 Annual Mean Sea Levels at Newlyn over 85 years, with an arbitrary 10 year averages and overall average trend. (Pugh 2004)

This noise within the data indicates the complexity of the system and highlights our partial understanding of the different contributions to the levels of the global ocean. The main contributions and their uncertainty (shown by the width of the bar) are shown in Figure 2.4.

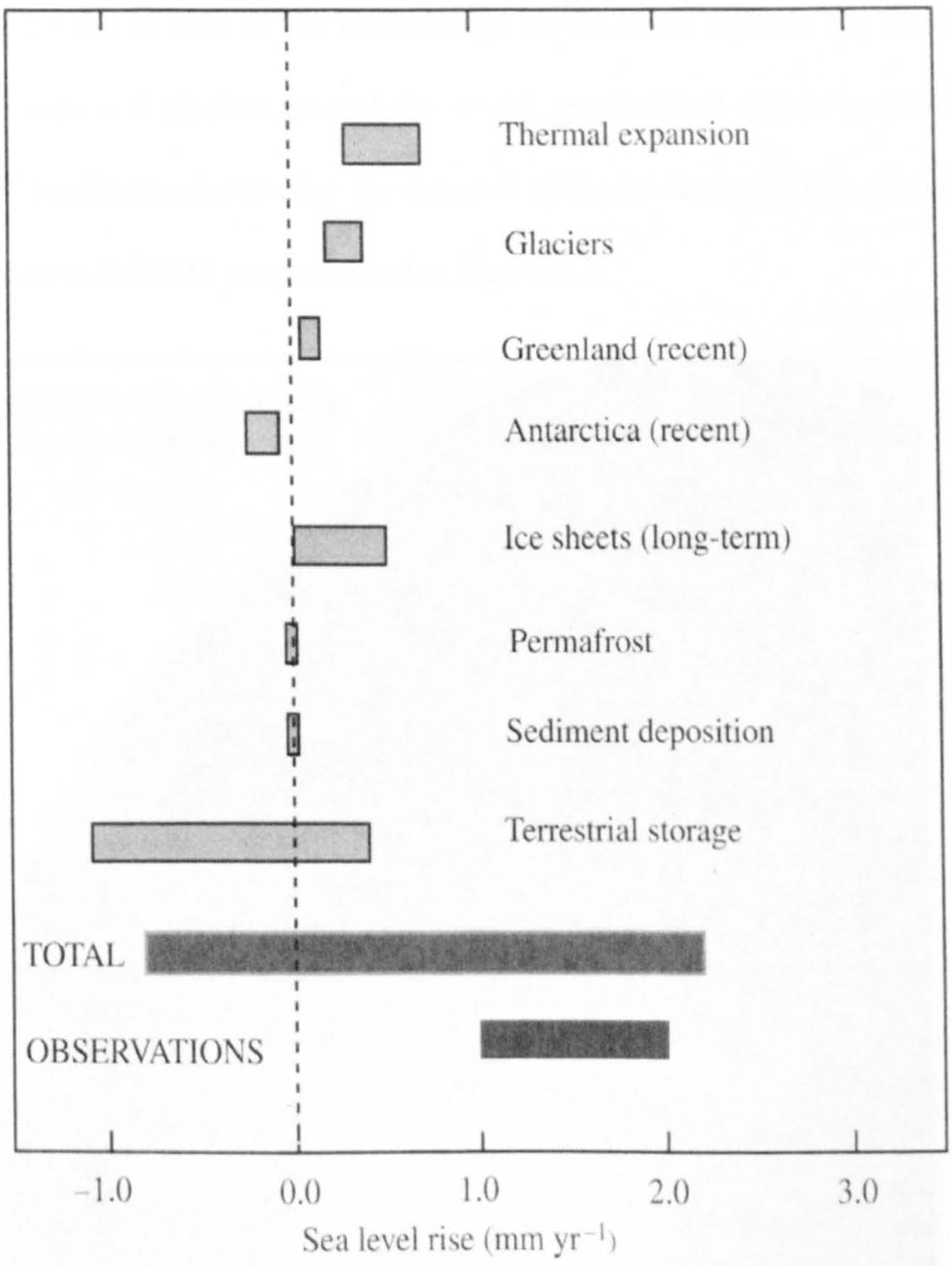


Figure 2.4 A summary of the various effects that contribute to mean sea level changes in the period 1910-1990. Note widths of the bars show the uncertainty of each estimate. IPCC (2001) in Pugh 2004

The most important factor driving future changes to sea level is the status of the Greenland and Antarctic ice-sheets. If the East Antarctic ice-sheet melted completely it would contribute up to +60m to global sea level, but this is very unlikely as it is land-based, at altitude and maintains a mean annual temperature of -55°C (Hansom and Gordon 1998). The West Antarctic ice-sheet however is less stable as it is floating in parts and is pinned in several places below sea level. If it melted it would contribute +6m to global sea level. The total melting of the Greenland ice-sheet, in comparison, would contribute +6m to global sea level.

Dawson *et al* (2001) concluded that the role of thermal expansion may have negligible impacts on the future rates of sea level change for Scotland and the key factors are melting ice-sheets, ice caps and glaciers around the world, gravitational effects and isostatic adjustment, as the UK landmass relaxes after the removal of the ice from the last glaciation. Best estimates of sea levels in 2050AD are presented in Figure 2.5.

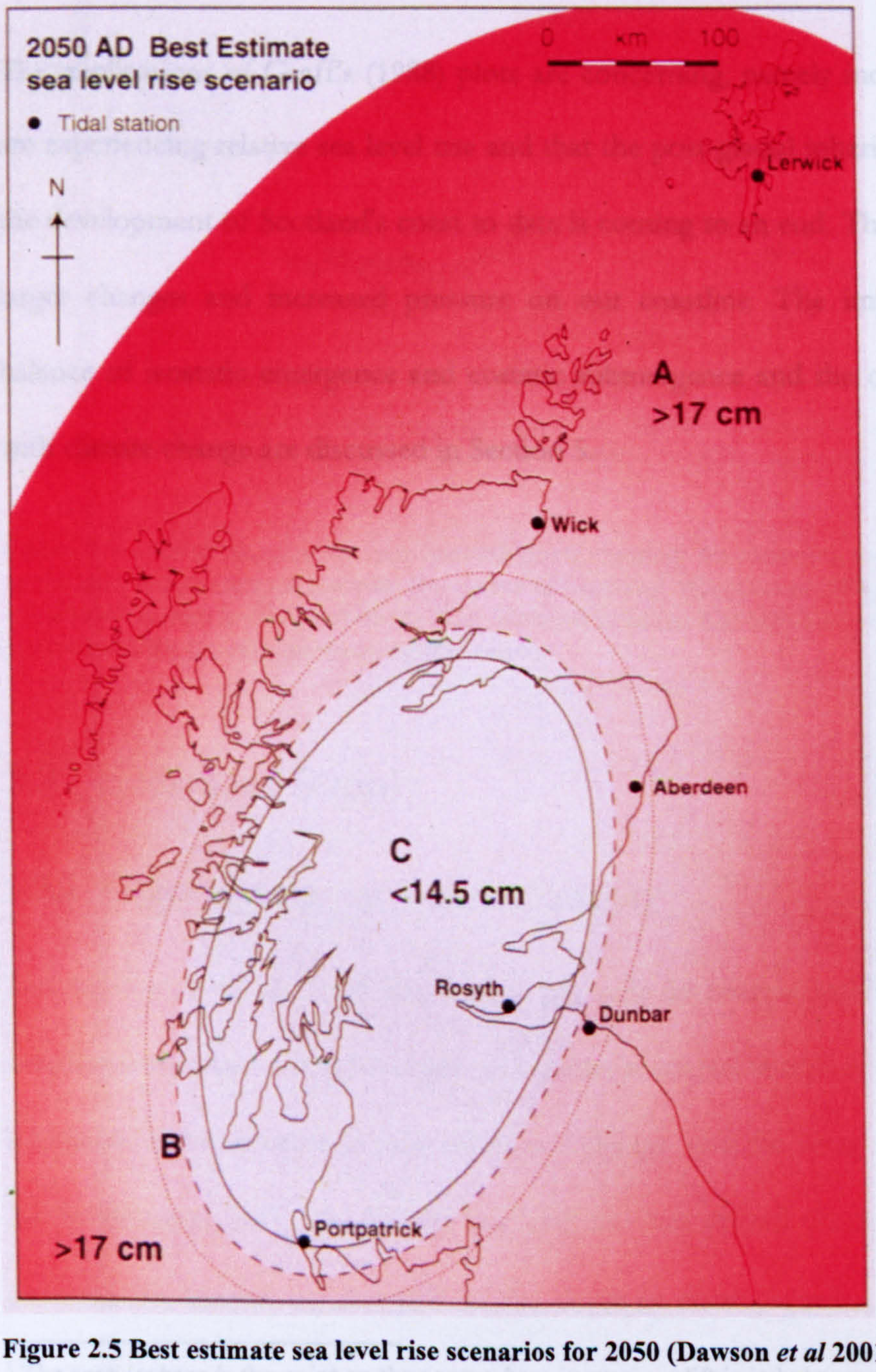


Figure 2.5 Best estimate sea level rise scenarios for 2050 (Dawson *et al* 2001)

The underlying trend behind Figure 2.5 is that central Scotland continues to benefit from the isostatic emergence, limiting to some extent the full impact of Eustatic sea level rise. However the area benefiting from isostatic inheritance is reducing with time as the eustatic component becomes increasingly important. The Dawson *et al* (2001) position seems to be corroborated by data from tidal recording stations within the Firth of Forth (Graff *et al* 1998, Figure 2.6). These plots show the annual maximum tide at four ports since the 1960s and suggest that the transition from emergence to submergence has already occurred, as the zero-isobase[1] passes the gauging station as it moves up firth towards the position of the former ice cap.

The implications of Graff's (1988) plots are concerning, namely increasing areas of Scotland are experiencing relative sea level rise and that the post-glacial inheritance which has favoured the development of Scotland's coast to date is coming to an end. The coming decades will see larger changes and increased pressure on our coastline. The implications of the varying balance of isostatic emergence and eustatic submergence and the other processes associated with climate change are discussed in Section 5.

[1] The zero-isobase is the point on the coast where isostatic uplift is in balance with eustatic sea level rise, i.e. sea levels are not changing.

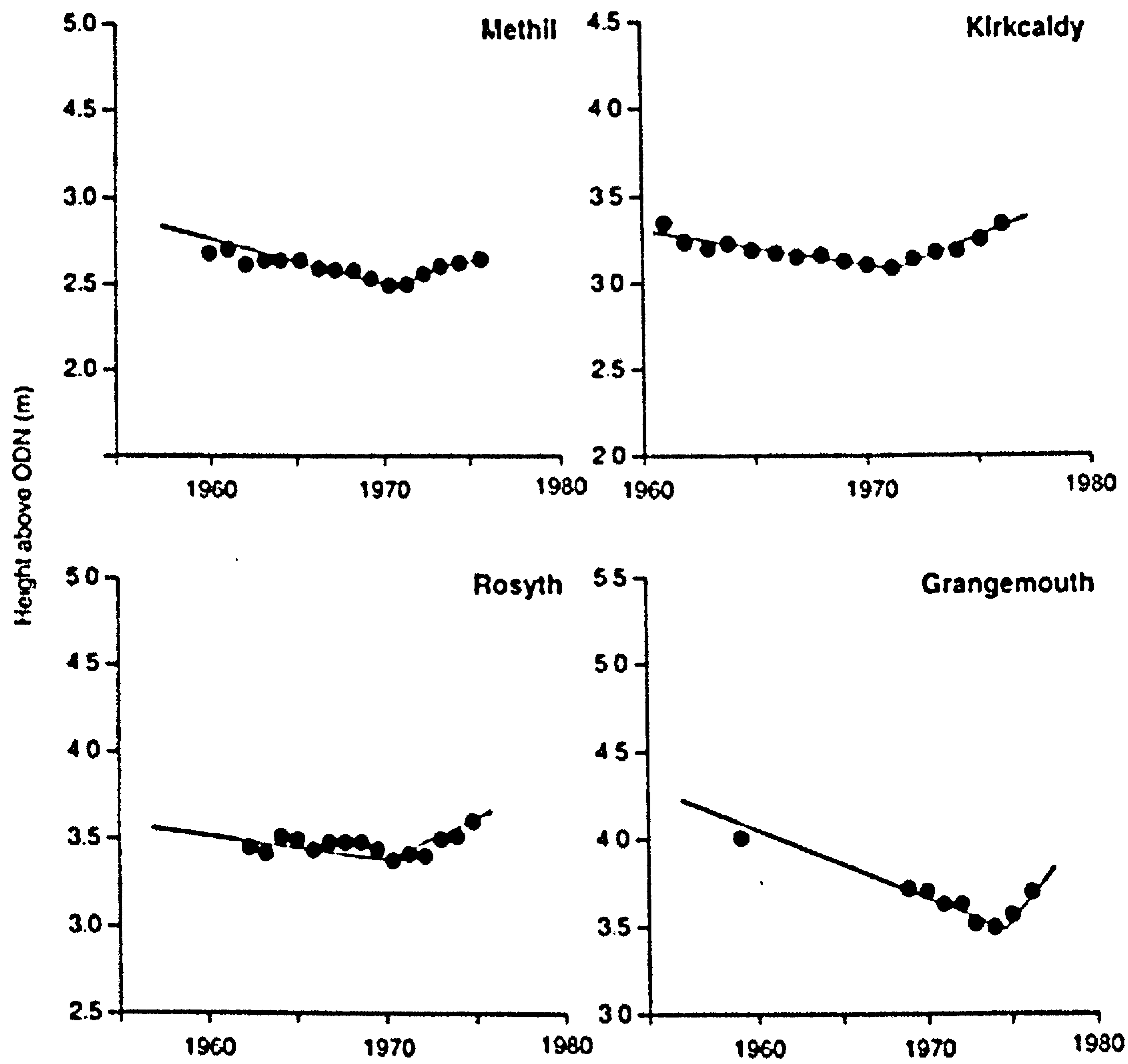


Figure 2.6 – Tidal maxima for four Scottish ports showing the changing sense of relative sea level rise, as the zero isobase moves towards the centre of Scotland. (Graff *et al* 1998). Up to 6m of mining subsidence has been observed in the East Wemyss area (nr Methill) however the pattern above is consistent with the interpretation given above.

2.3 Sediment Supply

2.3.1 General notes on sediment supply

The rapid rate of sea level rise during the early Holocene, resulted in the coastline being simply transgressed and submerged with minimal coastal modification, rather allowing coastal sediments and landforms to fully adjust and change with the rising sea levels (May & Hansom 2003). However, by 6.5 ka BP the sea level rise had slowed (Firth *et al* 1995), allowing wave processes to operate on one part of the shore to allow shoreface modification, rather than drowning.

In reality, sediment supply and sea level are intimately linked, not only controlling the sourcing of material, its eventual deposition, but the position and form that the deposition takes place. Sediment supply is a key control of coastal behaviour (i.e. a factor which greatly affects the position, health and continued presence of soft coastlines, Figure 1.2). The interaction of sea level (discussed previously) and sediment supply over the Holocene has produced a great variety of coastal assemblages. This section will outline the role of sediment supply over the Holocene.

At large spatial and temporal scales sediment supply is delivered by glaciers or ice sheets, large river systems or other reworked marine sediments which have become available due to relative sea level changes. Within Scotland the inheritance of Quaternary processes and sediments has had a strong influence on landscape development. The prevailing westerly weather systems within northern latitudes ensured that the Devensian glaciation, like those which came before it, was more erosional in the west, due to maritime influences, which produced the fiord-like coastline of the west coast (Figure 2.7). By contrast the east coast whose Devensian continental climate resulted little in erosion created a landscape fashioned by deposition and in some cases (like Aberdeenshire) little modification (Hansom & McGlashen 2004). This inheritance still affects the modern day coastal sediment pathways (Gordon 1997). Within Northwest Europe the main control over sediment delivery during the Quaternary was the Scottish and Irish Ice Sheet (SIIC) and the Scandinavian Ice sheets. Generally, sediment supply is dependant on two issues, namely the availability of sediments and the presence of delivery mechanisms. The following diagram (Figure 2.8) highlights the source, deposition areas and transport pathways of sediment around UK waters.

Figure 2.7 – Tends in erosion and deposition across Scotland reflecting the different ice sheet characteristics during the last ice age (Gordon 1997)

The implications of geological control, the position of repeated glacial erosion and deposits and the fluctuations of sea level over the Holocene have resulted in an array of coastal landforms, reflecting the changing dominance of these controlling processes. The mutual interaction of these processes has led to a great variety of quaternary landforms. Contrasting examples from the array of coastal features are considered: The Carse of Stirling, was formerly a shallow marine inlet, which was progressively isostatically emerged to its present altitude; left marine sediments and species, including numerous whale skeletons, to date the transition from marine to terrestrial landscapes (Graph #17, Forth Valley in Figure 2.2, Hansom & Evans, 2000). Unlike the central areas of Scotland, whose isostatic inheritance ultimately lifted the land above the Holocene transgression, the peripheral areas of the UK have been dominated by submergence since the removal of the ice (examples include Shetland, Orkney and Wick, Graph #1, 2 & 3, in Figure 2.2). This situation leaves these terrestrial areas devoid of any former shorelines as they and the majority of the quaternary deposits lie beneath the present day sea level.

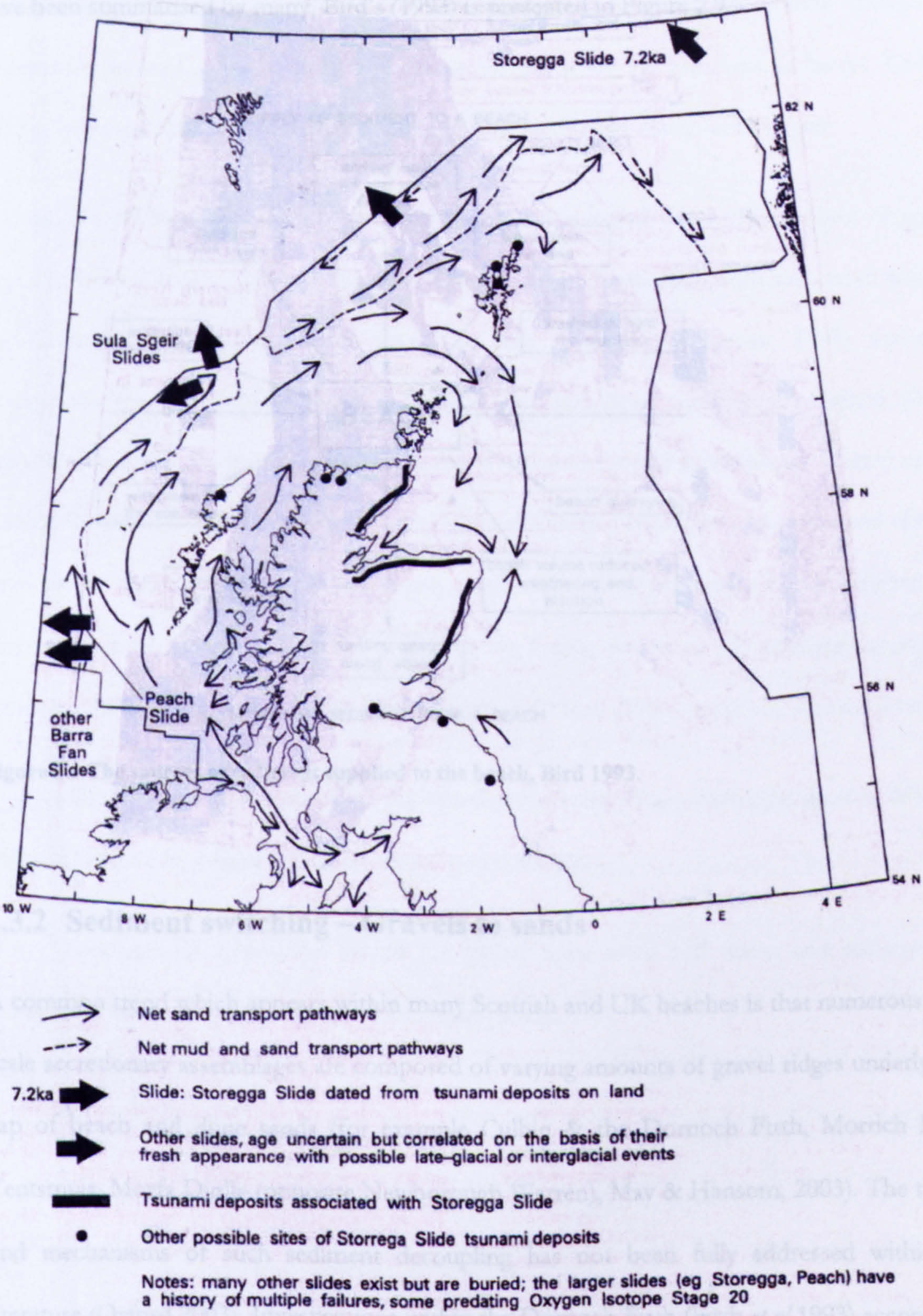


Figure 2.8 – model of sediment pathways from Gordon (1997)

Considering sediment movement at a smaller scale the dynamics operating within a beach have been summarised by many, Bird's (1993) is presented in Figure 2.9.

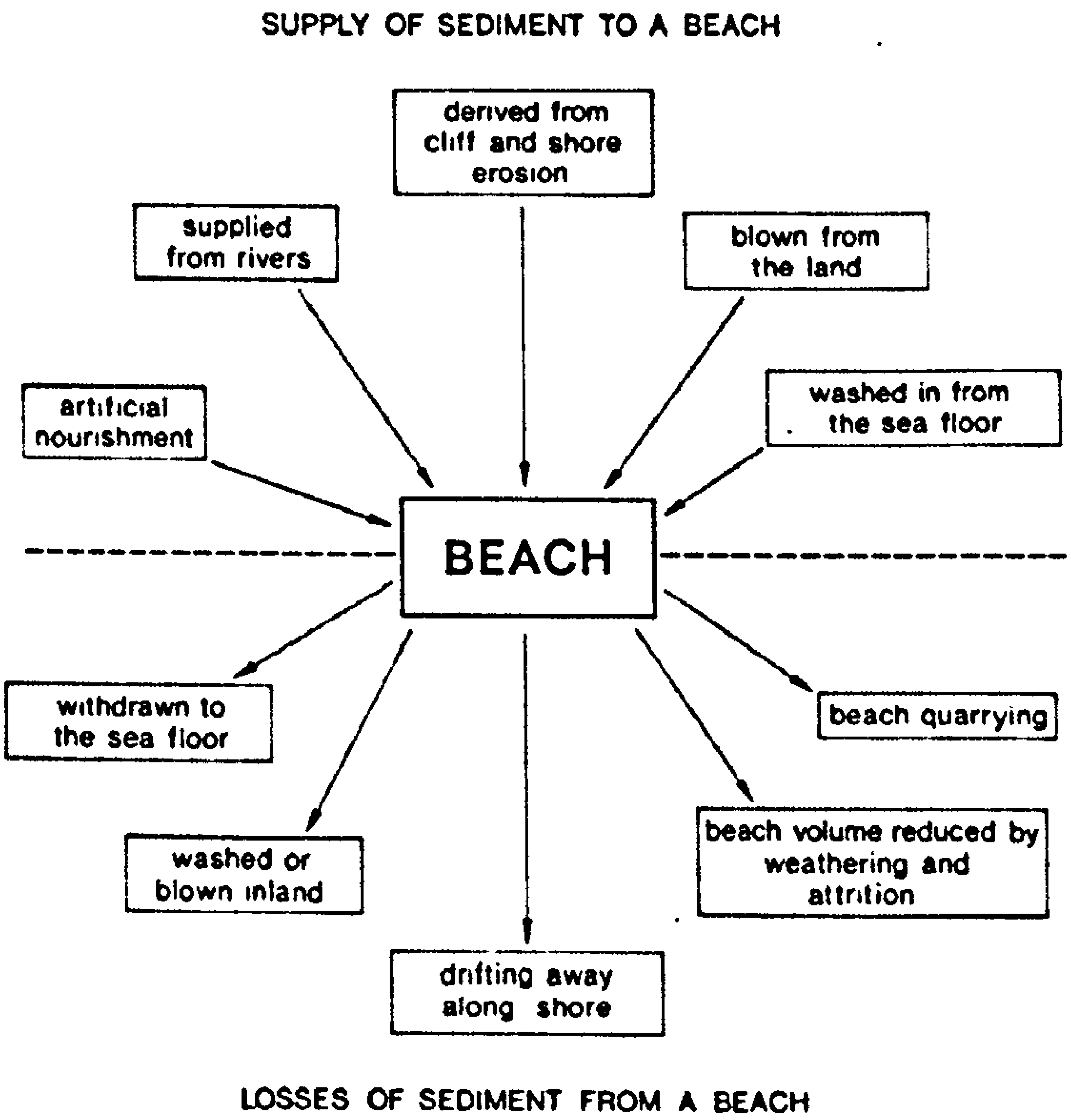


Figure 2.9 The sources of sediment supplied to the beach, Bird 1993.

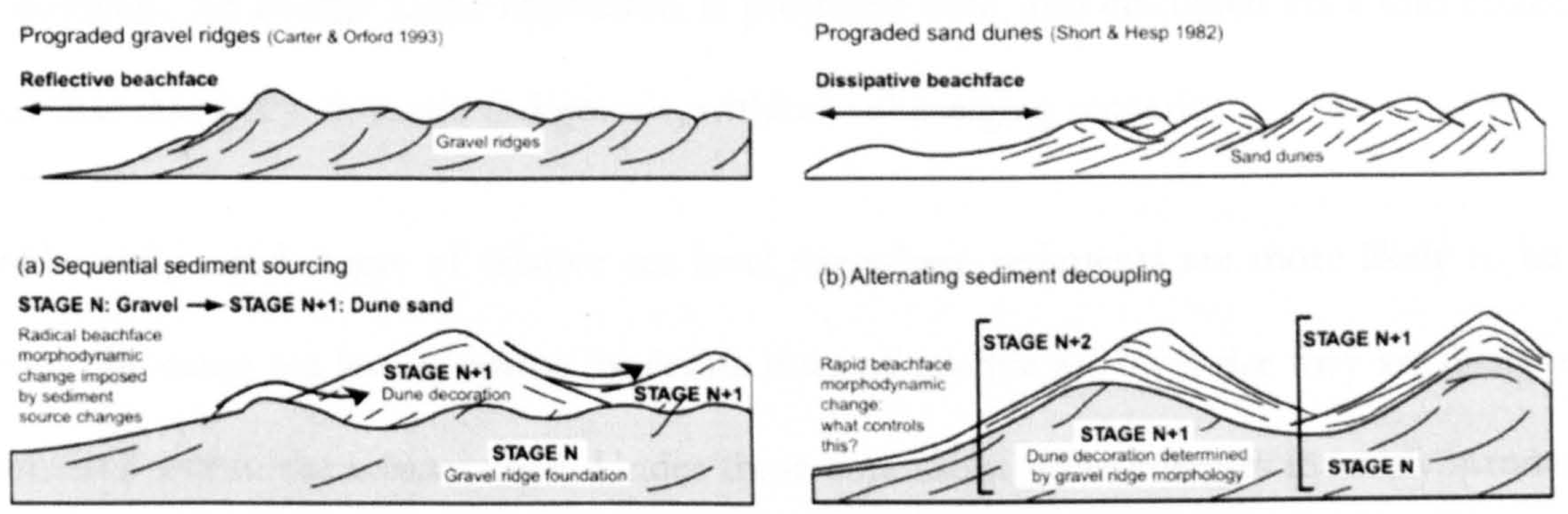
2.3.2 Sediment switching – Gravels to sands

A common trend which appears within many Scottish and UK beaches is that numerous large scale accretionary assemblages are composed of varying amounts of gravel ridges underlying a cap of beach and dune sands (for example Culbin & the Dornoch Firth, Morrich More, Tentsmuir, Morfa Dinlle (opposite Newborough Warren), May & Hansom, 2003). The timing and mechanisms of such sediment decoupling has not been fully addressed within the literature (Orford 2003). Investigations within the Dornoch Firth (Firth *et al* 1993) account for the spatial and temporal variation of the deposition of different sized fractions; however no review of the causal factors, or a link to other assemblages was proposed. Although site-specific factors vary the juxtaposition and possibly timing of this switch, there is likely to be some causal underlying explanation for this widespread phase change in deposition. Two possible underlying factors may be responsible, namely the sediment source changes or becomes exhausted, or there is hydrodynamic sorting along the sediment pathways (Orford, 2003). This topic will be considered in further detail within the discussion chapter.

'Several coastal dune field overlying multiple gravel-dominated beach ridges occur along the north of Ireland coast. Although these dune/gravel assemblages have been associated with the mid-Holocene deceleration of sea level rise rate (Orford and Carter, 1988) the exact mechanism for this superimposed succession has not been understood' Orford (2003). Comparable to the Scottish examples, gravel-cored sand-capped assemblages located on the north coast of Ireland, were investigated by Orford (2003). Part of the environmental changes that may be responsible for this construction and subsequent preservation is the higher than present sea level. To understand the evolution, the timing and cause of 'sediment decoupling' (changing from gravel to sand) has to be addressed. Orford (2003) proposed two mechanisms:

1. The different size units were deposited at different times, each relating to a different sediment source or exhaustion of the initial gravel source.

2. Synchronous deposition where the gravel units were laid down and subsequently covered by aeolian deposits in repeated cyclical phases.



Schematic views of the two models by which superimposition of dunes (dissipative conditions) are formed on gravel beaches (reflective conditions). (a) Sequential sediment sorting, where the gravel phase is followed by sand deposition. (b) Alternating Sediment decoupling, where gravel deposition is followed by a sediment switch and the deposition of sands. Source: Orford (2003)

Figure 2.10 Two options for the development of superimposed dunes on top of gravel ridges.

Using 3 sites in Northern Ireland, Orford (2003) discusses two possible mechanisms. Sheep Haven (Co. Donegal) and Magilligan foreland (Co. Londonderry) appear to have a series of gravel ridges superimposed by sand dunes. The third site, Murlough Dunes (north-east Ireland) has intercalated sand and gravel deposits, and hence can only be formed by concurrent gravel, then sand, deposition. This cyclical evolution was related by Orford (2003) to fluctuations in the sand supply: during periods of minimum sand availability the beach face adjusted to a reflective phase, allowing the construction of a gravel ridge, which is then capped by wind blown deposits. Orford (2003) found that the sand dominated on a cycle of 80-150yrs. He proposed accelerations in the relative sea level fall as the cause for the sand cycles, allowing the falling wave base to rework new sands onto the shoreface. Infrared-stimulated luminescence (IRSL) was used to date the superimposed sand units, but no evidence was presented to support cyclical accelerations in relative sea level changes. As this pattern of behaviour is only possible when sea levels fall, it is possible that there is a more universal explanation found in the hydrological behaviour of gravel sand sands.

It is possible to interpret sediment switching via the different hydrological behaviour of gravels and sands, via Hjulstrum's (1939) investigations into the entrainment and fall velocity of particles. An energy based hypothesis is proposed here, and discussed via a mid-Holocene coastline charged with sands and gravels, within a submerging scenario.

Unlike early rapid stages of relative sea level rise where sediments are more likely to be left behind by rising sea levels, during moderate rates of relative sea level rise they are likely to be mobilised within the coastal zone. Under these conditions wave energies intensify, producing an increasingly charged coastline with both sands and gravels being transported. Based simply on the size of the two sediment fractions, we can expect gravels to be present in two areas and sands in three:

- Gravels: Source zones and near shore areas with high wave energies.
- Sands: Source zones, near shore areas with high and lower wave energies.

Given the greater energy requirement to mobilise gravels they are primarily deposited and preserved in areas of the coastal zone which are accessed by high energy waves and unaffected by lesser waves i.e. at the limits of the swash. Lesser gravels and sand sized fractions may be present in the near shore, but will be transported away from these 'frontier areas' and deposited within areas experiencing calmer wave climates. This is similar to Orford's first situation, Figure 2.10a, but exhaustion of source areas is not necessary, simply changes in the carrying capacity of the coastal cell.

Under more varied sea level scenarios a similar situation is proposed. Where sands and gravels are both available during early stages (moderate relative sea level rise), gravels are deposited in 'frontier areas' and sand continues to calmer sections of the coast. As time progresses, wave climates reduce, due to the previous sedimentation of frontier areas and/or stabilising of the sea level, which then allows the sand sized fractions to be deposited. During falling relative sea level the wave climate remains low due to the emergence of formerly submarine features and sand is the only fraction accessible as it has overlain the gravels. However in situations where gravels are continuing to be delivered by fluvial mechanisms (e.g. Spey Bay, Gemmell (2000) or erosion of Holocene gravel ridge or terrestrial units (e.g. Nova Scotia, Carter *et al* (1998)) then gravels may still dominate. As such gravels can be interpreted as 'relict' sources, which generally relate to previously active stages of sourcing and movement. There are few cases where gravels are actively sourced, as in most cases they are resident within the coastal cell from previous periods when glaci-genic sediments were more actively mined.

Sediment switching has been touched upon (Carter 1989, Firth *et al* 1993, Hansom & Angus 2004) however to date our limited understanding is based on isolated observations from different locations with highly varied histories, and as such they remain to be rigorously tested. Believable scenarios exist: energy based discussions (presented in earlier paragraphs), sediment exhaustion mechanisms and cyclical phases of deposition. As such mechanisms of sediment switching remain problematic until the timing and mechanisms previously active during the construction of large gravel cored, sand capped assemblages are systematically investigated.

During these conceptual discussions it is easy too over-simplify reality. Sedimentary co-existence is problematic in Holocene sediments, since sand and gravels do exist together on the same sections of modern coast (e.g. Culbin and accretional limit of the Spey beach). However, the upper foreshore (populated by gravels for example) will only experience high wave energies that may coincide with high tidal states, conversely a sandy foreshore may be the operational beach for the majority of the time, namely during non-storm conditions. This highlights a limitation with our conceptualisation of the problem; not only is the landscape dynamically adjusting within three dimensions, but at different times, frequencies and at different rates: the coastal environment is composed of a combination of active and inherited components. Within large accretionary coastal systems, the role of inherited basement geology and the phasing of sea level changes are crucial in the separation or the co-location of deposits of varying sizes. For example the separation of gravel deposits of Meikle Ferry and Cuthill links and the younger sands of the mouth of the Dornoch Firth (Dornoch Point and Morrich More) (Firth *et al* 1993, May and Hansom 2004).

2.4 Other factors affecting coastline behaviour

The previous sections in this chapter have outlined the roles of sea level and sediment supply for coastal evolution, however there are other factors which also affect the position and form of coastal landforms.

2.4.1 Structural inheritance

The underlying geology plays an inherent role in the development of landforms, as is the container within which soft deposits accumulate, and the base level on which sediments and sea levels inundate or expose. Generally the underlying geology tends to be far less changeable, taking longer periods of time to adjust to alterations with its surroundings than soft landforms (Hansom 2001). The morphology and gradient of the geological surface plays an important role, as it controls the amount of planimetric change associated in changes to sea level. Under changing sea levels landforms distributed on shallow gradients will be draped over a wider zone, on steeper gradients the same landforms may be co-located. Similarly, the variability of the geological surface can also influence the evolution of landforms on or adjacent areas. The shallow gradient off the west coast of the Western Isles gradually dissipates energy as waves approach the coastline. The antithesis of this situation exists off the west coast of the Northern Isles, where waves are uninterrupted by the deep nearshore waters. The more resistive lithology of these cliffs increases their longevity, in comparison with most of the cliffs in England, which were formed during the Holocene.

Sanday, in the most part, is low-lying and topographically varied, which introduces an interesting control over the coastal processes. When the topographically varied under-lying geology is considered in conjunction with a rising sea level, the sourcing of drift material, topographic highs and topographic hollows provides a varied surface on which processes will operate, iteratively reflecting subsequent changes as the landscape becomes increasingly submerged. This emphasises the importance of structural control, as terrestrial forms are submerged and provide bathymetric control to marine processes, which in turn influence the development and subsequent evolution of littoral deposits.

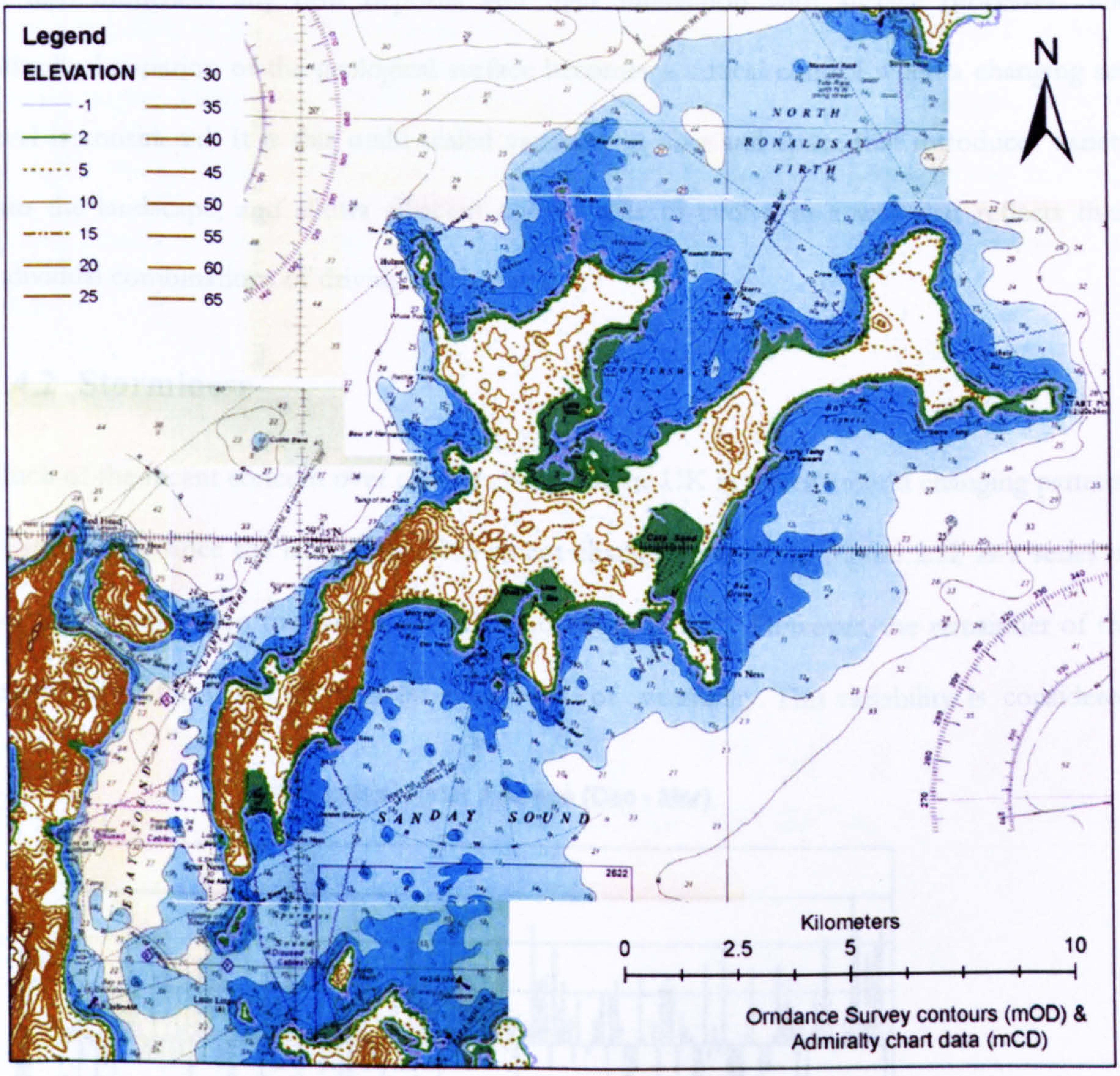


Figure 2.11 – structural control of Sanday, topography and bathymetry

The varied lithology of the UK is made more complex by the variations in antecedent conditions, which can greatly alter the behaviour of rocky shores. The role of antecedent conditions will be explained using examples of the chalk coasts of the southeast of England and the northern coast of Northern Ireland. Both geological units are derived from Cretaceous chalk; however the Northern Ireland units have developed differently, which have conditions will be explained using examples of the chalk coasts of the southeast of England and the northern coast of Northern Ireland. Both geological units are derived from Cretaceous chalk; however the Northern Ireland units were overlain by basalts, which have greatly increased their physical strength and reduced their erodability (Lyle 2005). In addition, the structures within the rocks influence their surface form or morphological variability, which in turn influences any drift deposits and their interaction with surface processes. The altitudinal variation of the geological surface becomes a critical control when a changing sea level is considered. It is this multi-scaled variation in time and space that introduces variety into the landscape, and allows adjacent coastal cells to evolve in a way that reflects their individual combinations of driving mechanisms.

2.4.2 Storminess

Much of the recent concern over climate change in the UK revolves around changing patterns of storminess since the late 1970s. This recent change is shown in Figure 2.12 as a series of positive values within the North Atlantic Oscillation Index[2]. However, the remainder of the graph, before the 1970s, shows a large amount of variability. This variability is considered

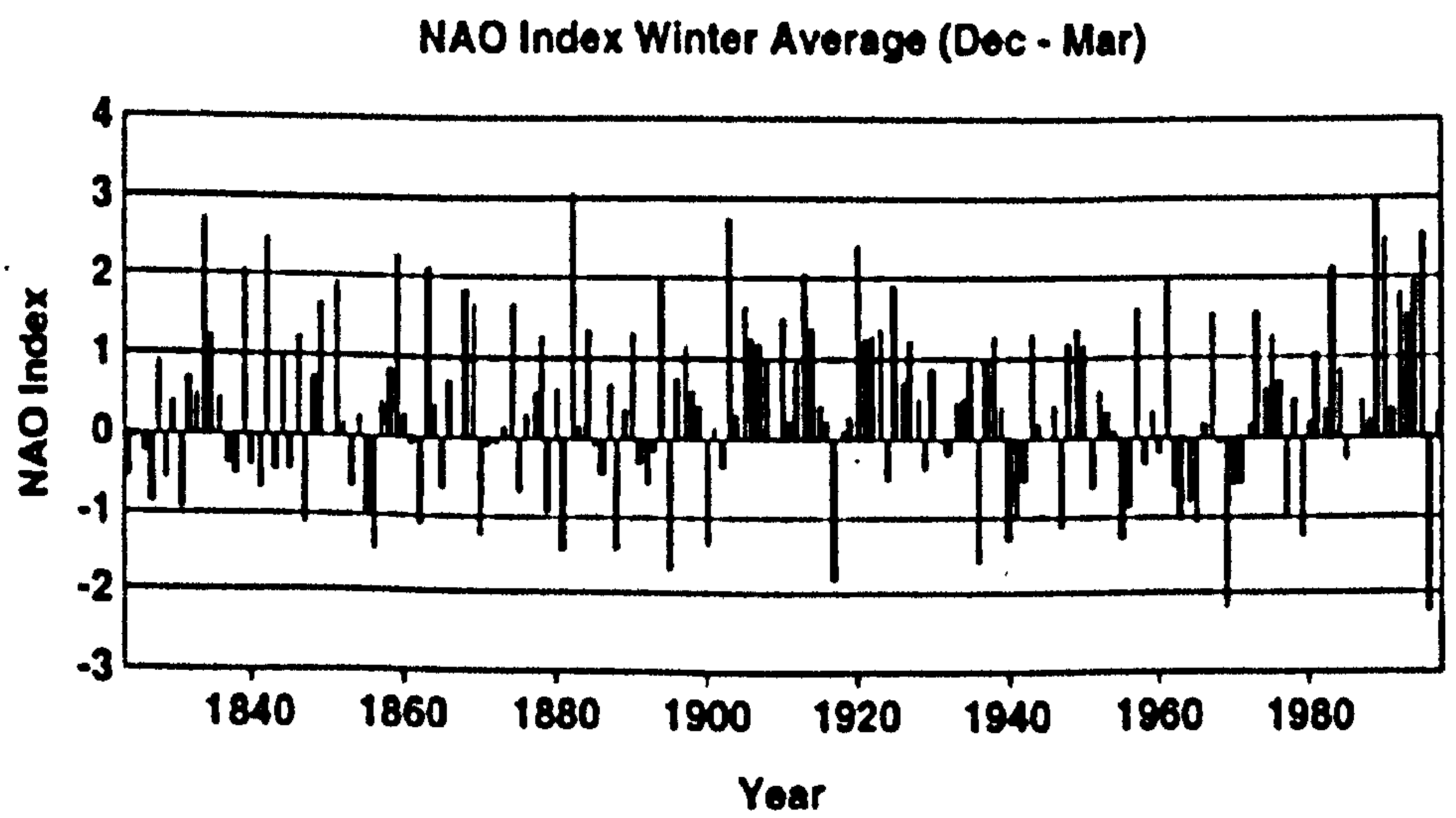


Figure 2.12 The North Atlantic Oscillation Index winter average calculated for December-March intervals. (Dawson *et al* 2001)

[2] The NAO is an index of atmospheric pressure difference between the Azores high and Icelandic low. Strongly positive index values should correspond with stormy conditions around Scotland, due to low pressure dominating the North Atlantic.

further in Figure 2.13, where gale days per year for Stornoway and Edinburgh are displayed, again showing considerable variation over the record. These variations have reduced the certainty for future storminess scenarios.

Acknowledging these limitations the British and Irish Council (BIC) Report (Jenkins *et al* 2002) suggests the number of deep atmospheric depressions passing across the UK will increase by 40% by the period referred to as the 2080s. Using data provided by the Proudman Oceanographic Laboratory, the BIC report suggests a likely increase in storm surges, reflected in higher wave height. That this may already be underway is suggested by increases in North Atlantic maximum wave heights of 2.5-7.5mma^{-1} over the period 1955-94 (Gunther *et al*, 1998).

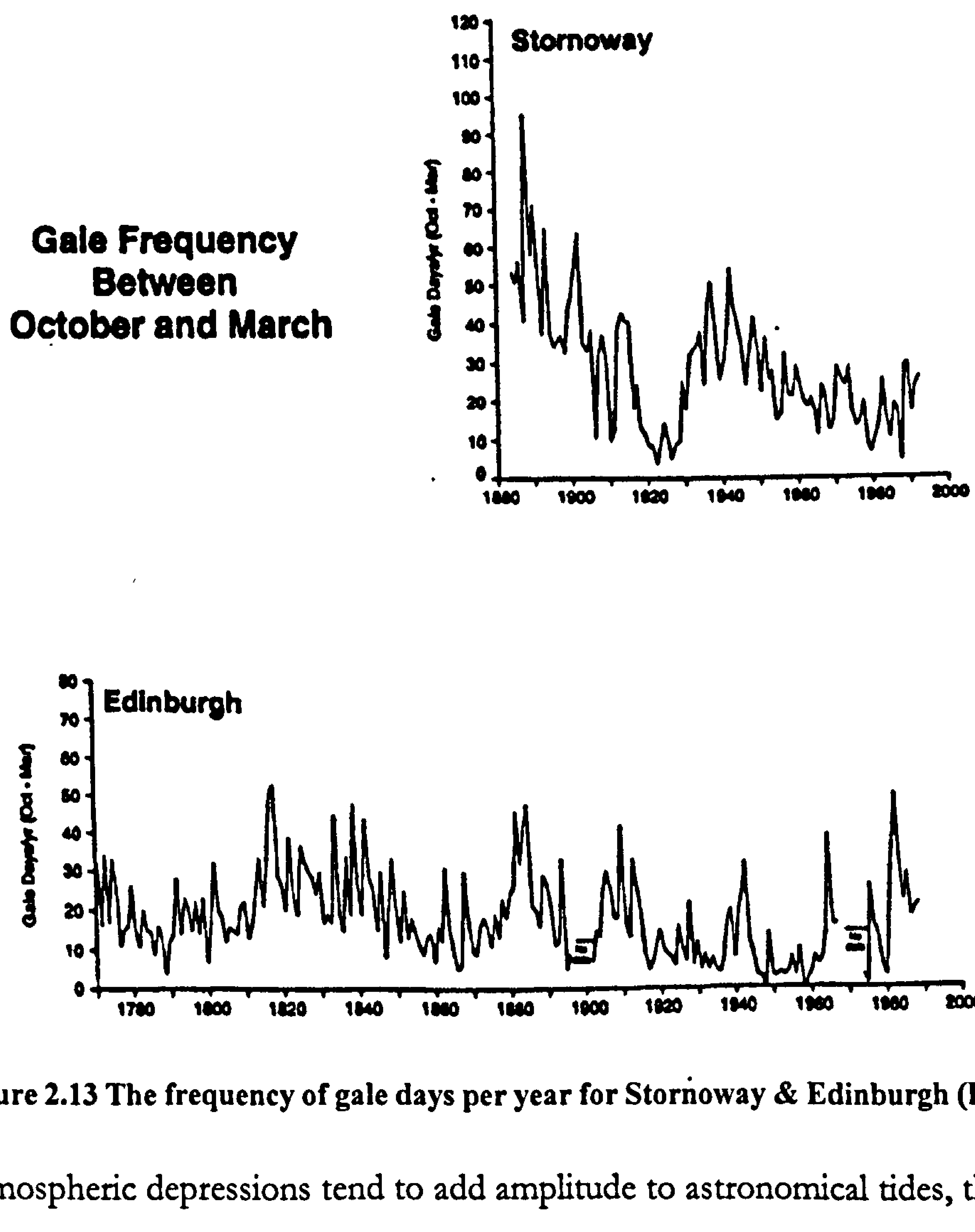


Figure 2.13 The frequency of gale days per year for Stornoway & Edinburgh (Dawson *et al* 2001).

Atmospheric depressions tend to add amplitude to astronomical tides, the worst case scenario being a deep depression storm surge with strong onshore winds coinciding with an extended across two high tides the subsequent flooding was widespread. The reduced atmospheric pressure and the track of the depression elevated the sea by 1.3m (Figure 2.15) which was magnified by the coastal configuration and the presence of the largely impermeable causeways to a level of 2.74m above predicted astronomical tide level (Angus & Rennie, *in press*). This super-elevated sea level greatly reduced the effectiveness of the nearshore in shoaling the incoming waves thereby exposing the landforms to far greater energy levels than regularly experienced. Sand dunes, machair and shingle beaches were modified by the storm. The gravel beach at Stoneybridge, South Uist is shown in Figure 2.16. This led to a contrasting situation where low altitude horisontal-landforms such as saltmarsh were largely undisturbed, whereas higher altitude and vertical fronted landforms such as sand dunes and machair cliffs were greatly effected (Angus & Rennie, *in press*). Like other storms, it is the combination of a variety of events and processes which combine to have a cumulative effect which was significant. This is the likely mechanism though which the landscape changes, noticeable punctuated changes relating to climatic events, within a more un-noticeable trend of minor change.

In addition to the physical threat of sediment removal posed by storm surges, there is the possibility of waves overtopping the dune ridge and flooding the dune grassland behind with sea water, augmenting the extent and salinity of any seasonal water behind the dunes (Hansom & Angus, 2001). Though overtopping of dunes is regarded as of low probability, some gravel ridges (for example at Stoneybridge, South Uist) have been overtopped in recent decades and encroached onto the machair surface (May & Hansom, 2003, Angus & Rennie *in press*). Any serious overtopping of this ridge would flood the Howmore basin and its lochs with saline water, which would then affect a wide area of machair and its associated habitats.

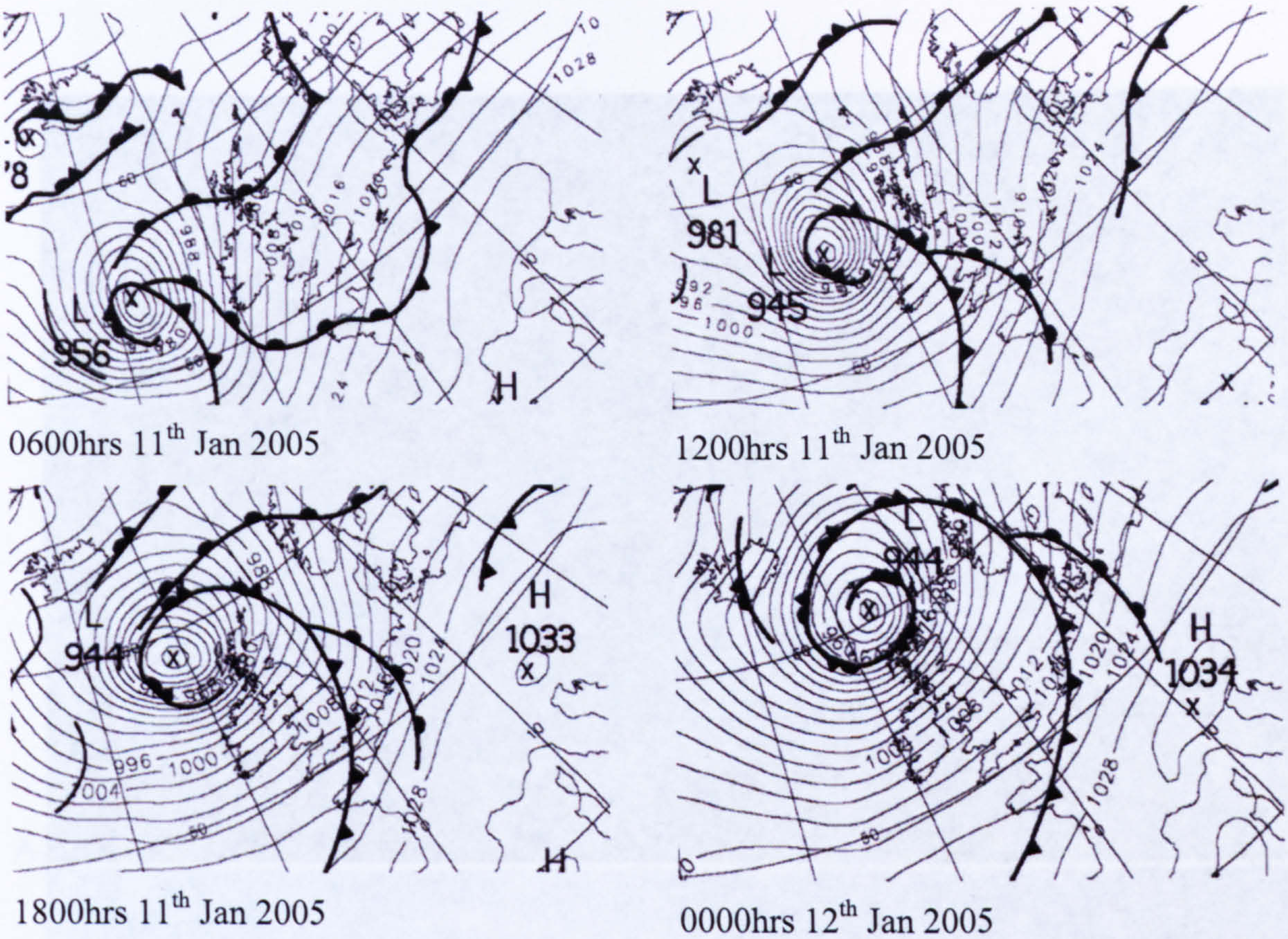


Figure 2.14 The atmospheric conditions which led to the Jan 11th storm surge and associated storm.

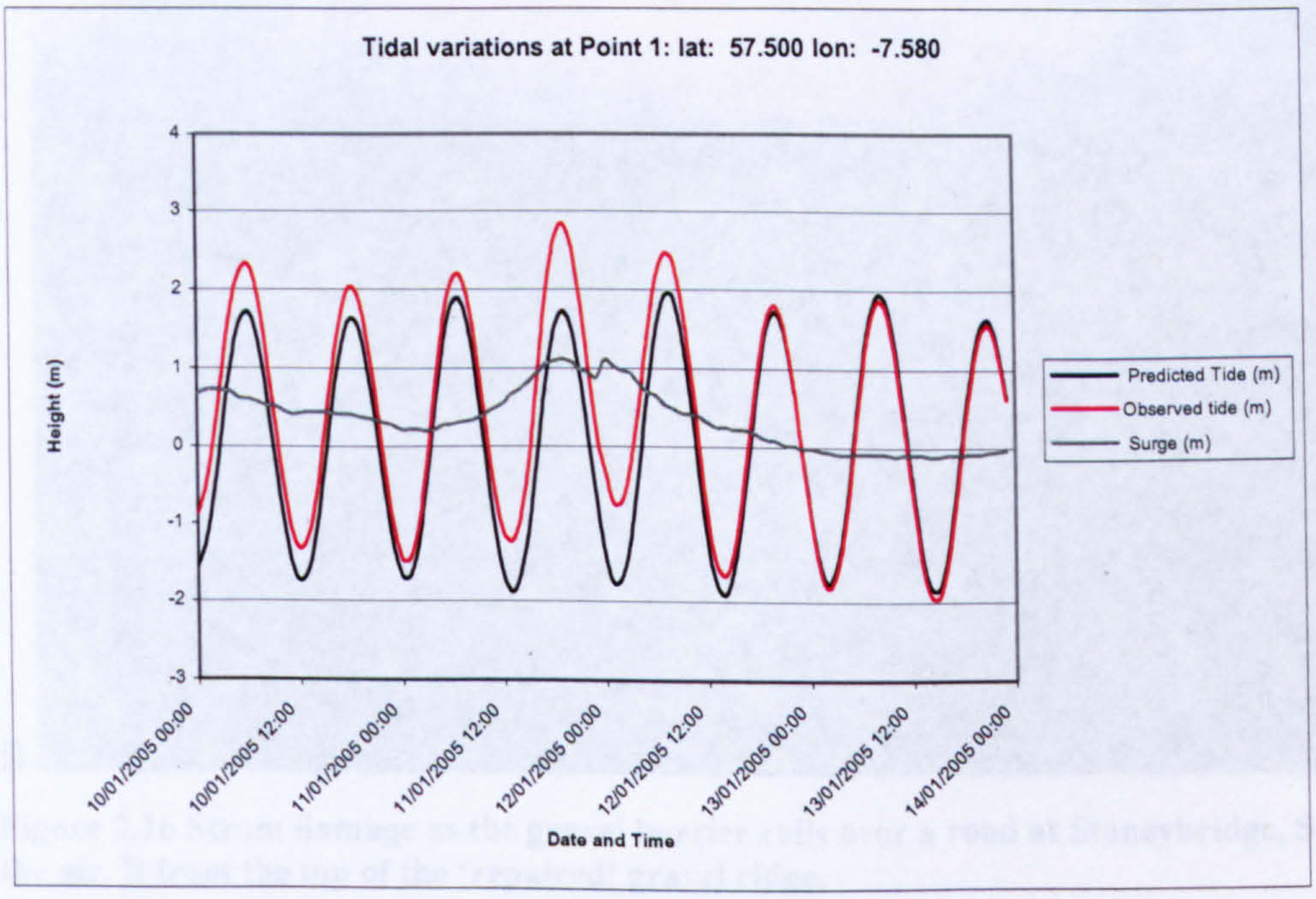


Figure 2.15 Met Office surge model showing peak offshore surge of just over 1m peaking in the middle of the night between 11th and 12th January. Note that the position uses decimal degrees instead of minutes, and the position is more conventionally represented as 57°30'N, 7°34'48"W. This position lies just SE of Ceann Ear in the Monach Isles, in some 15-20m of water (Chart Datum). © Met Office.

A

B

Figure 2.16 Strom damage as the gravel barrier rolls over a road at Stoneybridge, South Uists. A, from the air, B from the top of the 'repaired' gravel ridge.

2.5 Beach response to sea level rise

Increasingly it is now recognised that the world's sandy beaches are predominantly erosional, and Bird (1985, 1996) suggested that 70% were eroding, less than 10% were accreting and there was no change on the remaining 20-30%. In Scotland, Ritchie and Mather (1984) estimated 41% of Scottish beaches were erosional. The possible reasons for this bias include the progressive reduction of sediment availability for beach building over the Holocene (i.e. the system has reworked all available sediment within the near shore). Other factors include increases in mean and extreme sea level relating to changes in climatic patterns, increases in storminess (Dawson *et al* 2002) and human activities including the reduction of sediment delivery from within catchments by management of river flood peaks, river bank protection and widespread coastal protection, which has exacerbated the already limited coastal sediment budget, resulting in the widespread reorganisation of coastal sedimentary stores.

The behaviour of beaches are related to the balance between sea level and the sourcing of sediments i.e. what is being actively sourced and where is it being transported into. When the initial source runs out or is by-passed due to a higher sea level then the shoreface reacts and responds appropriately. This dynamic situation is exemplified by a submerged drumlin field in Nova Scotia (Carter *et al* 1989) and also Clew Bay, West Ireland.

2.6 Conceptual models of shorelines experiencing sea level rise

Morphological responses to sea level changes have usually been discussed using a simple classification of rising, falling and static sea level scenarios. A further common assumption is the conservation of beach volume, envisaging no lateral transfer of sediments along the shoreline, or losses out of the cell. The limitations of these and alternative approaches will be discussed after these initial models are introduced.

Carter (1988) outlines three models of shoreline response to sea level rise. The 'Bruun rule' (Bruun 1962) has been widely adopted and describes the changes expected where the beach profile translates via frontal erosion and delivers the eroded sediments to the lower profile during rises in relative sea level and vice versa for relative sea level fall (Figure 2.17B). Erosion (R in metres) is given by:

$$R = \frac{(x.s')}{z}$$

where x is profile width (m), s' is the sea level rise (m) and z is the profile depth(m). Alternatively the shoreface can 'roll-over' and migrate landwards at a rate proportional to the rate of sea level rise (Figure 2.12B). Wash-over processes are key, transferring sediments from the shore face to the back beach, the rate of barrier migration is related to the rate of sea level rise via the basement slope. The third alternative is 'over-stepping' where the barrier is left behind as rapidly rising sea levels submerge the features (Figure 2.17).

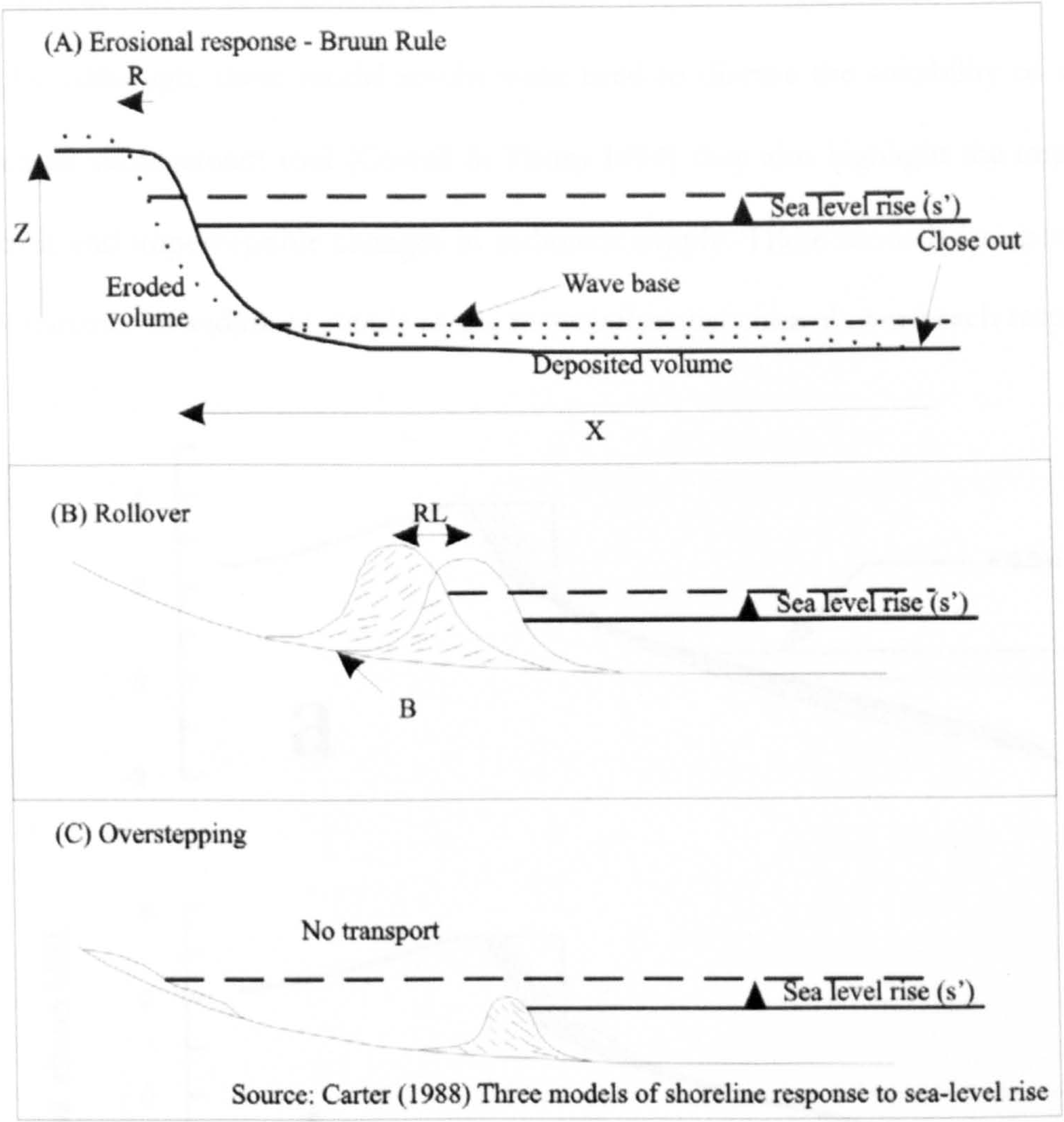


Figure 2.17 Conceptual models of shoreface adjustments under relative sea level rise (Carter 1988)

These one dimensional models only approximate the condition found. There are very few examples globally of coastal erosion being wholly attributed to sea level rise, as in most cases regional or local sedimentary losses may also play a part (Bird 1996). Critics of the Bruun rule note that the assumption that no lateral transfer of sediments is not generally met (Carter & Woodroffe 1994).

Cowell & Thom (1994) used the term Large Scale Coastal Behaviour to describe the changes to coastal systems over time scales of decades and spatial scales of kilometres. Their work documents computer simulation of shorelines, under differing rates of sediment supply variations and sea level rise. A 3m shoreline recession was produced by both a 0.5m increase in sea level and a 0.1% reduction in the along-shore transport budget. This dominance of sediment supply as a control over shoreline response is graphically demonstrated in Figure 2.18. Although, these model results were used to discuss the suitability of sediment feed as coastal management tool (Cowell & Thom 1994) they also highlight the implications of very small and imperceptible changes in sediment supply. These modelled responses point to the dominance of sediment supply as the most influential control over beach response.

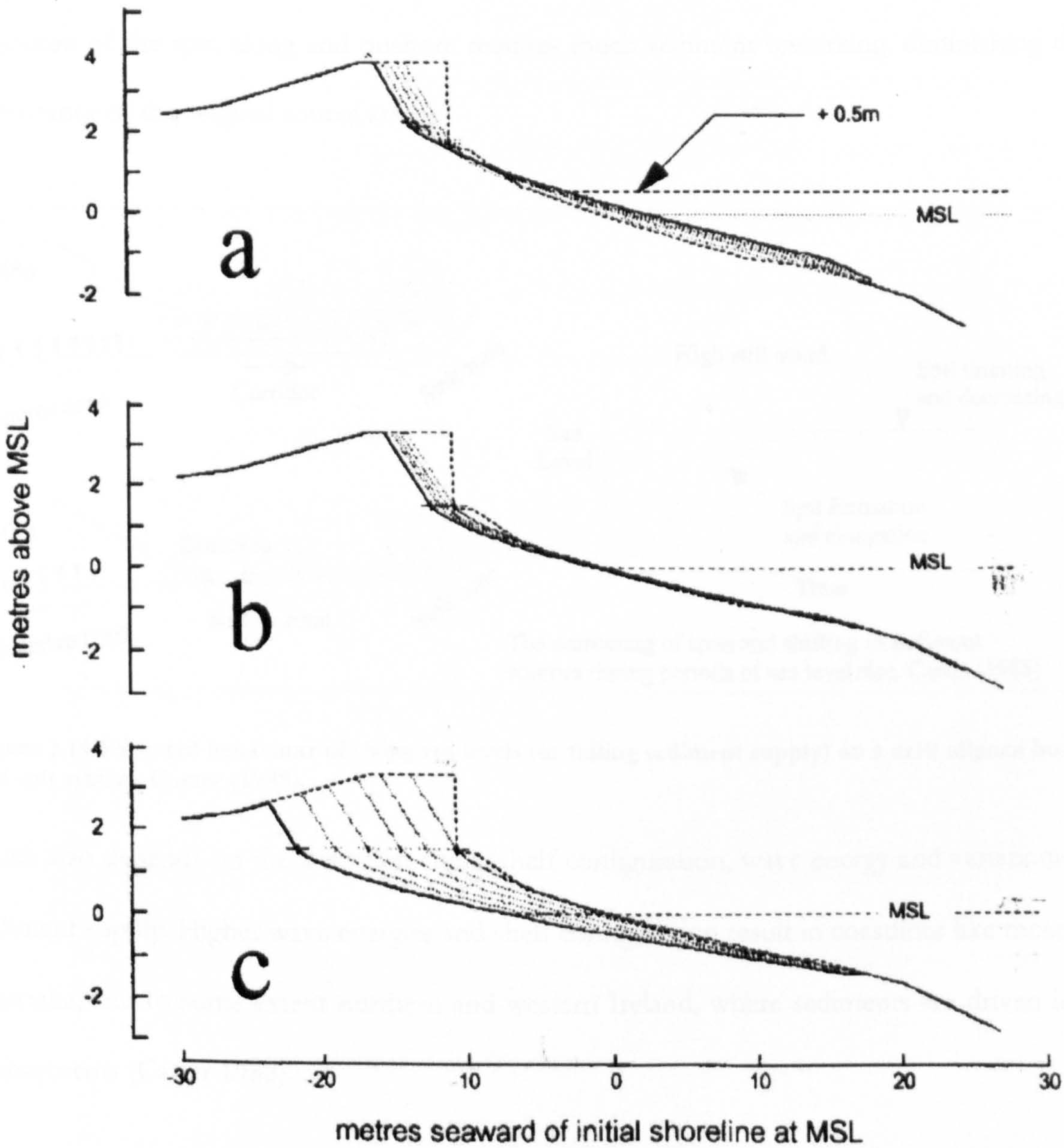


Figure 2.18 Modelled shoreline responses from (A) 0.5m rise in sea level, (B) 0.1% reduction in along-shore sediment supply and (C) a 0.5% reduction in along-shore sediment supply. (Carter & Woodroffe, 1994)

In response to the limitations of earlier models Carter (1988) provided a three-dimensional example of two transgressive shoreline models. The first profile (Figure 2.19A) occurs when rising sea levels erode the most seaward dunes, releasing sediment some of which is transported landwards via onshore winds. If the capacity of the dunes to capture the eroding aeolian sands is not exceeded then the dunes will translate landwards, keeping pace with sea level rise. The second situation summarises the behaviour of a spit system entering an embayment (B). The resultant assemblage will have truncated recurves at its proximal end, which feed distal extension in both onshore and along-shore directions (Figure 2.19B). This migration of the spit, along and onshore requires much sediment reworking, diminishing the importance of the original source area.

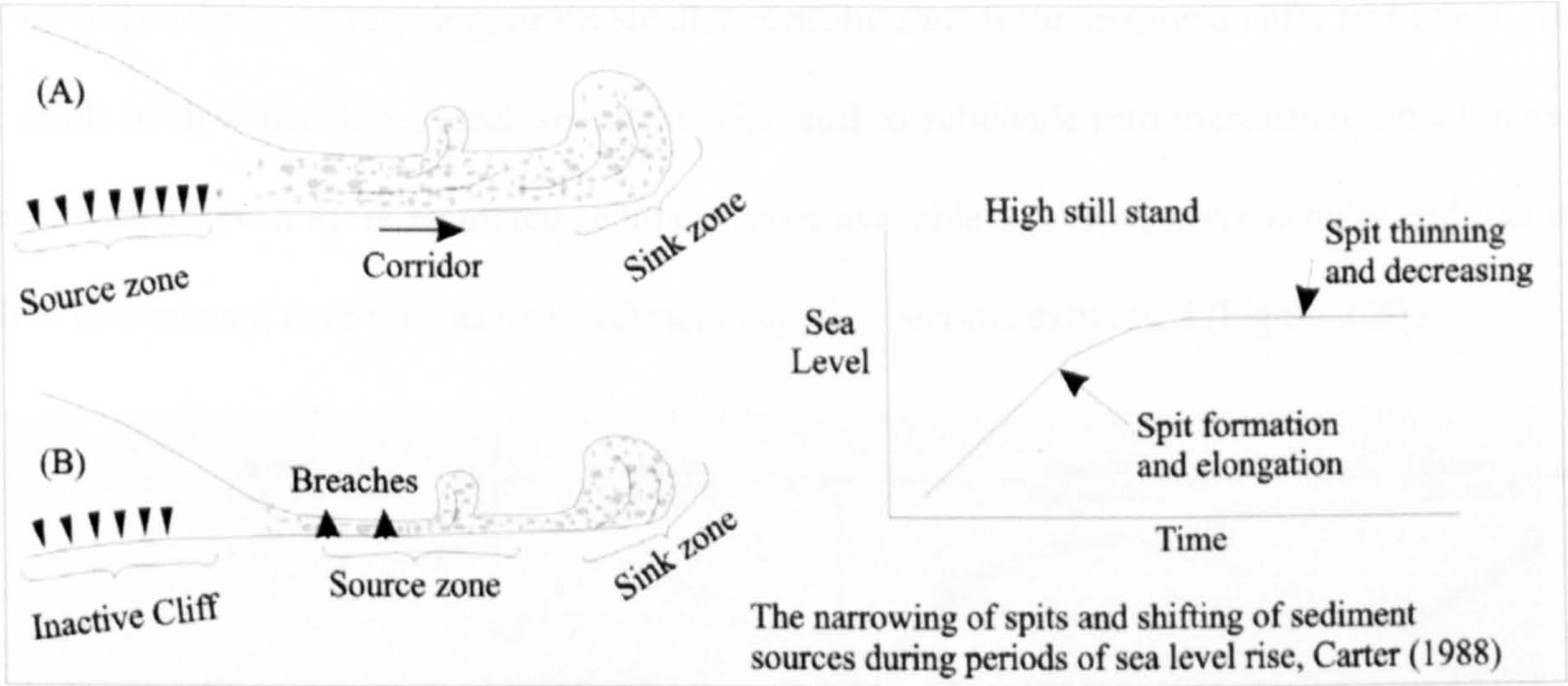


Figure 2.19 Expected behaviour of rising sea levels (or falling sediment supply) on a drift aligned beach and spit system, Carter (1988).

Much also depends on the basement angle/shelf configuration, wave energy and variations in sediment supply. Higher wave energies and shelf configuration result in coastlines like those in Australia, and to some extent northern and western Ireland, where sediments are driven into embayments (Carter 1988).

Carter (1989) using examples from Nova Scotia and Ireland, suggested that the rate, rather than the magnitude, of relative sea level changes drives the evolution of barrier coasts. Others agree (Orford 2003, May and Hansom 2003) that rapid relative sea level rise causes transgression without significant shoreface modification, whereas slower relative sea level rise is associated with widespread shoreface modification, often followed by sediment exhaustion in the long-term (Hansom 1999). This interplay between sea level rise and associated access to new sediments is a key control over the development of soft shorelines and forms a major part of the present thesis.

During still-stands shorelines have the opportunity to adjust into some form of morphological or sedimentary equilibrium. However, unlike periods of sea level rise or fall when new sediment sources become progressively available within the nearshore, during periods of slow sea level rise or during still-stands, sediment availability becomes scarcer, resulting in shorelines relying on recycling or on smaller contributions from erosional cliffs and rivers. As a result of slow rise in sea level, sediment cells tend to subdivide into increasingly small units, each with an even more restricted sediment store available to absorb wave activity and this is then exacerbated over time as new sediment supplies become exhausted (Figure 2.20).

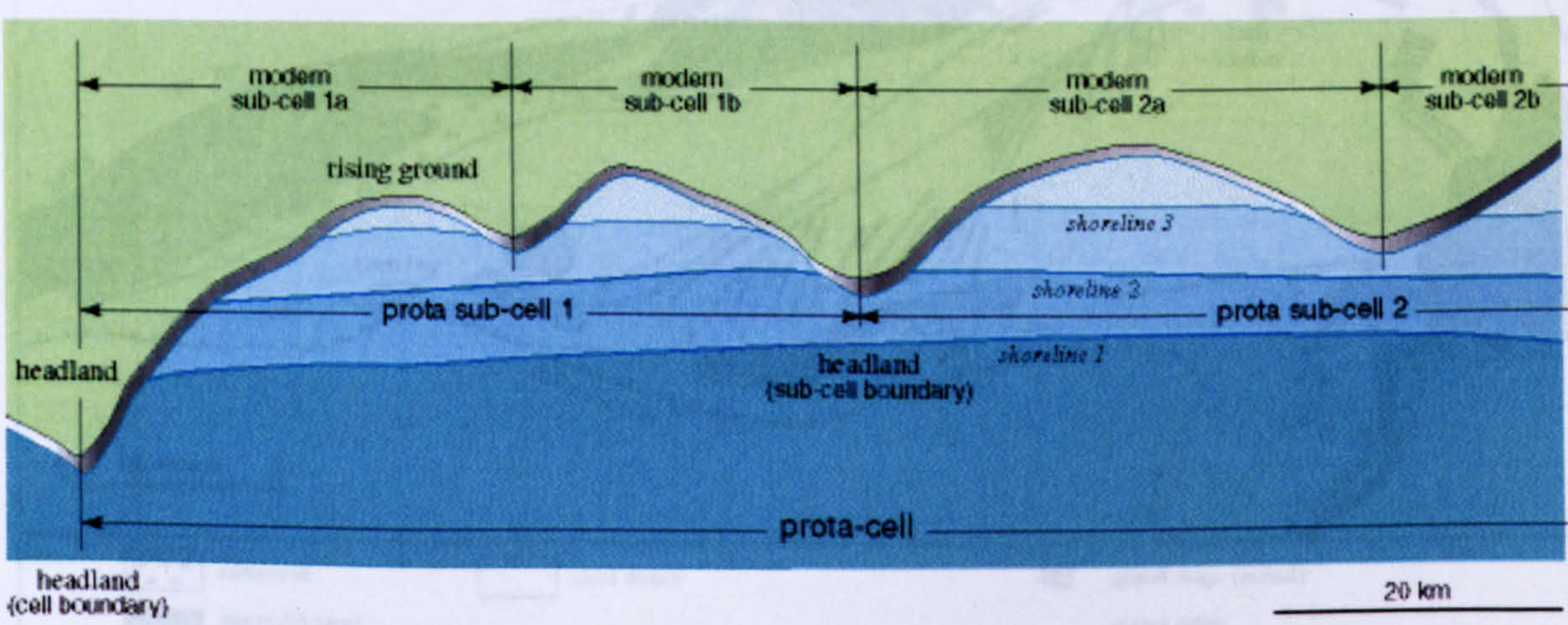


Figure 2.20 The processes of coastal recession favours an increase in barriers to longshore movement of sediment, after Hansom (2003). Figure 5.20 also illustrates this point.

This reduction in longshore and offshore contributions causes beach systems to increasingly recycle sediment stores in response to the incident energy (for example under periods dominated by oblique waves). This is typically manifested as up-drift erosion fuelling down-drift accretion resulting in sediment exchange on the shoreface and in the rotation of features from drift alignment to swash alignment (Hansom 2003). This long-term constant re-adjustment towards equilibrium is analogous to the short-term rotation of bay-head beaches to seasonal storm patterns, where sediment supply is short-term limited. For example Narrabeen Beach, New South Wales, Australia has a clockwise rotation during El Ninõ and an anticlockwise rotation during El Nina (Ranasinghe 2004).

Spits are particularly susceptible to the shifting of sediment sources as sea level changes. One of the finest examples of this is the large spit system at Culbin sands (Figure 2.21), where the relic ridges were sourced from the river Spey. This source subsequently was turned off as relative sea levels fell and Burgh Head rejoined the Scottish mainland. The continued extension of the flying bar at Culbin has been fuelled by the cannibalisation of earlier gravel ridge deposits (May and Hansom 2003).

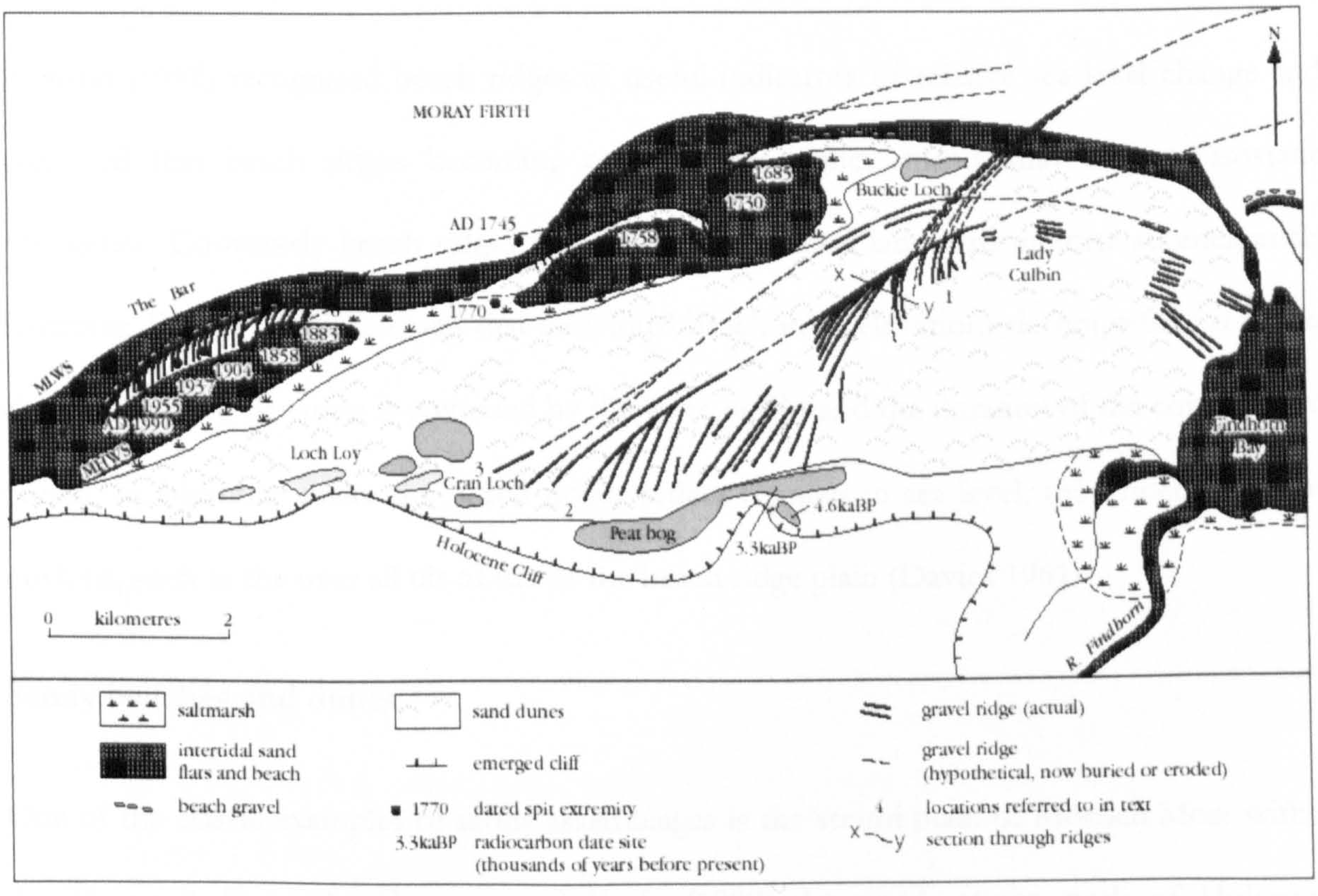


Figure 2.21 Present and relict ridge orientations within Culbin Sands (May and Hansom 2003).

Gravel beaches

During periods of slower sea level rise the upper part of the shoreface of large gravel units tend to be dormant for the majority of the year responding only to large magnitude storms. This allows the features to reside unchanged for relatively long periods of time, and allow smaller fractions to be preferentially removed, resulting in well ordered alongshore and up-shore sorting. Chesil beach is an extreme example of this, however there are lesser example elsewhere (May and Hansom 2003). As such these gravel assemblages can be envisaged as 'relict' features which were largely created on that beach and last modified under different, more extreme, conditions than those normally encountered. Many such systems are characterised by a steep coarse gravel upper shoreface, fronted by a low tide terrace of sands whose tapered leading edge migrates up and down depending on wave and tidal conditions. Active high energy systems tend to have a strong relation to a sediment source, whether this is associated with new material entering the cell via rivers or via the recycling of 'relict' gravels which were originally emplaced under different scenarios.

Johnson (1919) recognised beach ridges as useful indicators of relative sea level change and proposed that beach ridges becoming progressively higher inland, may indicate isostatic emergence. Conversely beach ridges decreasing in elevation landward indicate submergence. However, Davies (1958) stressed that individual beach ridge elevations do not reflect sea level changes because elevation is governed by the wave height and the duration of the construction period. In addition, where the beach ridges reflect changes in sea level, the evidence will be obvious, such as the over all tilt of the of the beach ridge plain (Davies 1961).

Sandy beaches and dunes

One of the classic examples of sandy assemblages is the strand plain of Morrich More within the Dornoch Firth. As Hansom and Leafe (1990) described, at the peak of Holocene transgression, where there was plentiful sediment supply, large amounts of sediment were transported onshore, forming ridges which extended from the Holocene cliff line. The narrow spacing between these early ridges, suggest plentiful sediment supply, which reduced after 6500years BP, which is reflecting in fewer and more widely spaced ridges towards the eastern active ridge. This interpretation supports the view that as sediment supply falls, beach ridges tend to build higher rather than creating additional ridges on the seaward face.

The eastward accretion of Morrich More throughout the Holocene, continues today and is associated by erosion of the north-western facing flank of the strand plain (Figure 2.22). The influx in sediment supply associated with relative sea level fall in the firths of Scotland resulted in a number of large sand and gravel assemblages being created in the Holocene. Other examples include Culbin Sands, Barry Buddon and Tentsmuir.

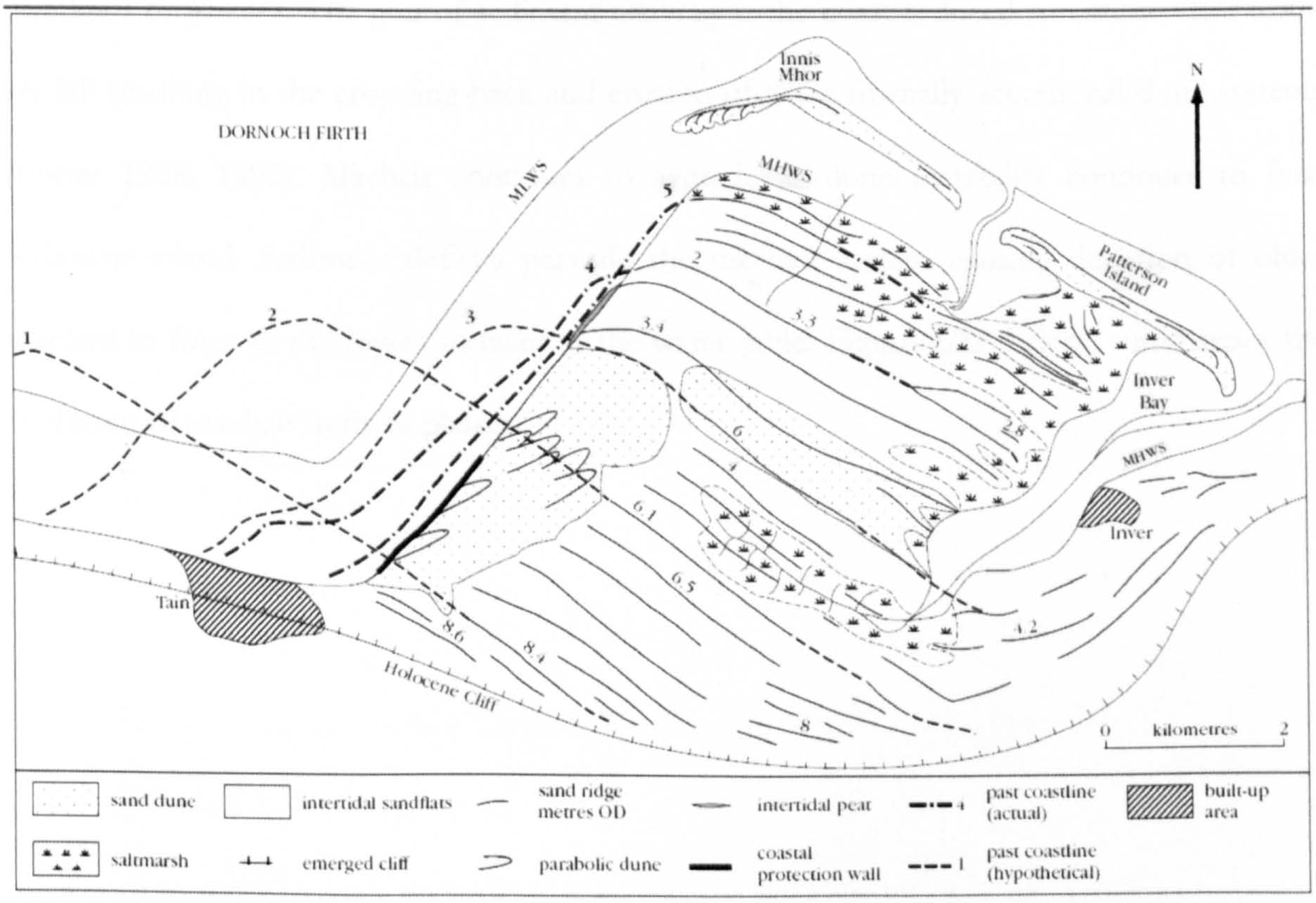


Figure 2.22 Morrich More is composed of a series of sand ridges capped by sand dunes, which form a strand plain extending into the southern half of the Dornoch Firth. (May and Hansom 2003) Heights of ridges are given in mOD.

Returning to sand assemblages in submerging areas the machair of the Western Isles started to form from around 6kyrs BP, however the development at different sites is asynchronous. Machair, a Gaelic term, describes a dune grassland system, which is unique to the Scottish and Irish Atlantic seaboard. Two thirds of the world's 30-40 kha are located in Scotland, the remainder in Ireland (Angus 1994). It is generally a flat low-lying coastal dune plain formed by windblown sand, which is dominated by calcareous shell sand. Most machair plains would have originally formed behind large dune cordons, but these may now be absent due to subsequent frontal erosion. These habitats rich in species are traditionally managed by low intensity agriculture and as such are a product of human involvement as much as natural processes.

Machair initiation coincided with the influx of sediments to the foreshore, as sea level rise started to slow, before 6,500 yrs BP (Ritchie, Hansom and Angus). The influx of shell rich sediment fuelled the construction of dunes, which in turn delivered sands inland to be stabilised by grasses. The glut of sediment arriving at the coast reduced sometime after 6,500 yrs BP resulting in the cropping back and erosion of these formally accretional dune systems (Carter 1988, 1992). Machair continues to aggrade as dune instability continues to feed sediment inland. Sediment deficits pervade the machair system causing deflation of older machair to form newer lower surfaces at the water table. Figure 2.23, below, summarises the evolution of machair in three phases.

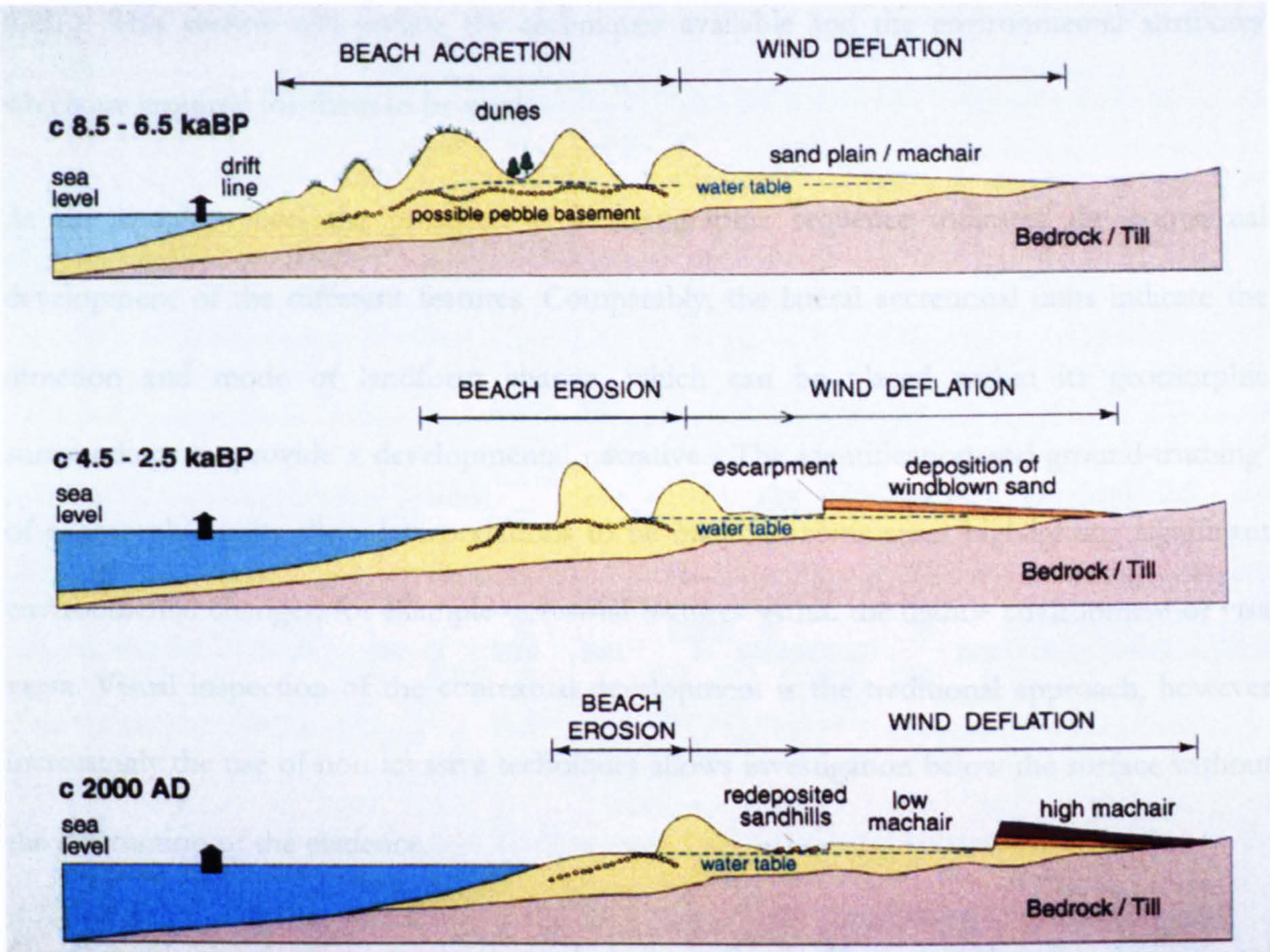


Figure 2.23 Evolution of machair from approximately 6,500 yrs BP to present, highlighting accretionary phase (positive sediment budget) and latter modification as sediment budgets reduce. Source: Hansom & Angus 2002.

2.7 Dating large scale changes at the coast, relative and absolute techniques

Two main types of dating techniques have been used to constrain the models of coastal change presented in the earlier sections: relative and absolute dating. Stratigraphic sequences provide 'relative' ages for horizons which can be compared with their surroundings to inform the general developmental sequence. These generalised approaches allow comparable geomorphic features to be linked in related but separate locations. With the onset of modern dating techniques came the ability to define absolute dates, for the demise of plants via radiocarbon dating and the deposition of sand layers via optically stimulated luminescence

(OSL). This section will outline the techniques available and the environmental attributes which are required for them to be used.

At the simplest level the presence of a stratigraphic sequence indicates the contextual development of the different features. Comparably, the lateral accretional units indicate the direction and mode of landform change, which can be placed within its geomorphic surroundings to provide a developmental narrative. The identification and ground-truthing[3] of geomorphic units allow interpretations to be made, in some cases highlighting significant environmental changes, for example terrestrial features within the marine environment or visa versa. Visual inspection of the contextual development is the traditional approach, however increasingly the use of non-invasive techniques allows investigation below the surface without the destruction of the evidence.

Geophysical investigations are increasingly being refined, allowing evidence to be gathered from hostile, far-reaching or delicate protected environments. Recent coastal examples utilising Ground-Penetrating Radar (GPR) include description of the internal sedimentology of gravel ridges in south-east England (Neal et al., 2003), prehistoric shoreface retreat scarps mapped from GPR profiles (Peterson, et al., 2001) and volumetric analysis of a New England barrier system was achieved using GPR together with coring (van Heteren, 1996). However, GPR may not be suited to all coastal situations as it requires relatively favourable ground water conditions, namely a not fully saturated soil horizon and the presence of fresh water rather than saline water. GPR is unable to distinguish the subtle variations between electromagnetic qualities of the sediments if they are surrounded by highly conductive saltwater (Sensor and Software 1996).

[3] Ground-truthing: a term used principally in Remote Sensing, when features or attributes on the ground are confirmed after being identified previously by other means (e.g. checking the presence of gravel ridges on the ground after locating them in aerial photography).

The relative techniques can be fixed in absolute terms by isolating or sampling certain attributes from the landforms. These can be obvious attributes like archaeological structures and developments that place the landforms not only within a temporal context but possibly environmental and cultural contexts too. Often a combination of techniques can be used to establish a developmental chronology. De la Vega *et al* (2000) used sedimentological approaches to account for the evolution of the Bay of Skaill, Orkney, during submergence and concurrent environmental instability. The sedimentological approach provided the environmental context to an area, which has an exceptionally rich archaeological record, namely the world heritage site of Skara Brae. Their approach utilised accretional units, which were spliced by datable samples, via radiocarbon dating, pollen, mollusc and ostracod analysis.

However, in many cases there may not be datable materials readily available, or there may be restrictions on the amount of disturbance that is acceptable. Sites may also have spatially discontinuous sedimentary units which can be difficult to place into the wider context. In this situation the geomorphology may provide a useful additional source of evidence. Given these limitations alternative approaches are required to fix the geomorphological changes in time. The identification of related assemblages and their juxtaposition can identify relative phases of development, which can be related to comparable features to those within the literature that have been dated. As such research should not rely exclusively on directly datable materials but should include dating indirectly (associations with archaeology for example) from disparate sources which may provide additional context beyond a single date. Possibly the best example of this inclusive method of all available approaches is the development of Glacio Isostatic Adjustment (GIA) models, where the amalgamation of separate discontinuous narratives are integrated into a model, which then can be used to further improve and test alternative forms of coastal development.

2.8 Summary of chapter 2

This chapter has outlined the current understanding of sea level, sediment supply and large-scale coastal evolution. Crucially, however, there is a bias within the literature towards accretional, emergent assemblages which are by their nature preserved and there are relatively few examples from submerging shorelines. Given the increasing dominance of relative sea level rise nationally and internationally (Dawson *et al* 2001, Bird 1988) it is crucial to understand the evolutionary stage of assemblages not only for academic interests; but also for improvements in coastal management necessary in increasingly large threatened areas. The geomorphic development of submerging coastlines and their future evolution has wider implications than just the geographic interests of the area. The presence, absence and dynamism of landforms are the very fabric on which many of the habitats, infrastructure and land-uses operate.

This chapter has summarised what is known about the main drivers of coastal change on submerging shorelines. It has highlighted the interdependence of these factors, for example the role sea level has on sediment supply. The literature documents certain environmental situations where the relative importance of these factors can be gauged, such as very subtle reductions in sediment supply can match the erosion cause by substantial increases in sea level (Figure 2.18 Carter & Woodroffe, 1994). The subject of sediment switching also remains largely untested, especially within areas experiencing relative sea level rise.

This thesis, therefore, aims to investigate the interaction between sediment supply, variations in sea level rise rates and structural controls within a submerging scenario to assess the dominance of these factors through the Late Holocene, through historical times to the present-day. The past and present changes to coastal configuration will allow modes of development to be related to changes in the driving processes, which will be used to consider changes which may be expected under a range of future environmental scenarios.

3 Methods

3.1 Introduction to methods

The aims introduced in Chapter One are repeated below, followed by the main research questions in order to set the context for the methods required to achieve these aims.

- Establish the phasing of coastal evolution over the Late-Holocene and identify changes in the sense and magnitude of driving processes; i.e. how the geomorphology reflects the changes in the driving mechanisms.
- Establish the historical-phases of coastal evolution, reflected within the changing geomorphology.
- Establish the present phases of coastal evolution, reflecting within the present geomorphology.

In order to achieve these aims and a number of specific objectives, the methods employed are laid out below. These include:

- Site selection of an accretional submergent shoreline with preserved relict and active features that reflect changes of sea level and sediment supply.
- Late-Holocene investigations to establish the nature of the oldest remaining geomorphic signatures relative to sea level and sediment supply.
- Historical investigations to establish the adjustments to the coastline over the last few hundred years, reflecting changes in sea level and sediment supply.
- Present investigations into the adjustments to the coastline.
- Contextualisation of Late-Holocene / Historical / Present changes to identify trends and improve understanding of dynamics on submerging shorelines.
- Use these trends to improve the strategic management of submerging shorelines.

3.2 Site selection

An early stage of this investigation was to find a suitable test site within which the interaction of sea level rise and sediment supply could be investigated. The factors relevant to these discussions are presented below.

This section outlines why Orkney was selected as a test site to investigate the changing role of sea level rise and sediment supply and the criteria for site selection within Orkney at Sanday.

Why Orkney? Orkney has:

- A submerging coast, with a relatively simple sea level curve and essentially has nine locations where peat is known to exist beneath marine deposits or high water mark (Sissons 1966).
- Individual basins with both sand and gravel assemblages.

Why Central Sanday[1]? Central Sanday has:

- A submerging shoreline with plentiful supply of sediment available.
- Extensive gravel ridges and sandy beaches that may yield a good sea level signature.
- No human modification to coastal sediment supply.
- Good archaeological and historical record.

This investigation focuses on the evolution of Central Sanday as a test site, by subdividing the area into three beach units, namely Lopness Bay, Newark Bay and Sty Wick. These morphological units will be introduced in turn before describing how the aims of the investigations will be achieved.

[1] The term 'Central Sanday' will be used in the remainder of this thesis and refers to the Central Sanday SSSI highlighted in Figure 3.2 and Lopness Beach.

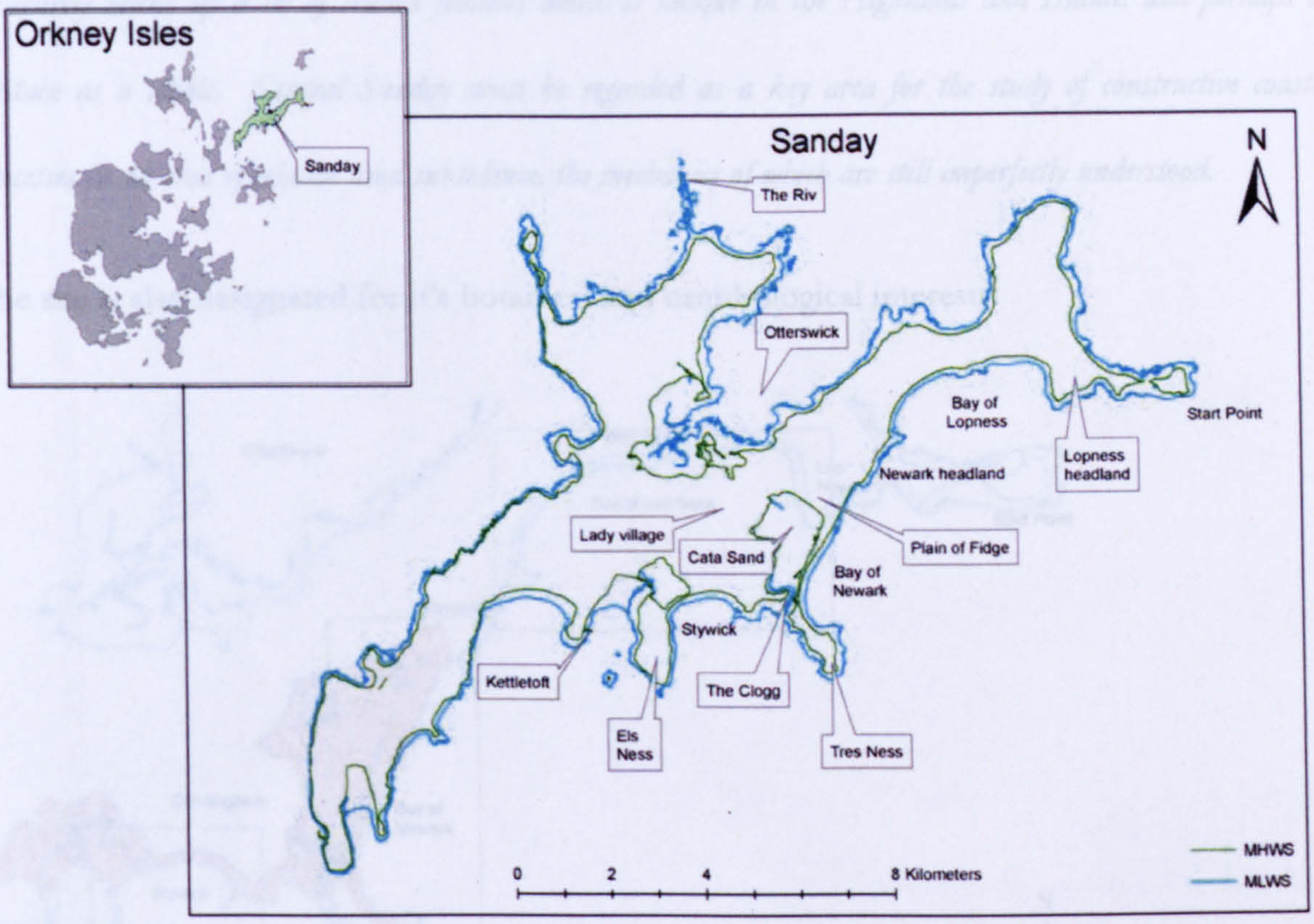


Figure 3.1 The Orkney Isles and Sanday, identifying the beaches of Lopness, Newark and Sty Wick.

3.3 Site description

Sanday's landscape exemplifies the interaction of geological inheritance and balances of more recent Holocene processes, hence its multiple designations (Figure 3.2). Central Sanday (Figure 3.2) contains a unique set of geomorphic features including spits, tombolos, sand flats, sand dunes and machair, all of which remain relatively unmodified by human activity (May & Hansom 2003). It has been recognised as a site of great scientific interest and notified as a SSSI and GCR for the following reasons (Central Sanday SSSI Citation).

Landforms

This site contains an outstanding assemblage of blown-sand and shingle landforms including tombolos (accumulations of sand and shingle connecting headlands and islands), spits, sand-flats, dunes and machair (links) of great complexity. Such an extensive area of machair is unusual outside the Outer Hebrides and the effects of severe deflation are particularly well demonstrated. The tombolos, bars, spits, and shingle ridges, *collectively make up a set of related features which is unique in the Highlands and Islands and perhaps in Britain as a whole. Central Sanday must be regarded as a key area for the study of constructive coastal processes in an area of relative land subsidence, the mechanics of which are still imperfectly understood.*

The site is also designated for it's botanical and ornithological interests.

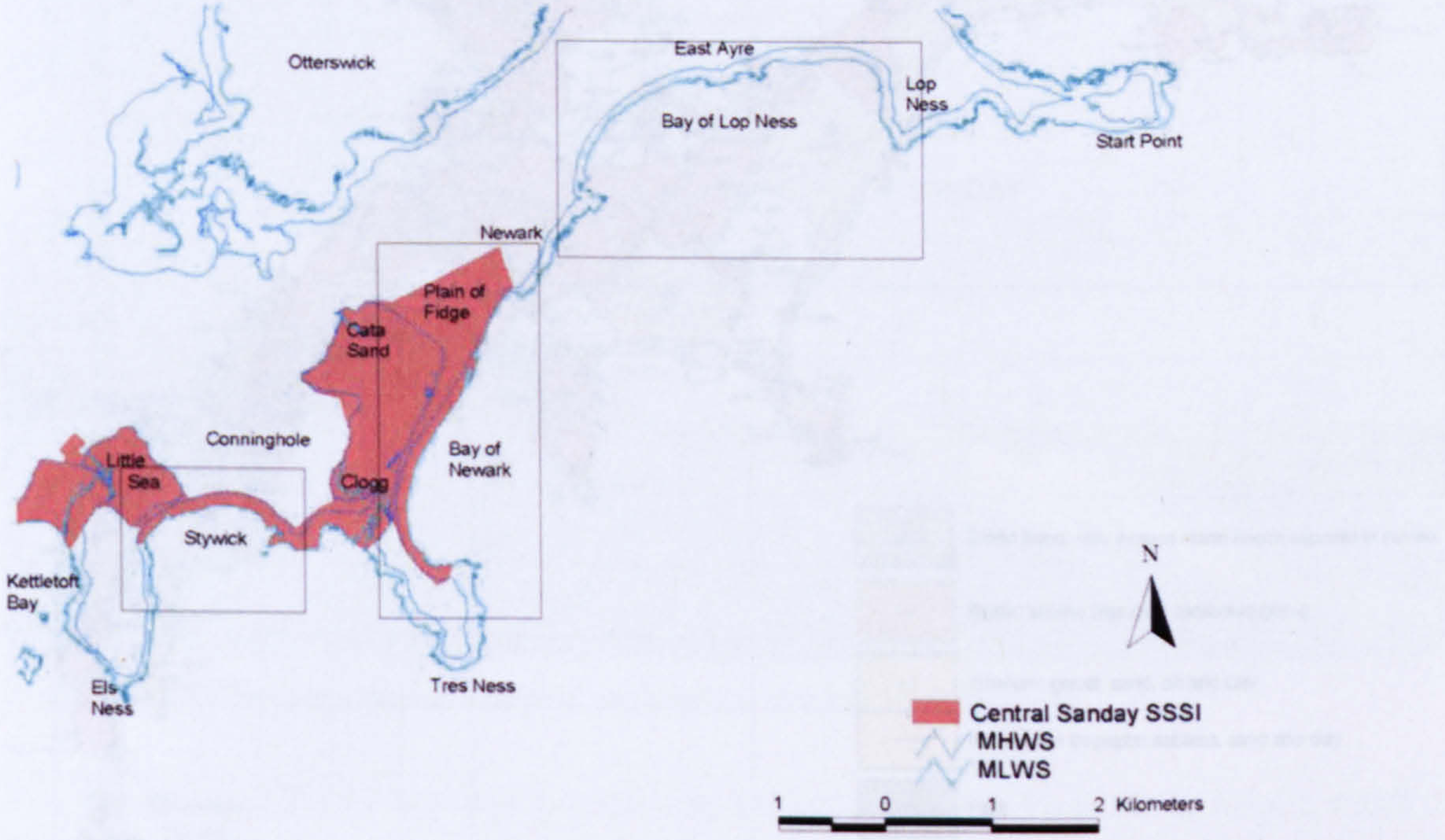


Figure 3.2 Site map of Sanday annotated with Geological Conservation Review (GCR), Site of Special Scientific Interest (SSSI) boundaries and notable locations.

Topographically the island can be divided into two unequal parts, namely the high ground of the southern peninsula, underlain by the relatively more resistant Eday Sandstones, and the low-lying softer Rousay Flags which make up the remainder of the island (Figure 3.3). The Rousay Flags have been shaped by geological and glacial processes have resulted in a lower more sculpted landscape, than that developed in areas underlain by more resistant lithology. The result is a more diverse base on which recent Holocene processes interact and operate. Critically, Central Sanday has gently sloping peninsulas and embayments, whose altitudes and juxtapositions are appropriately placed to allow coastal dynamics to interact with bedrock and sediment to produce landforms that have been preserved.

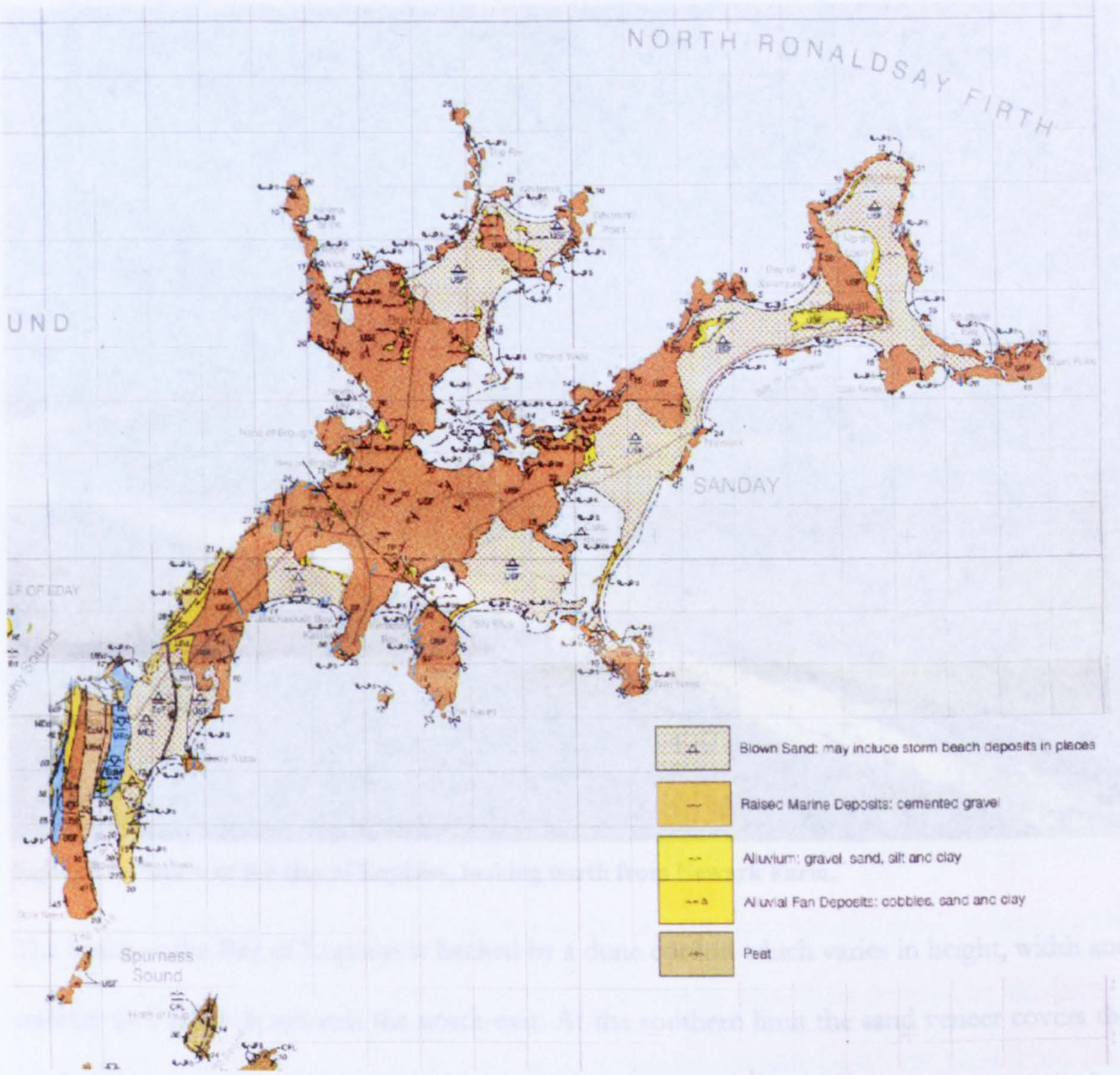


Figure 3.3 Geology of Sanday, Orkney, showing the approximately 1/3 of the island covered in windblown deposits (speckled) overlying the dominant Rousay Flags (brown) and the southern peninsula which is composed of Eday Flags (red) and associated units (pale blue). Source BGS (1999) Orkney islands Special sheet: Solid and Drift Geology.

The Bay of Lopness

Although the Bay of Lopness is outwith the GCR & SSSI boundary it is of general interest as it lies within the same sediment cell as the Newark system. As such it is included within the investigations. At 4.2km in length it is longer than the beaches of Newark and Sty Wick. It's form is controlled by three bedrock anchoring points, namely at Newark in the south, East Ayre in the centre and Lop Ness toward the north-east. Broad sand and gravel bays link these headlands.

Figure 3.4 Picture of the Bay of Lopness, looking north from Newark Farm.

The beach at the Bay of Lopness is backed by a dune cordon which varies in height, width and stability as it extends towards the north-east. At the southern limit the sand veneer covers the eroding till-capped headland of Newark, whilst further north the dunes remain relatively low (<5m) until ~200m west of the rock platform of East Ayre, when the dune height (8-10m AOD) and width increase (up to 40m). The eastern half of the beach is similar to the western half, with dune width and height increasing away from the centre of the beach. The western half of the bay has a relatively stable dune foot; however towards the east the edge is increasingly erosional until it finally undercuts directly the machair edge which is often marked by a field boundary or fence. Archaeological evidence indicates that this eastern limit of Lopness has been erosional for a significant period of time. A Bronze Age cist with crouched incumbent was exposed after frontal erosion associated with the Easterly winter storms of 2000. The site and its context have been summarised by Hansom (2001) and will be referred to later.

Bay of Newark

Within the Bay of Newark low till-capped islands are linked by gravel-cored tombolos, the most impressive of which is 2km long, connecting the island of Tres Ness to the machair of the Plain of Fidge (Figure 3.5). This linear gravel-cored tombolo is capped by a linear dune ridge and connects the till capped headlands of Newark to the north and Tres Ness to the south. In the north the dunes flank the two-tiered machair of the Plain of Fidge. The high and low machair areas are separated by a scarp face, which is deflated by wind and eroded by sheep scrapes and trampling. Stabilised parabolic dunes lie at the boundary of the machair and the intertidal sand flat of Cata Sand to the south. The dune-capped tombolo extends and thins towards the south, enclosing the sand flat and joining the headland of Tres Ness to the Sanday mainland. Low gravel ridge recurves are exposed on the landward side of the Newark tombolo (Figure 3.6). The gravels are laid down in two orientations, those located in the northern half of Cata Sand trending towards the north, and those located in the south, orientated to the southwest. To the west of the tombolo where it joins Tres Ness is the inlet of the Clogg, whose deep channel remains below MLWS. At present tidal floodwaters enter and leave Cata Sand via the Clogg, however a small freshwater spring also contributes water towards the north-western limit of the sands. To the west of the Clogg a gravel draped rocky shore fringes the machair of Conninghole, which extends towards Sty Wick further west.

(a)

(b)

Figure 3.5 The dune capped tombolo of the Bay of Newark from Tres Ness (a) and into the 'gaps' as the beach straightens up.

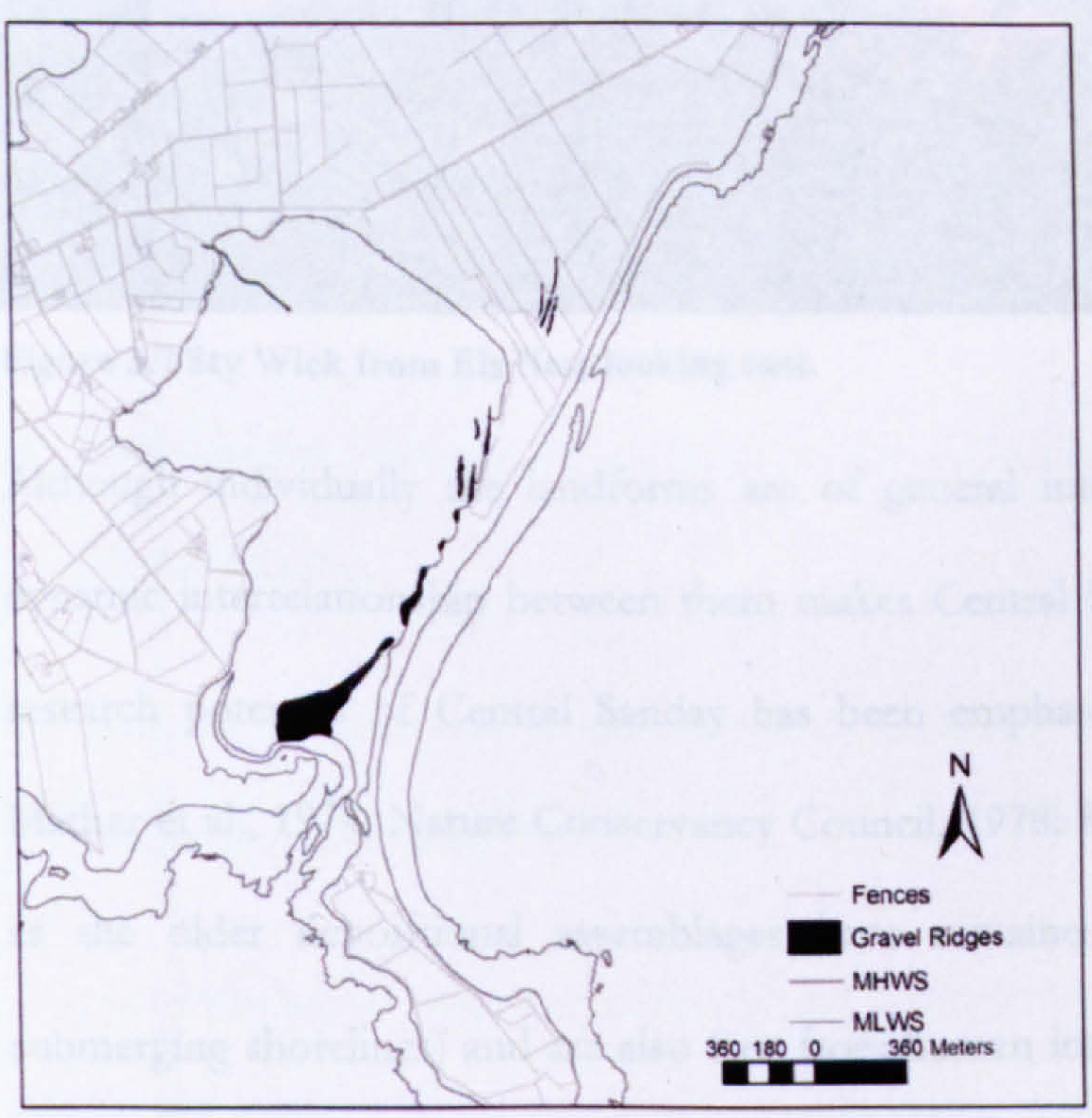


Figure 3.6 Map of the exposed gravel ridges within Cata Sand and the Plain of Fidge.

Sty Wick

Sty Wick, like the Newark dune system, is anchored by two till capped headlands that back onto machair (in the east) and form a tombolo (in the west) thus enclosing the intertidal sand flat of Little Sea. Tidal inundation occurs to the west of Els Ness, via Kettletoft Bay. The beach at Sty Wick's symmetrical bay has a gravel core, which is exposed most regularly towards the headlands. The sand dunes which fringe the tombolo (Figure 3.7) are low and poorly developed, however they increase eastwards up to 10m in height in the vicinity of blowouts in the east-centre section of the beach. The dunes then reduce in height to the east and resemble a stable machair cliff towards the headland to the west of the Clogg.

Figure 3.7 Sty Wick from Els Ness looking east.

Although individually the landforms are of general interest, collectively the complex and dynamic interrelationship between them makes Central Sanday of national importance. The research potential of Central Sanday has been emphasised since the 1970s (Steers, 1973; Mather et al., 1974; Nature Conservancy Council, 1978; Keast, 1994, May and Hansom 2003) as the older depositional assemblages have remained relatively intact (uncommon on submerging shorelines) and are also free from human interference. Thus the resultant island and coastline provides an opportunity to investigate the changes to coastal evolution under differing rates of sea level rise and sediment supply levels.

3.4 Late-Holocene investigations

The extensive marine gravel ridges of Central Sanday capped and fronted by subsequent sand deposits, make it an ideal test site for this project. One of the aims of this investigation is to account for the location of preserved relict features within their geomorphic and geological context, to establish phases of development and investigate the volumes of sediment during each stage of coastal evolution. A number of specific investigations were designed to address the above issues, and methods used to accomplish these investigations are outlined in section 3.4.1 to 3.4.5.

1) Investigate the location of surface gravel ridge exposures within central Sanday and place these within a geomorphic and geological context. Methods used to accomplish this are outlined in section 3.4.1, below. (aerial photography, geomorphological mapping and ground truthing).

2) Investigate the spatial extent of subsurface gravel ridges within Central Sanday, namely in two areas: (a) the Plain of Fidge and (b) Cata Sand.

3) Investigate the volumes of gravel ridges within Central Sanday, namely in two areas: (a) the Plain of Fidge and (b) Cata Sand.

4) Establish the influence of sea level on the availability of sediments in the evolution of Central Sanday.

5) Develop a conceptual model of coastal evolution for Central Sanday. Establishing the extent of surface landforms.

A geomorphological map was produced for Central Sanday, in order to establish the spatial extent and context of the key landforms, bedrock geology, Holocene deposits and habitat zones (Section 4.1.1).

The geomorphological base map was based on recent aerial photography of Central Sanday (summer 2004), provided by Scottish Natural Heritage. The imagery was scanned and incorporated into a GIS (ArcView 3.3 & ArcGIS 8) of the area via a technique known as rubber-sheeting. This is where the image is compared with known features whose precise location is taken from a map or ground survey. The digital image is then mathematically transformed (digitally reshaped) to fit the known precise locations and thus remove most of the tilt distortions and relief displacement inherent in the image. However, there are errors within this process: the "rubber-sheeted" image may not fit perfectly to the National Grid and thus there may be problems in precisely locating exactly the same points on both the map and the photographs. However the planimetric 'fit' for Central Sanday was good and accurate to +/- 5m. The GIS has the resultant geomorphic map, a number of 'layers' of information, including the Ordnance Survey data, aerial photography and ground truthed geomorphic information describing the landforms. The ground truthing was established by verification of the nature and extent of landforms in the field using aerial photographs / geomorphological map and GPS. The boundaries of these features were located on the ground, checked via GPS and plotted onto rubber-sheeted aerial photography within the GIS.

3.4.1 Establishing the spatial extent and form of subsurface gravels

In order to link the spatial extent of the surface gravels with their subsurface structure and extent it was necessary to employ several geophysical approaches, i.e. Ground-Penetrating Radar (GPR), Resistivity Imaging, Auguring and Excavation.

GPR has been used in a variety of coastal environments to investigate the subsurface structure of landforms as a non-invasive approach (Sensors and Software, 1999, Neal *et al* 2002). The literature suggested that the most suitable equipment for gravel and sand architecture would be the PulseEkko 100 system. Discussions with NERC Geophysical Equipment Pool (Edinburgh) staff confirmed this opinion and an application was made to NERC to use this equipment. Loan 609 was awarded for a pilot survey in 2001 together with subsequent investigations in 2002.

Given the juxtaposition of the gravel ridges, tombolo, machair and adjacent saltwater table, the pilot investigation had to ascertain the performance of the GPR in establishing subsurface architecture and the extent of ridges across a number of habitats. The tests addressed the following:

- Can the GPR adequately investigate the architecture and extent of the gravel ridges within the machair area of the Plain of Fidge?
- Can the GPR adequately investigate the architecture and extent of the gravel ridges within the tombolo or areas surrounding the intertidal sand flat of Cata Sand?

As these could only be addressed by field testing, a survey design was drawn up to include areas in which the GPR was expected to work well, together with areas which may be more problematic. Given the orientations of the known gravel ridges the profiles were arranged normal to the strike of the ridge, i.e. shore-normal on the tombolo and tangential profiles on the ridge recurves. In areas where no surface expression of the presence of gravel ridges was visible, the profiles were ordered into a grid estimated to capture any reciprocal set of ridges expected to be adjacent to the visible ridges and possibly emanating from the headland of Newark. This resulted in the following survey design, Figure 3.8.

Figure 3.8 Pilot GPR survey to ascertain the suitability of GPR for establishing the spatial extent and internal architecture of gravel ridges within Central Sanday.

The pilot investigations with the GPR on terrestrial areas was highly successful, however the GPR failed to give good returns in those areas adjacent to saltwater, so two other methodologies (Resistivity Imaging (RI) and auguring and test-pits) were investigated to complement the GPR and extend the subsurface coverage.

Figure 3.9 Proposed survey grid to establish the spatial extent and internal architecture of the Gravel ridges within Central Sanday, via GPR and RI investigations.

The GPR methodology

Subsurface profiling with GPR is analogous to seismic reflection, however GPR utilises electromagnetic energy rather than acoustic energy. The radio waves are typically in the range of 1 to 1000 MHz. Two antennae are placed on the ground, the radar energy is emitted from one, it passes into the ground and is partially reflected by subsurface features to the receiver antennae. The strength of the return signal is dependant on the lithologies, mineralogy and/or the character of the sediment interface (Sensors & Software 1996).

Systems work in three basic ways, namely: reflection, velocity sounding and transillumation (Figure 3.10). Sedimentological investigations generally use the reflection approach to produce a profile of subsurface sediments. As such, the remainder of this introduction will concentrate on reflection methods.

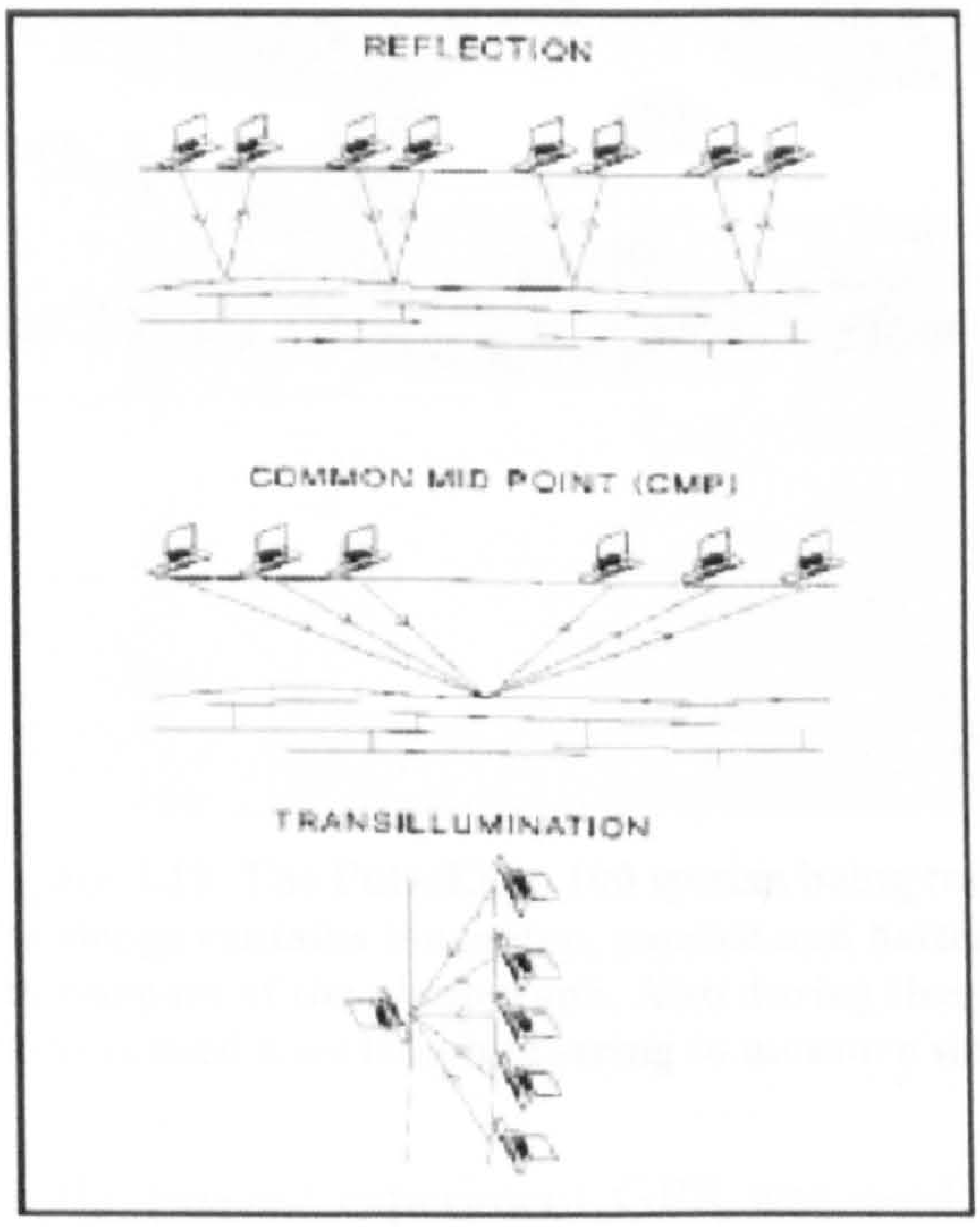


Figure 3.10 Three modes of GPR. Sensors and Software (1999)

The PulseEkko system consists of four main components, including the console, laptop, antennae units and ancillaries (cables and batteries), Figure 3.11.

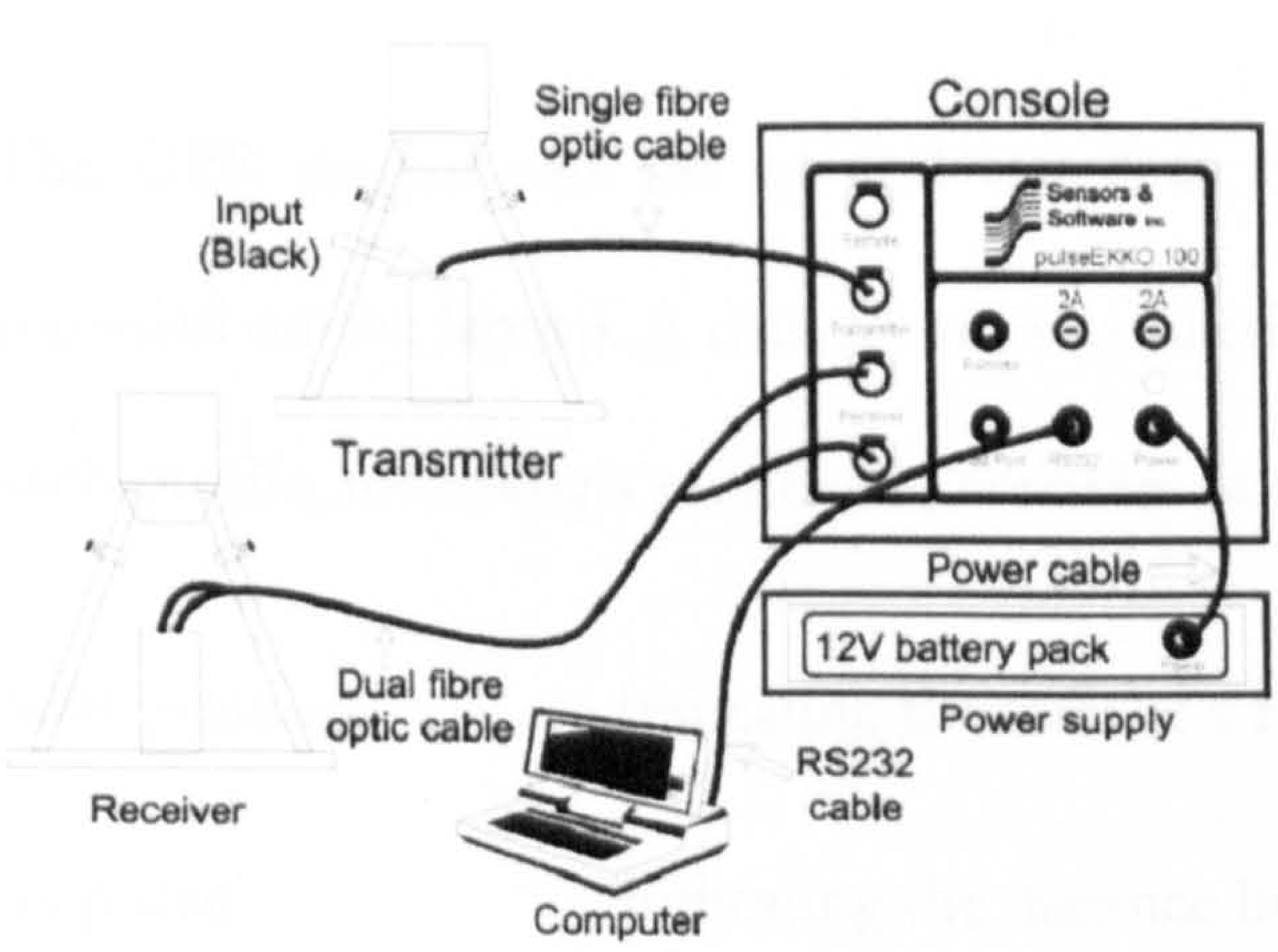


Figure 3.11 The PulseEkko 100 system Sensors and Software (1999)

Figure 3.12 The PulseEkko 100 system being tested in the dunes and sandflat of Cata Sand. Note the sledge contains the laptop, console and battery, and has been pulled closer to the antennas for the purpose of the photograph. Also during these early tests a cloth tape-measure was used, later surveys used a set length of string to measure step size.

In the present experiment GPR was used to reproduce the tomography[2] of known surface gravel ridges and to extend the survey into previously unknown subsurface areas in order to identify unknown gravel ridges and their extents. The internal architecture of the structures and their juxtaposition could then be used to clarify the ridge pattern, spit extension direction and thus inform coastal development.

The GPR system was set up and tested to ensure that the data were being successfully recorded on the laptop. A data-record was filled in to document the system specific set up for each profile, recording a number of variables (a selection of which is outlined below).

Start position	Indicating the start of a run or the continuation of another profile
Step size	Indicating the distance between recordings (normally 0.5m)
Antenna separation	The distance between receiver and emitter, a function of the antennae chosen (2m)
Operating mode	Step, indicating there were gaps between recordings

[2] Tomography is a technique used to obtain a 'plane section' through an object, e.g. an X-ray image.

Survey type	See Figure 3.10, in this investigation 'Reflection'
Title	Records the name of the profile being recorded
Gains	Identifies the amplification of the returned signal – basic gains were always used to negate the risk of over interpretation.
Correction	very basic filters were chosen to clarify the return signal, including a Dewow filter. A stack of 128 was also chosen to emphasise the returned signal – i.e. at each point the system was fired 128 times, the results of which were summed and recorded.

Profiles were setup with temporary bench marks, using wooden pegs (these needed to be non-metallic). The survey network was set designed to investigate the known, and attempt to capture subsurface extensions of the known-ridges (Figure 3.9). The GPR system was set up in its start position and was fired and moved along the profile, firing subsequently at each of the set step-sizes, between the sets of wooded survey pegs. The pegs were later surveyed using the same dGPS[3] setup and methods outlined within the beach surveys. At times the GPR system would freeze or crash, at which point in time the laptop operator would warn the antenna operator, reset the computer systems and reposition the antennae, before the survey could be restarted.

Precautions were undertaken during surveys, these including turning off all radio-related equipment (Phones, Radios and GPS equipment) prior to GPR surveys. In addition the console & laptop were kept a safe (>~7m) away from the antennae, to avoid interference. Some interference was unavoidable and presented the laptop operator with false readings. Farmers fences were known obstacles, however an overhead power cable linking the farm house at Tres Ness produced an unexpected reflector, which went unnoticed until we looked up!

[3] dGPS stands for differential Geo-Positioning System, where two GPS receivers work in tandem to estimate the position of survey points, with very high accuracy, usually better than a few cm in all three directions.

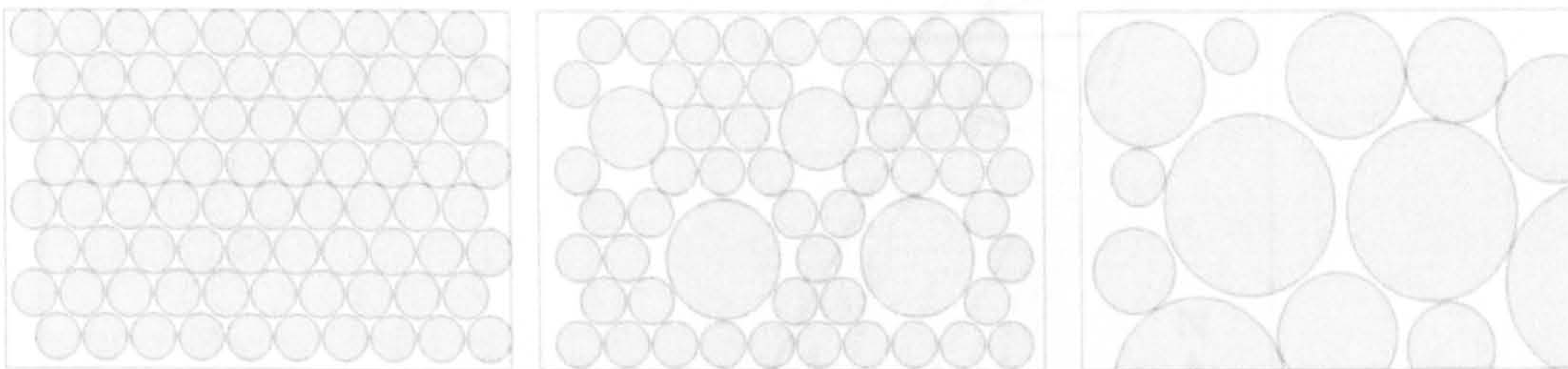
Results were copied over to an external hard drive before being interpreted and very basic gain functions being applied to highlight reflectors within the profile. A number of reflectors within profiles were identified and calibrated for depth, to help constrain the time-window conversion. Although Common Midpoint (CMP) tests were undertaken, auguring proved a more appropriate gauge of depth given the nature of the substrate and the ease of auguring a few test holes. This allowed the vertical axis to be constrained – rather than relying on the text-book values of speed through certain substrates. The dGPS surveys of the profiles captured the topography of the survey, which was incorporated with the GPR plot to reflect the tomography of the landforms.

Resistivity Imaging

The Resistivity Imaging (RI) investigations utilised a Campus 25 system, which consists of a central console, laptop, power supply and the array of electrodes. Passing an electric current between two electrodes and recording the voltage drop over the given distance calculates the resistivity of the subsurface. The array of electrodes employs different pairs of electrodes, thus increasing the distance between electrodes, which calculates the resistivity at increasing depths. The results present a profile of differing resistvites – relating to differences within the stratigraphic units.

Figure 3.13 The Resistivity Imager

RI has been successfully used in a variety of situations; frequently referenced examples are the identification of underground reservoirs and cavities. The approach has also been used within marine environments (Breesnev *et al* 2002, ShaaBan & Shaaban 2001), although as a technique it was unproven within intertidal areas. It was expected that the salt water remaining within the Cata Sand at low tide would lower the resistivity values but that the approach should differentiate between sand units and gravel units. This assumption was based on two trends that the RI should capture the varying lithologies of the sands and the gravels, and more likely the proportion of salt water remaining in the subsurface differentially altering the resistances of sand dominated or gravel dominated units.



Sand – high total grain surface area would result in a lower residue of saltwater, resulting in relatively higher conductivity results.

Sand & gravel – medium total grain surface area would result in a moderate residue of saltwater, resulting in relatively medium conductivity results.

Gravels – low total grain surface area would result in a larger residue of saltwater, resulting in relatively lower conductivity results.

Figure 3.14 Particle packing and changes in Resistivity

The survey grid was designed to extend the profiles from the Plain of Fidge into the intertidal area, crossing the gravel recurves approximately perpendicular to the ridge. The survey grid is shown below.

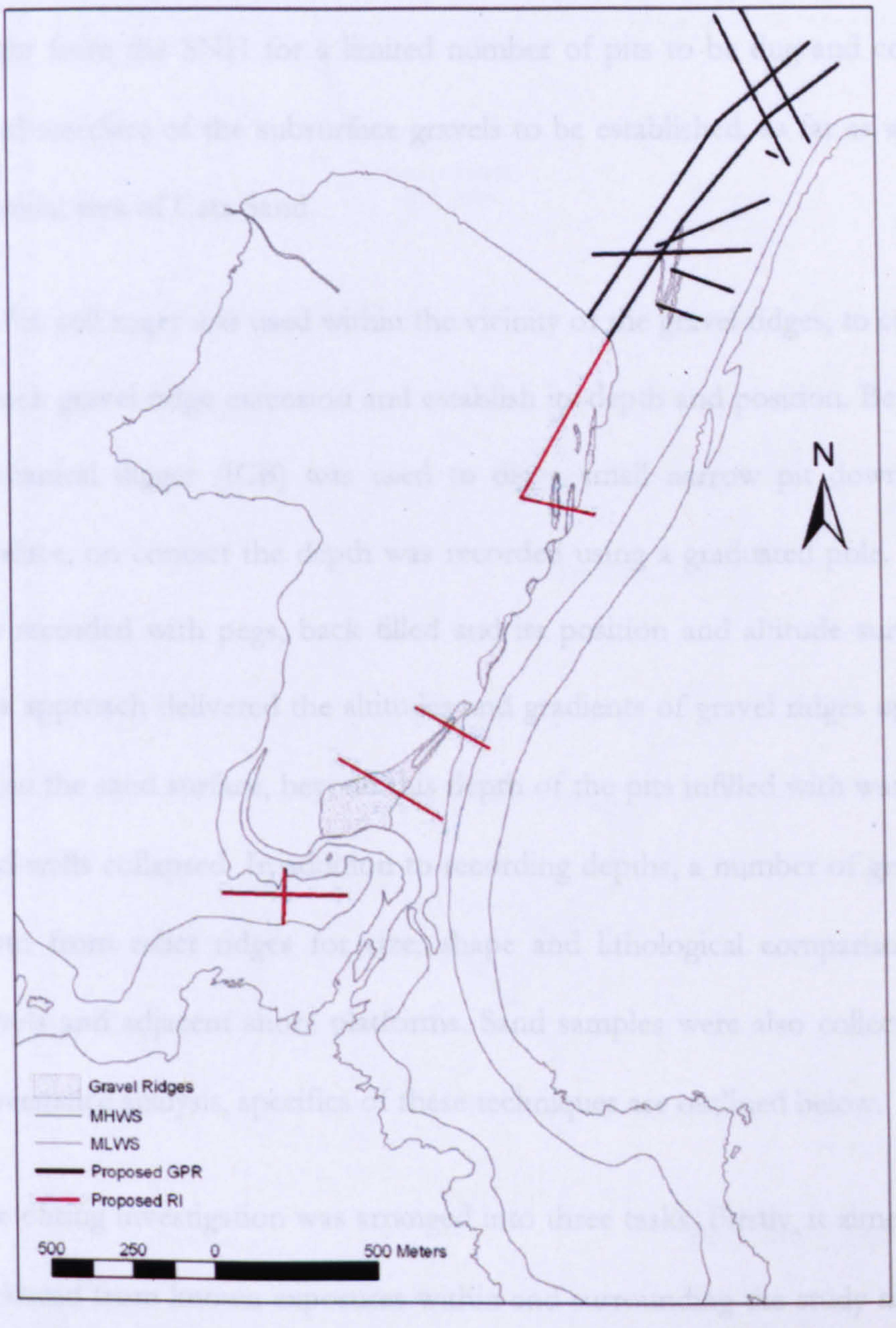


Figure 3.15 Proposed location of RI profiles, shown next to proposed GPR investigations.

Unfortunately the RI technique proved unsuccessful and was not able to differentiate effectively between variably saline saturated gravel and sand areas probably due to the variability of saltwater spatially, vertically and temporally within the intertidal sand flat.

Auguring and Excavation

Due to the poor performance of both geophysical techniques to extend the subsurface investigations into the salt-affected intertidal environments of Sanday, it was necessary to resort to coring and digging of test pits. Central Sanday is a SSSI and so permission was sought from the SNH for a limited number of pits to be dug and cored, to allow the sand gravel interface of the subsurface gravels to be established, as far as was possible, within the intertidal area of Cata Sand.

A 1.3m soil auger was used within the vicinity of the gravel ridges, to core down to the surface of each gravel ridge extension and establish its depth and position. Beyond a depth of 1.3m a mechanical digger (JCB) was used to dig a small narrow pit down to the sand / gravel interface, on contact the depth was recorded using a graduated pole. The location of the pit was recorded with pegs, back filled and its position and altitude surveyed later with dGPS. This approach delivered the altitudes and gradients of gravel ridges up to a depth of ca 2.5m below the sand surface, beyond this depth of the pits infilled with water and the unsupported sand-walls collapsed. In addition to recording depths, a number of gravel clasts were taken at depth from relict ridges for size, shape and lithological comparisons with modern beach gravels and adjacent shore platforms. Sand samples were also collected for particle size and provenance analysis, specifics of these techniques are outlined below.

The coring investigation was arranged into three tasks. Firstly, it aimed to trace the dip of the rockhead from known exposures within and surrounding the study sites, to establish as far as possible the geometry of the geological base upon which the Holocene sediments sit. Secondly, it aimed to establish the surface form of the gravel recurves of the northerly orientated ridges within the northern half of Cata Sand and thirdly, it aimed to establish the form of the Girthes: the south-westerly orientated gravels located towards the mouth of Cata Sand. The following survey grid (Figure 3.16) provided data for these three areas.

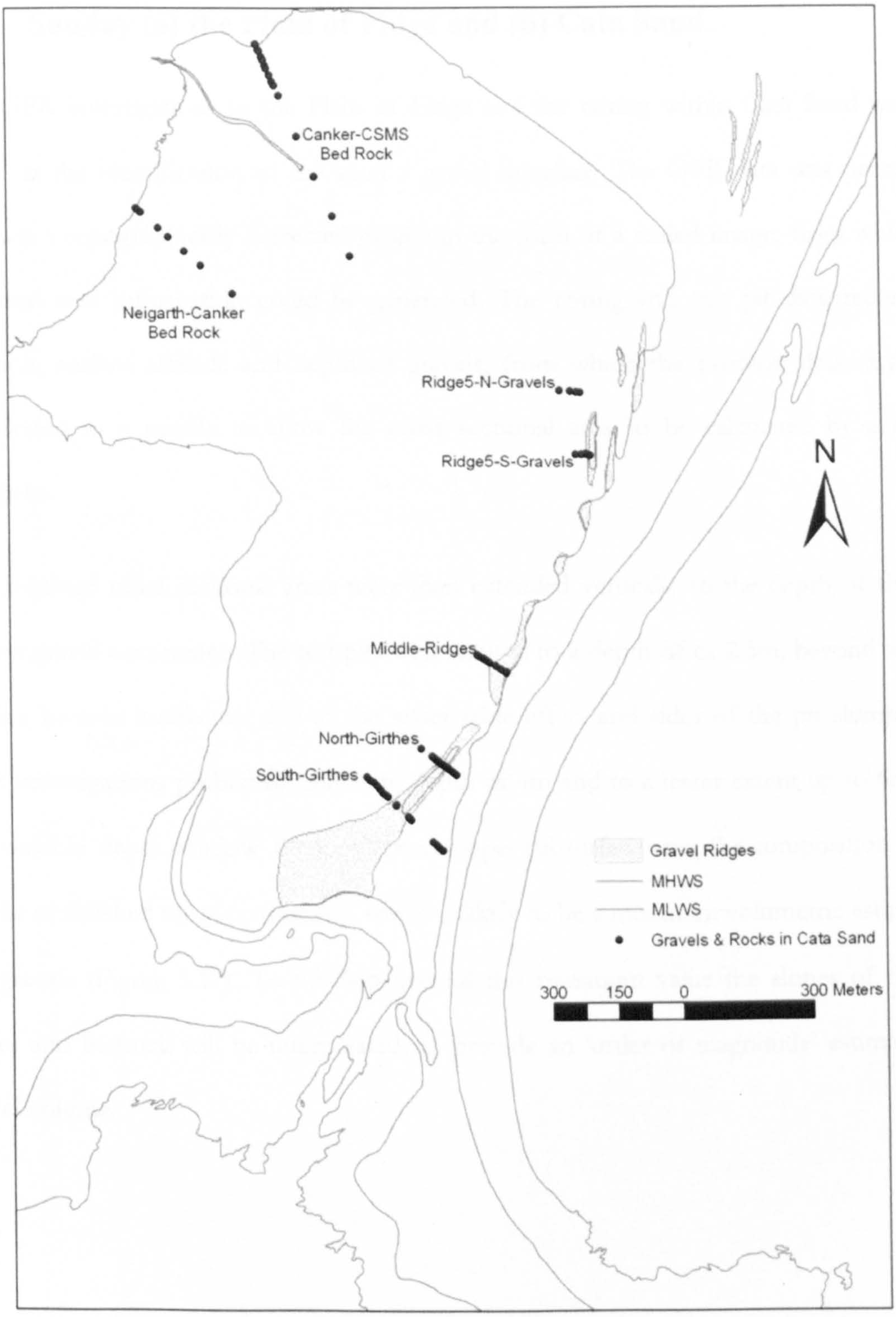
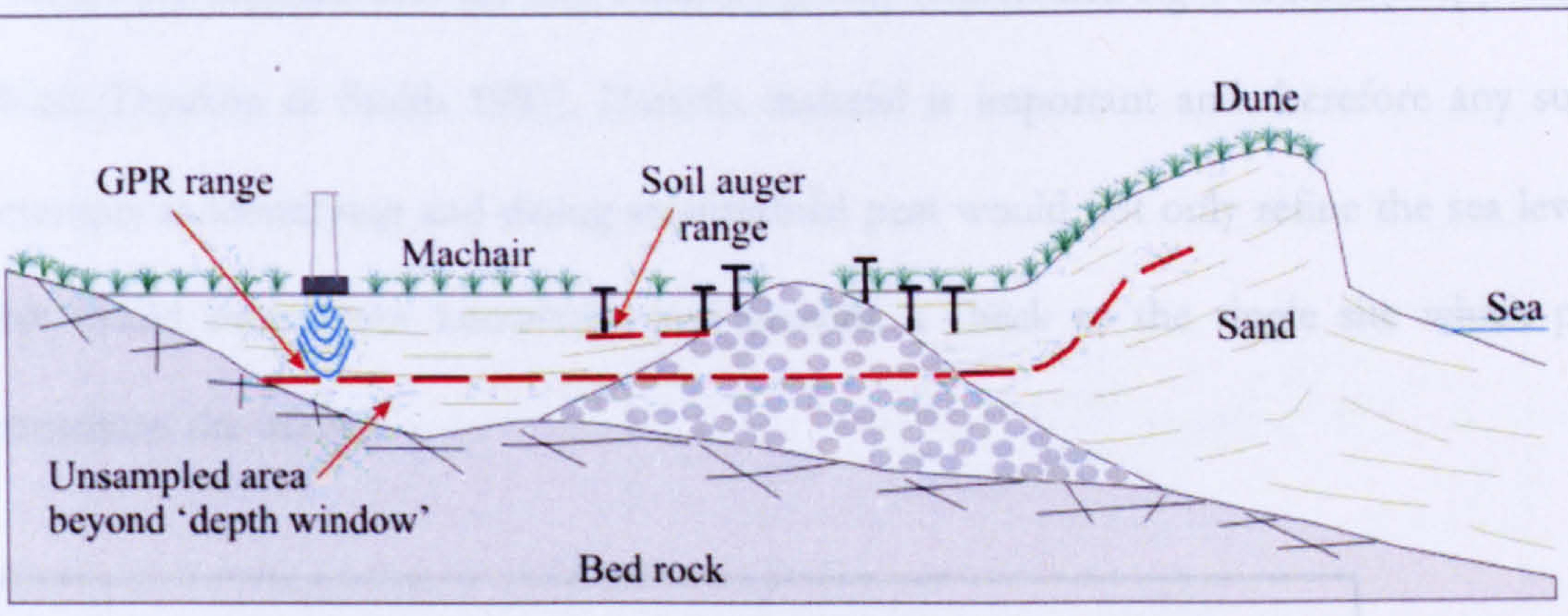


Figure 3.16 Map of subsurface ground truthing work, Central Sanday, Orkney. Note CSMS refers to the Cata Sand Mile Stone, located to the north of Cata Sand.

3.4.2 Establishing the volumes of gravel held in ridges within Central Sanday (a) the Plain of Fidge and (b) Cata Sand.

The GPR investigations in the Plain of Fidge and the coring within Cata Sand were both aimed at the identification of the sand / gravel interface. The GPR data was processed to produce a topographically corrected profile in the form of a scaled image, from which cross sectional area information could be generated. The coring and test pit data recorded the position, surface altitude and depth of gravels, from which the position data (x,y,z) were transferred to a profile to allow the cross sectional area to be calculated by a series of polygons.

The resultant cross sectional areas were then extended vertically to the depth of the lowest known gravel occurrence. The test pits were limited to a depth of ca 2.5m, beyond which the digging became ineffective due to the water table effect and sides of the pit slumping. The GPR investigations probed accurately to depth ca 4m and to a lesser extent up to 6m. Given this variable 'depth window' there will be an upper subsurface area, the composition of which will be established more confidently, which is likely to be a minimum volumetric estimation of the gravels (Figure 3.17). To develop beyond this minimum value the slopes of the gravel ridges and bedrock will be interpolated, to provide an 'order of magnitude' estimate of the gravel volume.



The 'depth window' beyond which subsurface investigations provide unreliable information.

Figure 3.17 Diagram showing the depth window for alternative techniques, depths are quantified in previous paragraph.

Volumes of each section of the gravel ridges will be generated from cross sectional areas (m^2) multiplied by gravel ridge lengths (m), derived from differential GPS surveys of the ridges. This will provide a gross and sectioned estimates of the gravel ridge complex.

3.4.3 Constraining a local sea level curve

Investigations on submerging shorelines often have the problem of a lack of data because the features are lost via frontal erosion or submergence (May and Hansom 2000) and the recycled remnants, if present, are subsequently relocated beyond high tide. However, landforms can remain intact when submerged intertidaly or offshore for a significant period of time, providing they are protected from wave energy and suffer limited recycling. For example blocks of peats are often wash up on submerging shorelines, providing clues to the likelihood of subtidal peat within the coastal cell.

Orkney's sea level curve, like many locations towards the periphery of the former ice-sheet, is imperfectly defined (Figure 3.18). In spite of nine locations of subtidal peat (Sissons 1966) local evidence is sparse and derived from one location (Bay of Skaill, De La Vega & Smith 1996). This has lead to an understandable bias during the construction of the sea level curve (Shennan *et al* 2002), towards the modelled results from adjacent regions where both sea level amounts and an understanding of the rheology of the area are better known. Unfortunately, in

Orkney the adjacent sites are also relatively poorly constrained e.g. Shetland (Hoppe 1965) and Wick (Dawson & Smith 1997). Datable material is important and therefore any successful attempts in identifying and dating an intertidal peat would not only refine the sea level curve but would extend our knowledge and provide a check to the single site which presently constrains the model.

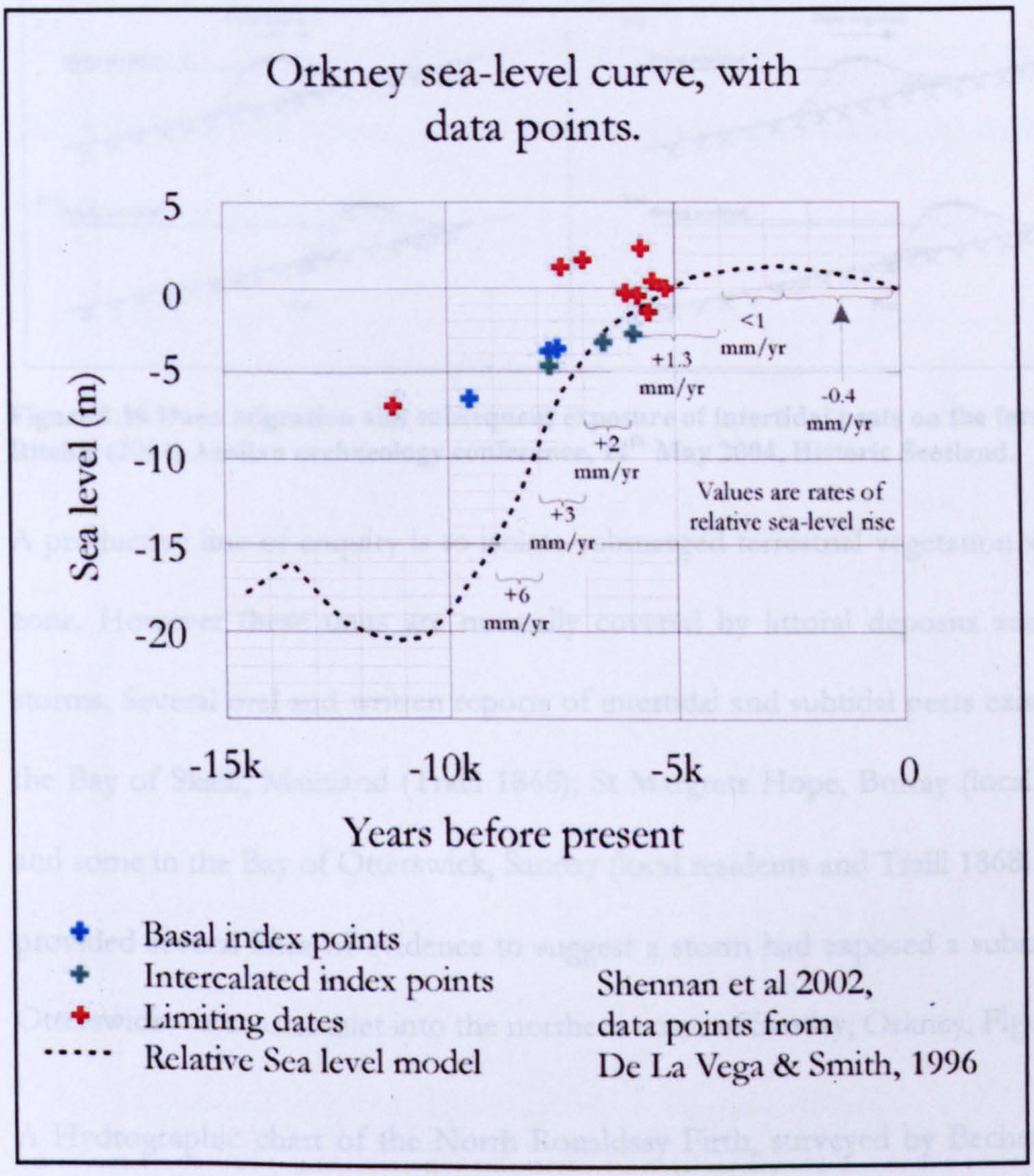


Figure 3.18 Orkney's modelled sea level curve (dashed line is Shennan *et al* 2002) and the only constraining points from Skaill Bay (De La Vega & Smith, 1996)

Intertidal peats are known to occur in Orkney, but caution must be exercised to ensure that the peat units are interpreted accurately, and to ensure that the appropriate environmental change is established. Figure 3.19, summarises how intertidal and terrestrial peats can reveal themselves on the foreshore. It is imperative that the samples are interpreted correctly as subaerial rather than sub-tidal units, otherwise inaccurate rates of submergence will result. Taxonomic classification of fauna should distinguish between intertidal and terrestrial species.

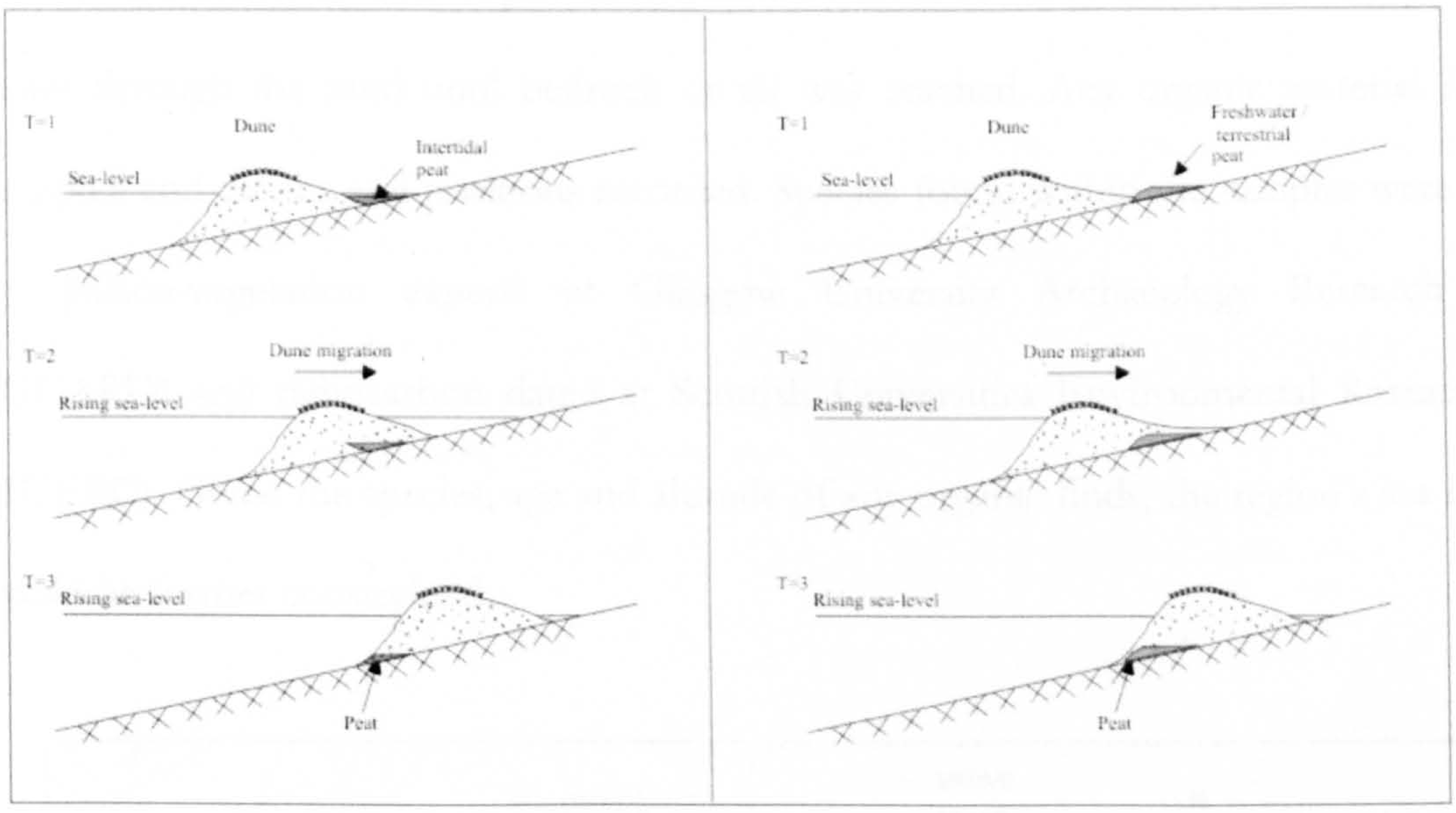


Figure 3.19 Dune migration and subsequent exposure of intertidal peats on the foreshore. After Ritchie (2004) Aeolian archaeology conference, 14th May 2004, Historic Scotland.

A productive line of enquiry is to isolate submerged terrestrial vegetation within the intertidal zone. However these units are normally covered by littoral deposits and visible only after storms. Several oral and written reports of intertidal and subtidal peats exist within Orkney, at the Bay of Skaill, Mainland (Traill 1868); St Margrets Hope, Burray (local scallop fishermen) and some in the Bay of Otterswick, Sanday (local residents and Traill 1868). A literature search provided several lines of evidence to suggest a storm had exposed a submarine forest within Otterswick – a coastal inlet into the northern coast of Sanday, Orkney, Figure 3.20.

A Hydrographic chart of the North Ronaldsay Firth, surveyed by Becher in 1847-48, is the earliest reference to the location of the submarine forest. It records '*Site of Submarine Forest*' between Lamaness Skerry and Helliehow, on the west coast of Otterswick. A number of Sanday's present residents confirm the view of Dr Traill (1868) that 'ample material for this investigation' was available, recalling seeing tree stumps at a variety of locations within Otterswick at extremely low tides. However since 1868, no account (scientific or otherwise) of the forest has been reported within the literature.

Coinciding with the largest astronomical spring tides of the year (providing the largest search area) a mechanical digger (JCB) was commissioned to prospect for buried peats in the Otterswick Intertidal area. A grid search from north to south of the area was adopted; digging holes through the sand until bedrock or till was reached. Any organic material found was sampled and depths and positions recorded. Species found within the samples were identified by palaeo-vegetation experts at Glasgow University Archaeology Research Division (GUARD) and radiocarbon dated at Scottish Universities Environmental Research Centre (SUERC). Given the species, age and altitude of any organic finds, the region's sea level curve could be further constrained.

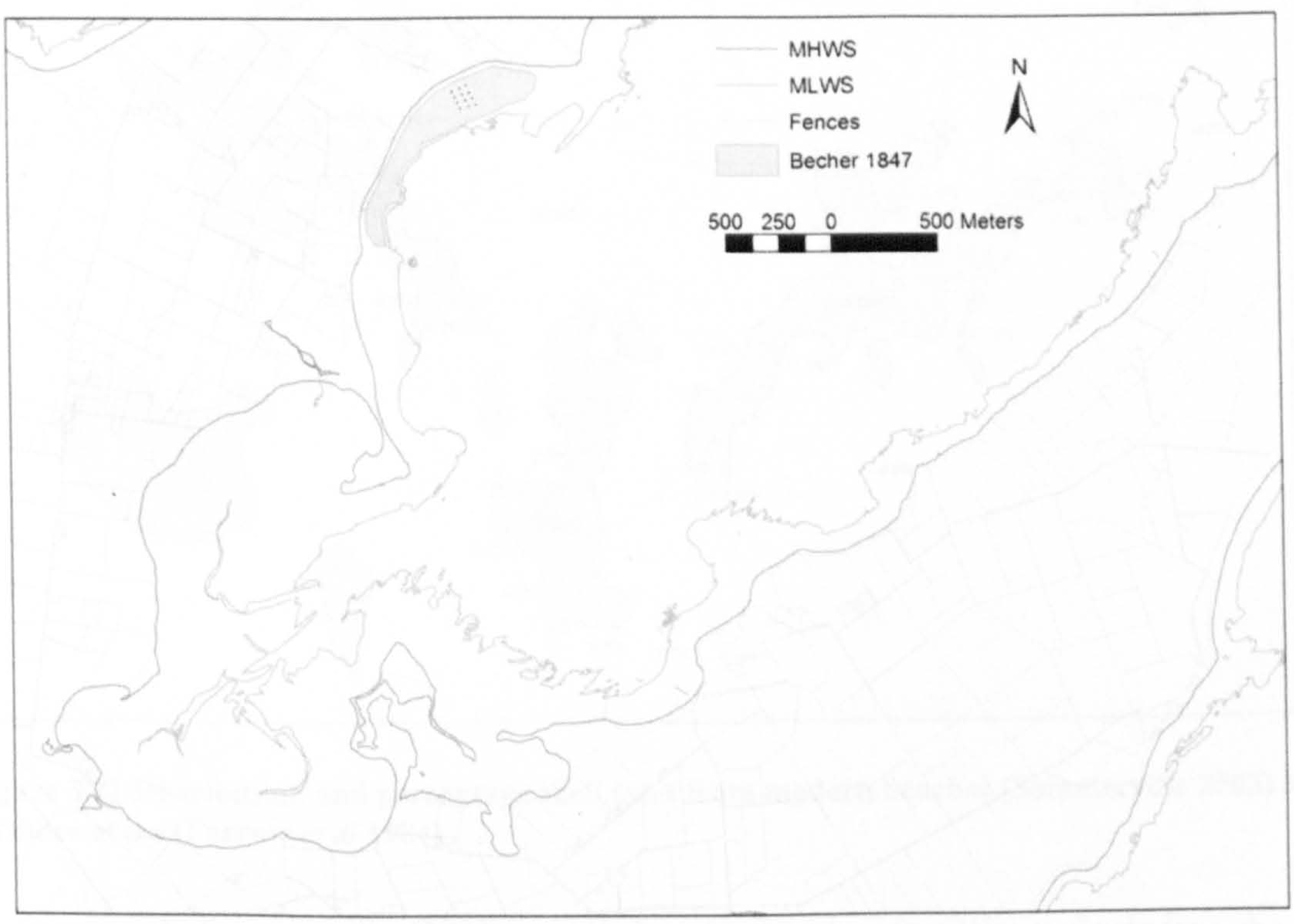


Figure 3.20 'Site of submarine forest' shaded in grey, source: Beacher 1847.

3.4.4 Sediment provenance

Island evolution during submergence is driven both by underlying bedrock geometry and the availability of sediments and so it is important to understand the sourcing pathways that have contributed to the sediment budgets of the Late-Holocene shorelines. Source areas for sands and gravels need to be established and the relative biological and minerogenic genesis of the sand also needs to be investigated.

Farrow (1984) investigated the variations in shell content around the Orcadian archipelago and showed that the distribution of shell sand varied considerably on the nearshore (Figure 3.21) and that production rates indicated the accumulation in the Orkney shelf to be in the region of 10cm/1000yrs and up to 64cm/thousand years. This was associated with a general accumulation rate of 540g/m^2/yr (Farrow *et al* 1984).

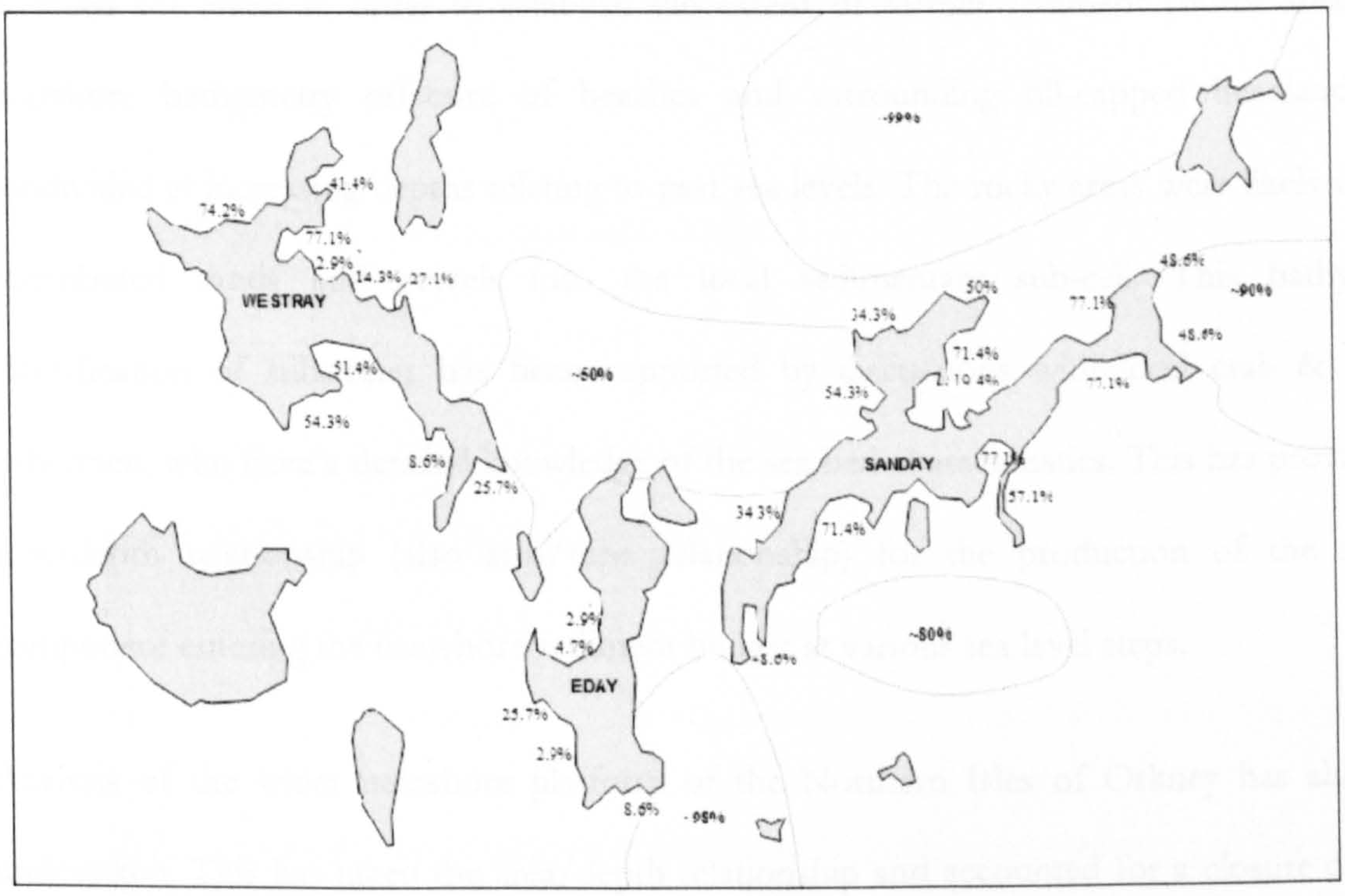


Figure 3.21 Distribution and percentage shell sand from modern beaches (Sommerville 2003) and offshore areas (Farrow *et al* 1984)

More recently Sommerville (2003) sampled many beaches in Orkney (including the beaches studied in this project) and conducted tests to investigate the proportion of calcium carbonate and brightness of grains via OSL (Optically Stimulated Luminescence). In addition to these secondary sources of information, basic grain size sampling was conducted on beach sands from the three study beaches of Newark, Lopness and Sty Wick. This was conducted for basic classification reasons, using a Coulter-counter system (which has the following specification Beckman Coulter, LS Particle Size Analyser, PIDS included, Fluid (water) module), which measures the A-axis of the particle. Given the high biogenic component of the samples, this size classification cannot be used as a proxy for weight, or used in any morphodynamic calculations without further conversion. Samples were collected from the exposed wet lower intertidal, to limit the chances of selecting aeolian size sorted samples, rinsed repeatedly in freshwater and kiln dried, before being processed via the Coulter-counter. Results are presented in Chapter 4.

Reconstruction of the Late-Holocene bathymetry of the island has also been attempted for previous sea levels in order to establish the extent of former sediment source areas. The nearshore bathymetry offshore of beaches and surrounding till-capped headlands was subdivided at increasing depths relating to past sea levels. The rocky areas were likely to have contributed sands and gravels into the local sedimentary sub-cell. This bathymetric identification of substrates has been supported by discussions with local crab & lobster fishermen, who have a detailed knowledge of the sea bed characteristics. This has provided an area/depth relationship (also area/time relationship) for the production of the mineral component entering the nearshore sediment budget at various sea level steps.

Analysis of the wider nearshore platform of the Northern Isles of Orkney has also been undertaken. This has taken the area/depth relationship and accounted for a closure depth to establish the changing potential of biogenic production as sea levels have risen and flooded the archipelago's underwater terrace. This does not account for the mobility of biogenic particles under tidal currents, however it will help clarify the role of local biogenic production, in the approximation of sediment budgets.

3.5 Historical investigations

Given the early occupation of the Orcadian archipelago (~3.6ka BC, Renfrew 2000) it was expected that there was a long record of human occupation on Sanday. Though the early inhabitants left no documentary evidence, the distribution of their settlements has been used to highlight the shape of the island. It is not until the 16th century that more detailed documentary sources exist. However, together the archaeology and historical evidence provides information on a long period of change in the human landscape. Maps are obvious sources of information; however literature and poetry also inform us of the ways that the islands have changed over the centuries.

3.5.1 Prehistoric archaeological evidence

Two central organisations which hold archaeological information for Scotland were approached regarding the distribution of archaeological interests on Sanday. The Royal Commission Historical and Ancient of Monuments in Scotland (RCHAMS) and Scottish Coastal Archaeology and Palaeo Environmantal Committee (SCAPE) both provided spreadsheets of name, location and basic background information of archaeological sites.

To investigate the relationship between prehistorical archaeological evidence and the evolution of the island, all of the known archaeological sites on Sanday (compiled from the Royal Commission of Historic and Ancient Monuments of Scotland and Historic Scotland databases) were age-sorted, checked for duplicates and then entered into a Geographical Information System. The distribution of archaeological interests was analysed and compared against other mapped data, particularly the geological map, to try and associate areas settled at particular time periods and match the information with the geomorphology. If the model is broadly correct, then there should be no 'old / BC' archaeology within the region of the gravel spit and adjacent areas. A map displaying the archaeological settlement positions mapped against known geology and geomorphology should clarify any relationship.

3.5.2 Maps, charts and literature sources

A significant collection of historical maps of Orkney and Sanday exists dating onwards from the 16th century. Understandably much of the earlier work by early European sailors and cartographers summarises the relative position of the islands within the archipelago, rather than accurately accounting for the islands' juxtaposition detailing the coastal outline. Although surveying confidence improves with more recent editions, early maps can be used to highlight important trends. This valuable chronological dataset traces the changes Sanday has gone through during the historical period.

If direct quantification of the differences is to be undertaken, efforts must be made to ensure that the comparisons are appropriate and checks with survey datum and projections are essential to ensure like is being compared with like. Unfortunately given the poorly defined and inconsistent altitudes of coastal delimiters (high and low water mark) in the First and Second Edition OS maps, direct quantifiable comparisons are problematic. Sadly this problem extends to the bathymetric information as well, with much of the island being surveyed in the 1850s. Commander Becher's Admiralty chart of North Ronaldsay (Becher 1848-9) and Orkney (Becher 1850) are still used within the latest version of the Admiralty chart; rendering any change between charts artefacts of the plotting procedure. Comparisons were made between the historical bathymetric work and other surveys including the offshore investigations undertaken for this research and an SNH survey of Sanday's surrounding waters. Older Admiralty charts tend to display soundings accurate to the 1/6 fathom, i.e. 1foot or 0.3m, and as such height changes will be presented with this confidence level. Unfortunately given the draft of the survey vessel used during the SNH habitat survey, nearshore comparisons were not able to be made.

Caution in the interpretation of results is important given the mixed sources of these data. Errors arise from numerous sources including, different datum, alternative surveying techniques, density of depth sampling points and interpolation and averaging during the compilation of the chart. In addition it is known that early cartographers pushed errors out to the edge of their maps and sheets and 'lost' errors in coastlines and lakes (Cole, 1998). Large systematic errors may stem from the non-uniformity or poorly defined levels to which the depths on the chart are reduced (Van der Wall & Pye 2003).

An extensive literature search was undertaken to glean as much information about the coastal changes that have occurred on Sanday. Searches within University of Glasgow and National Libraries illuminated very old documents, maps and etchings including William Daniell's survey of the Islands around Scotland in 1821. The Orcadian libraries uncovered some maps showing early field boundaries. In addition a variety of other sources were discovered, ranging from poetry, paintings and personal stories, which told of wide ranging environmental change. For example the Statistical Accounts outline tax reductions due to the incidence of wind-blow events during the Little Ice Age (Sommerville 2003). Individually, these may deliver little insight, however collectively they may support trends uncovered within other investigations. Insights from these sources will be included in the discussion chapter to provide additional context for the evolution of the island.

3.6 Present geomorphic investigations

In order to establish the way in which the current geomorphology adjusts to current changes in sediment supply and sea level a series of investigations was undertaken. Fluctuations within the sediment budget should manifest themselves in changes in the beach slope, position and volume of sediment at the dune foot and position of the dune crest. These geomorphic changes to the coast have been established by directly quantifying changes to the coastline via GPS profile surveying of changes to the terrestrial beach and dunes, together with radio-echo sounding coupled with GPS position-finding equipment to extend into the near-shore sub-tidal zone.

3.6.1 Terrestrial profile surveying

A base line survey of all of the three beaches within the Central Sanday area (Lopness, Newark and Sty Wick) was first conducted in March 2001 (the first year) and repeated bi-annually to trace the inter-seasonal and intra-seasonal changes to the beach face and dune during the duration of the research. This sampling frequency was chosen as a resource-effective approach that would deliver the changes within the year (end of winter to end of summer) and between years. Profiles were spaced at 100m intervals – following the criteria outlined in Gemmell (1999) this spacing identified as statistically effective to capture the most of change on the beach without over sampling. The shore parallel transects originated at the temporary bench marks at the back beach, machair or stable dune area (detailed below) and extended to approximately MLWS. Surveys were timed to coincide with low spring tides in order to allow the maximum beach area to be captured and allow overlap with MHWS nearshore survey by boat.

The surveying was conducted using a Leica S500 differential GPS unit. At each of the three beaches, a base station was positioned on a prominent dune summit and marked by a temporary benchmark. These temporary benchmarks were then linked into the Ordnance Survey gird via an OS milestone & benchmark located at the northernmost point of Cata Sand (HY704414). Thus all surveys were repeated from the same reference point in order to ensure the objectivity of repeated observations. Repeat surveys were processed from the temporary benchmarks by a process known as forcing; where the base station is relocated at the same ground position for subsequent surveys and the position is entered as a 'Control Point'. All survey data was then post-processed from the 'Control Point'. The rover unit was set up for each surveyor, with individual stationary height and walking height set. Profiles were walked and stationary points were recorded at each break of slope to capture the detail of the dune and beach form from the back dune area to approximately LWST.

Data was processed using SkiPro surveying software (v2.50) and checked for errors before being transformed from WGS84 to OSGB36('02). This resulted in positions being displayed in Eastings and Northings and orthometric heights above Ordnance Datum (Kirkwall). The data were copied into a spreadsheet and interrogated to ensure that only the transects remained and all other points were not used in comparisons. These were converted into a text file and incorporated into a GIS (within ArcView v3.2, ArcScene v8.3) to compare successive surveys. Part of the SKiPro processing procedure established the errors within the survey data, this is termed the ambiguity status. If the SkiPro software could not resolve the ambiguities ($\delta X=$, $\delta Y=$ & $\delta Z=$) the survey points could not be used within the remainder of the analysis.

Within the GIS each set of profile data was converted into a Triangular Irregular Network (TIN). The TIN is composed of irregularly shaped triangles with a data point at each corner, which form a surface. This surface is converted into a 1m resolution grid, with each grid located over common datum – to ensure that positional data overlie each other. Using the map calculator function within ArcView 3.3, calculations were performed between grids to calculate the changes occurring over a 6 month period (beach1summer) subtracted from (beach1march). To ensure only the area overlapped by both surveys is included, the result was multiplied by a surface whose perimeter overlays both profiles. The resultant change surface can then be shaded appropriately to highlight the gains and losses experienced between surveys.

An artefact of the TIN approach is over-interpolation between profiles, where limited supporting data exists. Any change data reported here was derived from points close to the profiles, thus relating more to the changes at the profiles than the interpolations between profiles. Patterns within individual profiles will be discussed, before the general trends between profiles are presented to account for the whole beach. The change surface ($beach_{t=1} - beach_{t=2}$) can also draped over one of the survey grids to produce a 3D shaded digital terrain model, which can be viewed, manipulated and navigated within using ArcScene (ArcGIS v8). Oblique images have been used to provide topographical context to the changes.

3.6.2 Near-shore subtidal surveying

To extend topo-surveys beyond the intertidal, near-shore surveying was also carried out to coincide with the summer surveys. This allowed the supra-tidal biannual morphological changes to be compared with annual changes to the near-shore. Winter offshore surveys were not conducted due to logistics and safety issues relating to rough nearshore sea conditions in winter and short daylight length. The nearshore surveys were carried out using a 7m Rigid-hulled Inflatable Boat (RIB) with a 90 Mercury power-plant and a 8 Yamaha auxiliary engine. Soundings were recorded on a SonarLite system with a transom mounted transponder harmonised with the dGPS surveying system. Although the RIB could manoeuvre and survey in depths as shallow as 0.3m, a member of the boat team wore a dry-suit and assisted in the shallows. Safety procedures were adopted throughout all boat work, including the use of lifejackets, VHF radios on and offshore and all boat occupants were RYA Powerboat certified prior to the first season.

Offshore surveys were organised to coincide with MHWS to ensure that there was an overlap between terrestrial surveys (undertaken at MLWS). Due to the subdued nature of the offshore profile the transect spacing was set at 200m, aligned with every alternate terrestrial profile. A spotter located at the temporary benchmark of each profile and using a radio, talked in the surveying boat along a shore-normal bearing, aligned with a large target at high water mark. For profiles heading offshore a spotter on the boat updated the driver with corrections to ensure they remained online with the temporary benchmark and high water mark targets. Profiles extended from a depth of approximately 15m (beyond closure depth) into the surf zone. As a further accuracy check a Garmin ETreck handheld GPS, with pre-loaded waypoints was used offshore to ensure the accuracy of the offshore survey lines.

The surveying procedure utilised slightly different settings due to software improvement between years. The Leica S500 differential GPS unit was used with a SonarLite echo-sounder. Due to timetabling clashes the Departmental GPS system was unavailable, as such an identical Leica system was loaned from NERC GEP (Loan #691). During the 2001 season the Sonarlite's clock was synchronised with that of the GPS and a stopwatch. At the beginning of each profile the time was noted. Onshore the GPS data was processed and along with the SonarLite data was then cropped appropriately and joined using the time as the identifier.

The 2002 summer season utilised a Leica GPS system, however due to software upgrades an alternative approach was attempted. Due to the software upgrade the Leica console could import data from a separate source. The SonarLite was linked into the GPS via a data cable, through which it output depths at a frequency of 1Hz. The unit held this depth value in a memory cache and when it recorded a surveying point it would copy the latest depth reading. Due to the significant operating costs of the boat, we needed to be confident that the results were of an acceptable standard, prior to shore-based post-processing. To this end the GPS base-station set to radio corrections to the rover (located on the boat) that would then calculate its position and accuracy in real-time.

3.6.3 Geomorphological mapping

A geomorphological map was drawn up of Central Sanday, to establish the spatial extent and context of the key landforms, bedrock geology, Holocene deposits and habitat zones. The methodology was outlined in Section 5).

3.7 Conceptual model of the evolution of Sanday's coast

Integrating the subsurface GPR investigations, the geomorphology and bathymetry of the area, and the sea level history should allow a model of the coastal evolution of central Sanday to be produced. The time-steps of the model will be approximate but chosen to provide insights into coastal change at different time periods. The presence of rocky headlands is the base of the model – the canvas on which the different layers of geomorphology were painted (deposited), rubbed out (recycling of sediments) and re-painted (deposited again). As the coastline is submerged by rising sea levels the former deposits will be eroded, recycled and re-deposited as younger landforms at different locations, heights and orientations all reflecting more recent sea levels and sediment supply conditions. Fortunately in central Sanday several fragments of these former beaches have been preserved as gravel ridges indicating shorelines whose orientations do not conform with that of the present one. These represent earlier time-steps and are located towards the southern end of Cata Sand. Subsurface investigations will also identify any ridge extensions beyond by their surface exposures.

Establishing the position of the earliest coastlines is more problematic, since no geomorphological features are likely to survive from that time. It is nevertheless possible to approximate coastal development based upon the altitudes derived from the sea level curve (Figure 3.18) and matching these against landform height, orientation and altitude derived from the coastal bathymetry. Where sea level impinges upon bedrock surfaces, reconstruction of the former coastline is possible with a reasonable degree of confidence. A lesser degree of confidence will be attached to soft sections of the coastline, since these are likely to undergo significant fluctuations in shape and volume. In spite of this constraint, it should be possible to sequentially construct shorelines based upon the orientation of surviving geomorphology, sea level curve derived altitudes and existing bathymetry.

Matching the altitudes of gravel ridges to any sea level is fraught with uncertainty and assumption. It is assumed that the intertidal altitudes of the ridges in Cata Sand and under the Plain of Fidge have not undergone significant winnowing and settling and so provide an accurate height. Comber (1993) used the altitude of emerged gravel ridges in association with sea level curves to approximate an age for gravel ridge deposition. He found that down-drift height reduction in altitude along recurves meant that recurved sections of gravel ridges could not be related to sea level. However, straight sections of emerged gravel ridge often bore a predictable local relationship to sea level. Comber (1993) used a conversion between mean sea level and gravel ridge altitude of ca. 3.2m (± 0.9m) for the active straight ridges on a part-buried gravel spit system at Culbin on the Moray Firth coast of the Scottish mainland. Following Comber (1993), the assumption here is that the similar part-buried gravel ridges in Sanday were ca. 3.2m above the mean sea level[4] during formation. Fortunately, this coincides exactly with the maximum altitude of gravel deposition elsewhere on Sanday at present.

The model of coastal evolution derived from the above procedure should provide an "order of magnitude" estimate of the amount of coastal change that has occurred in Sanday (Chapter 4). Work is ongoing to estimate the volume of source material and the volume of deposition in order to produce an approximate sediment budget over time.

Corroboration

Given the expected time window during which the shape of Sanday has become radically altered and the relatively well-preserved Neolithic records, on the island, there may be a comparable signal within archaeological distributions on the island. A map displaying the archaeological settlement positions mapped against coastal position derived from the model should clarify the relationship.

[4] Mean sea level was estimated as the midpoint between published Admiralty values for MHWS and MLWS.

4 Results

4.1 Present geomorphology

A fundamental underpinning of the understanding of the way in which the sites on Sanday (Figure 4.1) have developed over the Holocene is to have a detailed knowledge of the surface geomorphology of the site in question. This following section presents geomorphological maps of the sites and reports the main features and points of relevance to the project aims.

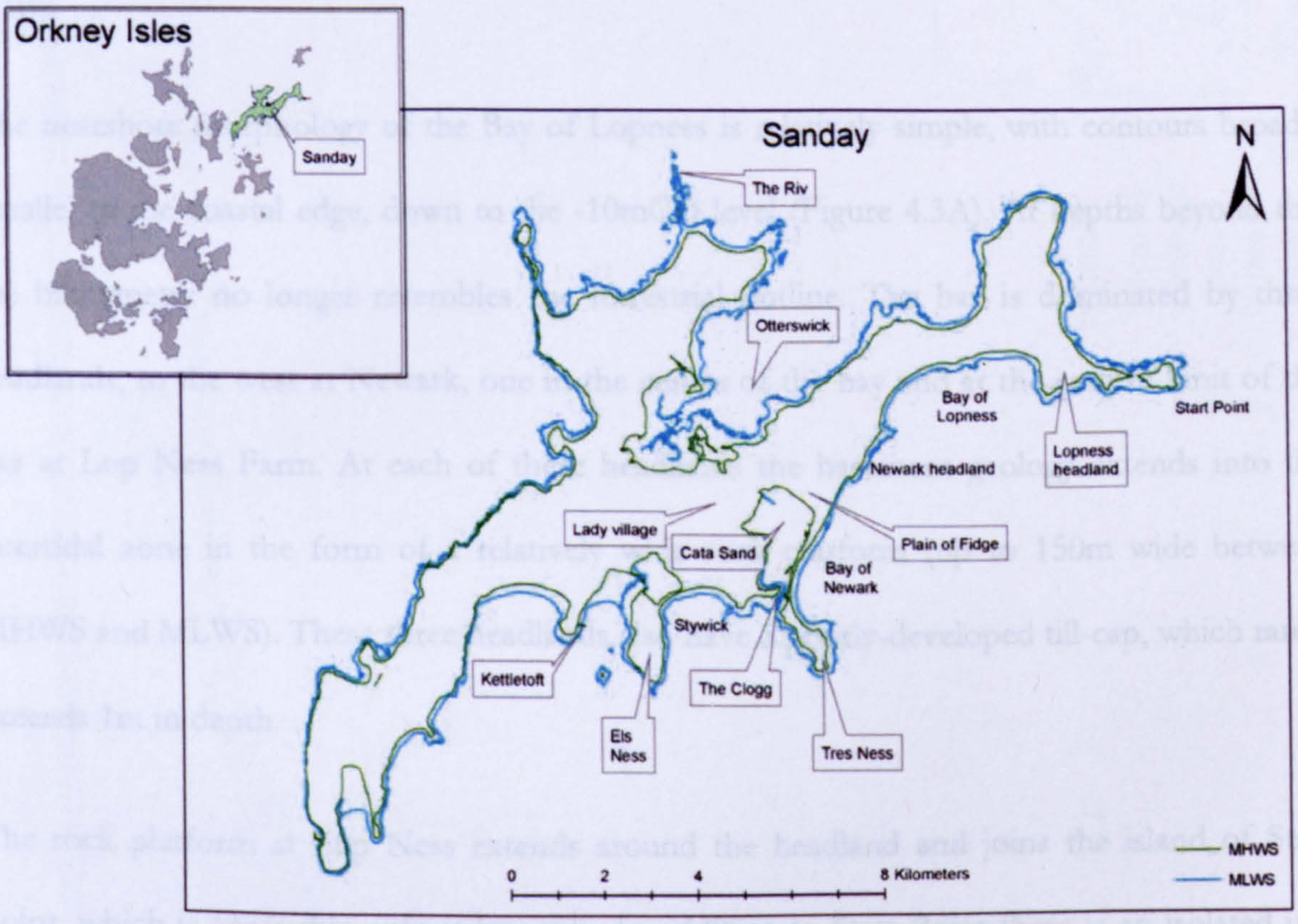


Figure 4.1 Location map of Sanday, showing areas of interest for this project

Note all altitudes, unless stated otherwise, are based on Ordnance Datum (Kirkwall) which has been taken from a spot height located on the milestone at Cata Sand (59°15'28.8817"N, 2°31'19.97211"W, Elliptical height 54.017m, Orthomettric height 3.35m OD(Kirkwall) Processes via OSGB36('02)).

The GCR and SSSI site of Central Sanday contains a unique set of assemblages including spits, tombolos, sand flats, sand dunes and machair, which remains relatively unmodified by human activity (May & Hansom, 2003).

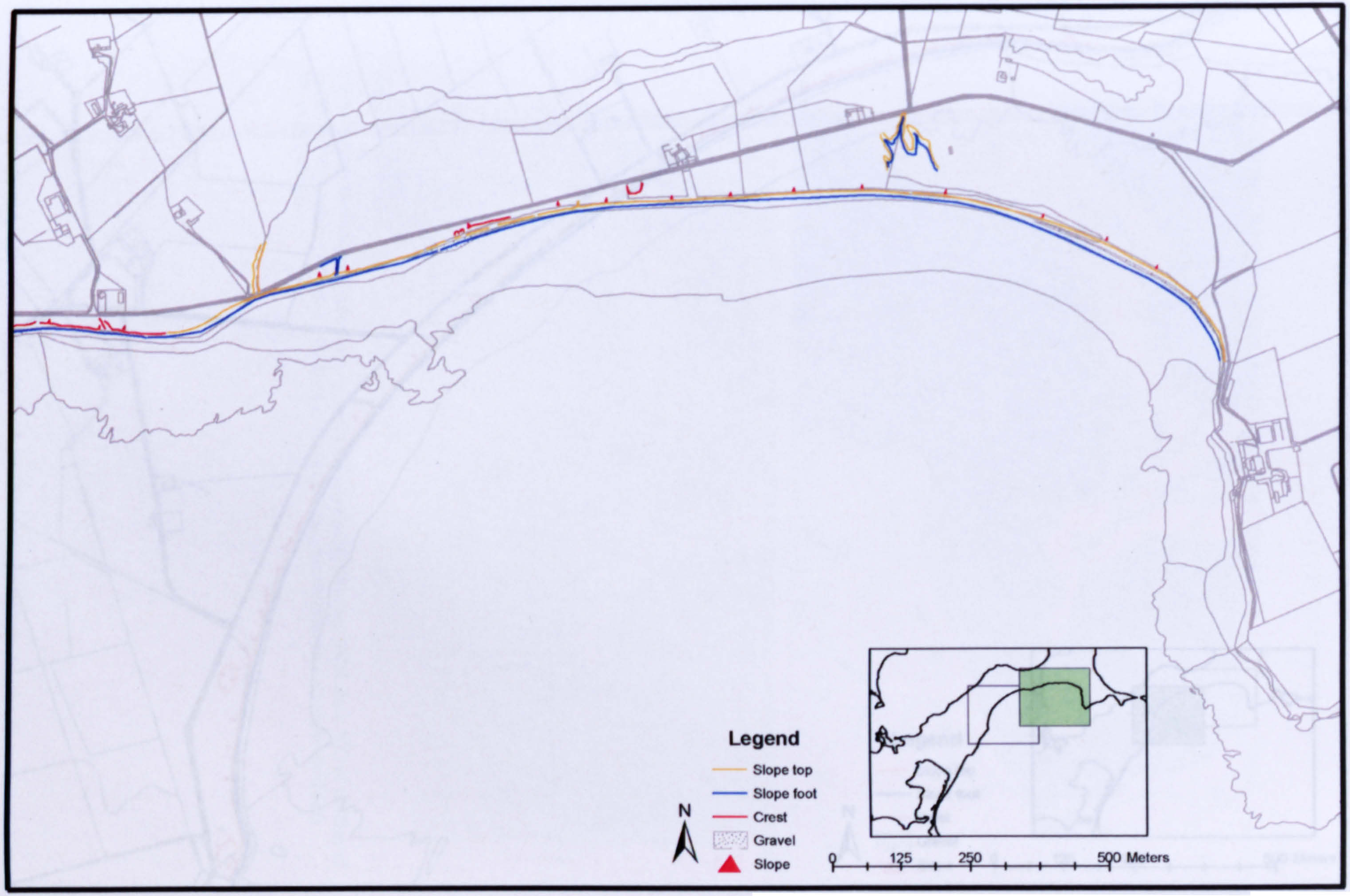
4.1.1 Lopness - surface and nearshore geomorphology

The surface geomorphology of the Bay of Lopness was introduced within Chapter 3 to provide context for the methodology. The following section contains the geomorphological map (Figure 4.2), also documents the bathymetry (Figure 4.3A) and geology of the bay (Figure 4.3B).

The nearshore morphology of the Bay of Lopness is relatively simple, with contours broadly parallel to the coastal edge, down to the -10mCD level (Figure 4.3A). At depths beyond this the bathymetry no longer resembles the terrestrial outline. The bay is dominated by three headlands, to the west at Newark, one in the centre of the bay and at the eastern limit of the bay at Lop Ness Farm. At each of these headlands the basement geology extends into the intertidal zone in the form of a relatively wide rock platform (up to 150m wide between MHWS and MLWS). These three headlands also have a poorly-developed till-cap, which rarely exceeds 1m in depth.

The rock platform at Lop Ness extends around the headland and joins the island of Start Point, which is accessible only at low tide. In addition to Start Point there is an isolated un-named topographic high, approximately 1.5km off the Newark headland at a depth of -9m (Figure 4.3A).

Lopness (East) coastal geomorphology



Lopness (West) coastal geomorphology

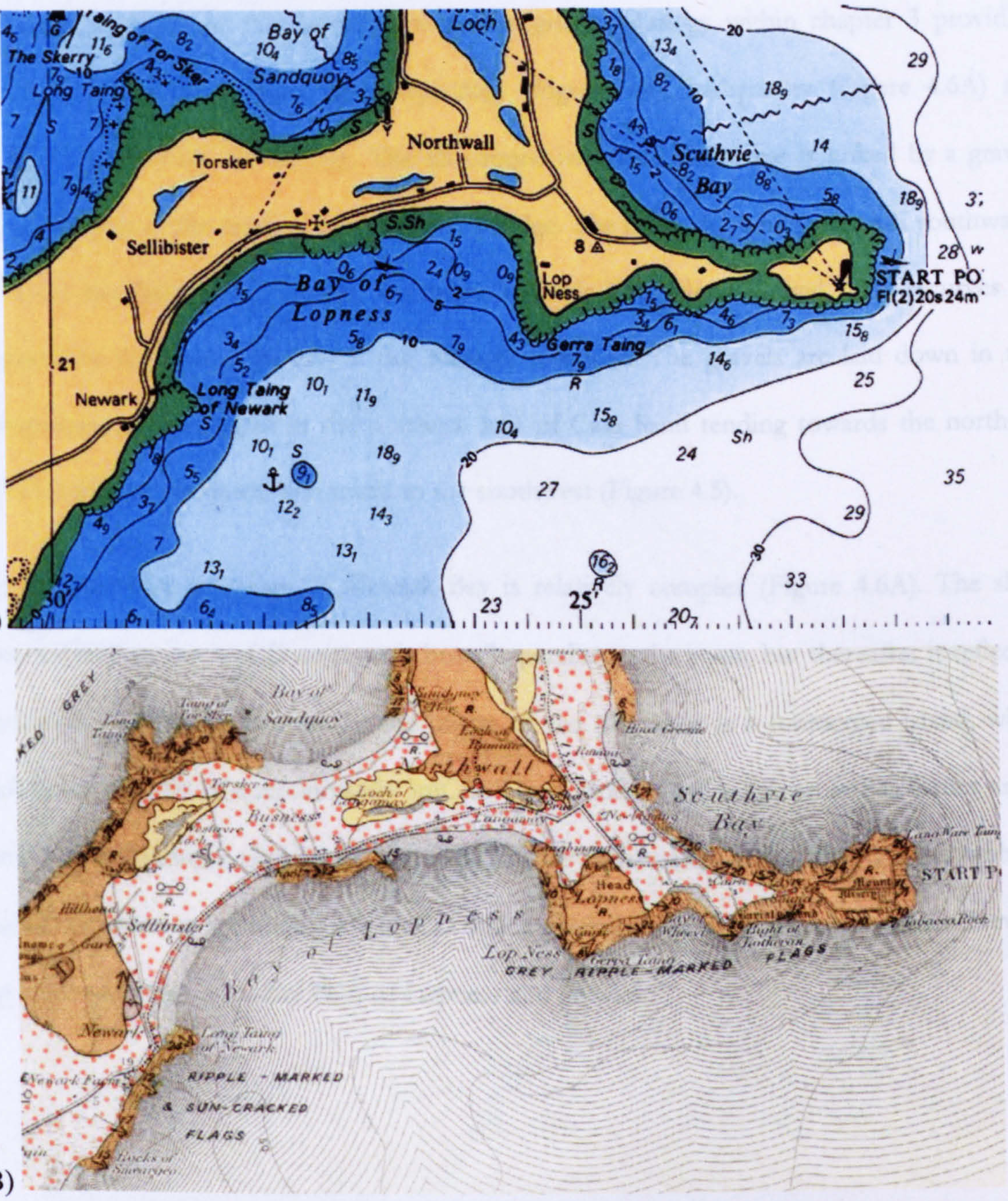


Figure 4.3 (A) Bathymetry (Admiralty chart 2250) and the (B) Geology (BGS sheet XX) of the Bay of Lopness Note geology is shaded with Rousay Flags (brown), windblown deposits (speckled) and alluvium (yellow).

4.1.2 Newark - surface and nearshore geomorphology

This section augments the introduction to the geomorphology within chapter 3 providing greater detail on the surface geomorphology (Figure 4.4), bathymetry (Figure 4.6A) and geology (Figure 4.6B) of the bay. The till capped island of Tres Ness is linked by a gravel-cored tombolo to the machair of the Plain of Fidge. The linear dune ridge extends southwards from the headland of Newark to the north towards Tres Ness. Gravel ridge recurves are exposed on the landward side of the Newark tombolo. The gravels are laid down in two orientations, those located in the northern half of Cata Sand tending towards the northand those located in the south, orientated to the southwest (Figure 4.5).

The nearshore morphology of Newark Bay is relatively complex (Figure 4.6A). The slope from MHWS to the 5mCD contour is broadly parallel to the coast, but thereafter it reflects a more varied basement control. In the centre of the bay there is a submerged island, which shallows to a depth of approximately 3mCD. This former island is known as Baa Gruna and is composed of bedrock (Robby Grieve, local lobster fisherman, *pers com* 2001). It lies within a shallow platform at approximately 6mCD which extends 2km offshore, which makes Newark Bay shallower than the other Bays of Lopness and Stywick.

Newark (North) coastal geomorphology

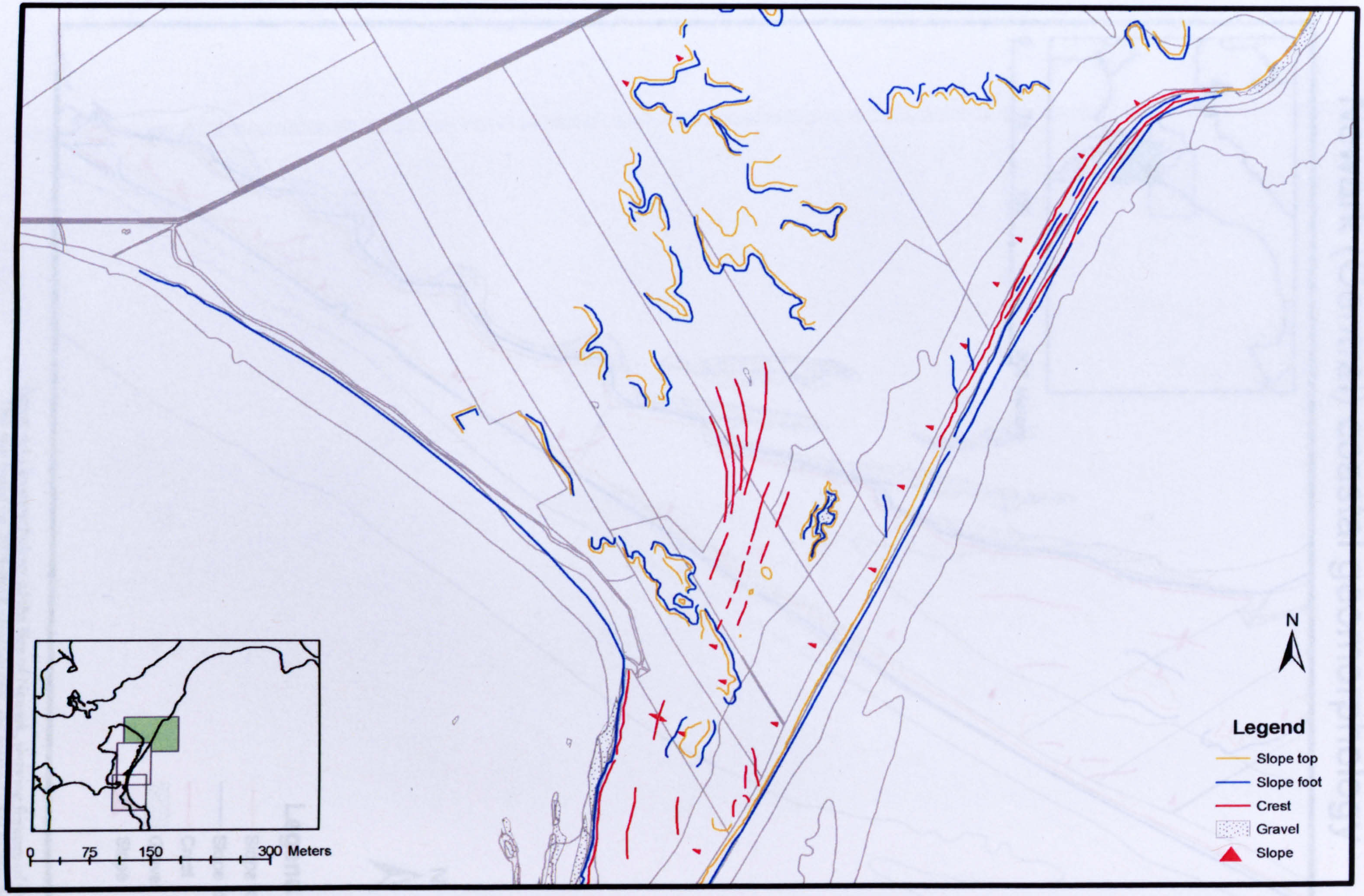


Figure 4.4 Geomorphology of the Bay of Newark, showing features of interest.
This was based on 2004 aerial photography, see method s for further details.

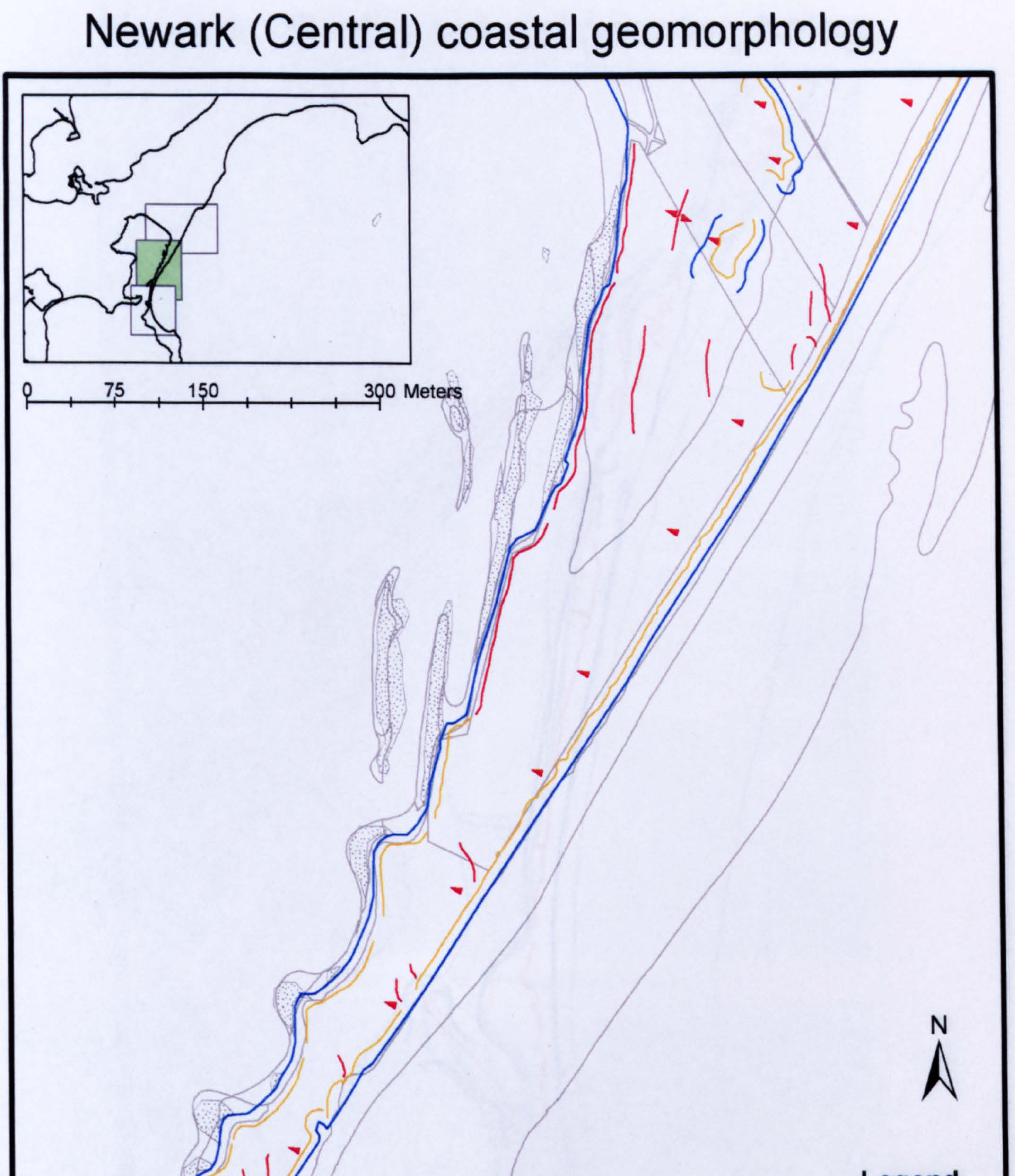


Figure 4.4 Geomorphology of the Bay of Newark, showing features of interest. This was based on 2004 aerial photography, see method s for further details.

Newark (South) coastal geomorphology

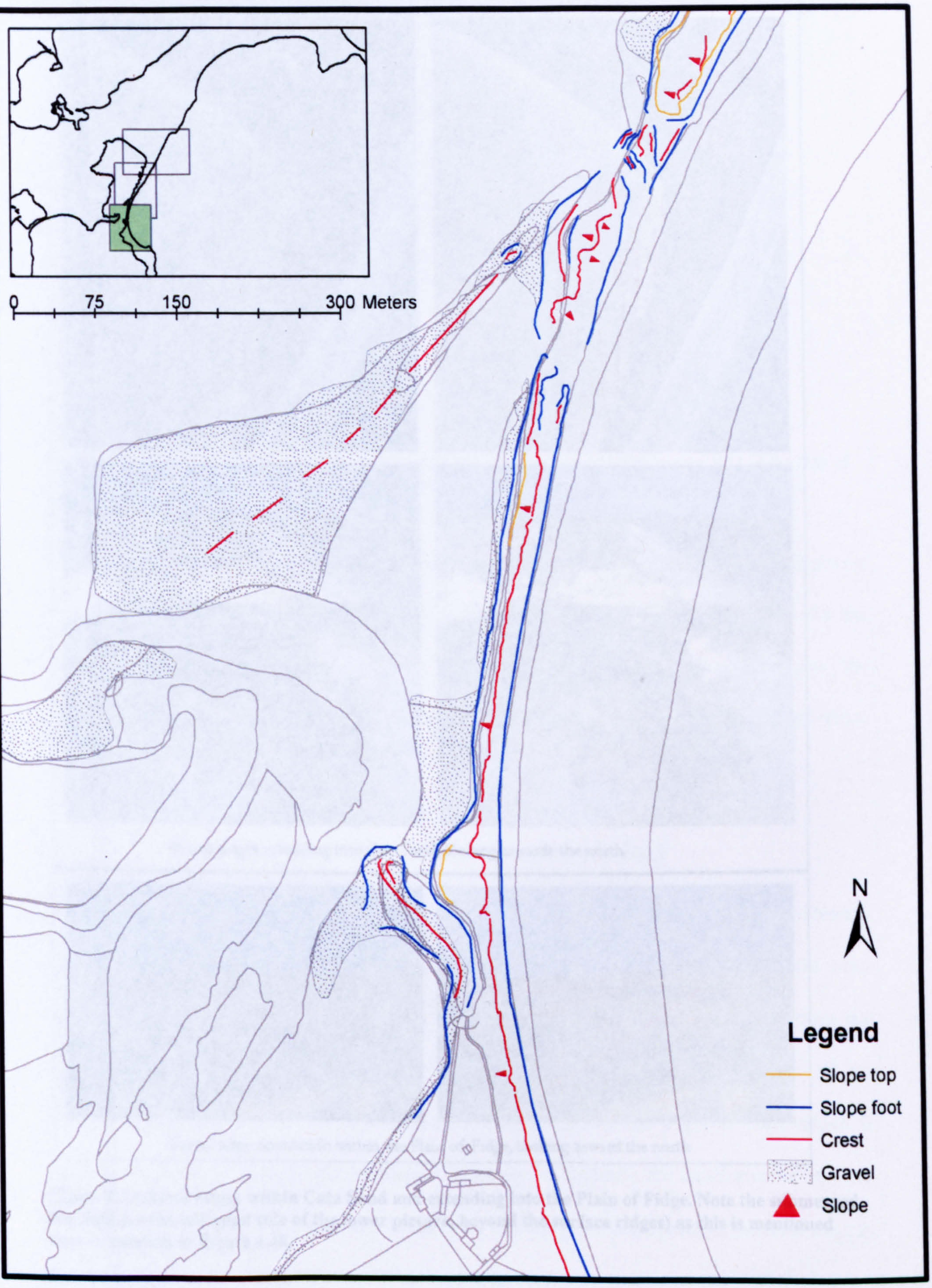
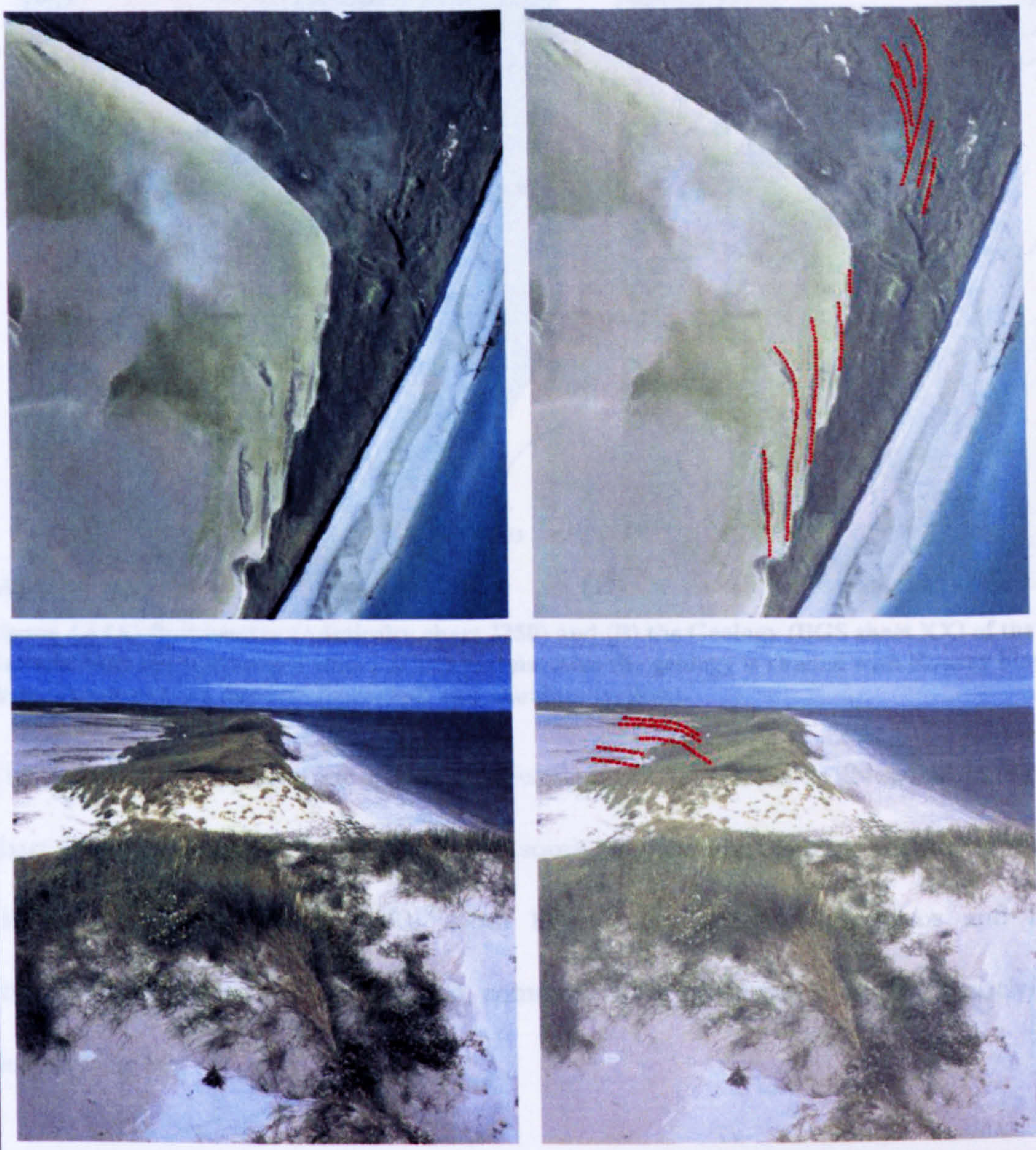
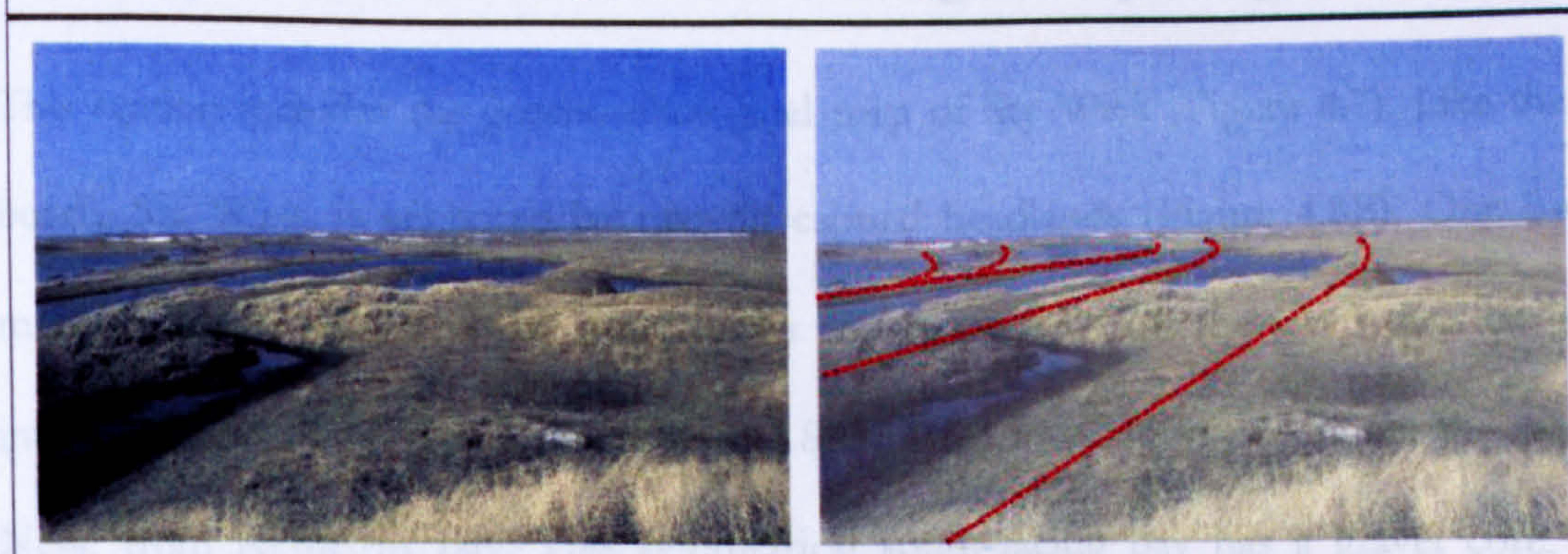


Figure 4.4 Geomorphology of the Bay of Newark, showing features of interest. This was based on 2004 aerial photography, see method s for further details.

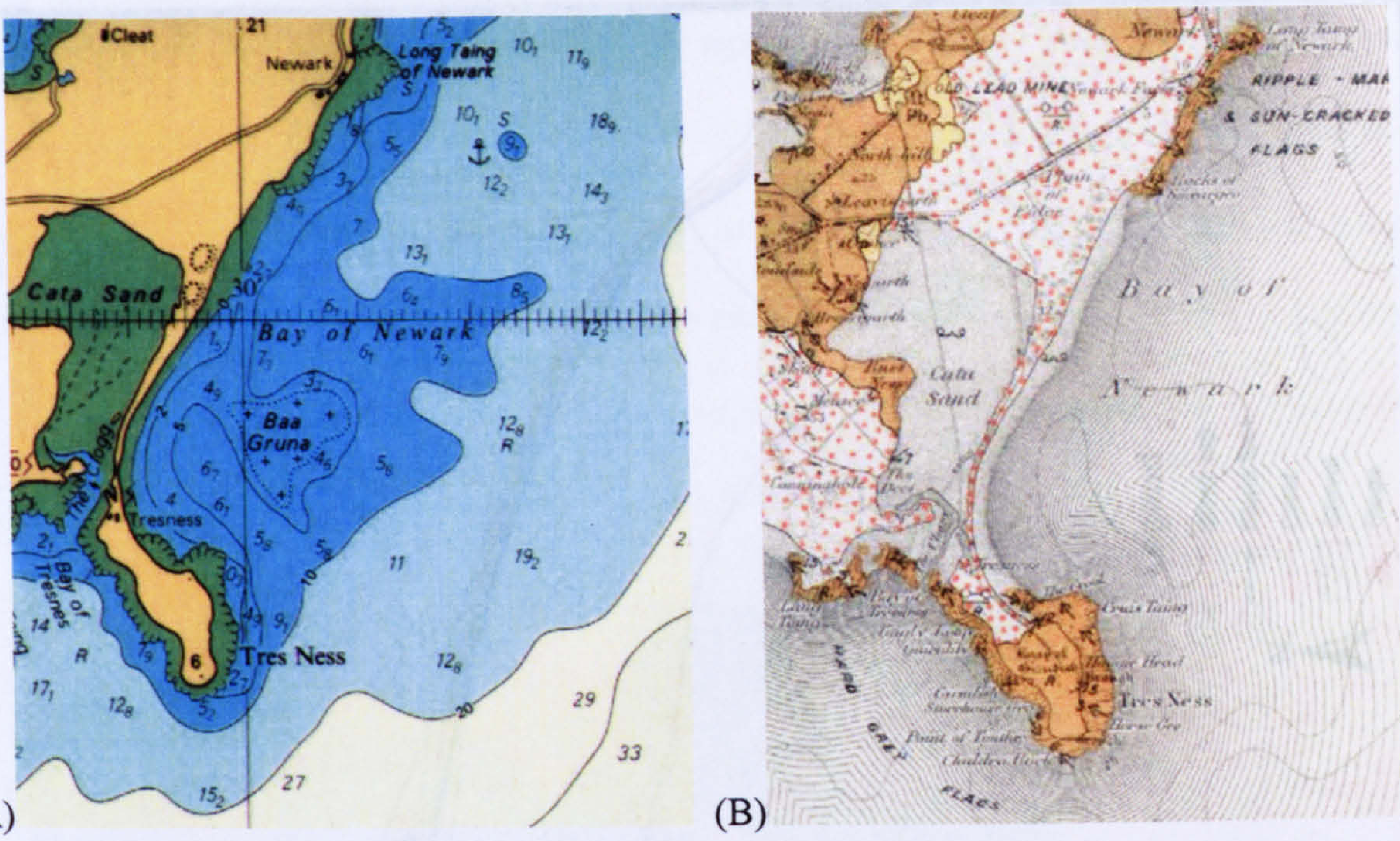


Gravel ridges extending into Cata Sand, looking towards the north



Gravel ridge orientation within the Plain of Fidge, looking toward the north

Figure 4.5 Gravel ridges within Cata Sand and extending into the Plain of Fidge. Note the submerged flat field (on the left hand side of the lower picture, beyond the surface ridges) as this is mentioned later in relation to Figure 4.48.



(A) (B)

Figure 4.6 (A) Bathymetry (Admiralty chart 2250) and (B) the Geology (BGS sheet XX) of the Bay of Newark Note the submerged island of Baa Gruna. Also the geology is shaded with Rousay Flags (brown), windblown deposits (speckled) and alluvium (yellow).

The presence of topographic highs at Newark Farm (identified as 'Newark' in Bathymetry chart Figure 4.6A) and Tres Ness to the south provide the bedrock anchor points for the Holocene deposits (Figure 4.6B). Both have rocky intertidal platforms and have the characteristic poorly-developed till cap, common to the Northern Isles, which rarely develops deeper than 1m.

4.1.3 Sty Wick - surface and nearshore geomorphology

This section includes the geomorphological map of Sty Wick (Figure 4.7). Like the Newark beach, Sty Wick, is anchored by two till capped headlands (Figure 4.8B). One backs onto machair (in the east) and the other forms into a tombolo (in the west) thus enclosing the intertidal sand flat of Little Sea (Figure 4.8A). Tidal inundation occurs via the west of Els Ness, from Kettletoft Bay. This symmetrical south-facing bay has a gravel core, which is exposed increasingly towards the headlands. Although individually the landforms of Newark and Sty Wick are of general interest, collectively the complex and dynamic interrelationship between them makes Central Sanday of national importance.

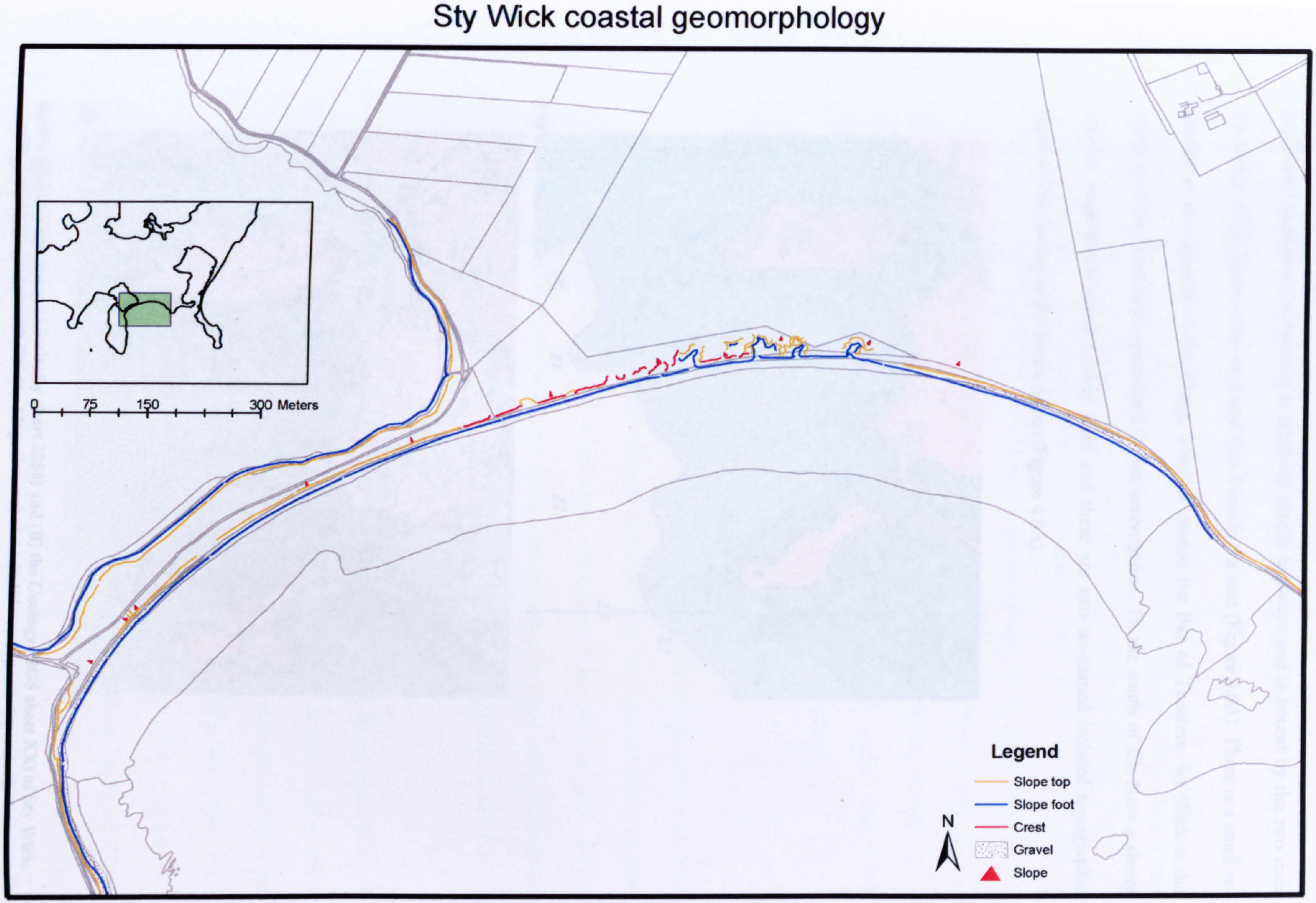


Figure 4.7 Geomorphology of Sty Wick, showing features of interest.
This was based on 2004 aerial photography, see method s for further details.

Sty Wick's nearshore bathymetry is relatively simple in nature and is bound by the two rock platforms of Els Ness in the west and Tres Ness in the east (Figure 4.8A). There is a small re-entrant at the opening to the Clogg, which is named the Bay of Tresness. Sty Wick is the steepest of the three bays considered in this investigation. To the south of Els Ness a skerry extends southwards called Foskey Reef and there are two un-named isolated topographic highs within the bay with depths of 9m (Figure 4.8A).

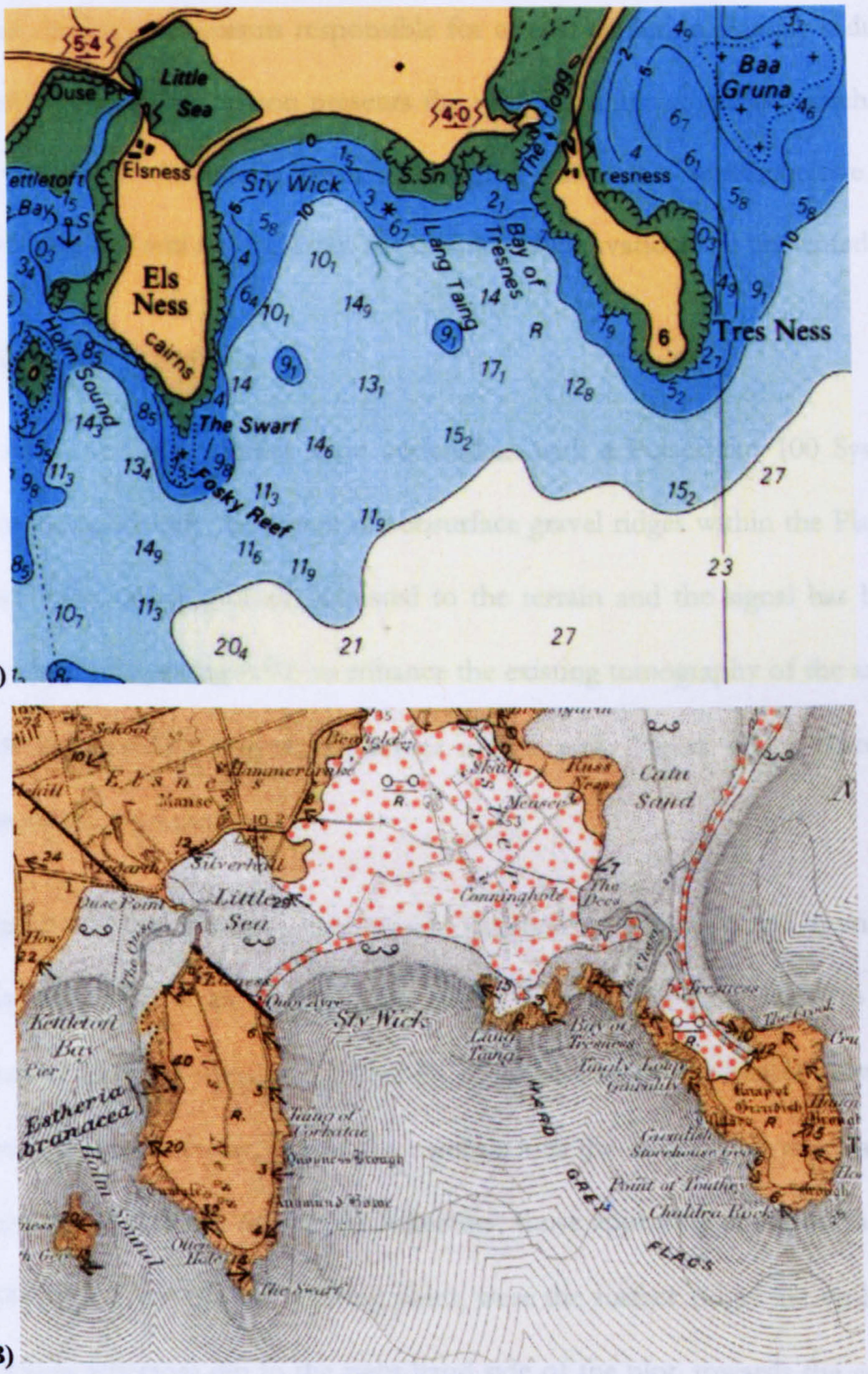


Figure 4.8 (A) Bathymetry (Admiralty chart 2250) and (B) the Geology (BGS sheet XX) of Sty Wick. Note the geology is shaded with Rousay Flags (brown) and windblown deposits (speckled).

4.2 Late-Holocene geomorphological changes - subsurface investigations

A considerable part of the results section will report on results of investigations which inform geomorphic change over the last 450 years up to 2003 using historical maps and present day surveying. However much of Sanday, like most landscapes, holds evidence from much wider spatial and temporal scales. The Late Holocene geomorphology of Sanday reflects the two main driving mechanisms responsible for coastal evolution, namely sediment supply and sea-level changes. This section presents the subsurface investigations which have identified some of the Late Holocene geomorphological changes. Representative results from GPR investigations and reports from the coring and excavations are presented below.

4.2.1 GPR results

A series of GPR profiles were undertaken with a PulseEkko 100 System using a 50 mHz antenna to identify the extent of subsurface gravel ridges within the Plain of Fidge. The plots have been topographically adjusted to the terrain and the signal has been magnified with a constant gain setting (x50) to enhance the existing tomography of the area under investigation Although profiles were taken across a wide area (Figure 4.9) a representative selection of results are presented below.

Figure 4.9 shows a west-east transect (labelled A) which started in an flat isotopic field and extended beyond the visible gravel ridges and into the sand dunes to the east; and a north-easterly trending transect (labelled B) which started on the visible gravel ridges and extended towards the northeast, across the machair into the dunes. The west-east profile (Figure 4.10) showed several sets of dipping reflectors; those appearing at the surface of the plot between 200-250m from the east starting point, were the surface ridges are visible in Figure 4.9. These striking reflectors dip to the right hand side of the plot, towards the eastand were interpreted as representing lateral seaward accretion towards the east. In addition to these, several previously unknown ridges or 'buried ridges' were confirmed via auger inspection between 100-130m from the east starting point (ridge crest at 1.2-1.3m depth). The clarity of the buried ridges, even at depth, reinforces the interpretation of a large composite structure composed of ridge suites, as the constant gain applied to the plot does not counteract the deterioration of signal strength with depth.

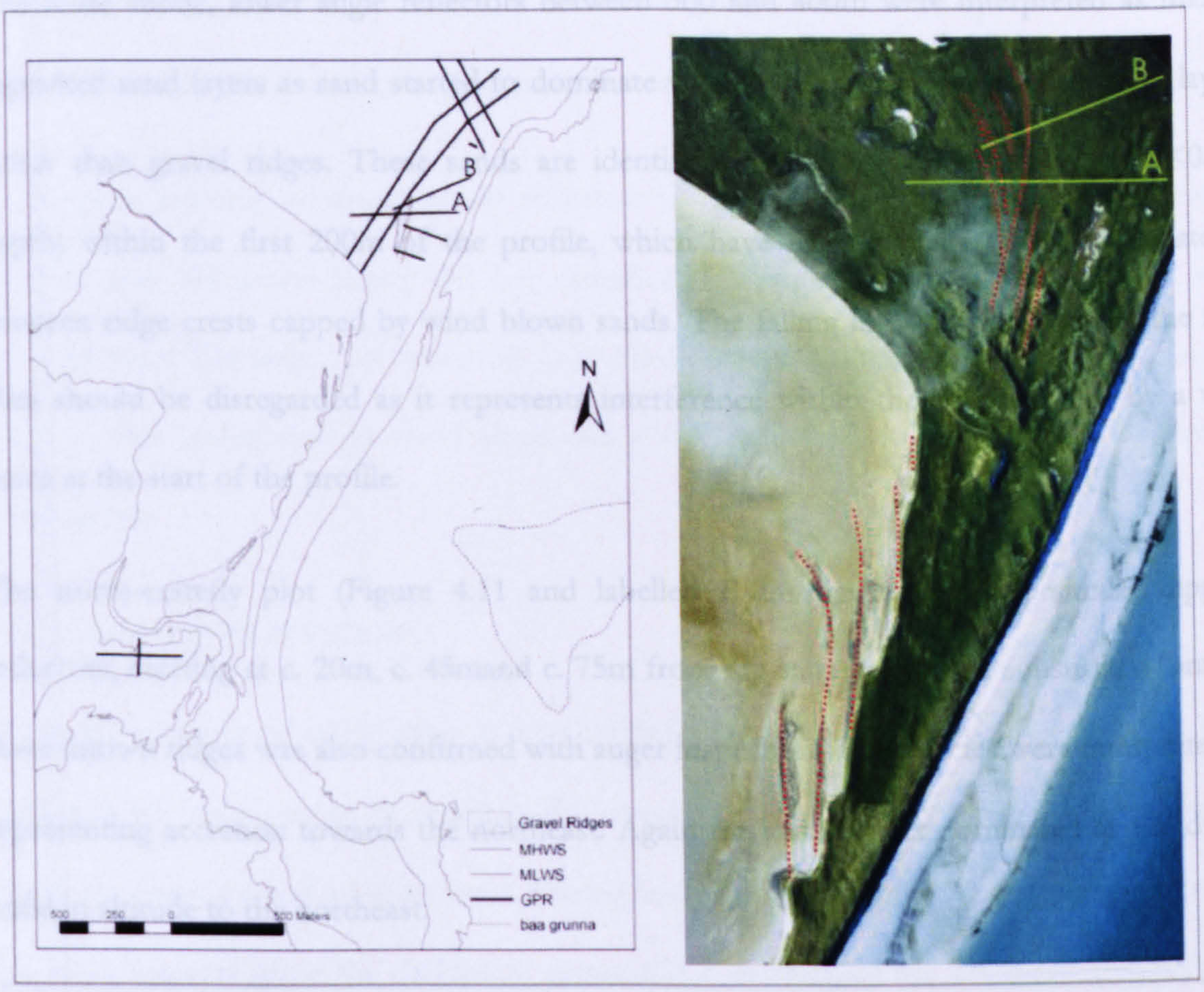


Figure 4.9 Visible surface gravel ridge orientations (red dotted line) and GPR survey grid (yellow lines) within the central Sanday site, annotated with the representative West-East profile (A) (see Figure 4.10) and the representative North-East profile (B) (see Figure 4.10), within the GPR survey grid within the Plain of Fidge

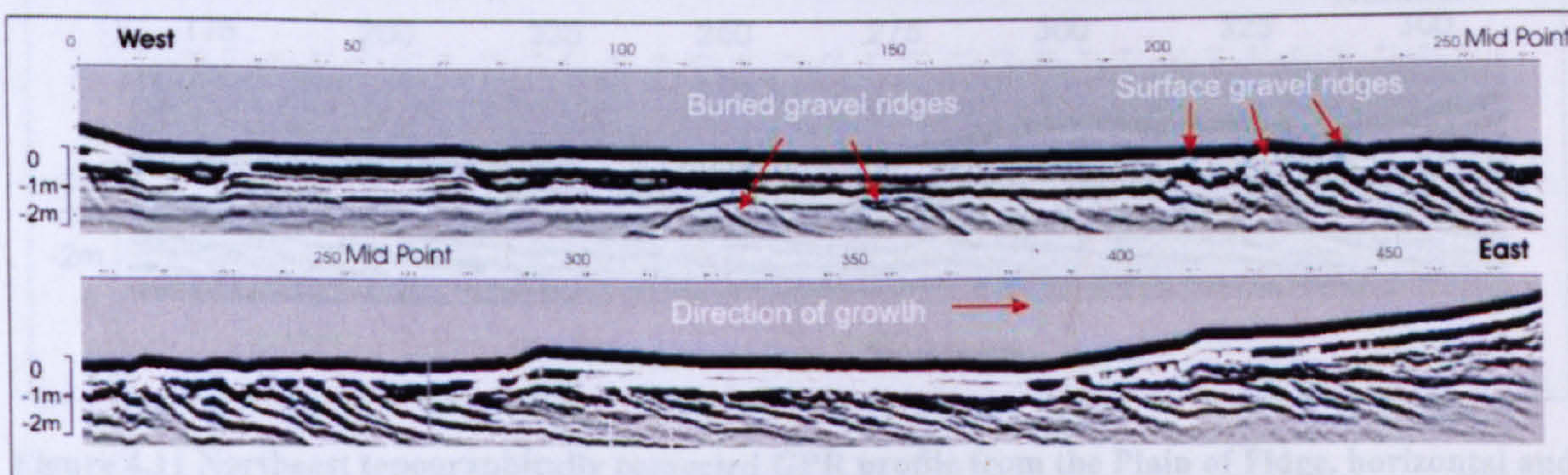


Figure 4.10 West-East topographically corrected GPR profile from the Plain of Fidge (Labelled A in Figure 4.9), horizontal and vertical scale in m. Note reflectors at 120m from the west margin, crest at 1.2-1.3m relative depth. Also note the flat field beneath which the buried gravel ridges lie, as this is mentioned later in relation to Figure 4.48.

Sand veneer dominates from c. 300m (Figure 4.10) as the dunes build in altitude to the east. The more subtle, lower angle reflectors between 300 and 400m were interpreted as marine deposited sand layers as sand started to dominate within the system, identified as sand layers rather than gravel ridges. These sands are identified by the horizontal reflections (<0.5m depth) within the first 200m of the profile, which have been interpreted as finer material between ridge crests capped by wind blown sands. The falling limb of a reflector in the first 10m should be disregarded as it represents interference within the signal caused by a wire fence at the start of the profile.

The north-easterly plot (Figure 4.11 and labelled B in Figure 4.9) had similar dipping reflectors, cresting at c. 20m, c. 45mand c. 75m from the start point. The subsurface form of these known ridges was also confirmed with auger inspection. These facies were interpreted as representing accretion towards the northeast. Again the sand veneer dominated as the dunes build in altitude to the northeast.

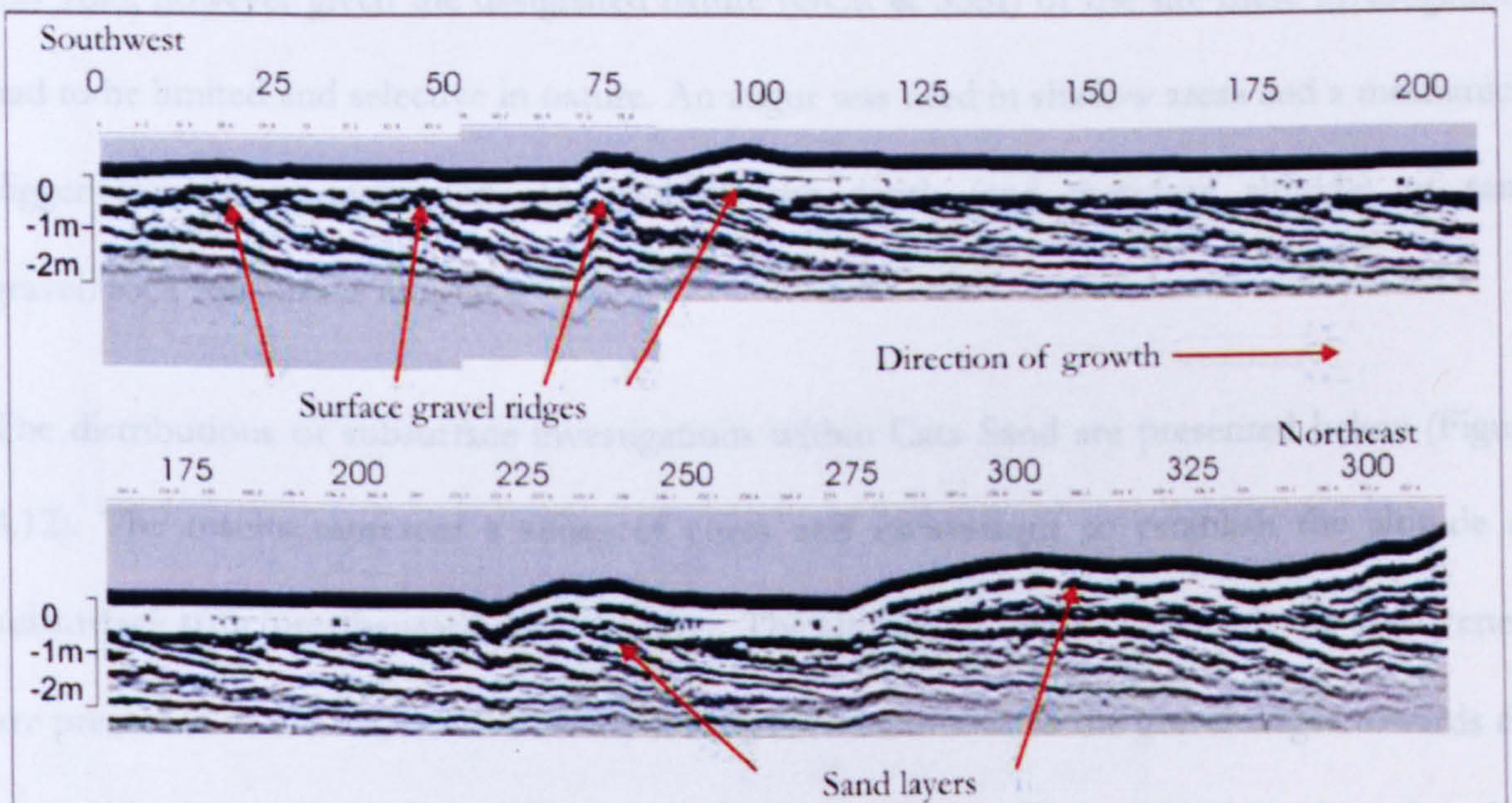


Figure 4.11 Northeast topographically corrected GPR profile from the Plain of Fidge, horizontal and vertical scale in m. Note surface exposures at ca.22m, ca.50m, ca.75m & ca.100m. See text for details.

The GPR surveys confirmed that the limited and intermittent surface ridge exposures were indeed interconnected with more extensive subsurface structures forming a substantial spit complex, which suggested the development of a gravel spit complex extending from the south-west to the north-east. The GPR investigations also found that previously unknown buried ridges complement the existing pattern to the west of those visible at the surface.

A complete absence of strong gravel reflectors in the northern extensions of the profiles suggests that the gravel ridges did not extend this far north: only sand reflections were detected here. The large spit system in Cata Sand and the southern section of the Plain of Fidge is thus understood to stand alone and is not partnered by a comparable southward trending spit.

4.2.2 Coring/excavations

Given the presence of saline water in the Cata Sand area the geophysical investigations (both GPR and RI) were unable to establish the extent of the subsurface palaeo-geomorphology within the intertidal and adjacent areas. Coring and excavation methods were employed to fill this void, however given the designated nature (GCR & SSSI) of the site these investigations had to be limited and selective in nature. An augur was used in shallow areas and a mechanical digger for deeper inspections to establish the depth (and therefore altitude) of sand gravel/rock subsurface interface.

The distributions of subsurface investigations within Cata Sand are presented below (Figure 4.12). The results represent a series of cores and excavations to establish the altitude of subsurface structures beneath the sand layer. The altitude of bedrock beneath the sand veneer are presented in the two north westerly transects and altitudes of the gravel ridges towards the east. Altitudes are in m above OD (Kirkwall). Figure 4.13 to Figure 4.19 show the subsurface extent of gravel and bedrock within the intertidal areas, thereby extending the survey beyond freshwater dominated habitats.

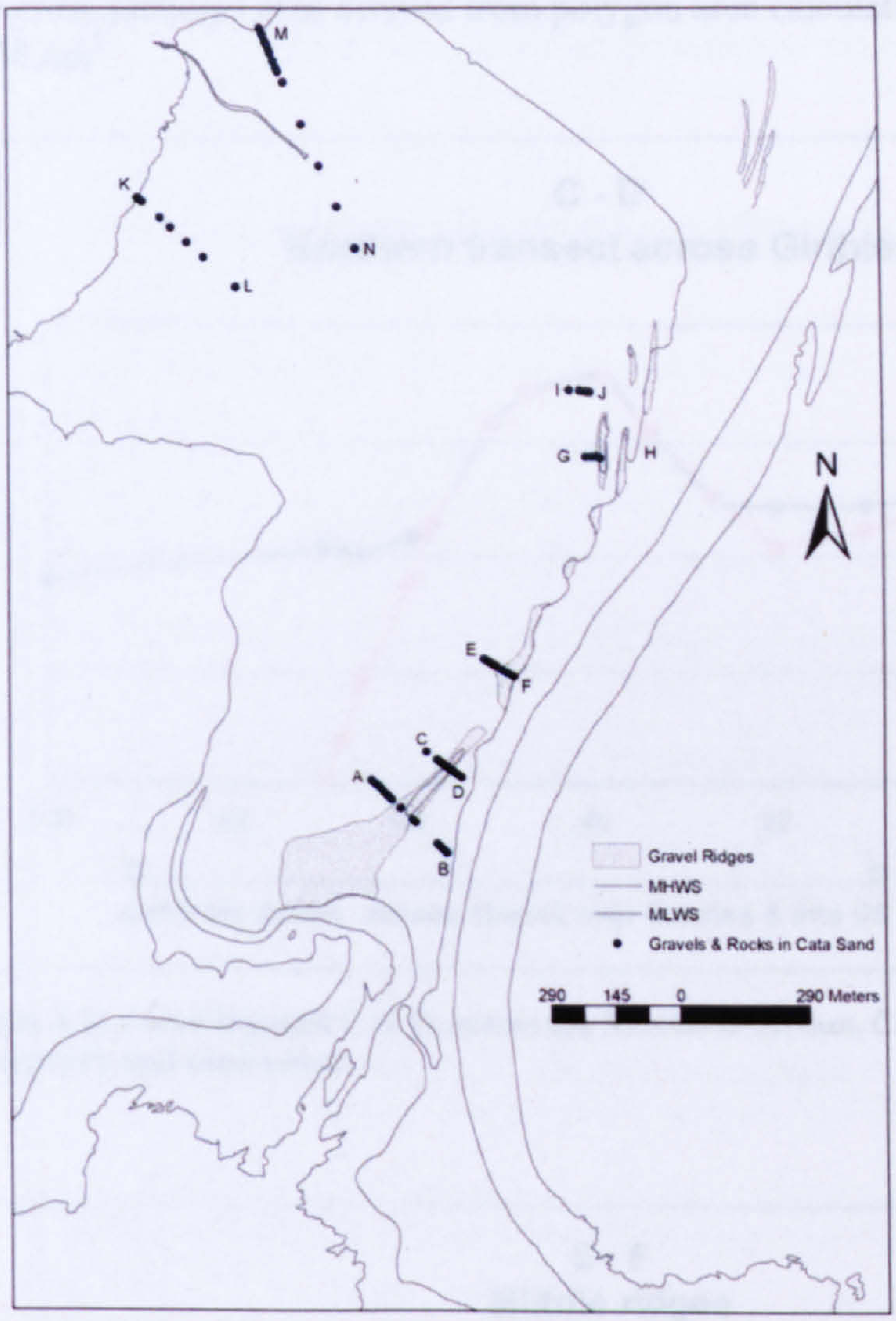


Figure 4.12 Location of subsurface investigations within Cata Sand.

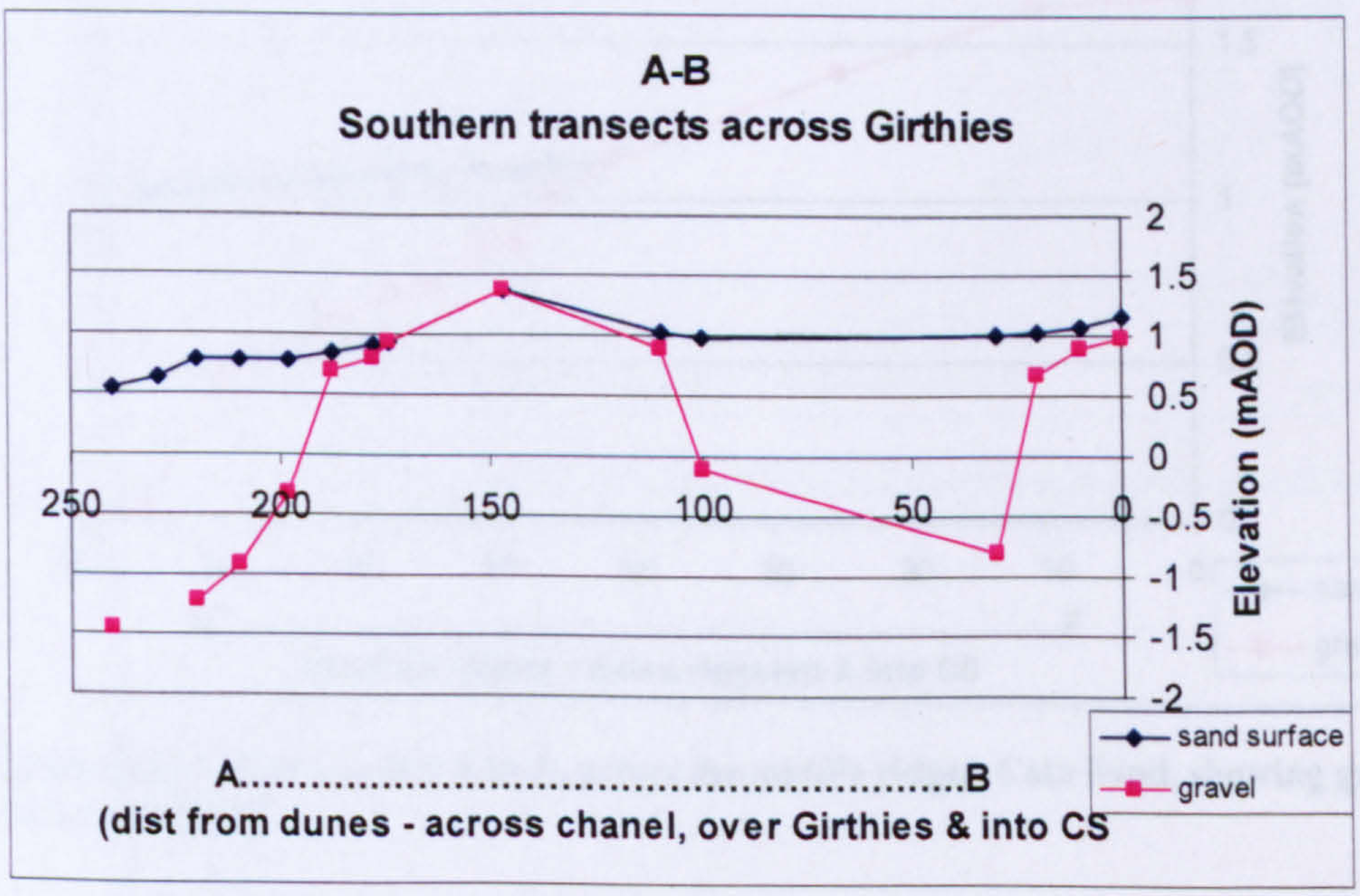


Figure 4.13 Cored transect A to B, across the South-Girthies, Cata Sand, showing gravel topography and sand veneer.

The cross sectional area derived from polygon area calculations the above transect was 3,458.6m^2.

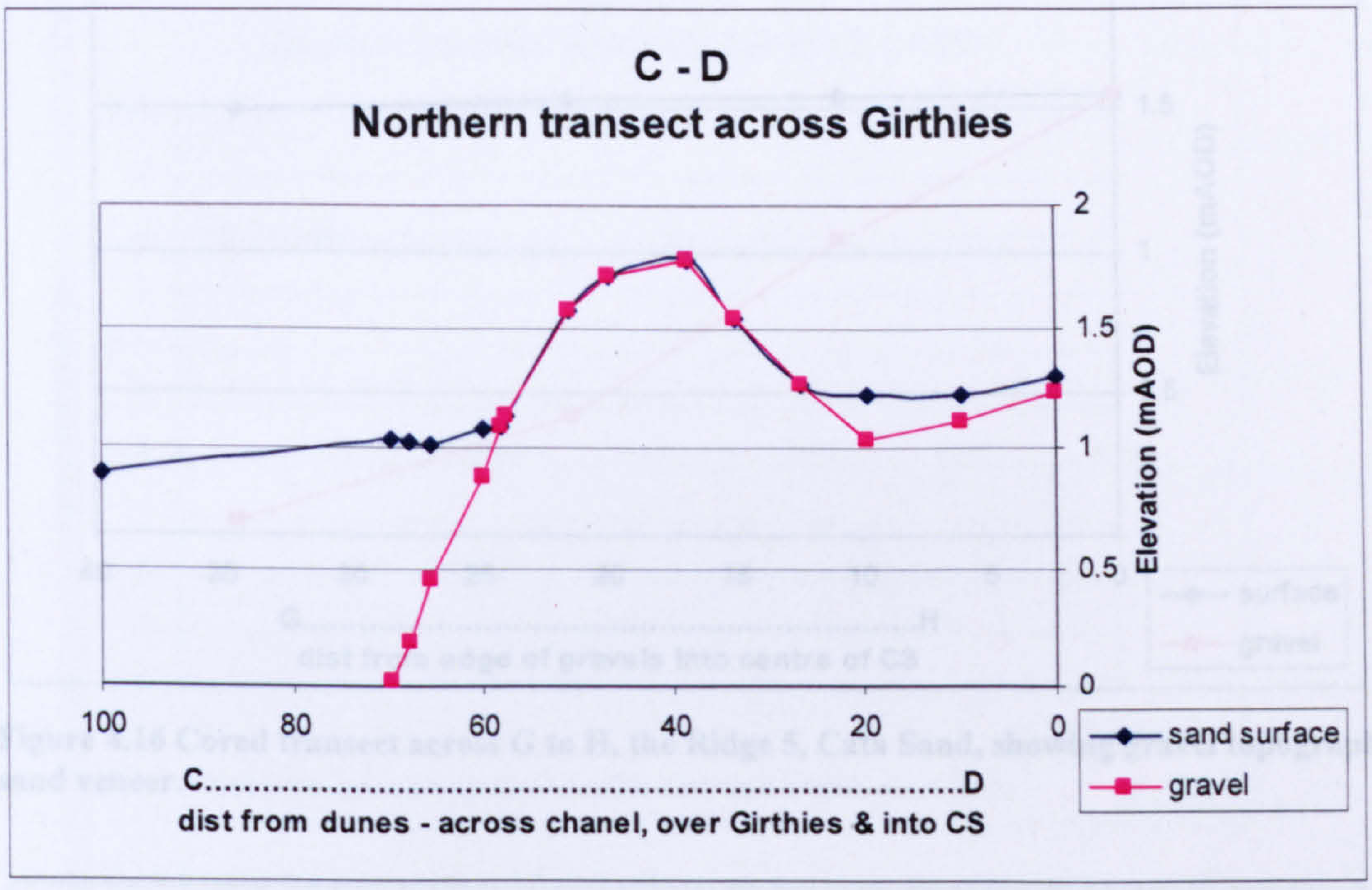


Figure 4.14 Cored transect C to D, across the Northern-Girthes, Cata Sand, showing gravel topography and sand veneer.

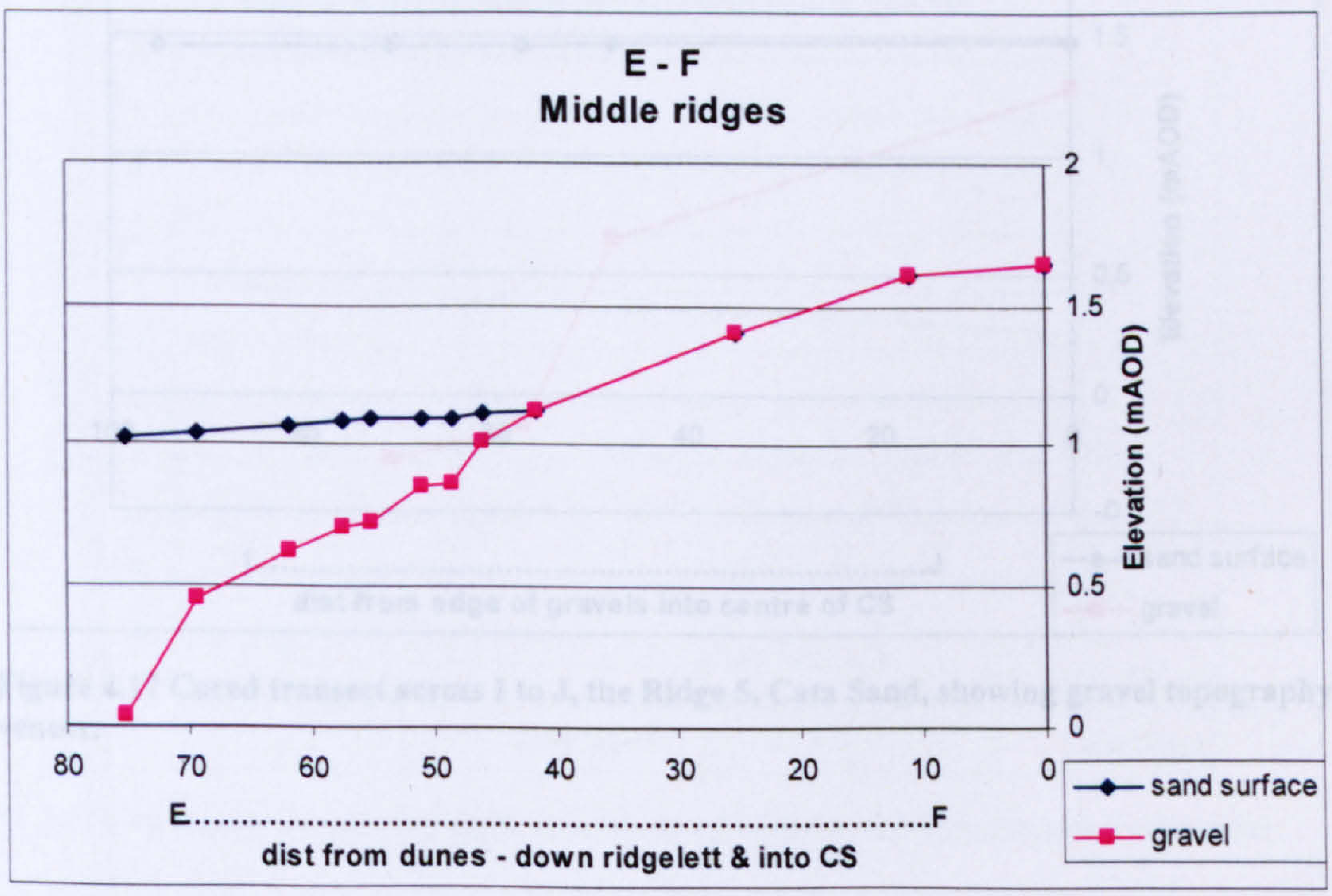


Figure 4.15 Cored transect E to F, across the middle ridges, Cata Sand, showing gravel topography and sand veneer.

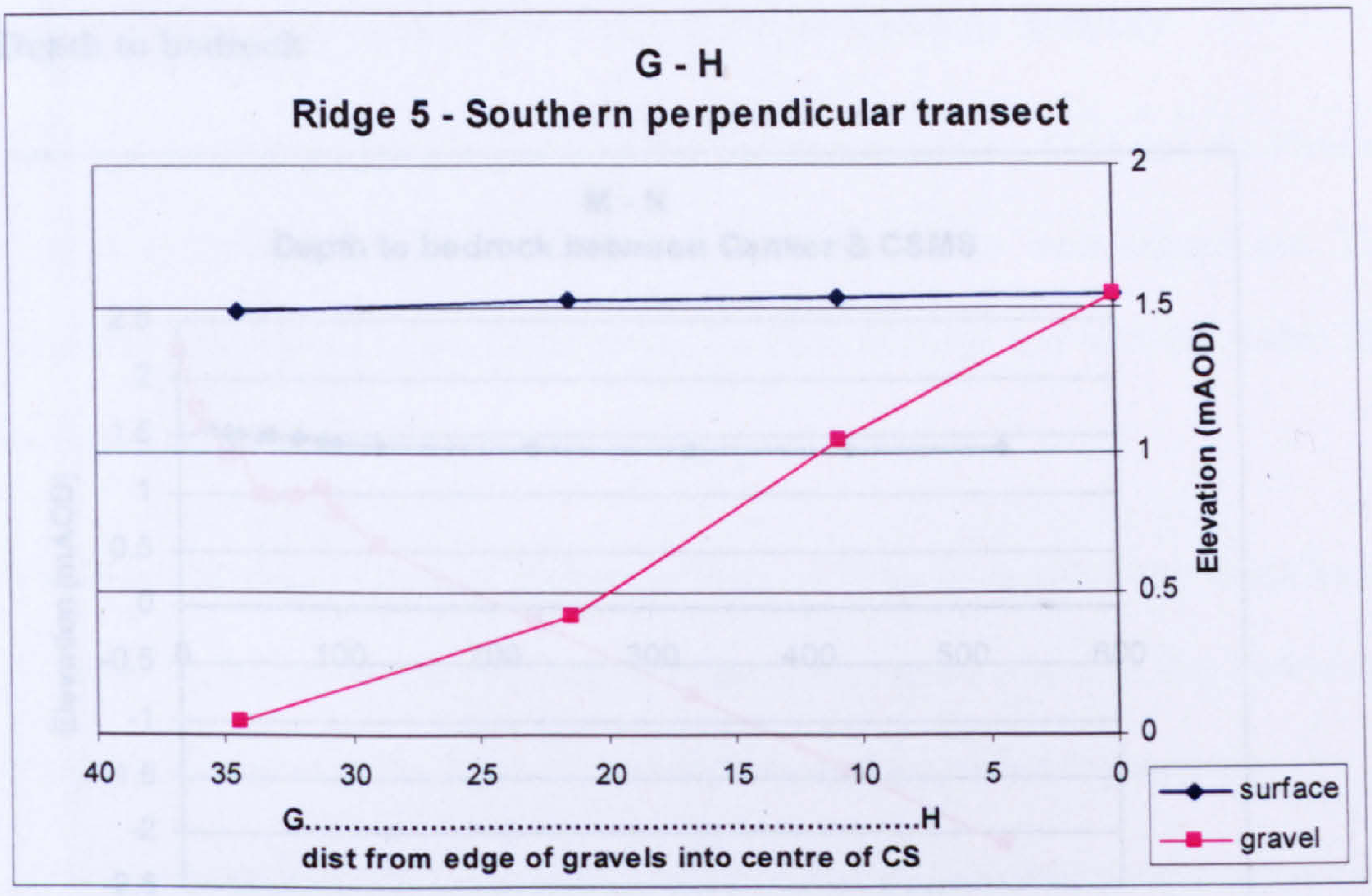


Figure 4.16 Cored transect across G to H, the Ridge 5, Cata Sand, showing gravel topography and sand veneer.

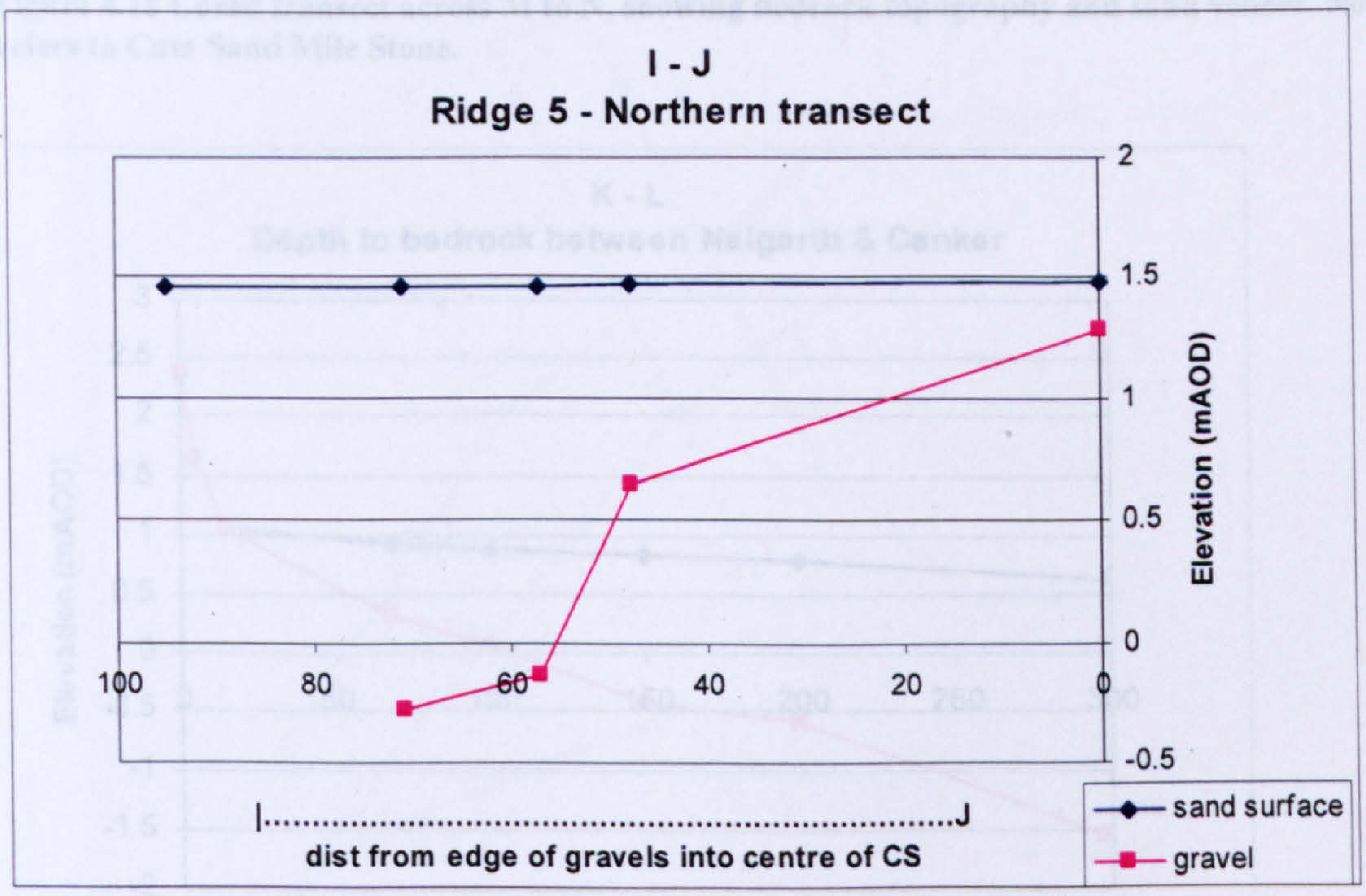


Figure 4.17 Cored transect across I to J, the Ridge 5, Cata Sand, showing gravel topography and sand veneer.

Depth to bedrock

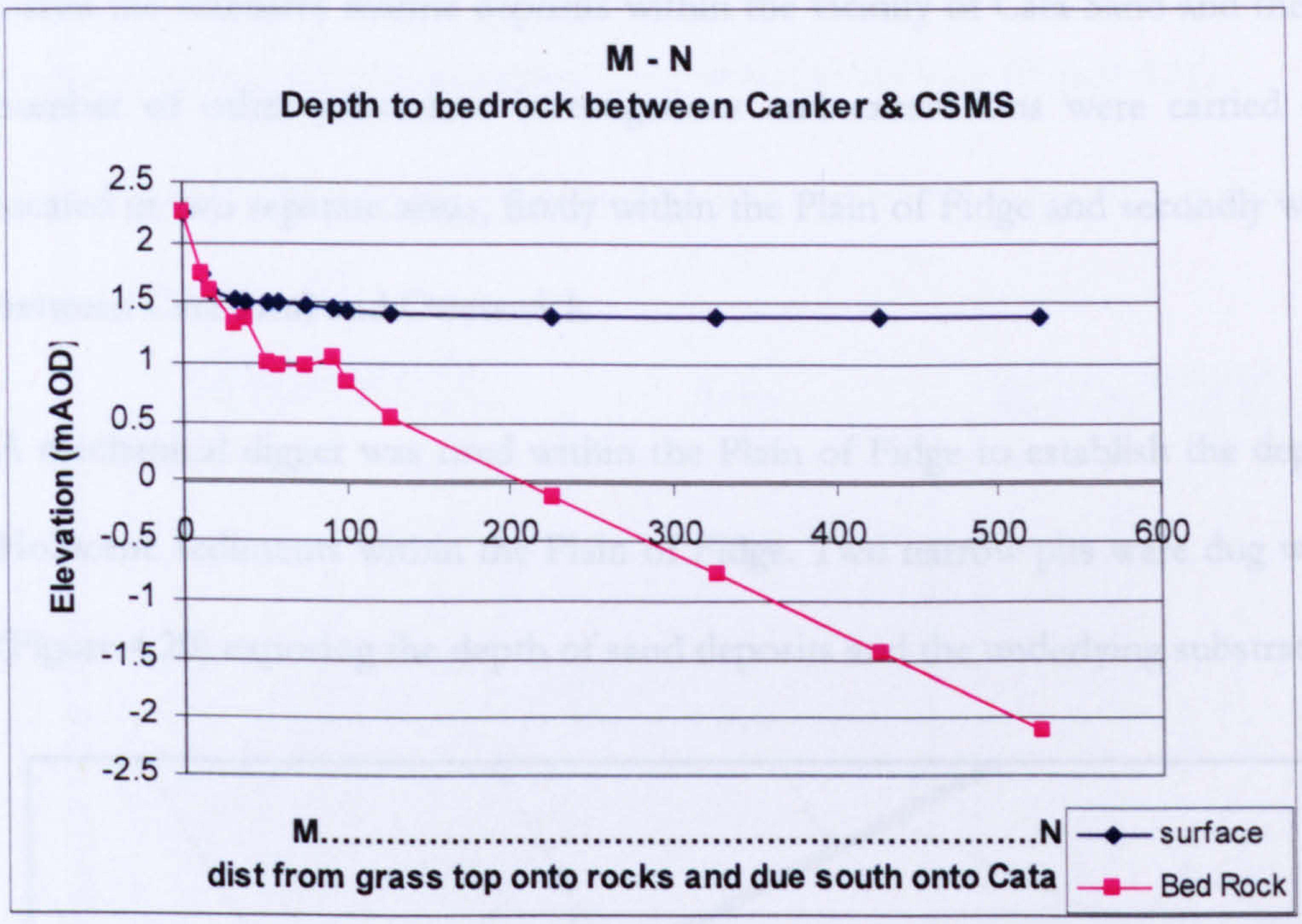


Figure 4.18 Cored transect across M to N, showing bedrock topography and sand veneer. Note: CSMS refers to Cata Sand Mile Stone.

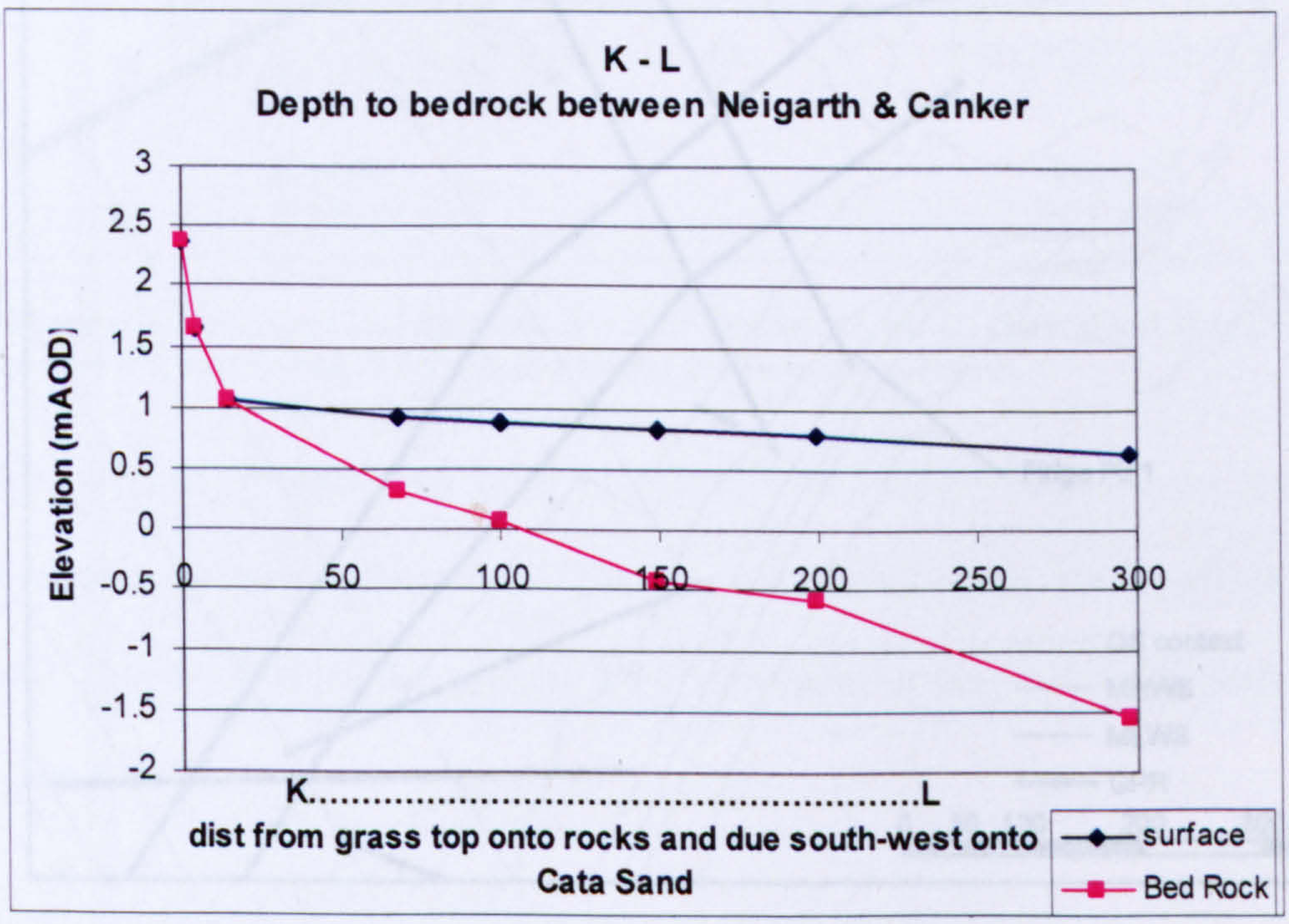


Figure 4.19 Cored transect across K to L, showing bedrock topography and sand veneer.

4.2.3 Other subsurface investigations in Central Sanday

Given the extensive marine deposits within the vicinity of Cata Sand and the Plain of Fidge a number of other subsurface investigations and excavations were carried out. These were located in two separate areas, firstly within the Plain of Fidge and secondly within the isthmus between Cata Sand and Otterswick.

A mechanical digger was used within the Plain of Fidge to establish the depth and nature of Holocene sediments within the Plain of Fidge. Two narrow pits were dug within the machair (Figure 4.20) exposing the depth of sand deposits and the underlying substrate.

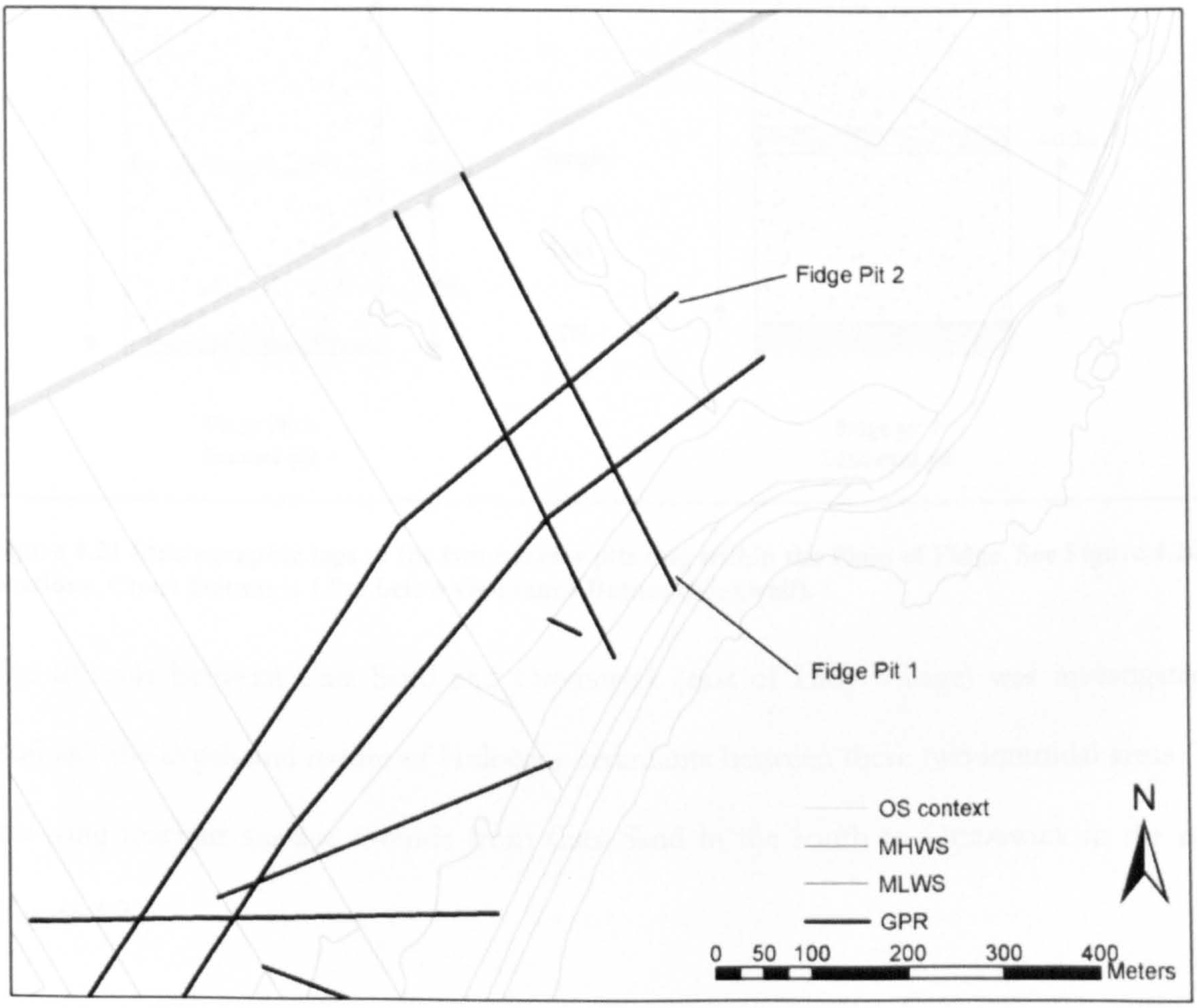


Figure 4.20 Location map of narrow pits dug within the Plain of Fidge.

Figure 4.21 shows the stratigraphic logs of the two test pits within the Plain of Fidge. Both test pits were dominated by sands; however gravel was also present in both. Test pit 1 had a thin layer of well rounded beach stones (shingle) 1.6m and 2.4m below the machair surface. The second test pit, located landward of the first (Figure 4.20) had a similar layer of beach stones at 1.5m depth and extended 2.2m towards a till base (Figure 4.21).

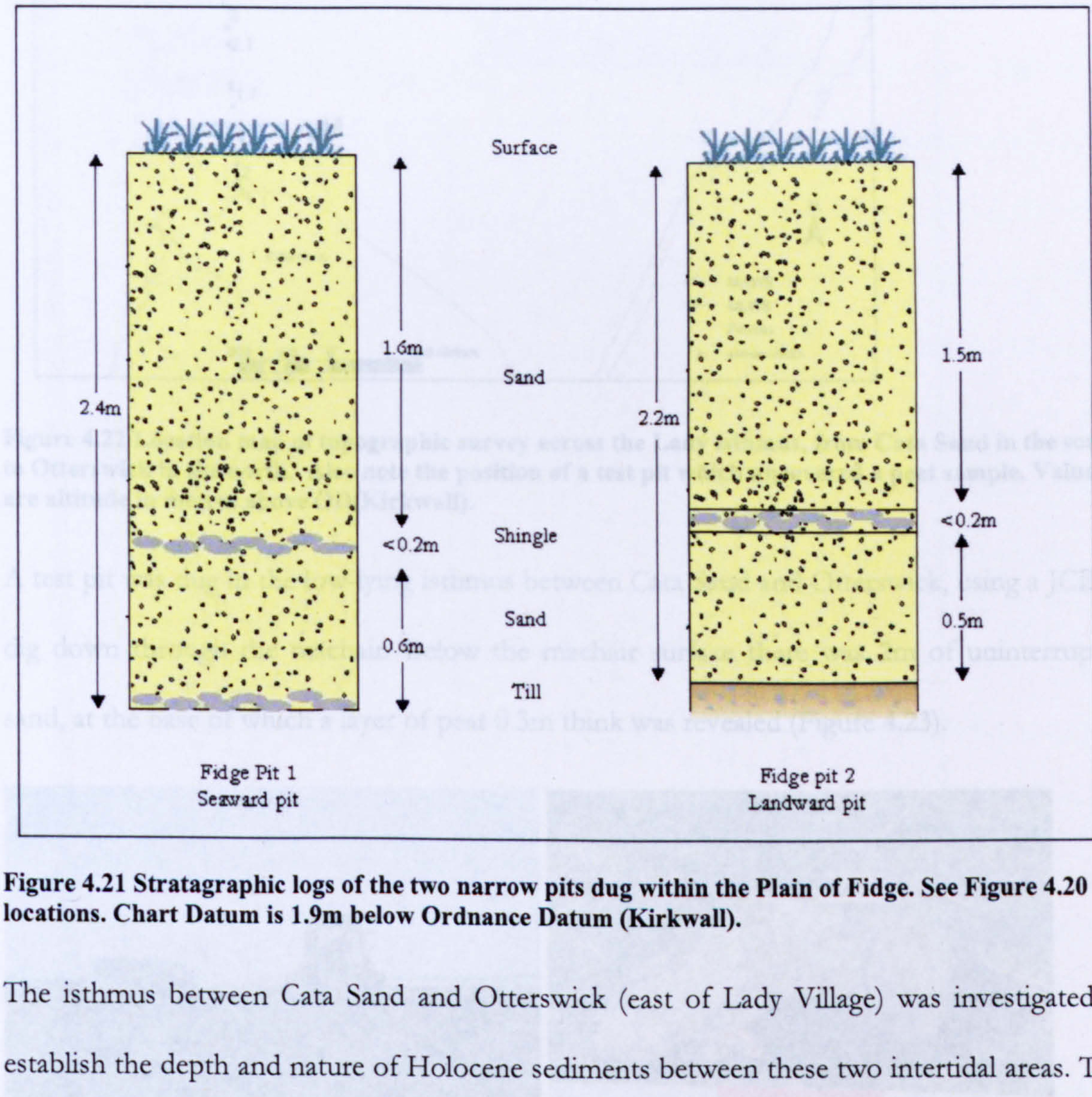


Figure 4.21 Stratagraphic logs of the two narrow pits dug within the Plain of Fidge. See Figure 4.20 for locations. Chart Datum is 1.9m below Ordnance Datum (Kirkwall).

The isthmus between Cata Sand and Otterswick (east of Lady Village) was investigated to establish the depth and nature of Holocene sediments between these two intertidal areas. This low-lying machair surface extends from Cata Sand in the south to Otterswick in the north (Figure 4.22).

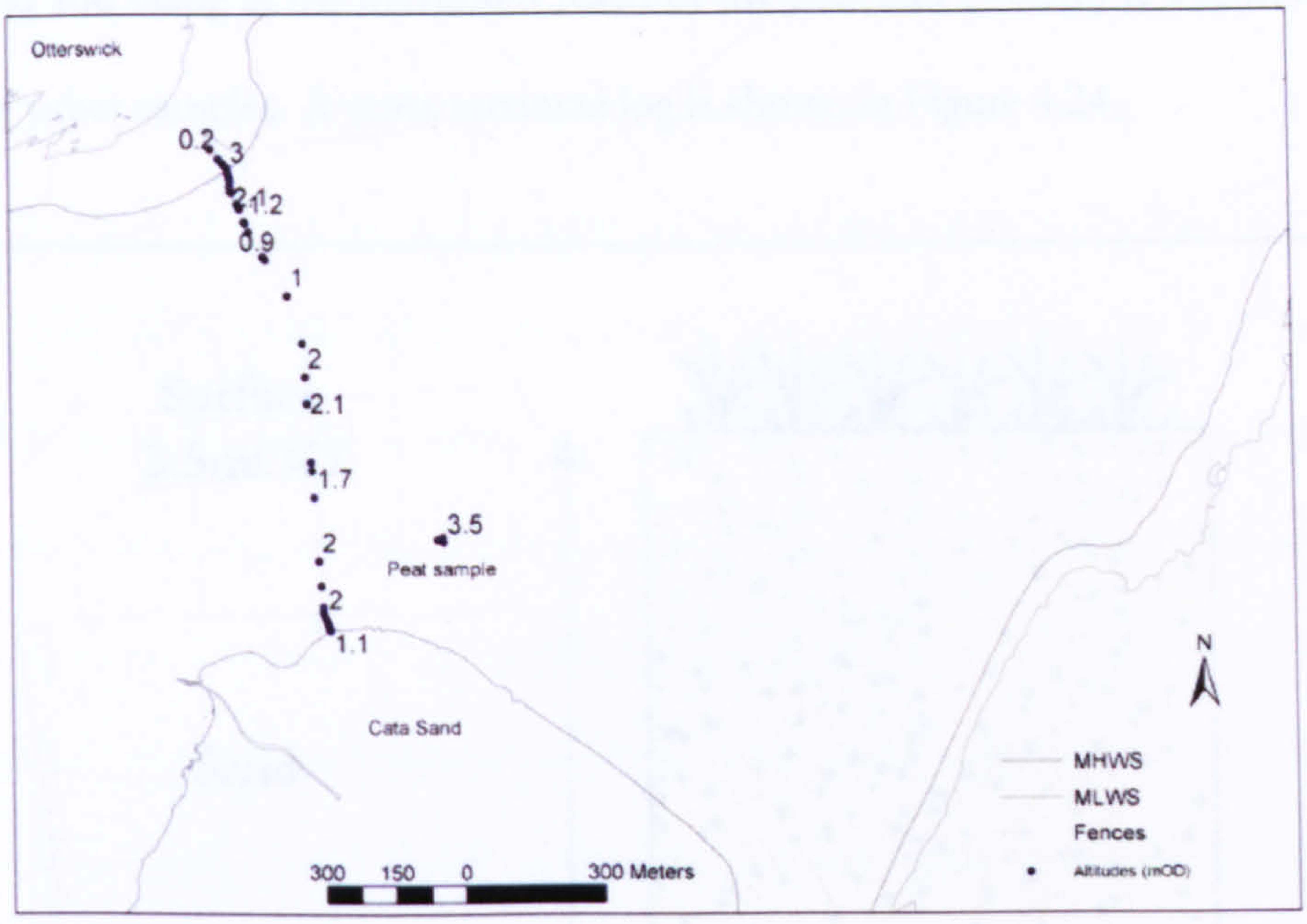


Figure 4.22 Location map of topographic survey across the Lady isthmus, from Cata Sand in the south to Otterswick in the north. Also note the position of a test pit which uncovered a peat sample. Values are altitude in metres above OD(Kirkwall).

A test pit was dug in the low-lying isthmus between Cata Sand and Otterswick, using a JCB to dig down through the machair. Below the machair surface there was 2m of uninterrupted sand, at the base of which a layer of peat 0.3m think was revealed (Figure 4.23).

Figure 4.23 Picture of test pit within the Cata Sand in background and the peat sample found 2m below machair surface, at 1.5mAOD.

Although the sample was not formally identified, it was composed of well rotted and compacted dark brown vegetation. The sample had a very high organic content and its interior was entirely absent of sand. Unfortunately given the depth of the pit, the frequent slumping of sand and being at the maximum reach of the JCB arm (<2.5m) it was not possible to remove any other samples. A cross sectional log is shown in Figure 4.24.

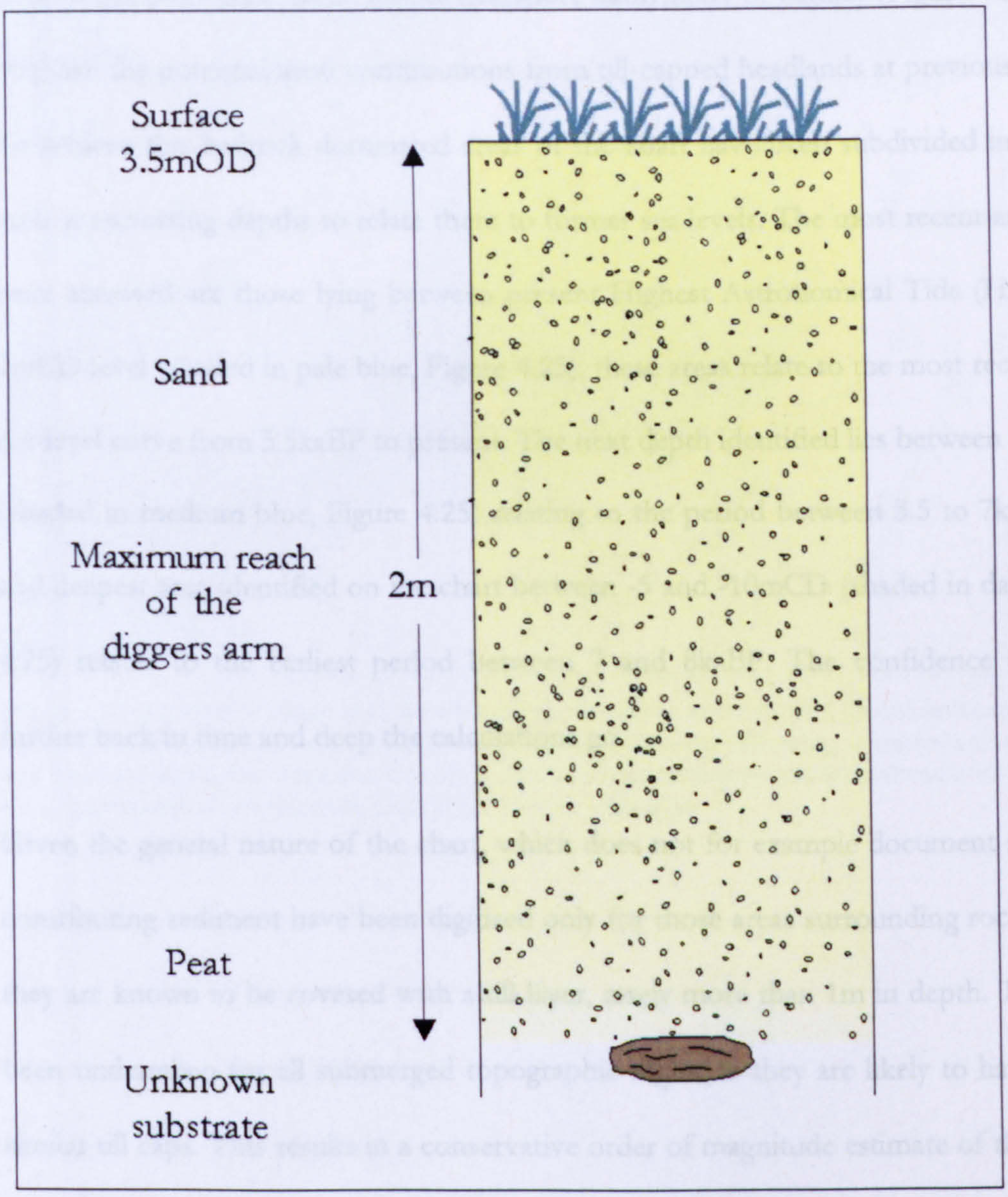


Figure 4.24 The stratagraphic log for the peat sample found within the isthmus between Cata Sand and Otterswick. Chart Datum is 1.9m below Ordnance Datum (Kirkwall).

4.2.4 Bathymetric chart analysis & previous sea levels

Given the shallow and varied nature of the nearshore, the submerging nature of the region and the likelihood of changing sediment supply sources as sea-level rose towards present it is essential to consider the nearshore bathymetry and the possible role it has played on the present and previous development of the coastline. As terrestrial areas have been consumed under the rising sea levels, the sea level curve and bathymetric chart can be considered together, to approximate the additional land claimed by the sea for each time period. To quantify the terrestrial contributions to the coastal zone during the Late Holocene a spatial analysis has been undertaken on the nearshore bathymetry of Sanday (Figure 4.25) in order to establish the potential areal contributions from till-capped headlands at previous time periods. To achieve this bedrock dominated areas of the chart have been subdivided into time-slices, each at increasing depths to relate them to former sea levels. The most recent areas of till that were accessed are those lying between present Highest Astronomical Tide (HAT) and the -2mCD level (shaded in pale blue, Figure 4.25), these areas relate to the most recent part of the sea-level curve from 5.5kaBP to present. The next depth identified lies between -2 and -5mCD (shaded in medium blue, Figure 4.25) relating to the period between 5.5 to 7kaBP. The final and deepest area identified on the chart between -5 and -10mCD (shaded in dark blue, Figure 4.25) relates to the earliest period between 7 and 8kaBP. The confidence diminishes the further back in time and deep the calculations go.

Given the general nature of the chart, which does not for example document substrate, areas contributing sediment have been digitised only for those areas surrounding rock headlands, as they are known to be covered with a till layer, rarely more than 1m in depth. This zoning has been undertaken for all submerged topographic highs, as they are likely to have or have had similar till caps. This results in a conservative order of magnitude estimate of the area of these production zones during the three time periods (Figure 4.26). For each of the three sediment sub-cells there is a bold trend of a reduction in potential source areas up to the present day. The areas have been normalised to areas per thousand yearsand show an order of magnitude reduction in the case of the Newark and Lopness sub-cell (Figure 4.26A) and a 1/3 reduction for Sty Wick (Figure 4.26B)and Kettletoft Bays(Figure 4.26C)between each of the time periods.

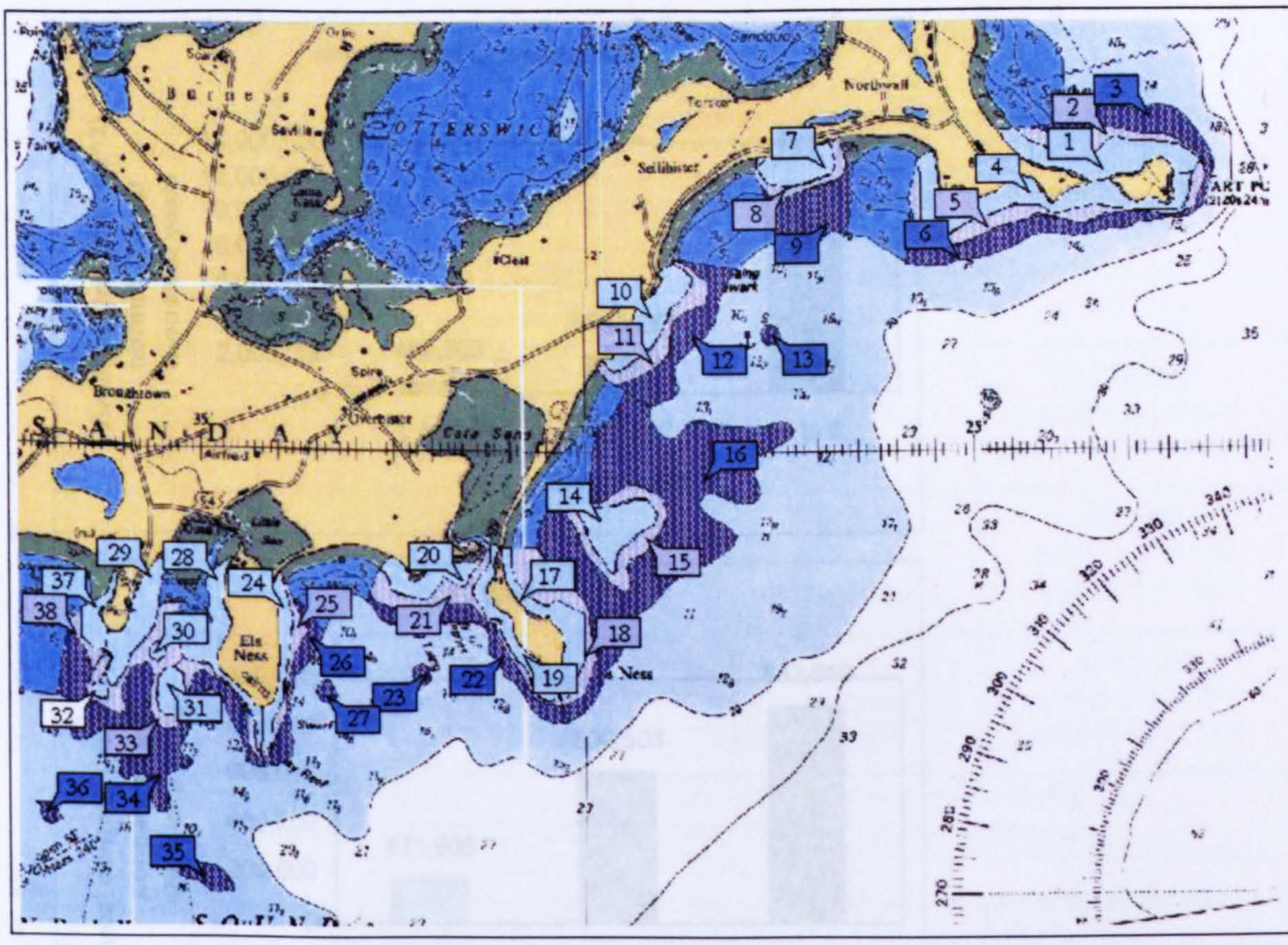


Figure 4.25 Admiralty Chart (#2250) with potential source areas for till, gravel and sand at previous sea levels. Each area has been quantified and grouped into the following sediment sub-cells, Newark and Lopness Bays, Sty Wick and thirdly Kettletoft. Numbers show individual rocky areas which have been aggregated to produce the final sub-cell area estimates.

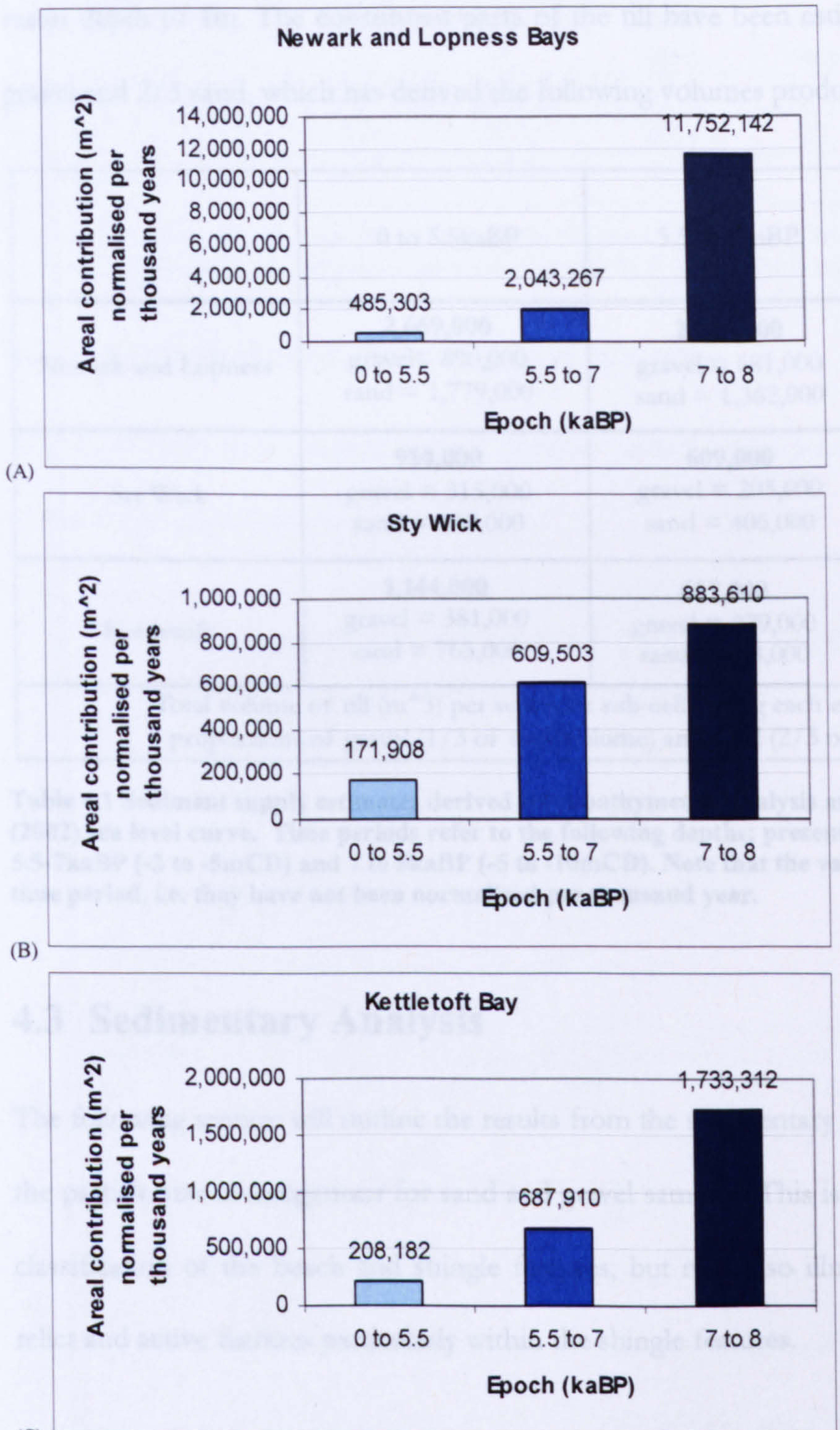


Figure 4.26 Changing sediment-contributing areas (m^2) for (A) Newark and Lopness, (B) Sty Wick and (C) Kettletoft, over the following time periods: present to 5.5kaBP (0 to -2m CD), 5.5-7kaBP (-2 to -5mCD) and 7 to 8kaBP (-5 to -10mCD). Note that the values have been normalised to areas (m^2) per thousand years.

The areal calculation has been multiplied by an estimate of till depth to establish possible volumes of sediment supply. The depth multiplier was derived from measurement of the depths of till caps from the headlands of Tres Ness, Lopness and Newark, which produced a mean depth of 1m. The constituent parts of the till have been estimated at an arbitrary 1/3 gravel and 2/3 sand, which has derived the following volumes produced in each sub-cell.

	0 to 5.5kaBP	5.5 to 7kaBP	7 to 8kaBP
Newark and Lopness	**2,669,000** gravel= 890,000 sand = 1,779,000	**2,043,000** gravel = 681,000 sand = 1,362,000	**11,752,000** gravel = 3,917,000 sand = 7,834,000
Sty Wick	**954,000** gravel = 315,000 sand = 630,000	**609,000** gravel = 203,000 sand = 406,000	**883,000** gravel = 294,000 sand = 589,000
Kettletoft	**1,144,000** gravel = 381,000 sand = 763,000	**687,000** gravel = 229,000 sand = 458,000	**1,733,000** gravel = 577,000 sand = 1,155,000
Total volume of till (m^3) per sediment sub-cell during each epoch (**bold**) and proportions of gravel (1/3 of total volume) and sand (2/3 of total volume)			

Table 4.1 Sediment supply estimates derived from bathymetric analysis and epochs from Shennan *et al* (2002) sea level curve. Time periods refer to the following depths: present to 5.5kaBP (0 to -2m CD), 5.5-7kaBP (-2 to -5mCD) and 7 to 8kaBP (-5 to -10mCD). Note that the values are total values over the time period, i.e. they have not been normalised per thousand year.

4.3 Sedimentary Analysis

The following section will outline the results from the sedimentary analysis, by firstly reporting the particle size investigations for sand and gravel samples. This is not only important for the classification of the beach and shingle features, but may also illuminate trends between the relict and active features particularly within the shingle features.

4.3.1 Particle size analysis of sand samples

Table 4.2 displays a summary of particle size distributions for Lopness, Newark and Sty Wick beaches and the proportion of shell sand ($CaCO_3$) at each of the beaches.

	clay	silt	fine sand	medium sand	coarse sand	> coarse sand	% $CaCO_3$
Lopness	0.45	0.9	24.9	47.7	26.1	0	77
Newark	0.26	0.8	29.7	45.1	24.1	0	57
Sty Wick	0.19	0.87	35.5	46.7	16.7	0	Not sampled

Table 4.2 Particle size analysis (% of total) from Lopness, Newark and Sty Wick beaches, collected as grab samples from the lower intertidal area. Note the % $CaCO_3$ data is from Sommerville 2003.

4.3.2 Particle size analysis of gravel samples

The gravel units were sampled using a Wolman plate (to measure their B axis) from a variety of active and relict features (Figure 4.27).

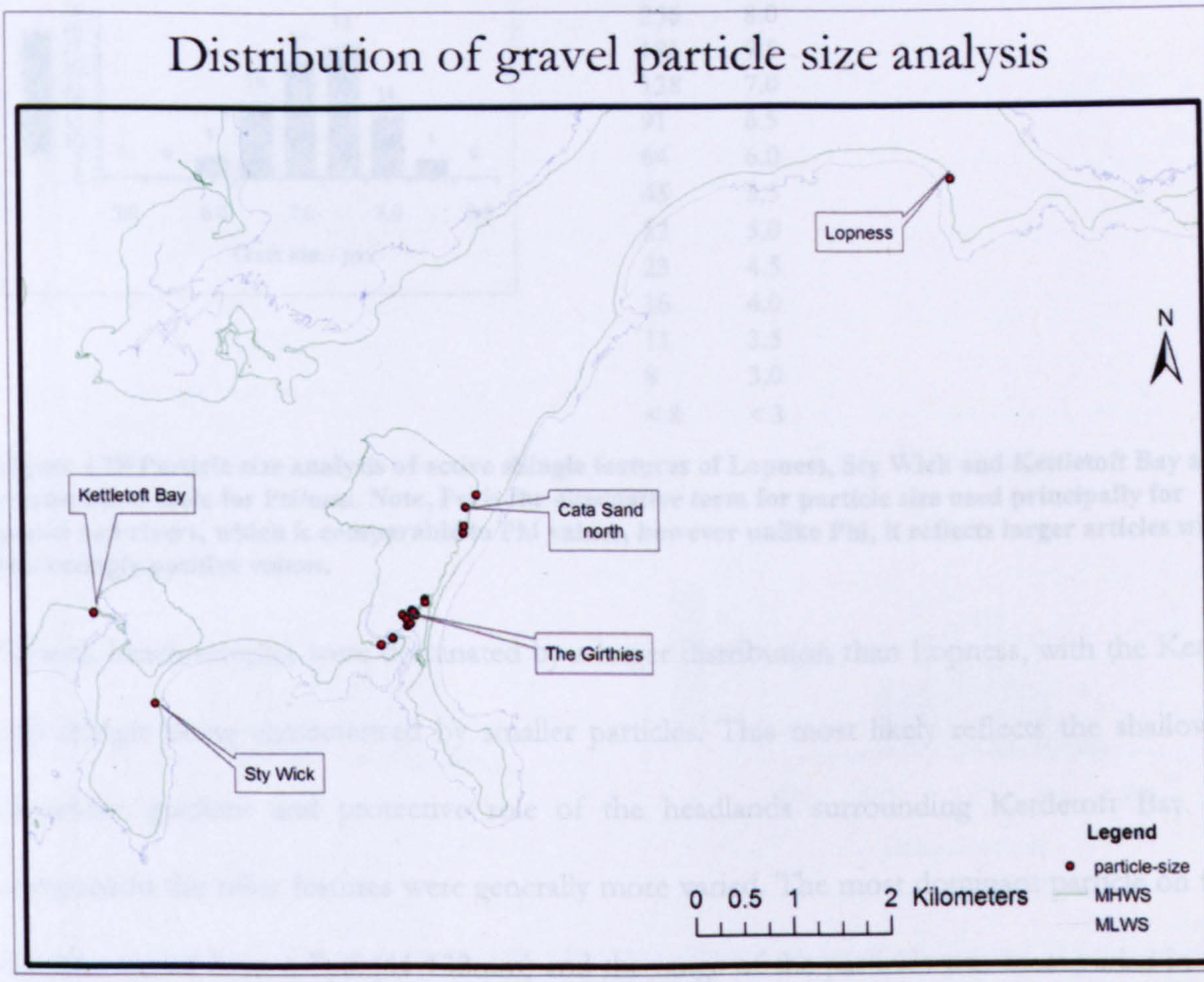
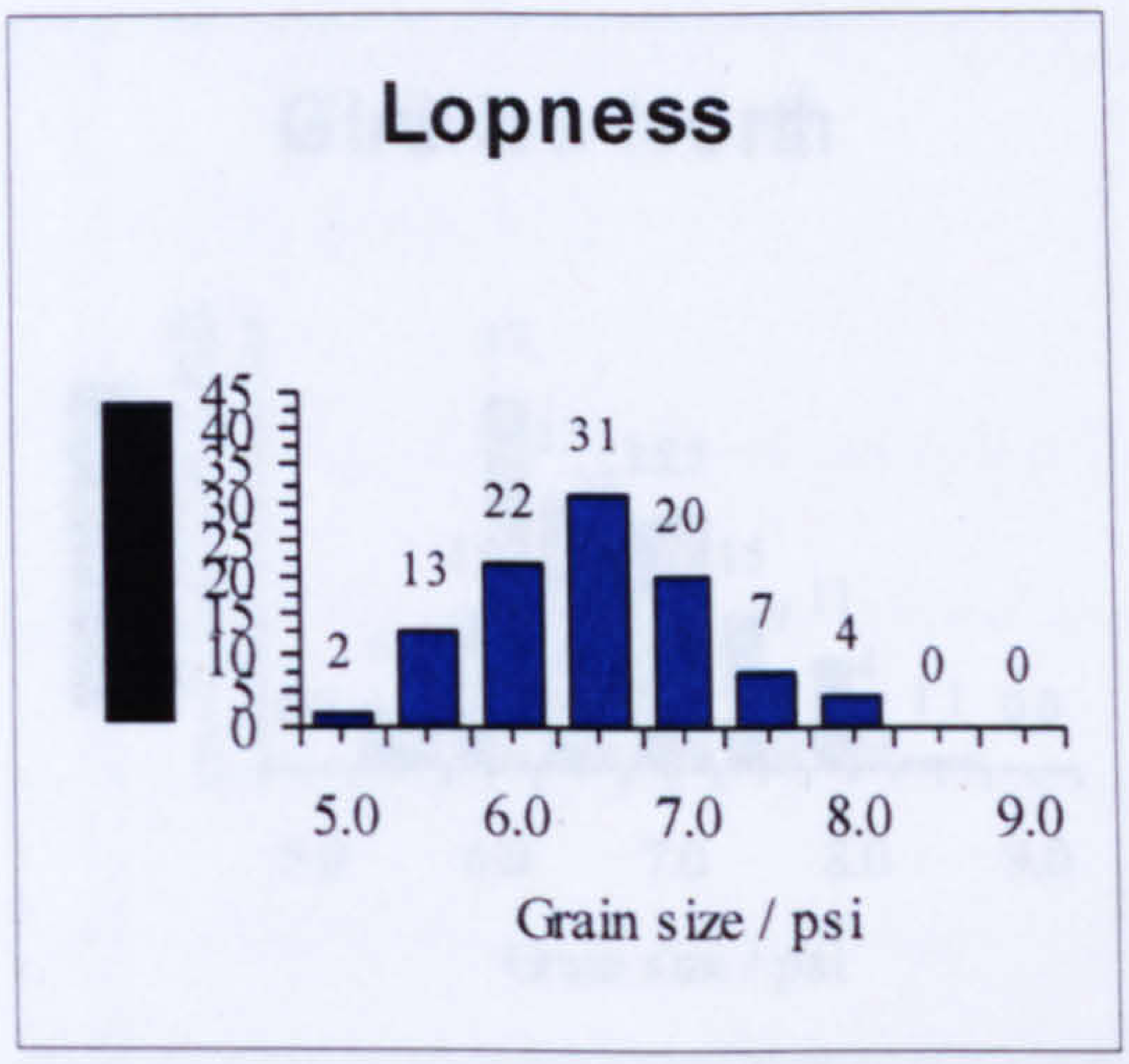
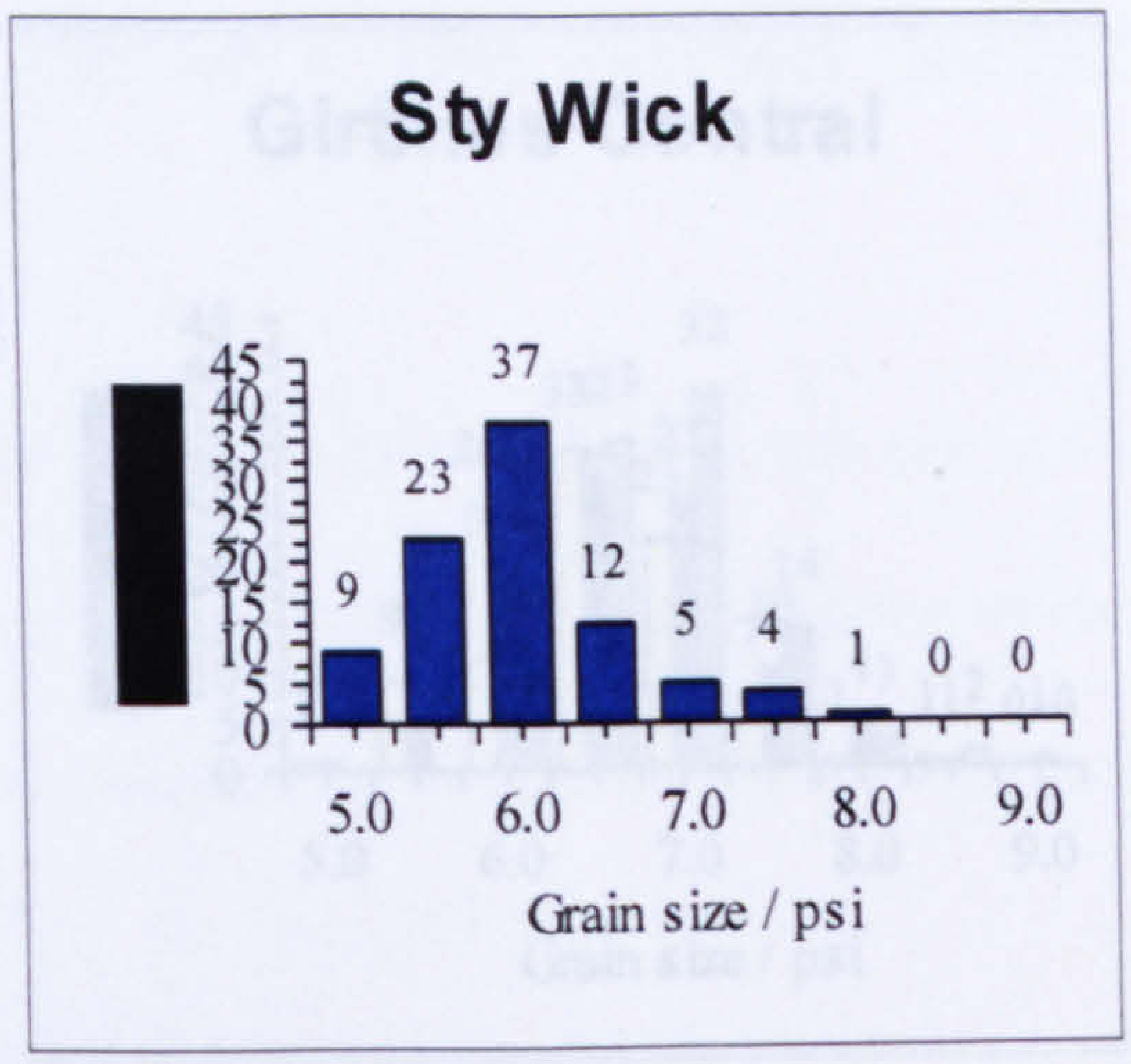
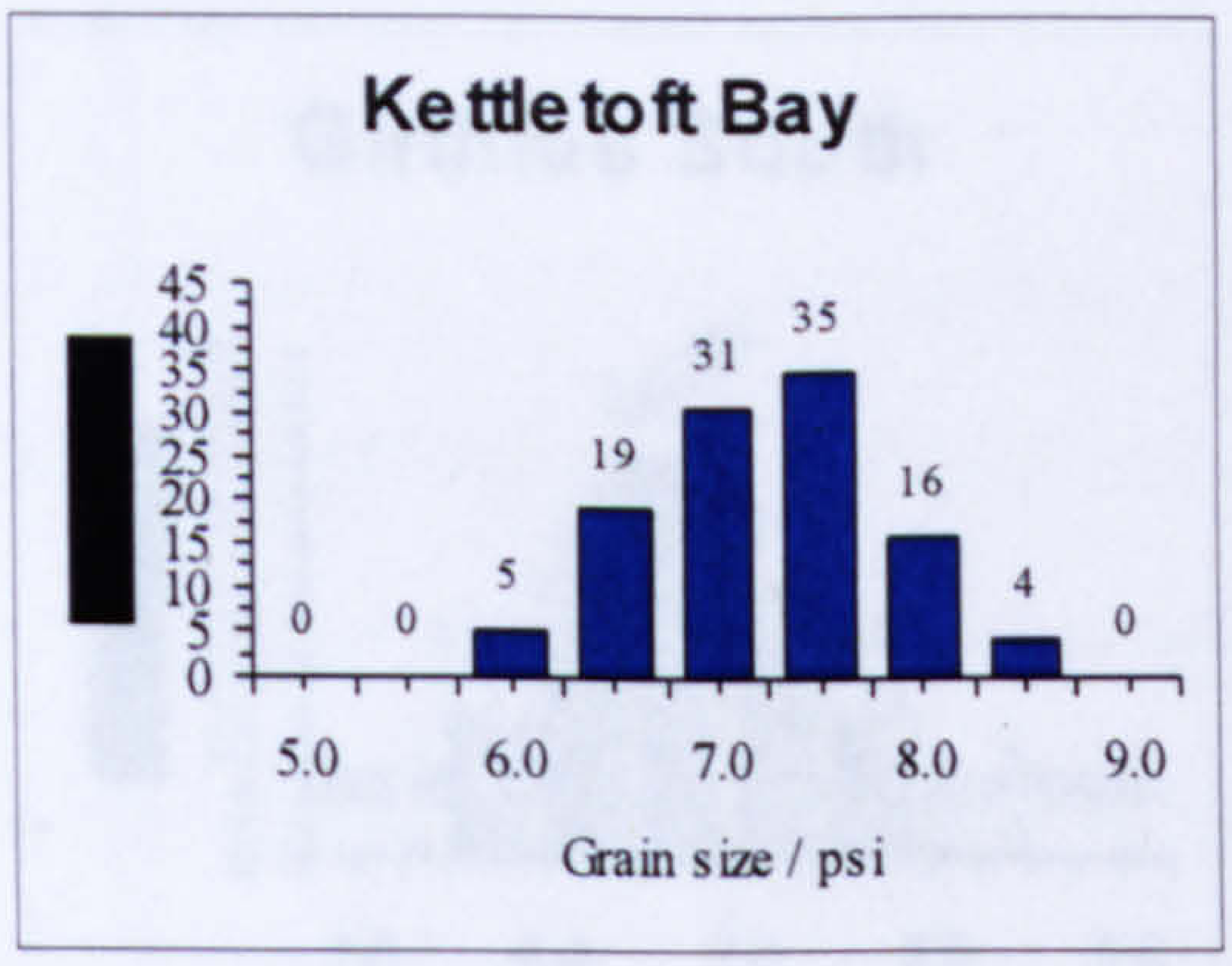


Figure 4.27 Sampling points for the particle size analysis of shingle features

The following charts (Figure 4.28 & Figure 4.29) will document the different particle size distributions of active features and relict landforms, to provide a basic comparison between these locations.







mm	Psi
512	9.0
362	8.5
256	8.0
181	7.5
128	7.0
91	6.5
64	6.0
45	5.5
32	5.0
23	4.5
16	4.0
11	3.5
8	3.0
< 8	< 3

Figure 4.28 Particle size analysis of active shingle features of Lopness, Sty Wick and Kettletoft Bay and a conversion table for Psi/mm. Note, Psi is the alternative term for particle size used principally for gravel bed rivers, which is comparable to Phi values, however unlike Phi, it reflects larger articles with increasingly positive values.

Stywick beach samples were dominated by a larger distribution than Lopness, with the Kettle toft shingle being characterised by smaller particles. This most likely reflects the shallower nearshore gradient and protective role of the headlands surrounding Kettletoft Bay. In comparison the relict features were generally more varied. The most dominant particle on the Girthies varied from 6-7psi (64-138mm) and the range of the particles was most varied in the central point and was most sorted at the southern end, towards the edge of the Clogg channel. Samples taken from the ridges within northern Cata Sand were to be finer than the samples from the 3 active beaches. The size distribution of particles of the southern edge of the Clogg was finer than those within the active deposits within Stywick. These particle size distributions will be discussed further in Chapter 5.

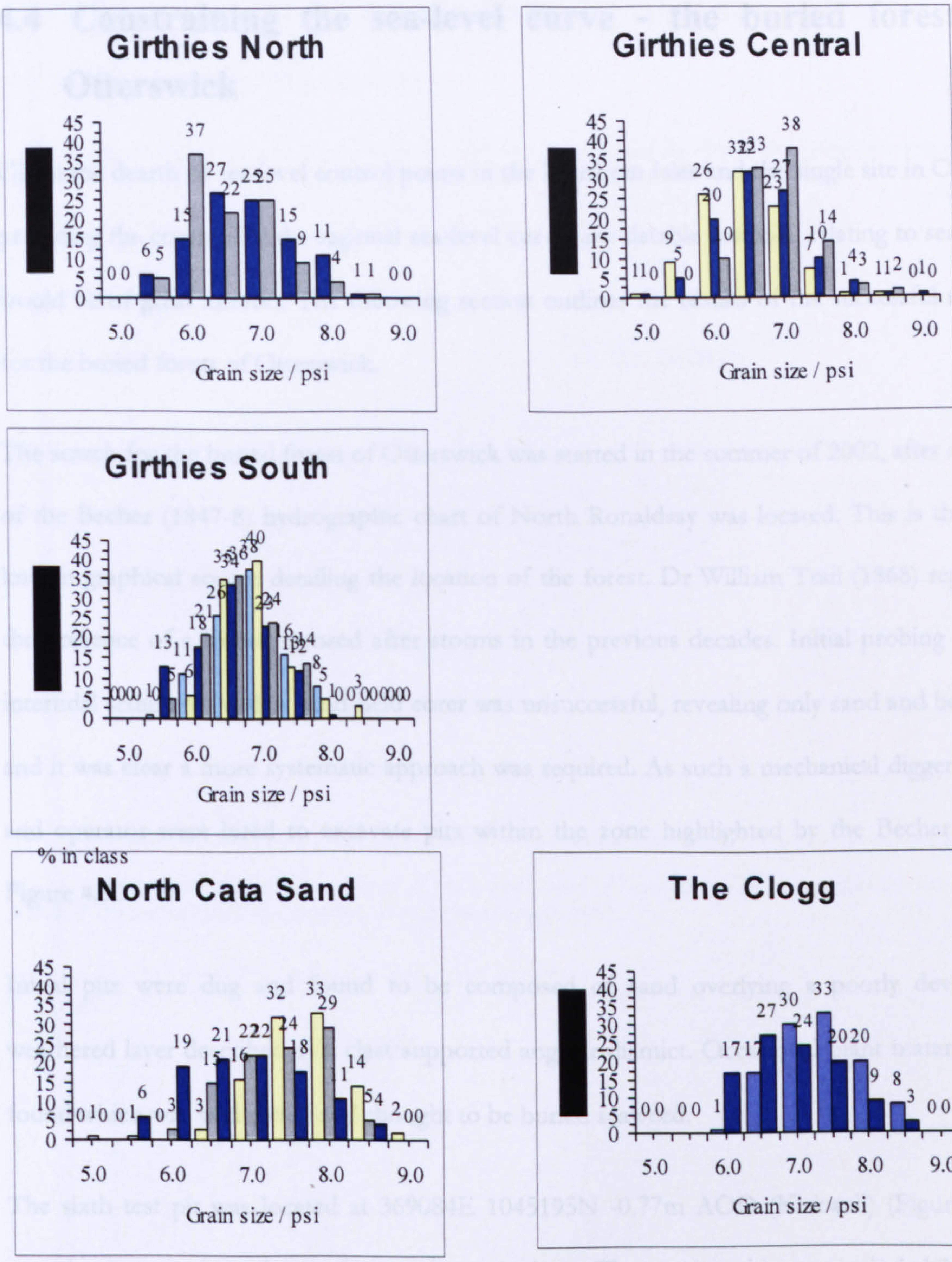


Figure 4.29 Particle Size analysis for the relict features within Cata Sand, see Figure 4.27 for locations. These graphs are composed of a number of sample points, each depicted by a different coloured bar.

4.4 Constraining the sea-level curve - the buried forest of Otterswick

Given the dearth of sea-level control points in the Northern Isles and the single site in Orkney providing the control for the regional sea-level curve, any datable material relating to sea level would be of great interest. The following section outlines the results of the successful search for the buried forest of Otterswick.

The search for the buried forest of Otterswick was started in the summer of 2002, after a copy of the Becher (1847-8) hydrographic chart of North Ronaldsay was located. This is the first known graphical source detailing the location of the forest. Dr William Trail (1868) reported the presence of a forest exposed after storms in the previous decades. Initial probing of the intertidal sediments with a hand-held corer was unsuccessful, revealing only sand and bedrock and it was clear a more systematic approach was required. As such a mechanical digger (JCB) and operator were hired to excavate pits within the zone highlighted by the Becher chart, Figure 4.30.

Initial pits were dug and found to be composed of sand overlying a poorly developed weathered layer described as a clast supported angular diamict. Occasional plant material was found which was well rotted and thought to be buried seaweed.

The sixth test pit was located at 369084E 1045195N -0.77m AOD (Kirkwall) (Figure 4.30) contained a prominent layer of vegetation at its base. The stratigraphic unit included 75cm of sand, which was underlain by 10-15cm of shell fragments and a 10-15cm layer of peat interlaced with branches of trees (Figure 4.31). At 1.1m below the surface the vegetation layer gave way to a thin layer of bleached-grey oxidised till layer which lay on top of weathered bedrock. During the excavation the sand remained dry only for a few minutes after which the vertical edges started to slump and fill the hole with sand and water. This made the profile recording relatively rushed; surfaces were measured but before they could be cleaned and photographed the facies were obscured.

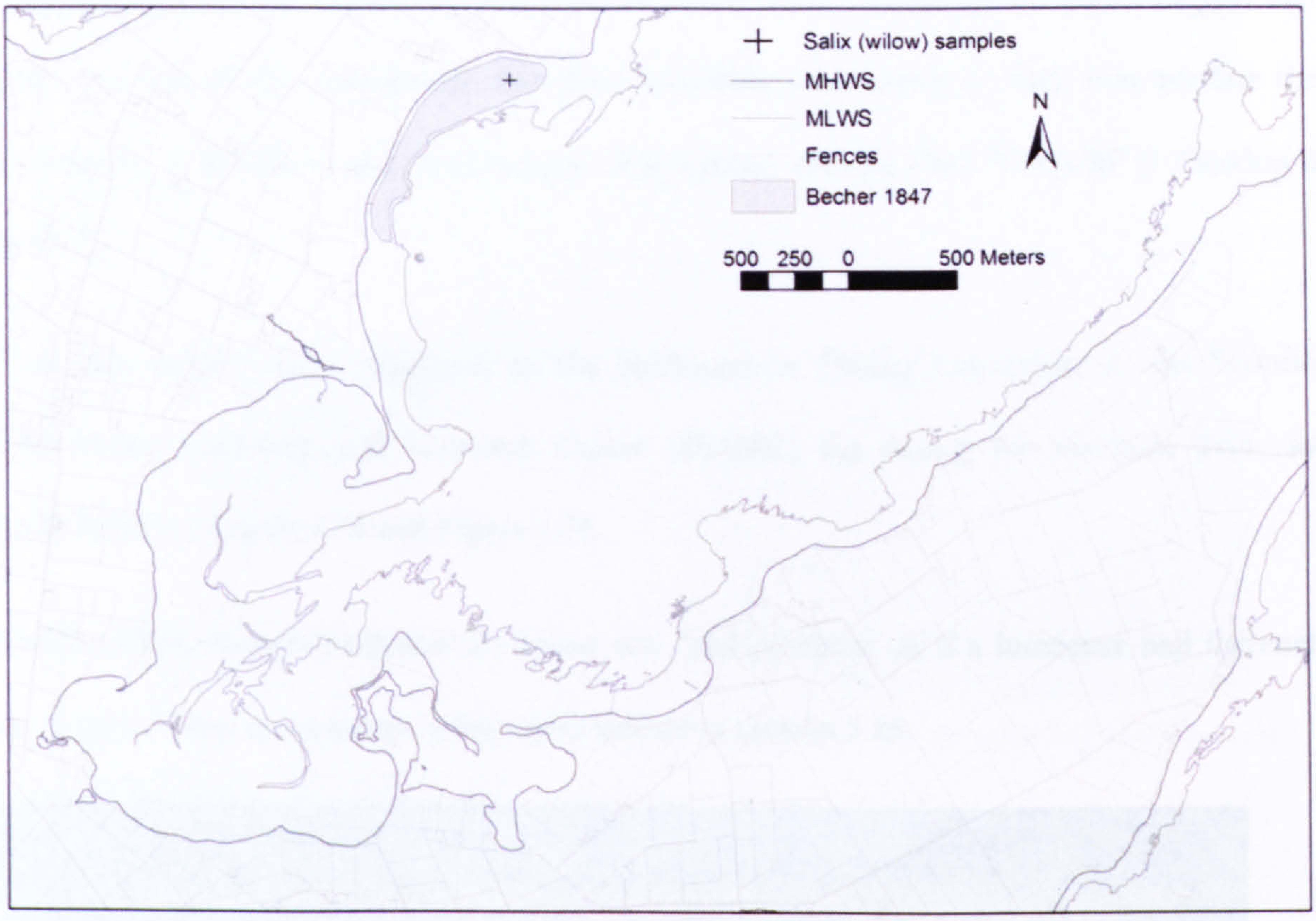


Figure 4.30 Extract of the Becher Chart of 1847, annotated to show the exact location of the submarine forest of Otterswick and the location of samples taken in 2002.

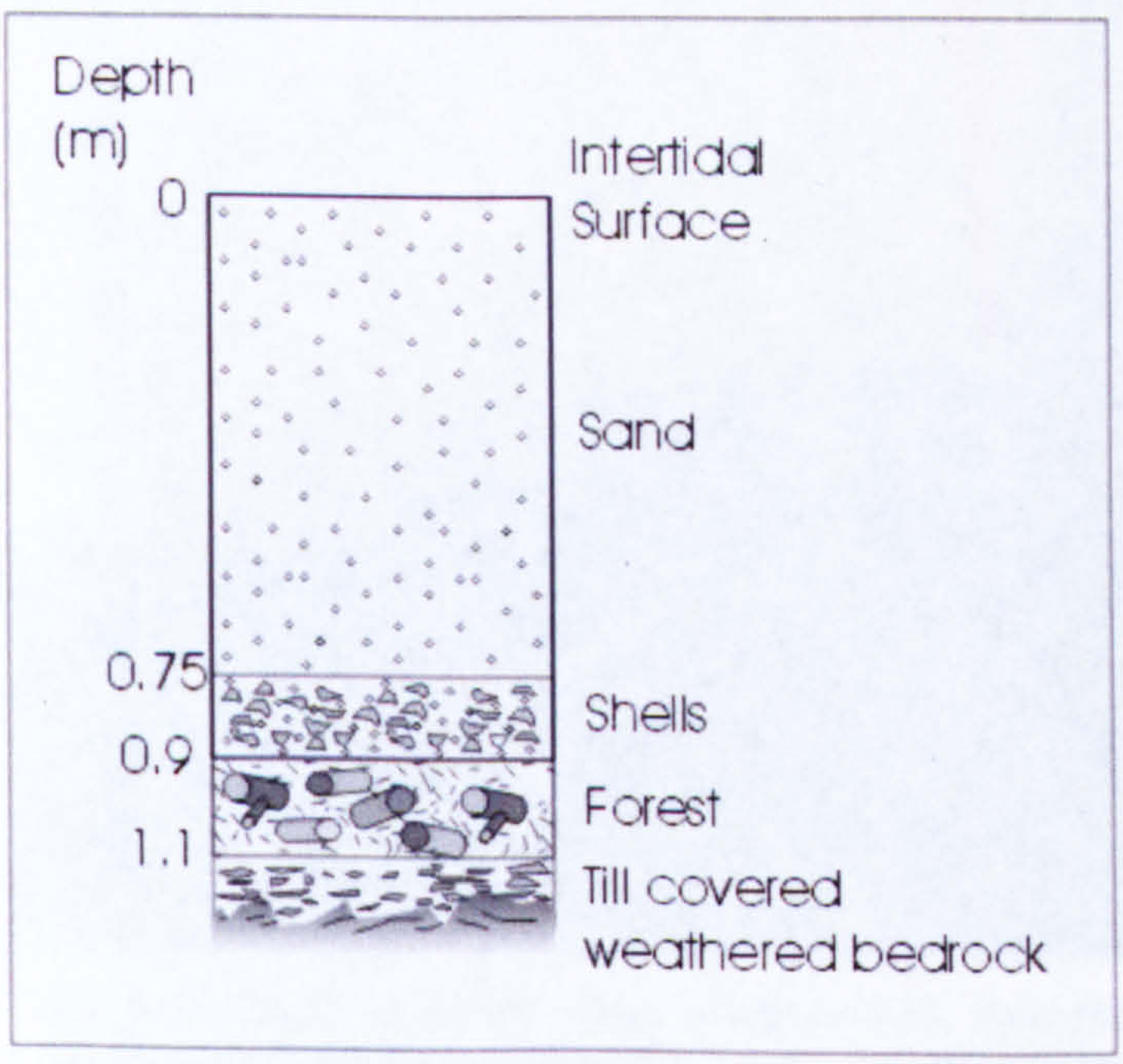


Figure 4.31 Stratigraphic log of buried wood samples from Otterswick

Approximately 10 samples of wood were removed, including some significantly sized trunks (A-axis: 40cm by 20cm diameter). Samples were taken to Glasgow University Archaeological Research Division (GUARD) and identified as willow (*Salix*). Initial age estimates suggest that given the size of the samplesand thus their suitability as a source of fuel, they predate the occupation of the island and the clearance of woodland, around 3000 ^{14}C yrs BP (J. Gordon *et al* 2002).

Two sub-samples were submitted to the Radiocarbon Dating Laboratory at the Scottish Universities Environmental Research Centre (SUERC) for dating, the resultant dates are summarised in Figure 4.35 and Figure 4.36.

Traill's (1868) account indicates the forest was 'laid prostrate' as if a hurricane had flattened the forest. This interpretation is discussed further in section 5.13.

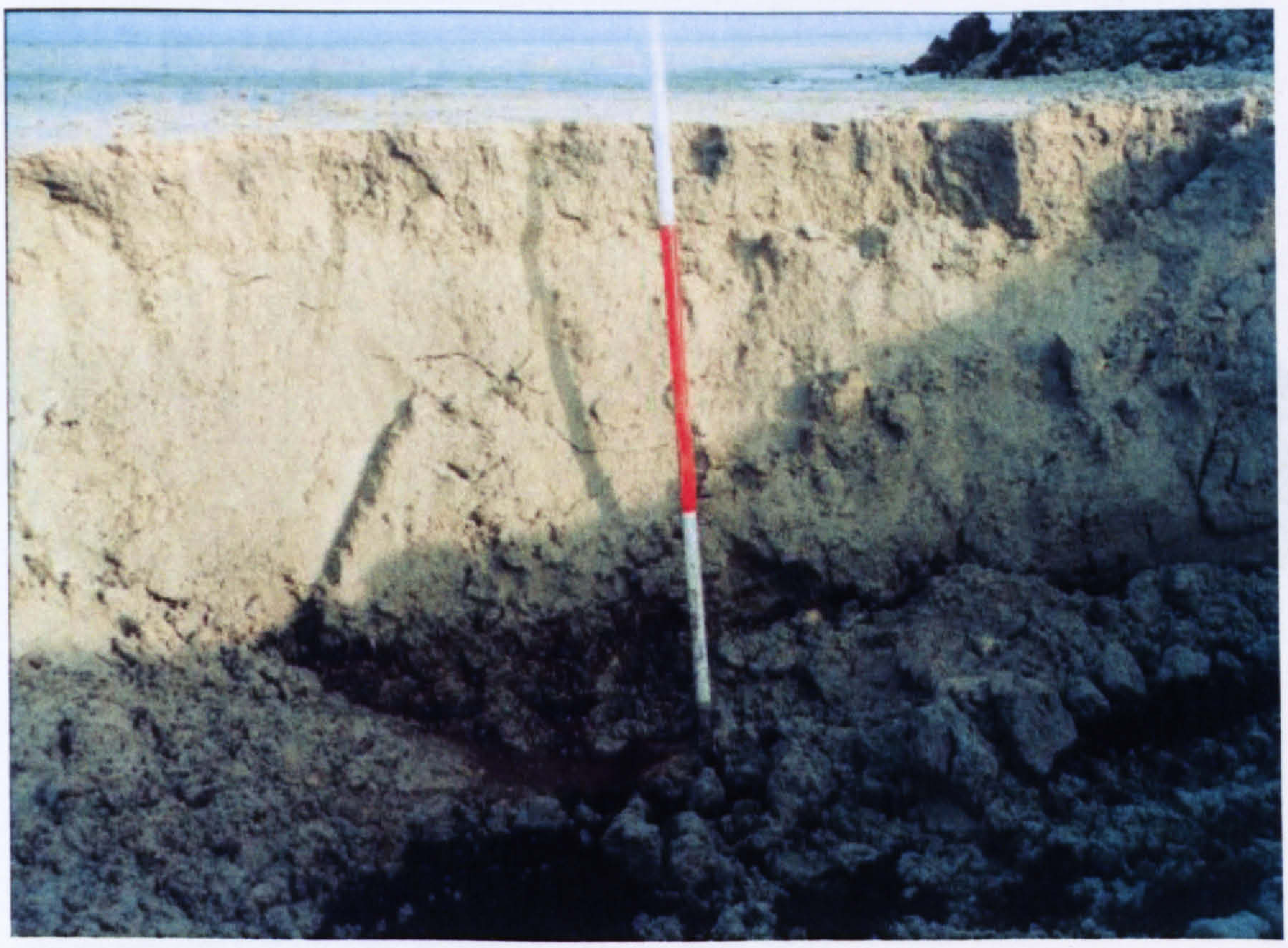
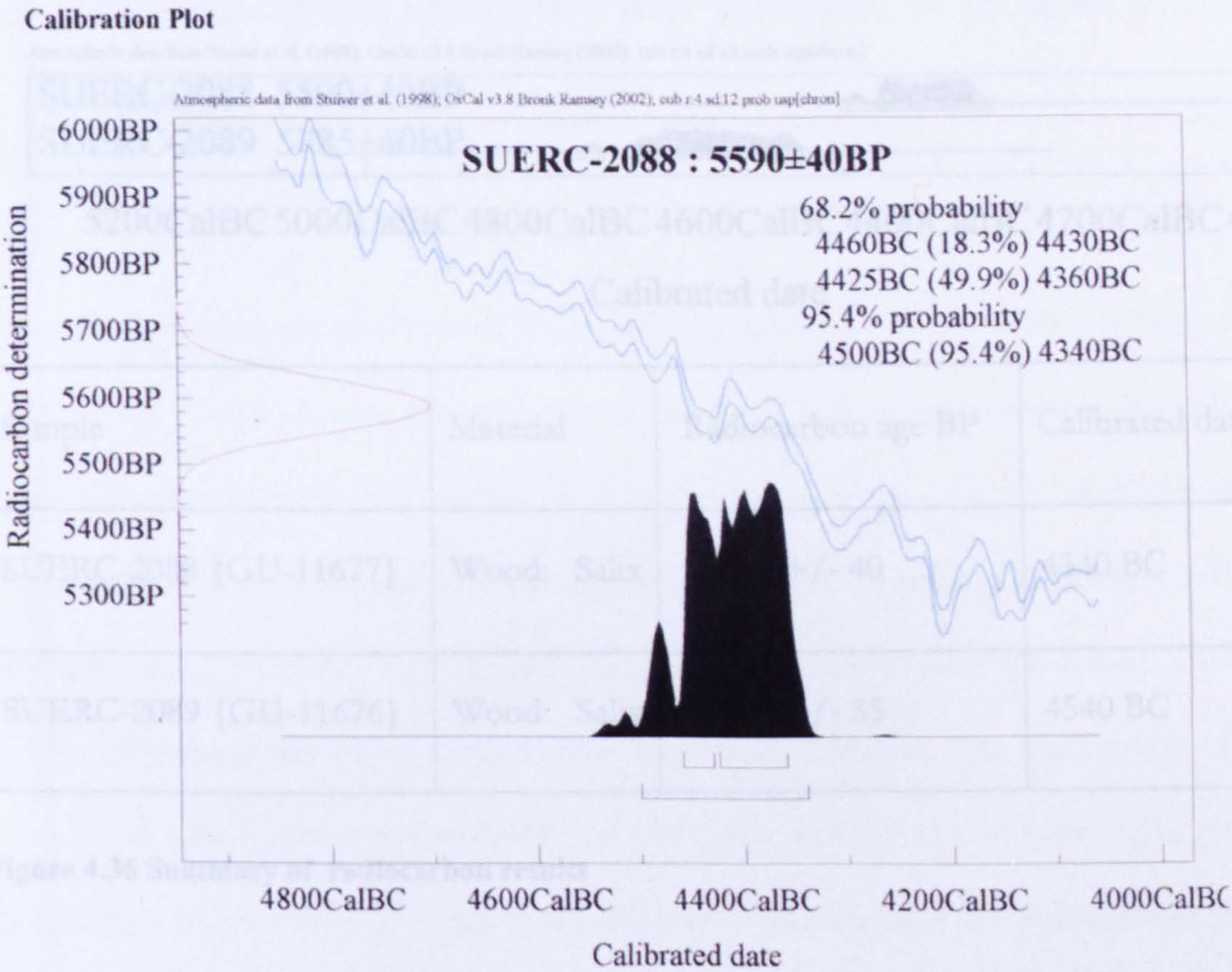


Figure 4.32 Photo of profile shown in Figure 4.31. Note the sand layer lies above a shell layer, below which the peat and till is visible. The peat is spatially limited - present in the foreground but not towards the wall of the pit.

Figure 4.33 Peat exposure in the base of the pit. Note the peat layer (brown) with interlaced branches (orange), surrounded by slumping sand.

Figure 4.34 One of the retrieved samples, identified as Willow (*Salix*)



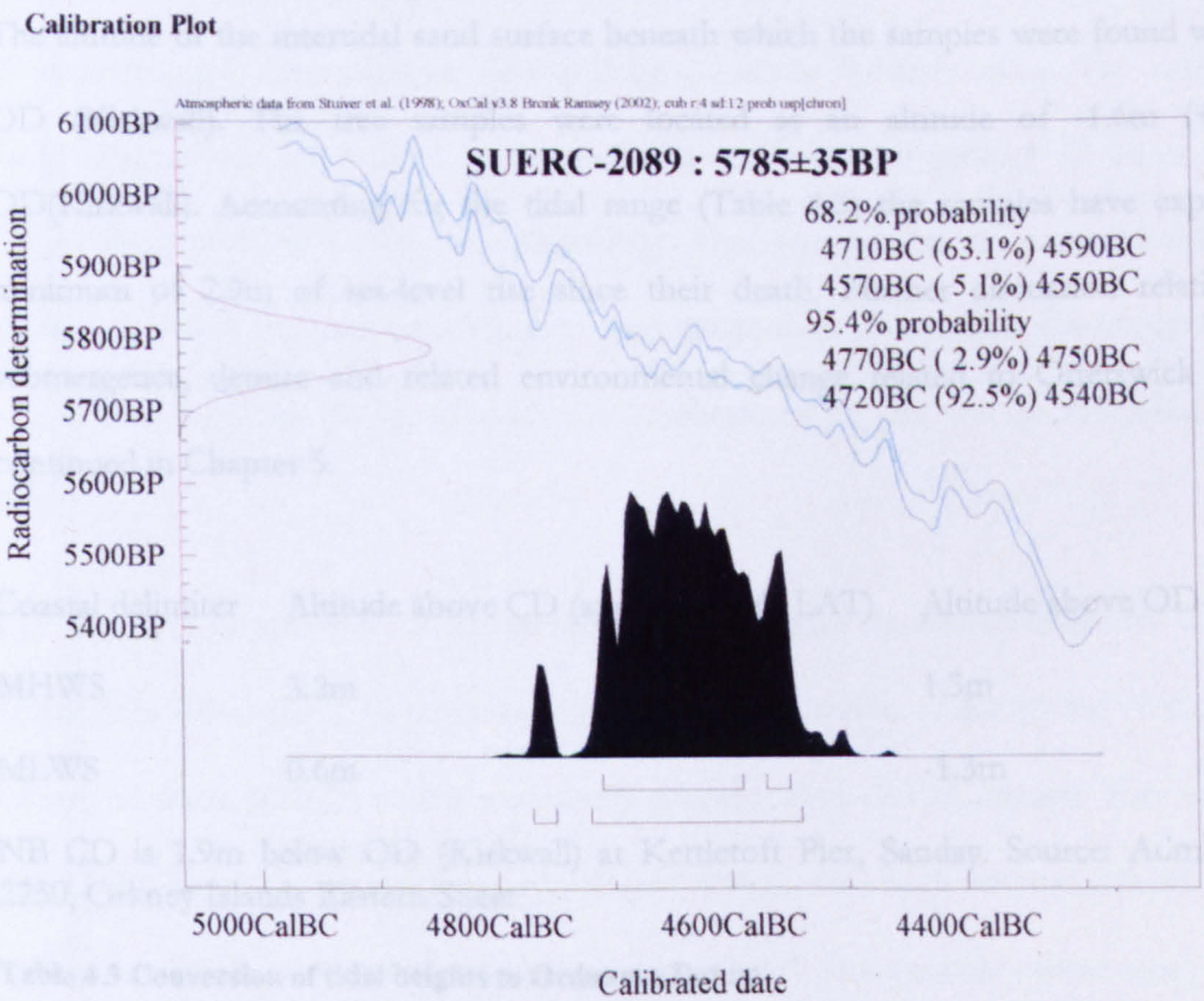
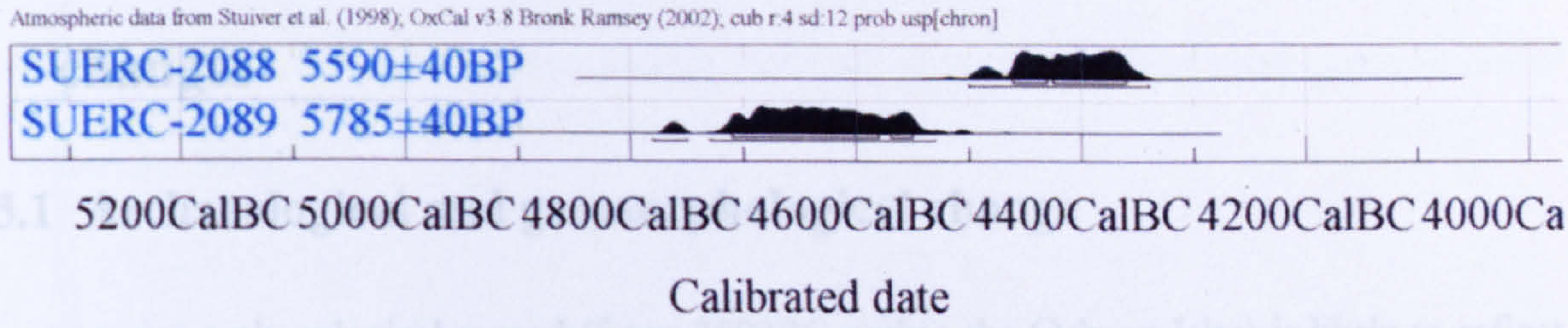


Figure 4.35 Radiocarbon date results for two samples from the Otterswick submerged forest.



Sample	Material	Radiocarbon age BP	Calibrated date
SUERC-2088 {GU-11677}	Wood: Salix	5590 +/- 40	4340 BC
SUERC-2089 {GU-11676}	Wood: Salix	5785 +/- 35	4540 BC

Figure 4.36 Summary of radiocarbon results

The altitude of the intertidal sand surface beneath which the samples were found was -0.77m OD (Kirkwall). The tree samples were located at an altitude of -1.6m (+/- 0.1m) OD(Kirkwall). Accounting for the tidal range (Table 4.3) the samples have experienced a minimum of 2.9m of sea-level rise since their death. Further discussion relating to the submergence, demise and related environmental change related to Otterswick forest are continued in Chapter 5.

Coastal delimiter	Altitude above CD (approximately LAT)	Altitude above OD (Kirkwall)
MHWS	3.2m	1.3m
MLWS	0.6m	-1.3m

NB CD is 1.9m below OD (Kirkwall) at Kettletoft Pier, Sanday. Source: Admiralty Sheet 2250, Orkney Islands Eastern Sheet.

Table 4.3 Conversion of tidal heights to Ordnance Datum

4.5 Archaeological and historical evidence of geomorphological changes

4.5.1 Archaeological and geomorphological change

The extensive archaeological record (from 3600BC within the Orkney Isles) is likely to reflect some of the coastal changes experienced on Sanday. To investigate whether any relationship exists between archaeological evidence and the evolution of the coast of the island, all known archaeological sites on Sanday (compiled from the Royal Commission of Historic and Ancient Monuments of Scotland and Historic Scotland databases) were age-sorted, checked for duplicates and entered into a Geographical Information System. The distribution of features of archaeological interest was analysed and compared against other mapped data, particularly the geology, geomorphology maps, to try and identify which areas of the island may have been subjected to change during periods of the past. Figure 4.37 displays the archaeological site positions mapped against known solid geology (i.e. minus the drift cover). The majority of the archaeological sites are located on areas of exposed basement geology. Areas of aeolian on marine derived sediment carry no archaeology. This suggests that the present terrestrial areas of Sanday which have no archaeological sites either were not suitable for occupation or did not exist at the time of occupation. The implications of this will be discussed further in chapter 5.

The discovery of previously unknown archaeology towards the eastern extremity of the Bay of Lopness in 2000 as part of this research project also provides a clue to the evolution of that section of coast. In 2000 during a southerly gale, the dune cliff at Lopness farm was cut back exposing a burial cist on the foreshore (Figure 4.38A). Although other structures were noted at the time by the local farmer further along the beach face (possibly other cists), these were destroyed in the gale. The remaining cist was reported and an emergency excavation was carried out on the intact cist at Lopness in 2000, overseen by GUARD. Radiocarbon dating of the crouched incumbent (Figure 4.38B) age dated the bones to 3.5kaBP (Robertson and Downes 2000) and the overlying sand layers from the sand dune behind were dated at 3kaBP (Sommerville 2003).

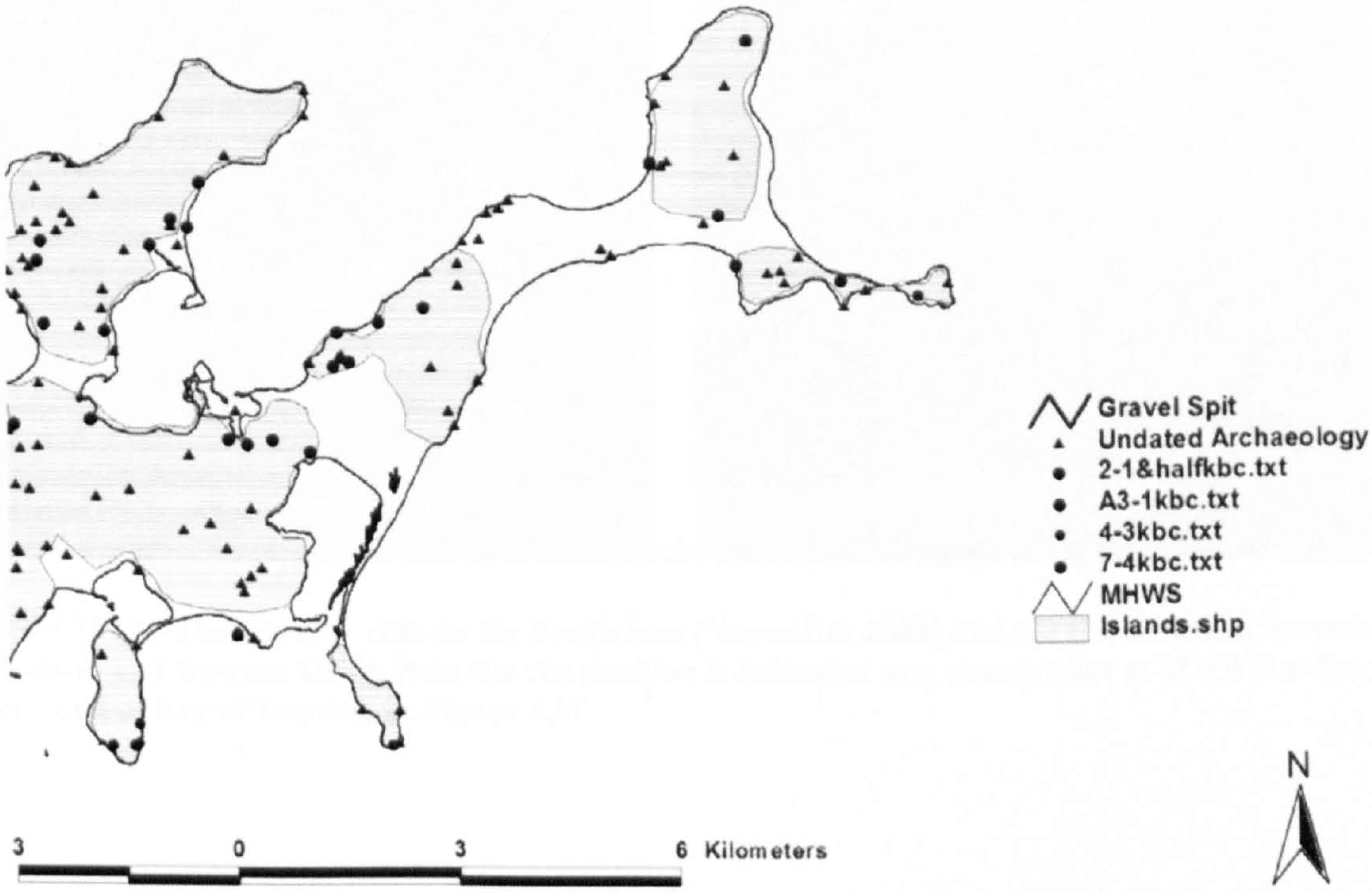


Figure 4.37 Distribution of archaeological sites on Sanday and the distribution of basement geology (grey shading) at ground surface i.e. non-marine & non-aeolian dominated areas of the island

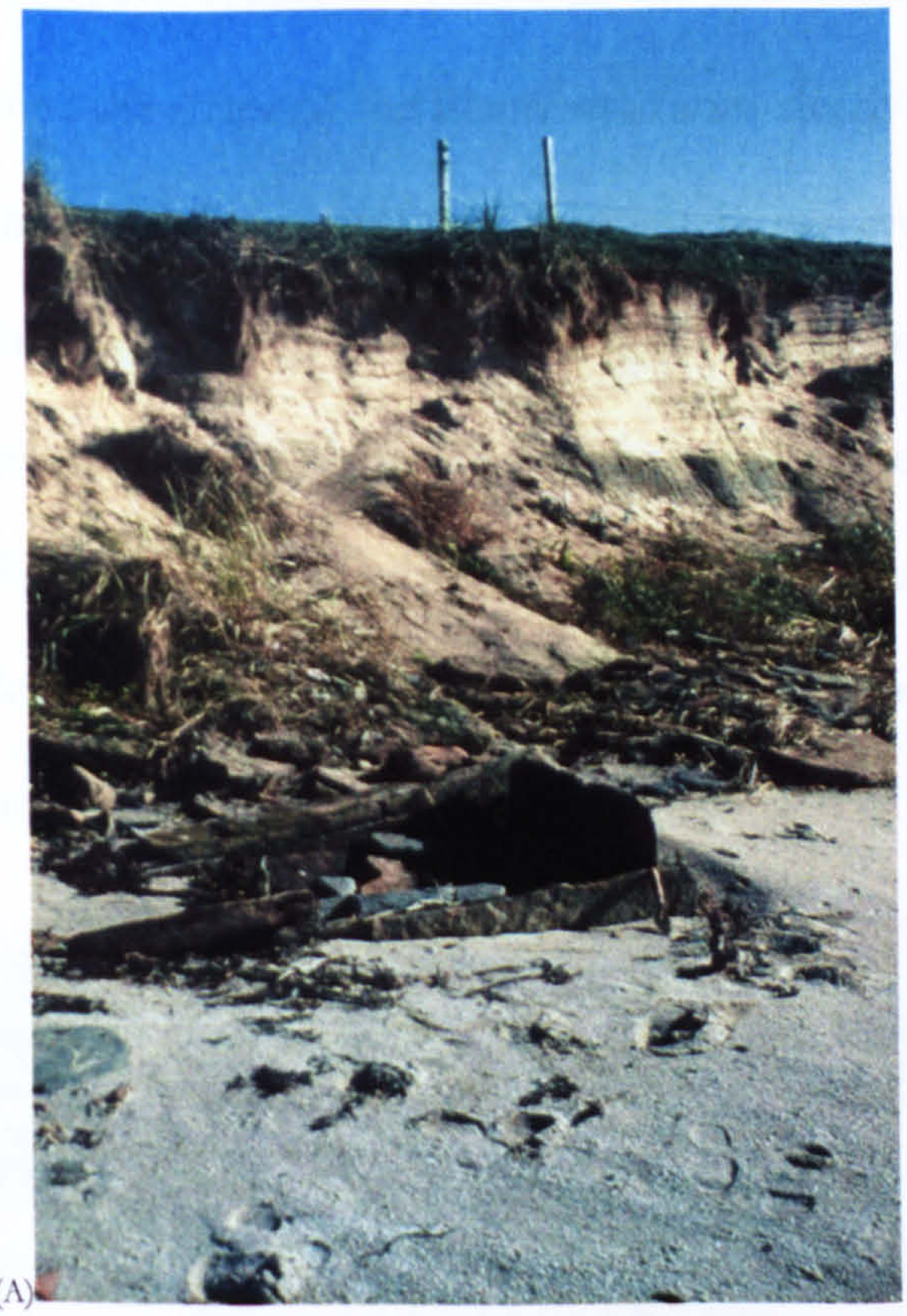


Figure 4.38 (A) The Lopness cists on the beach face (November 2001) and (B) the crouched incumbent (Robertson and Downes 2000). Note the cist position is indicated as a circular dot at MHWS at the eastern end of Bay of Lopness in Figure 4.37

4.5.2 Historical geomorphology: the earliest maps

An extensive search was undertaken to identify historical maps of the Sanday and the Northern Isles of Orkney. Over 50 maps were found and those of particular interest are described below and their significance is discussed in Chapter 5. These historical sources not only document the areas of interest to the cartographer reflecting historical interests and values, but provide an essential suite of evidence documenting the physical and environmental changes during the last 450 years.

The earliest broadly accurate cartographic representation of the Orkney Isles dates to the Venetian cartographer Paolo Forlanis. His map of Scotland was produced between 1558-66 (Figure 4.39) and is helpful in terms of the detail, both of individual islands and their respective coastlines. However the individual detail of the islands is poorly represented. By 1682 the shape of the island was more clearly presented by van Keulen (Figure 4.40). By 1693 the archipelago were more accurately surveyed by Greenville Collin (Figure 4.41). Although Sanday's outline is only generally representative, the annotations highlight more significant changes to the island. This is the earliest reference to 'Runnabreck' (Reinabrake) arrowed on Figure 4.41, formerly a productive peninsula, with a chapel. The area today is a rocky foreshore consumed by chronic coastal erosion. References to the demise of the 'Ba' Green' are discussed in chapter 5.

Figure 4.39 Orkney Islands, Forlani (1560), N.L.S

Figure 4.40 Sanday after van Keulen (1682), Left: rotated so text can be read and Right: approximate orientation to north

Other coastal changes are also visible (Figure 4.41) when the 1693 map is compared with the present coastline, these differences include:

- Cata Sand was a wide embayment with no narrow opening. This area is presently a channel called the Clogg (Shown in detail in Figure 4.49),
- Start Point is still connected to Sanday and Blatchford's (1846) it is called Start Head.
- There were rocks within Lopness Bay marked as 'x' marks
- And finally Little Sea, the inlet at the head of Kettletoft Bay had no spits guarding its mouth.

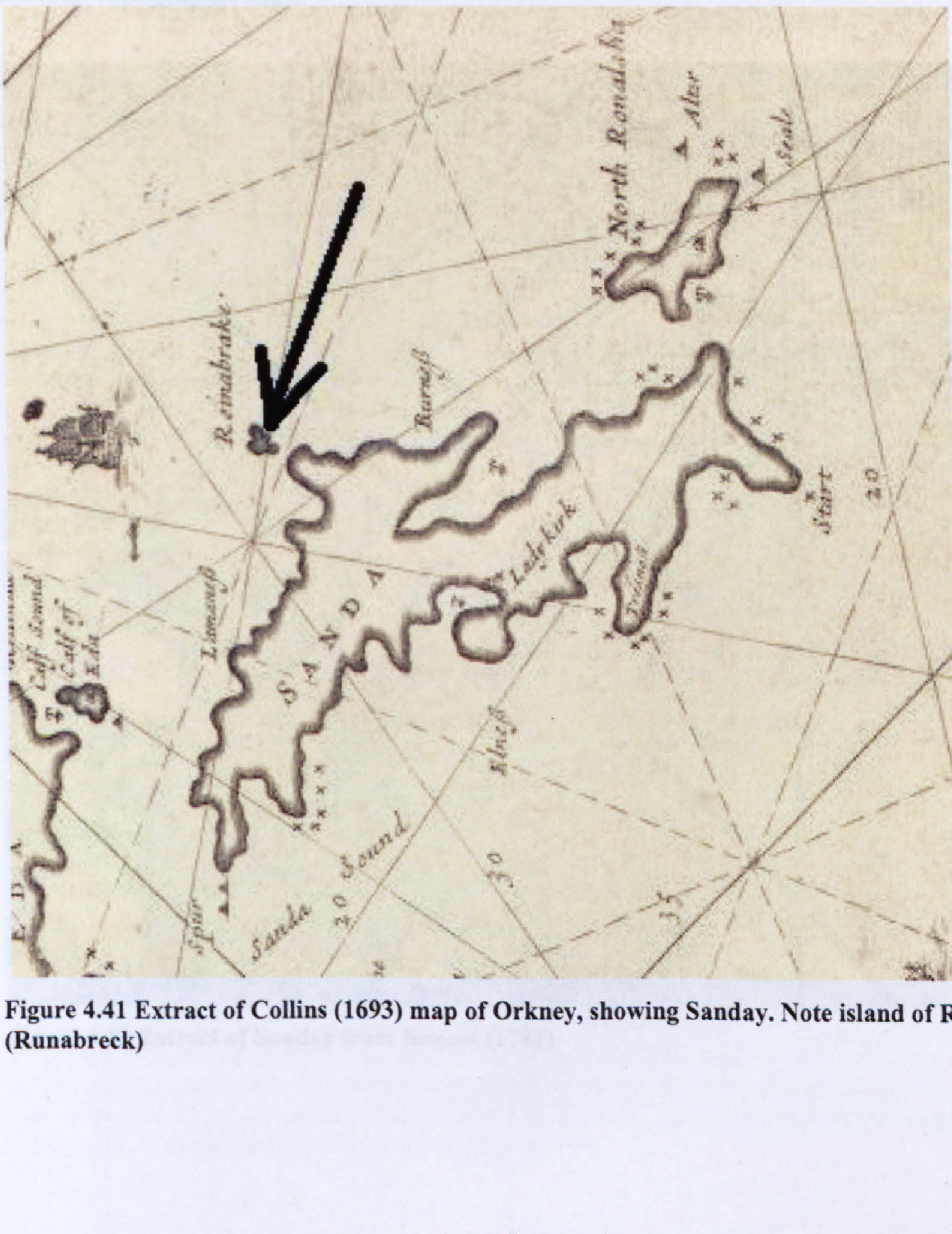


Figure 4.41 Extract of Collins (1693) map of Orkney, showing Sanday. Note island of Reinabreck (Runabreck)

By the late 18th century cartographical skills were improving and the detail and proportion started to resemble modern representations of the island. Bennets' (1781) map of Orkney is representative of this trend. Closer inspection of Sanday (Figure 4.42) also shows Start Point as a peninsula and it documents the sand flats of Cata Sand and Little Sea with narrower openings, which is comparable to the modern day shape. The tombolo linking the island of Tres Ness with Sanday is very narrow, so to is the isthmus linking the northern peninsula of Burness (north of the 'a' in SANDA, Figure 4.42). The lochs between Lopness and Otterswick are of considerable size, the island of Riv, near Whitemill Bay, is represented as a skerry (intertidal rocks). The map also highlights the shallows associated with Ba Grunna: the subtidal topographic high.

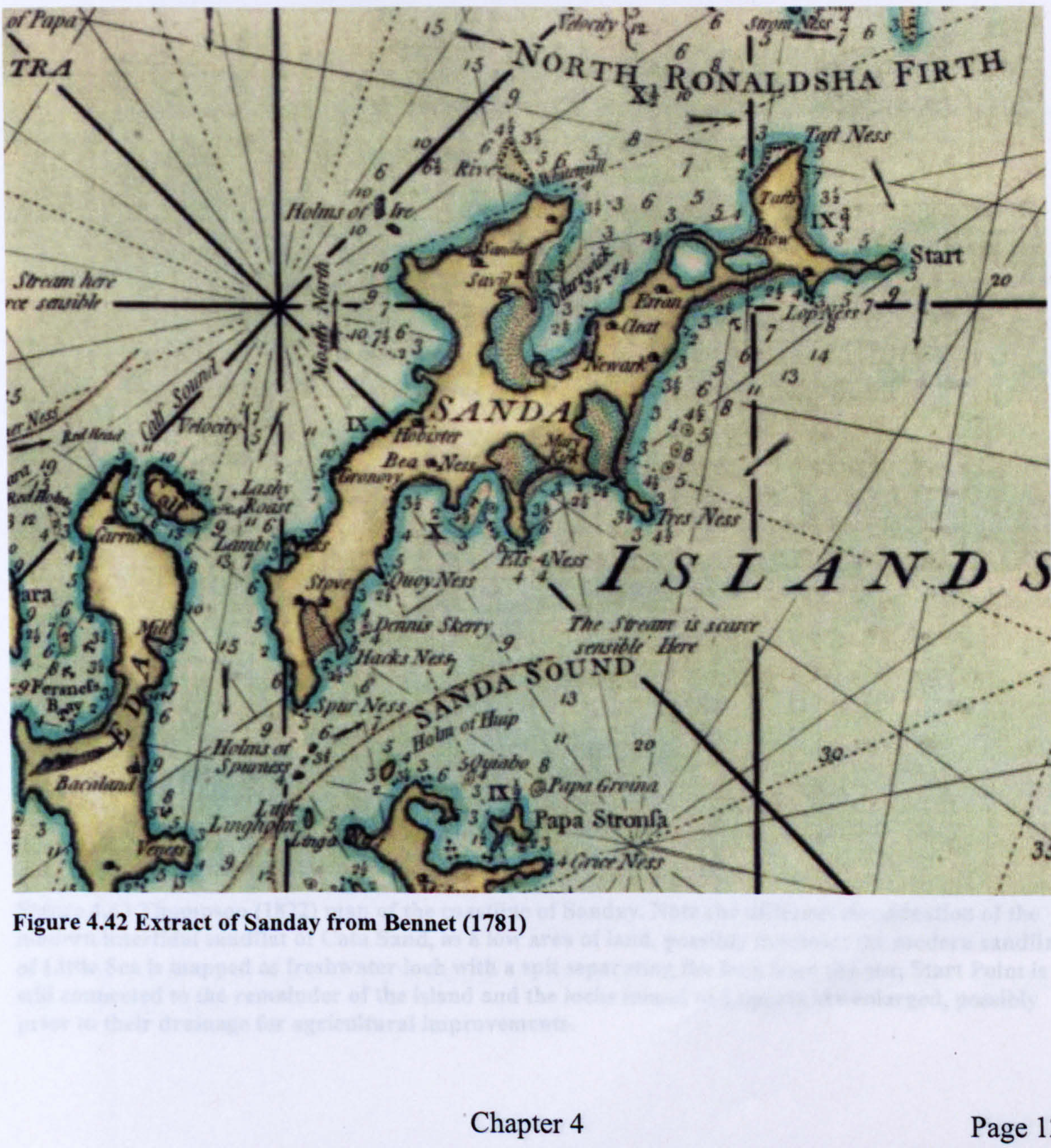


Figure 4.42 Extract of Sanday from Bennet (1781)

Interestingly, the Thompson map (1822) clearly shows Cata Sand as a non-intertidal depression, with the Clogg (the present drainage channel) blocked (Figure 4.43). Thompson's representation of a non-tidal Cata Sand was repeated in Groome's (1896) map (Figure 4.46), but Blatchford produced a map in 1846 (after Thompson and before Groome), which displayed Cata Sand once again as an intertidal sand flat (Figure 4.44). Blatchfords map was the last record of Start Point joined to the remainder of Sanday, as the Hydrographic Chart (1850) clearly shows the separation (Figure 4.47). Groome's (1896) map may be a replica of Thompson (1822), however apart from visual similarities there is no other supporting information. An alternative possibility is that the Clogg has 'clogged' up again, due to a build up of coastal sediments.

Figure 4.43 Thompson (1822) map of the coastline of Sanday. Note the different classification of the modern intertidal sandflat of Cata Sand, as a low area of land, possibly machair; the modern sandflat of Little Sea is mapped as freshwater loch with a spit separating the loch from the sea; Start Point is still connected to the remainder of the island and the lochs inland of Lopness are enlarged, possibly prior to their drainage for agricultural improvements.

Figure 4.44 Blatchford (1846) – Cata Sand is present and represented as an intertidal sandflat, with no spits guarding the Clogg (arrowed)and Start Point remains attached to the remainder of Sanday.

Figure 4.45 Start Light House in 1821 (Source: William Daniell 1821), prior to separation of the islet from the main island.

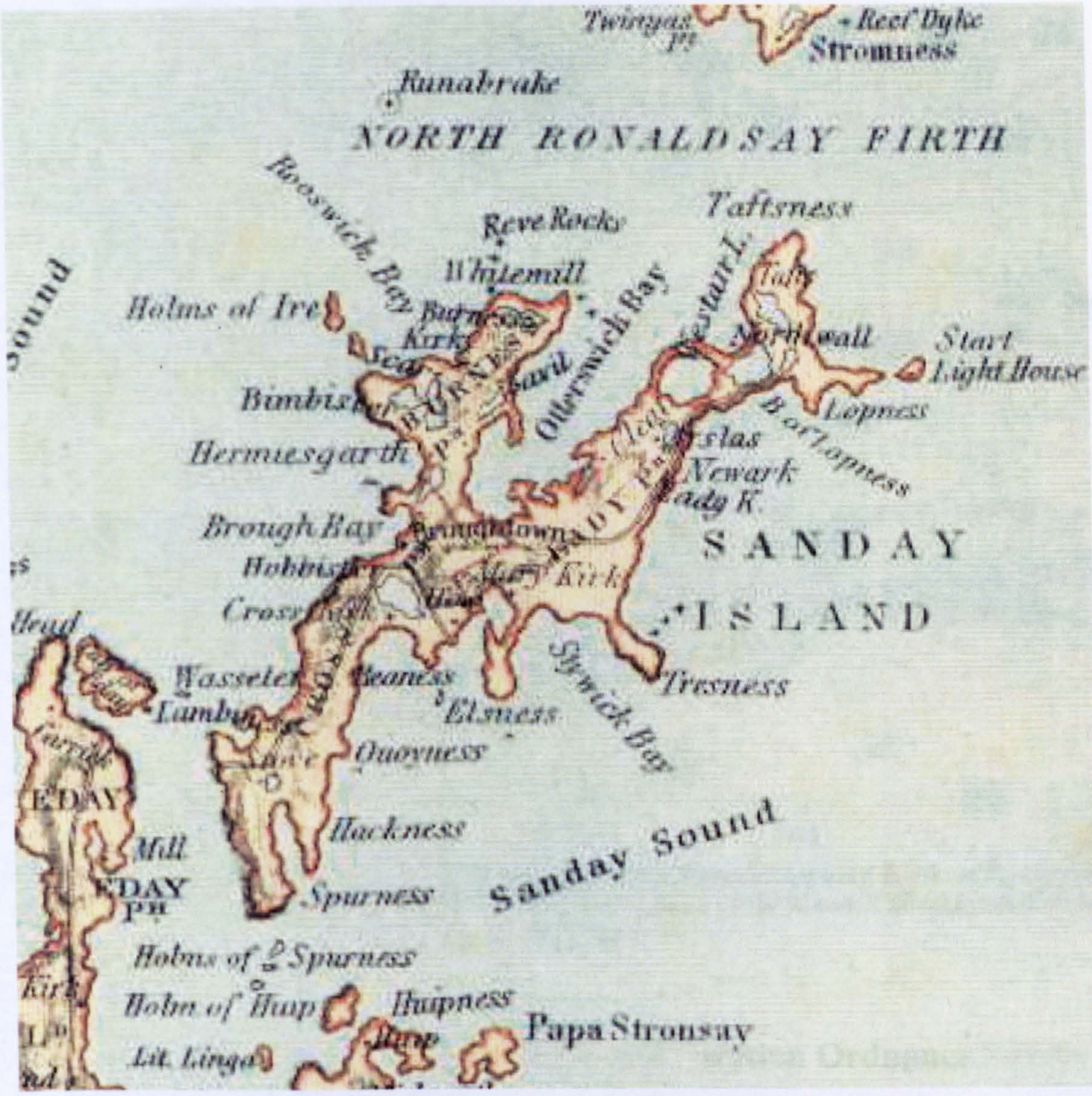


Figure 4.46 Groome (1896) Cata Sand is absent and represented as a terrestrial area and Start Point has separated from the remainder of the island.

Evidence of an artificial cut to open Clogg was searched for, however no evidence was found. Low lying machair does flood during winter months and a cut may have been used as an attempt to drain the flooded winter loch/loch. However, this may have unexpected implications in areas experiencing relative sea level rise. This is discussed further in Chapter 5.

Figure 4.47 An extract of the 1850 Hydrographic Chart (Becher) used here as the earliest mapped evidence of the separation of Start Point from the remainder of the island. The remainder of this chart is discussed in the Hydrographic Section (Figure 4.53).

4.5.3 Historical Change: 1st and 2nd edition Ordnance Survey Maps

'In Scotland there has been no legal definition of the foreshore boundaries but ancient custom has decreed that the extent of the foreshore shall be limited by mean spring tides. The OS therefore decided to survey the high and low water marks of … an average spring tide (termed MHWS or MLWS)… Before 1935… in Scotland these lines were called High and Low Water Mark Ordinary Spring Tides.' (OS, 1980, OS leaflet New Series no70) Thus, the first edition and modern data are attempting to plot the same line, however the datum of that line cannot be confirmed. In the 19th century this was made more problematic by the remote location of the islands, local datum and the relative poor quality of metadata for early historical OS maps. Given these shortcomings no quantifiable cartographic comparisons could be made between the first and second editions of the Ordnance Survey. However there are deviations between the 1st Edition representation of the island form and that of the present version of the OS data, which will identify more recent historical changes across the island.

The 1st Edition Ordnance Survey map of Sanday (1882) shows a number of clear differences from the present geomorphology, which reflect more than cartographic errors. The map includes a small loch within the central Plain of Fidge (Figure 4.48) in the flat area adjacent to the exposed gravel ridges. The linear strip of land separating the larger body of water from the smaller one, shares the position with one of the exposed gravel ridges. The area of flooding is comparable with that shown in bottom section of Figure 4.5.

Further south the tidal entrance to Cata Sand has also been subject to significant change (Figure 4.49). Although the MLWS has not altered much from the LWMOST, the HWMOST is different from the present MHWS. The eastward extension of The Dees is a clearly a recent dune-cap on top of the gravel which overlies a bedrock base.

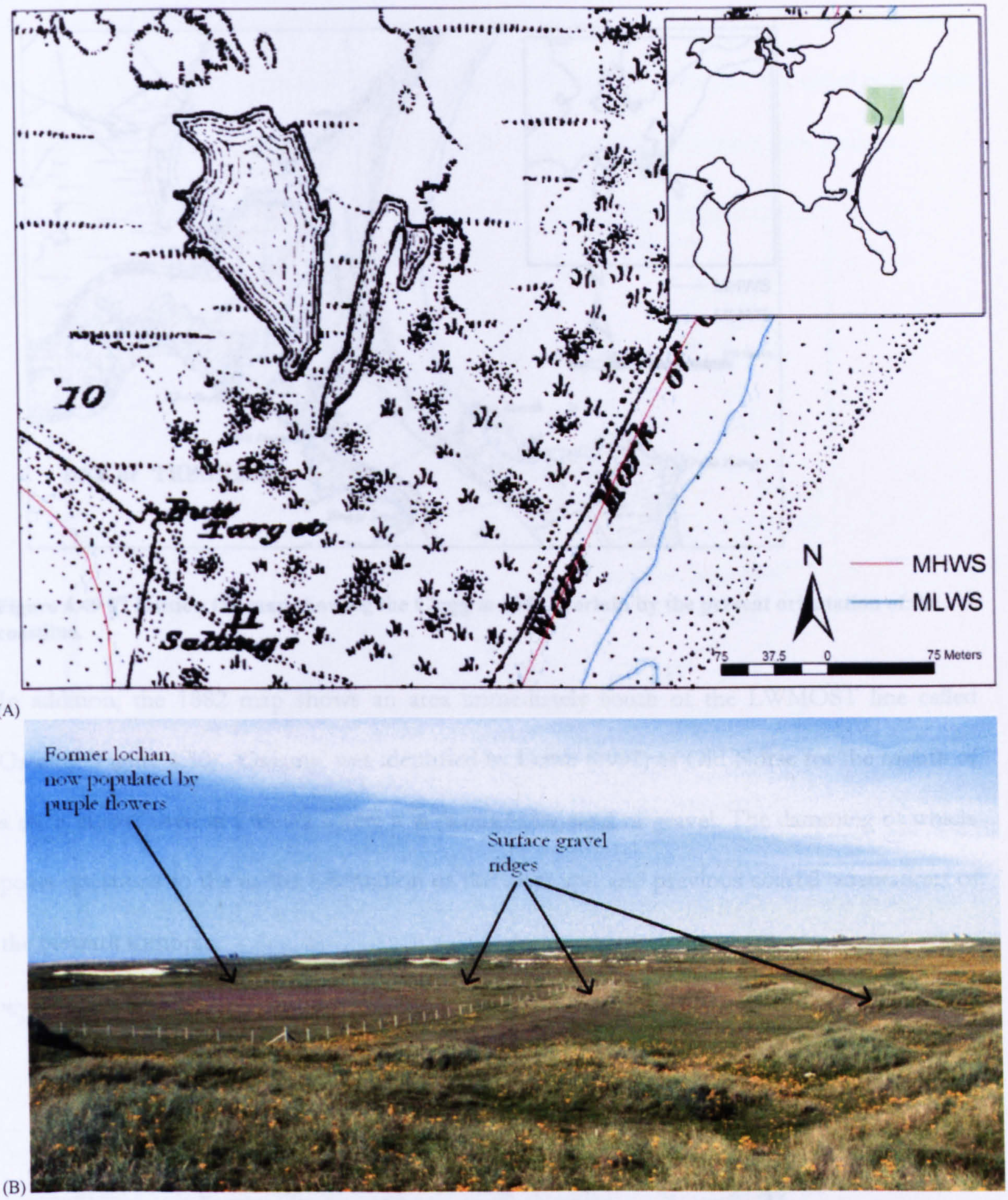


Figure 4.48 1st Edition OS map (1882) overlain by the present position of the coastline, Note the small loch within the Plain of Fidge

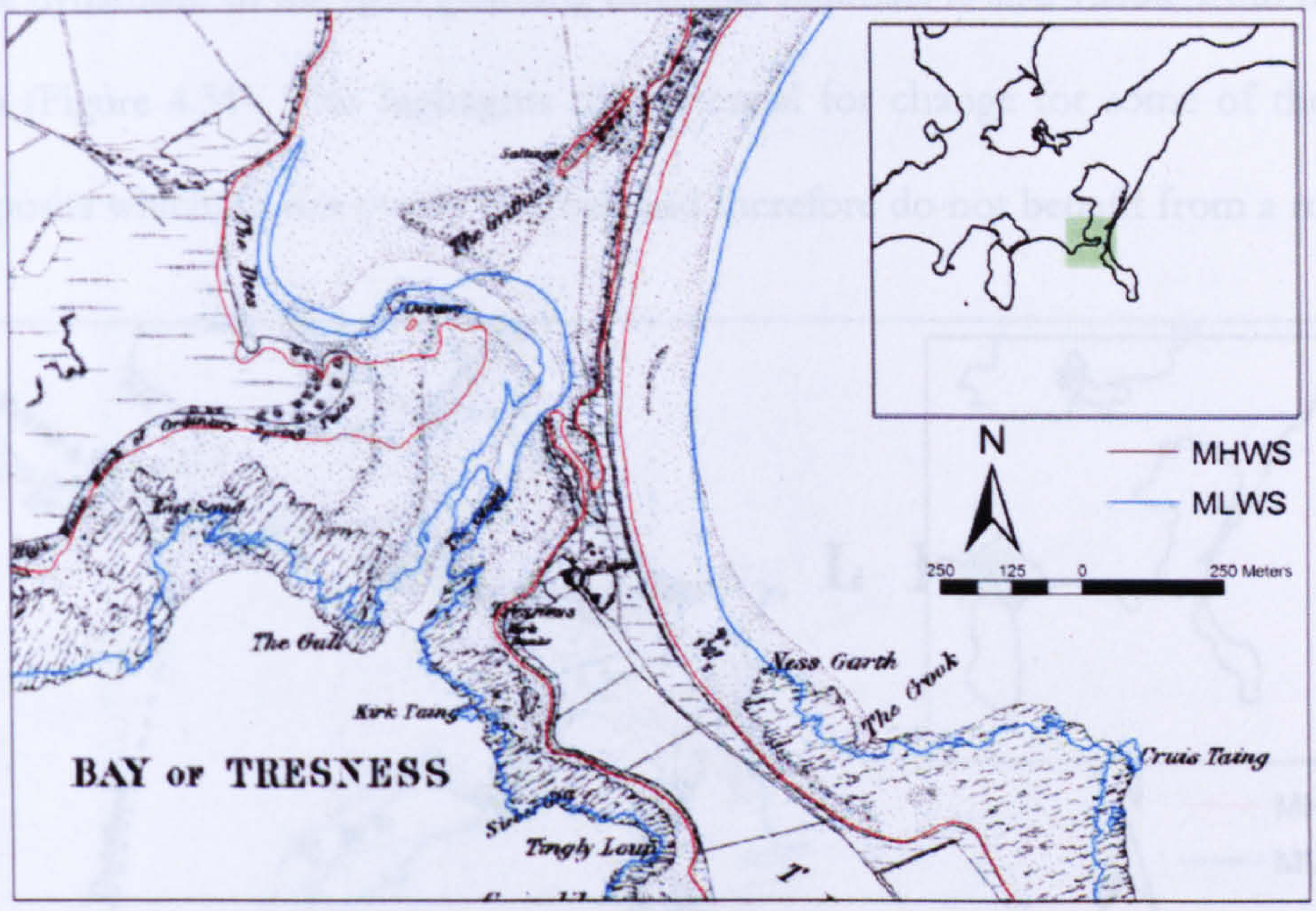


Figure 4.49 1st Edition OS map showing the Clogg in 1882 overlain by the present orientation of the coastline.

In addition, the 1882 map shows an area immediately south of the LWMOST line called Ossamy (Figure 4.50). 'Ossamy' was identified by Lamb (1992) as Old Norse for the mouth of a river, always used in Orkney where it is dammed by sand or gravel. The damming of which, poses questions to the earlier orientation of the Dees spit and previous coastal orientations of the Newark tombolo.

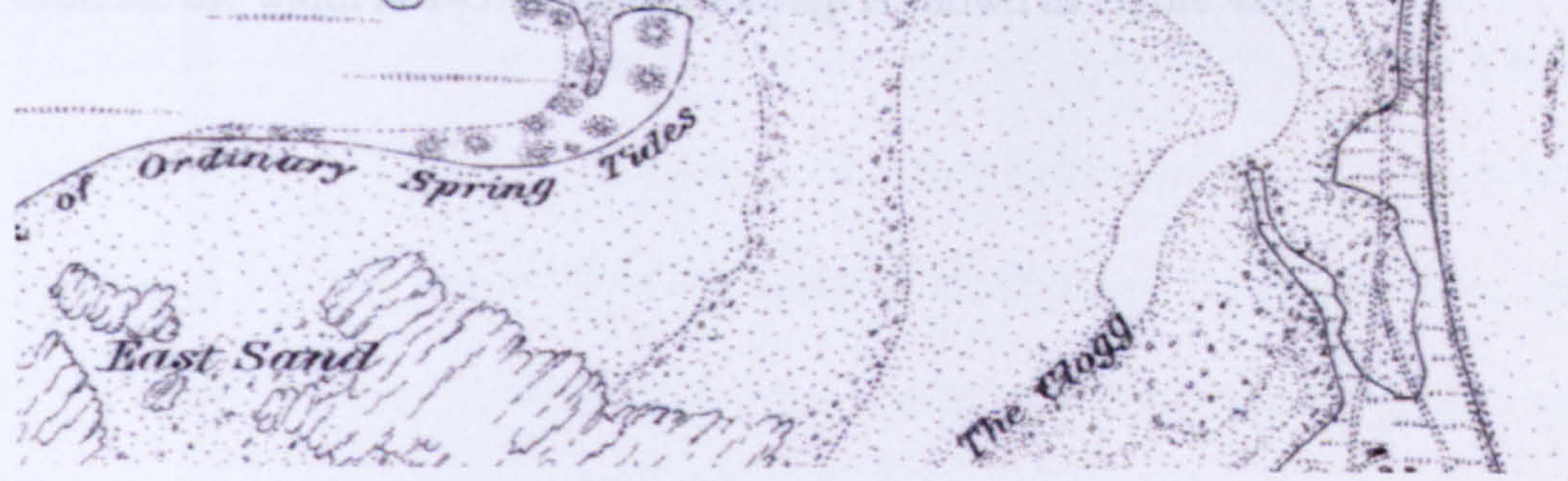


Figure 4.50 An enlarged section of the Clogg in the 1st Edition OS map (1882)

The dynamism of the spits guarding intertidal sandflats is also visible from the mouth of Little Sea (Figure 4.51). This highlights the potential for change for some of the more ephemeral deposits which do not overly bedrock and therefore do not benefit from a rock anchor.

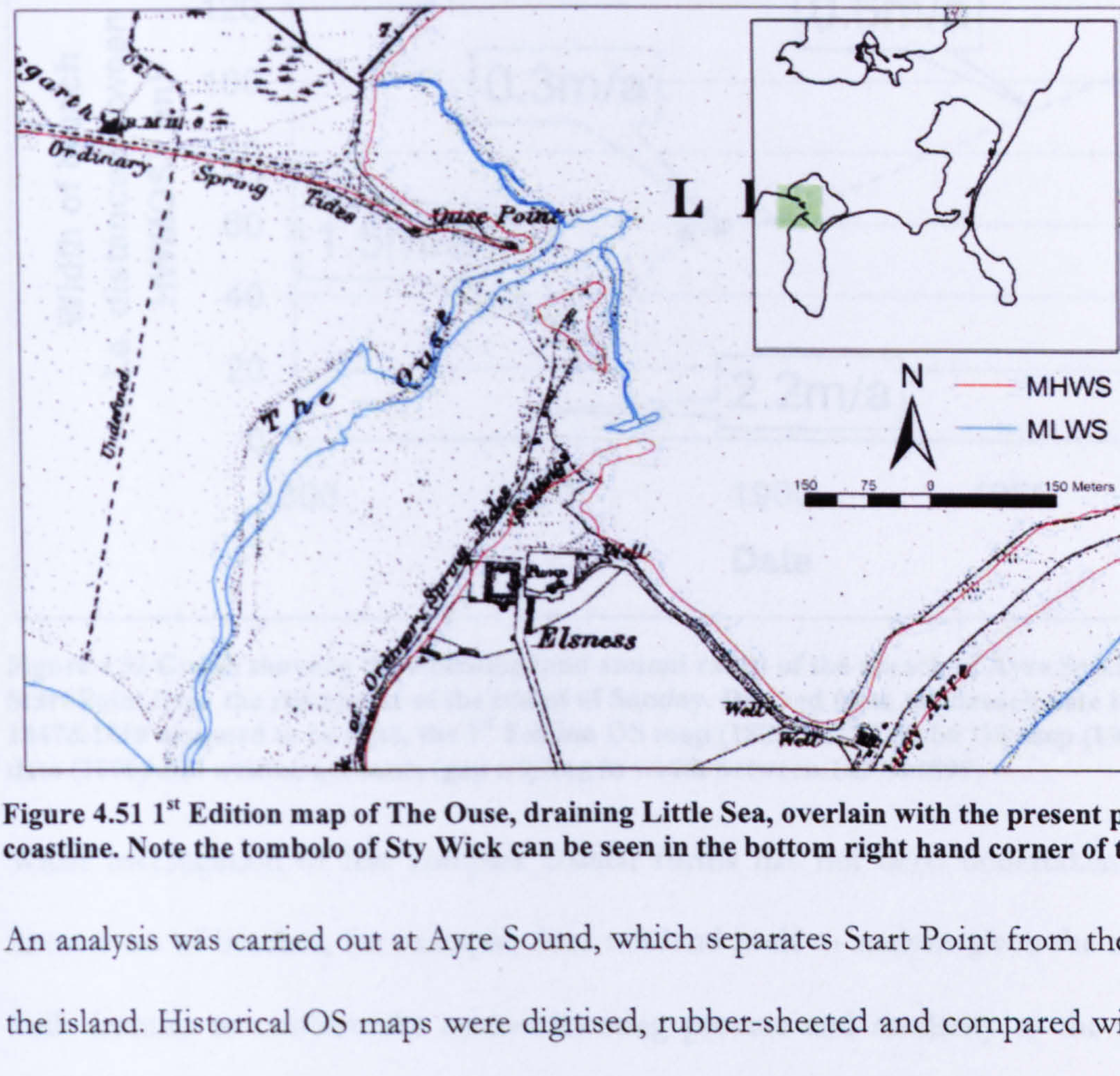


Figure 4.51 1st Edition map of The Ouse, draining Little Sea, overlain with the present position of the coastline. Note the tombolo of Sty Wick can be seen in the bottom right hand corner of the map.

An analysis was carried out at Ayre Sound, which separates Start Point from the remainder of the island. Historical OS maps were digitised, rubber-sheeted and compared with current OS map data to trace the widening of Ayre Sound. Further to these map sources a written account (Trail 1868), stated that the gap had tripled in length between 1857 and 1890. The average rate between 1882 and 1903 was used to derive a distance in 1890, which was reduced to a third to estimate the width in 1857. The relationship is shown in Figure 4.52.

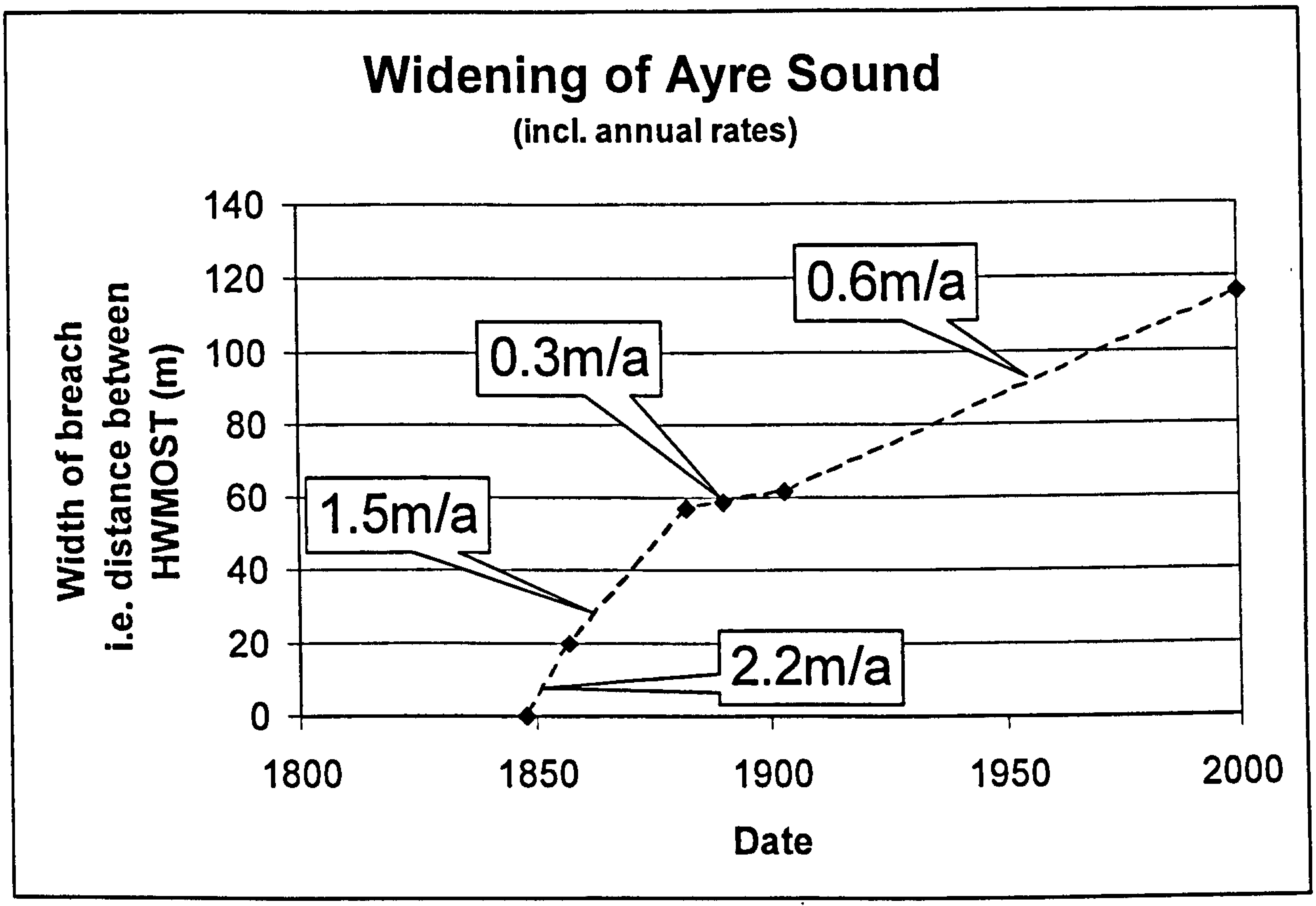


Figure 4.52 Graph showing the widening (and annual rates) of the breach of Ayre Sound separating Start Point from the remainder of the island of Sanday. Derived from the breach date between 1847&1850 assumed to be 1848, the 1st Edition OS map (1882), 2nd Edition OS map (1903), Present OS data (2000) and written accounts (gap tripling in width between 1857&1890)

Wider investigation of less complex coastal forms has not been undertaken as the simple linear form of beaches, for example, does not lend itself to analysis given the near absence of built features to confirm the rubber sheeting process and similarity to the likely mode of adjustment: transgression or regression (i.e. the change looks very similar to the possible error in the procedure).

4.5.4 Historical change: bathymetric charts

Given the shallow and varied nature of the underlying basement geology and the long-term subsidence of the region, many clues to the recent behaviour of the island persists within the nearshore. For this reason all of the available bathymetric charts have been investigated for geomorphic change. Unfortunately the present Admiralty Chart (Sheet number 2250) is derived directly from the Becher (1847-8) survey, so differences between these maps do not reflect actual changes but more likely interpolation and plotting differences during the cartographic process. For this reason no direct analytical comparisons can be made, however other coastal changes are apparent when these charts are compared against other terrestrial maps. Spatial analyses of the bathymetric charts have also been carried out to establish the potential source areas at previous lower palaeo-shorelines. These results were presented in Section 4.2.4.

Given the size of the Becher chart and the fine details of areas of interest, extracts have been selected (Figure 4.53) and the full version is enclosed at the rear of this thesis. The 1847-8 map only includes the northern half of Sanday and although an exhaustive search was carried out, the southern counterpart has not been located. However, the 1850 Admiralty chart, Surveyed by Becher, covers the whole island at a smaller scale.

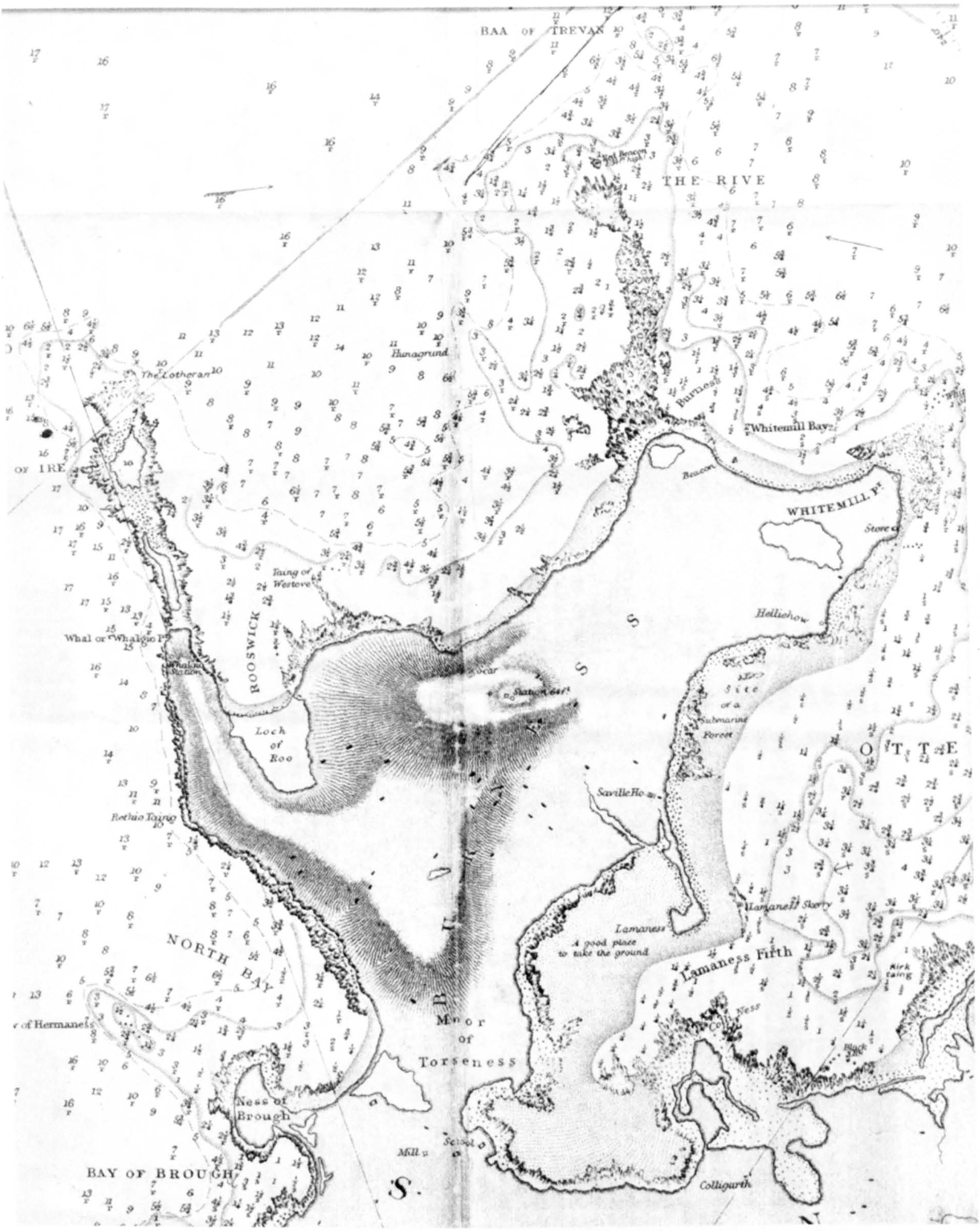


Figure 4.53 An extract from the Becher (1845) chart of the northern half of Sanday.

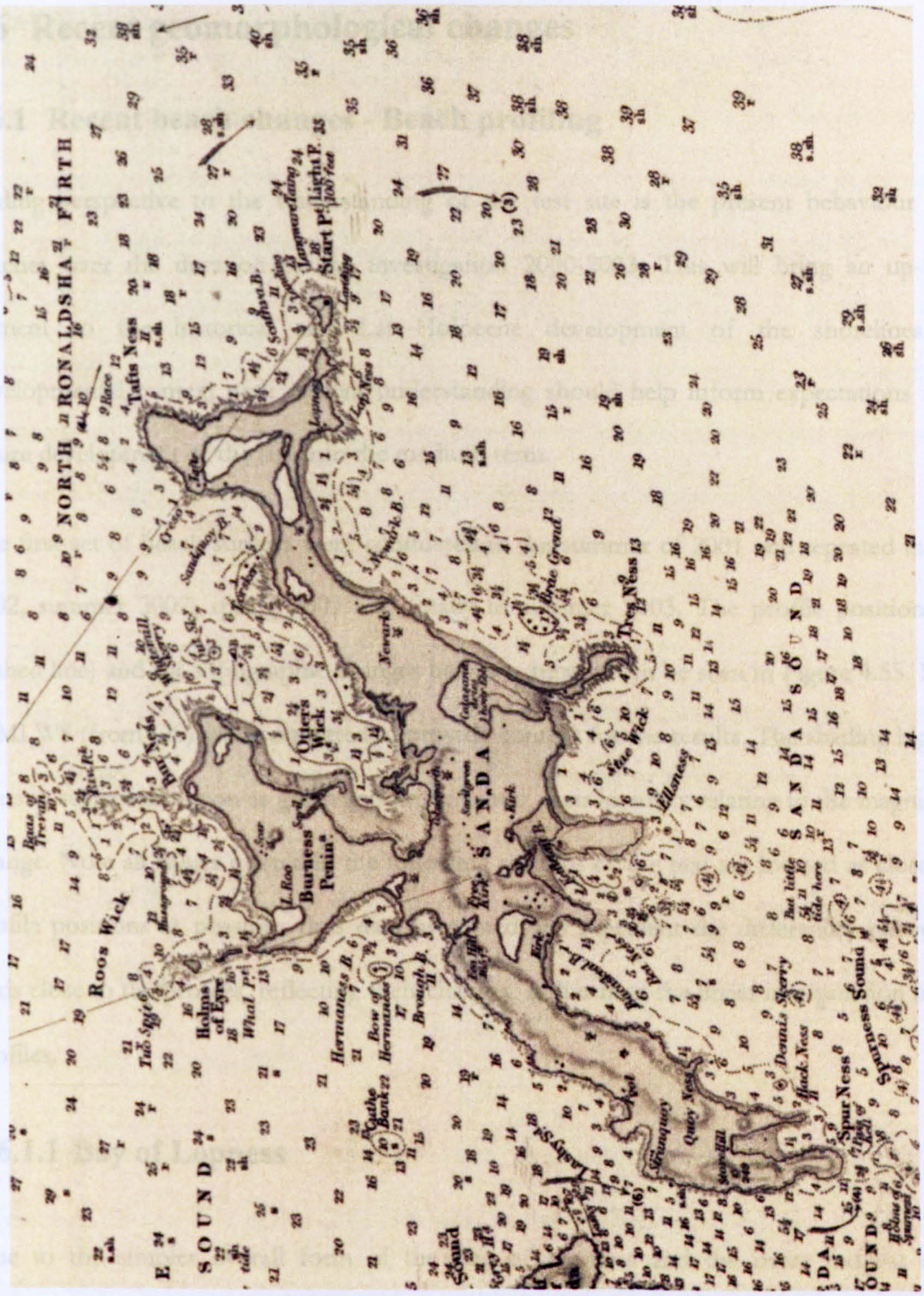


Figure 4.54 Hydrographic Chart (1850) surveyed by Commander Becher

4.6 Recent geomorphological changes

4.6.1 Recent beach changes - Beach profiling

Adding perspective to the understanding of the test site is the present behaviour of the beaches over the duration of the investigation 2000-2003. This will bring an up-to-date element to the historical and Late-Holocene development of the shorelines. This developmental context with current understanding should help inform expectations for the future development of the site into the medium term.

The first set of beach surveys were conducted in the summer of 2001 and repeated in spring 2002, summer 2002, spring 2003 and finally in summer 2003. The profile positions (grey hashed line) and the topographic changes between surveys can be seen in Figure 4.55. MHWS & MLWS (from OS) are also plotted to provide context for the results. The shading highlights gains in surface elevation as green and losses as red, their intensity relating to the magnitude of change. Note all values quoted in the following sections of the text are located as close to the profile positions as possible; thus data presented will represent the differences between the grids close to the profiles, reflecting their changes, rather than the linear interpolation between profiles.

4.6.1.1 Bay of Lopness

Due to the simpler overall form of the Bay of Lopness and the more modest changes established during the surveys the physical changes will be displayed using a single overview diagram, rather than the oblique images used in the Newark section. Unfortunately the summer 2001 survey data became corrupted and was unusable therefore comparisons with this data set cannot be made.

Spring 2002 – Summer 2002

An accretional wedge developed between spring and summer 2002 across the western end of the beach (Figure 4.55). It rarely exceeded 0.5m in depth and was at its widest at the western-most transect, narrowing towards the 10th transect. Between Transects 10 and 20 this narrow wedge continued to persist at MHWS, rarely exceeding 0.5m in height. In addition, between these transects lower down the beach there was a consistent lowering of beach elevations by approximately 0.5m. Very little change was noted above MHWS. Towards the headland in the centre of the bay (Transect 25) the topographic changes on the beach were negligible.

Further along the beach the first transect to show changes in height was number 29, which increased in height by 0.48m midway between high and low water. However, the remainder of the eastern half of the beach displayed a different, more changeable trend. Fluctuations occurred in the upper beach area in the dune face, however at MHWS there was little change. Further down the beach, however, there was a consistent loss of height, increasing eastwards from 0.3 and 0.5m (Figure 4.55). Due to unforeseen data quality issues the transects from the eastern end of the bay were unusable.

Summer 2002 – Spring 2003

The changes to the beach at Lopness between Summer 2002 and Spring 2003 were more subtle than the previous period (Figure 4.56). The western half of the bay was characterised by small changes in height, in places just reaching 0.5m of accretion (transects numbers 2-10). However this positive signal at the western extremity of the bay adjusted to a more varied signal towards the central headland (transects 13-25). Minor fluctuations in height were seen on the upper half of the beach where there were parallel patterns of comparable gains and losses (transects 13-18).

Transects 18 and 19 show an area of loss of up to 0.5m in height. Unfortunately transect 22 was misplaced in March 2003and this has skewed the results in that area. However, like the previous survey, few changes were recorded at the headland. Subtle upper-middle beach losses continue just past the headland (transects 26-28), where these losses are joined by comparable gains further down the beach face (>0.5m). In the centre of the eastern half of the bay (transects 34&35) there was little change on the beach face, although there were some changes (up to 1m both gains and losses) on the dune face.

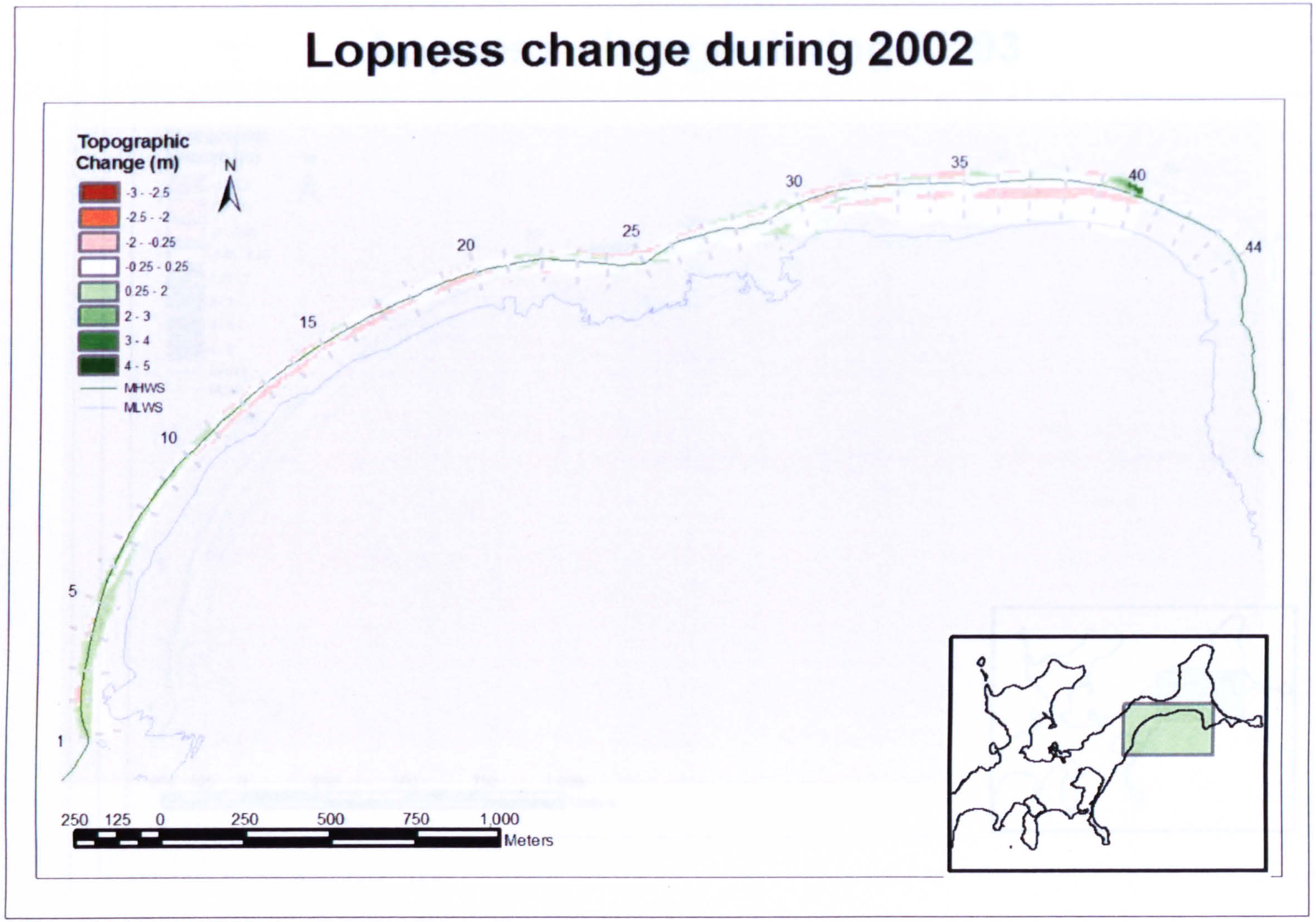


Figure 4.55 Lopness topographic change, Spring '02 to Summer '02

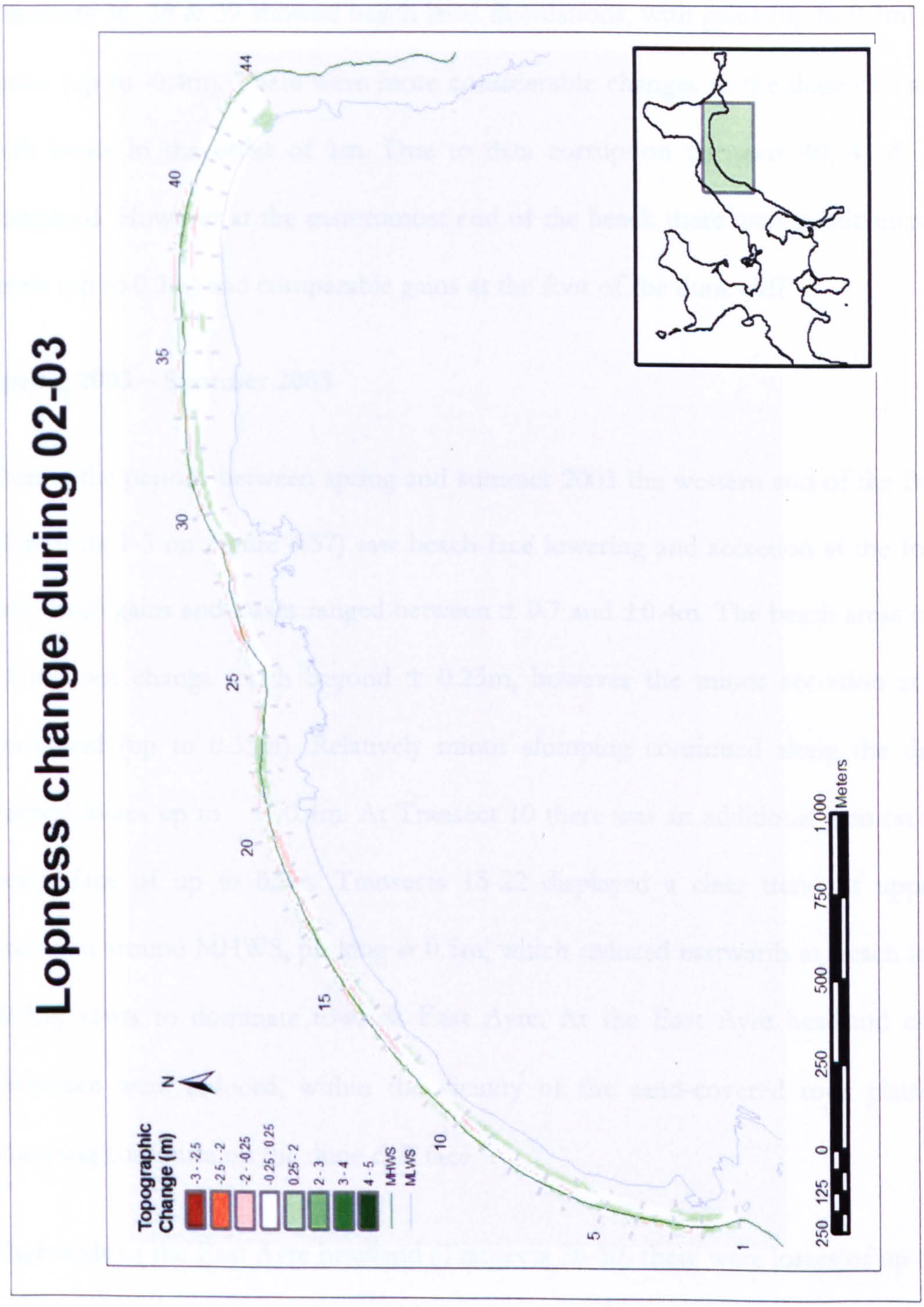


Figure 4.56 Lopness topographic change, Summer '02 to Spring '03

Transects 36, 38 & 39 showed beach level fluctuations, with gains (up to 0.7m) exceeding the losses (up to -0.4m). There were more considerable changes to the dune cliff at this location with losses in the order of 1m. Due to data corruption transects 40, 41 & 42 cannot be compared. However at the easternmost end of the beach there were subtle increases in beach levels (up to 0.3m) and comparable gains at the foot of the dune cliff.

Spring 2003 – Summer 2003

During the periods between spring and summer 2003 the western end of the Bay of Lopness (Transects 1-5 on Figure 4.57) saw beach-face lowering and accretion at the foot of the cliff face. Both gains and losses ranged between ± 0.7 and ±0.4m. The beach areas of Transects 6-14 did not change much beyond ± 0.25m, however the minor accretion at the cliff-foot continued (up to 0.35m). Relatively minor slumping continued along the dune face with vertical losses up to -0.4m. At Transect 10 there was an additional gain on the mid-lower beach face of up to 0.5m. Transects 15-22 displayed a clear trend of upper beach face accretion around MHWS, peaking at 0.5m, which reduced eastwards as beach lowering (up to -0.5m) starts to dominate towards East Ayre. At the East Ayre headland changes on the shoreface were reduced, within the vicinity of the sand-covered rock platform, however slumping continues on the dune cliff face.

Eastwards of the East Ayre headland (Transects 26-30) there were losses of up to 0.5m on the beach face, with little change around and above MHWS. These subtle changes peter out towards the eastern end of the Bay, with localised small variations towards the upper beach.

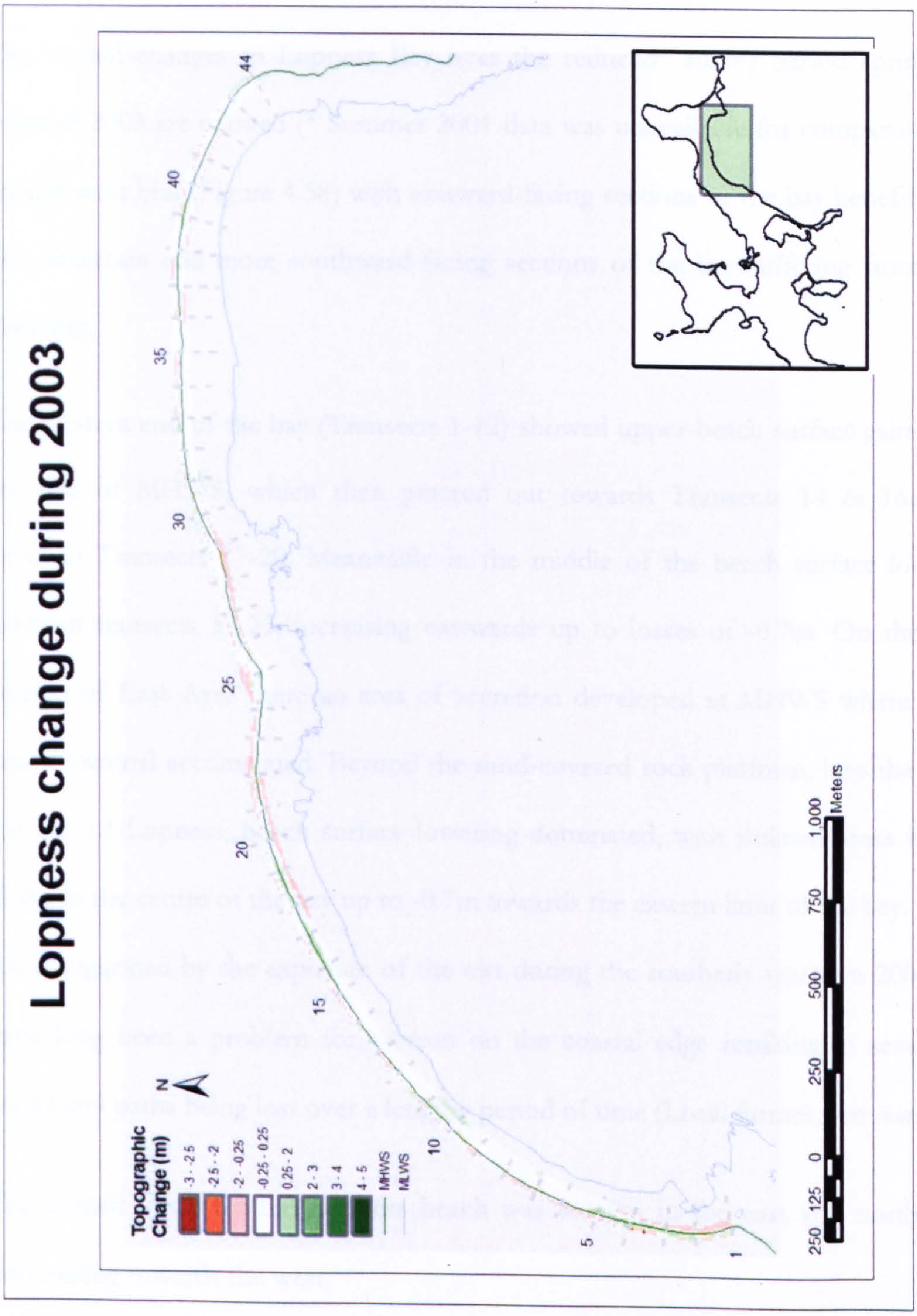


Figure 4.57 Lopness topographic change, Spring '03 to Summer '03

Spring 2002 – Summer 2003

The overall changes to Lopness Bay over the reduced* survey period spring 2002 and to summer 2003 are marked (* Summer 2001 data was unavailable for comparisons). There was an east-west bias (Figure 4.58) with eastward-facing sections of the bay benefiting from beach face accretion and more southward-facing sections of the bay suffering from beach surface lowering.

The western end of the bay (Transects 1-12) showed upper-beach surface gains of 0.5m along the line of MHWS, which then petered out towards Transects 14 & 16and reappeared between Transects 17-20. Meanwhile in the middle of the beach surface losses dominated between transects 17-23, increasing eastwards up to losses of -0.7m. On the eastern-facing section of East Ayre there an area of accretion developed at MHWS where up to 0.7m of beach material accumulated. Beyond the sand-covered rock platform, into the eastern half of the Bay of Lopness, beach surface lowering dominated, with isolated areas falling by up to -0.4m in the centre of the bay up to -0.7m towards the eastern limit of the bay. This is a larger trend suggested by the exposure of the cist during the southerly storm in 2000. Such storms have long been a problem for erosion on the coastal edge resulting in several fence lines, tracks and paths being lost over a lengthy period of time (Local farmer, *pers com,* 2001).

The overall trend for the Lopness beach was erosion in the east and north and accretion dominating towards the west.

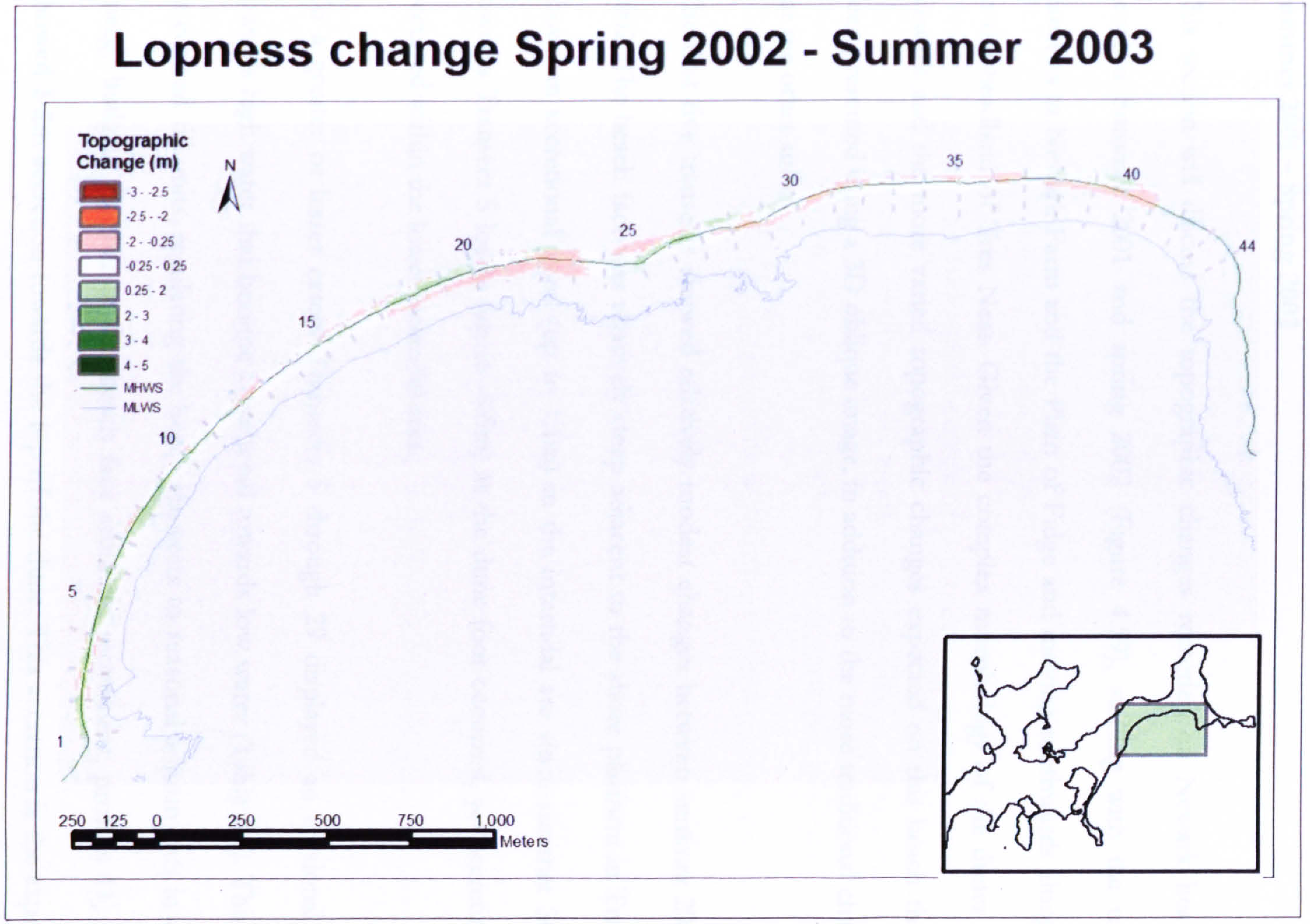


Figure 4.58 Lopness topographic change, Spring '02 to Summer '03

4.6.1.2 Bay of Newark

Summer 2001 – Spring 2002

This section will discuss the topographic changes recorded on Newark beach and dunes between Summer 2001 and spring 2002 (Figure 4.59), starting with the most northerly transects at Newark Farm and the Plain of Fidge and moving southwards along the tombolo to the headland of Tres Ness. Given the complex morphology of the dunes at the Bay of Newark and the more varied topographic changes expected on this beach the results have been presented using a 3D oblique image, in addition to the more traditional change map used for the other sites.

The first five transects showed relatively modest changes between summer 2001 and spring 2002. The beach face was relatively steep adjacent to the shore platform in Transect 1-3 and shows an accretional trend (up to 1.1m) in the intertidal are since summer 2001. However towards Transect 5 losses (up to -0.5m) at the dune foot occurred, yet accretion up to 0.4m occurred within the lower intertidal area.

To a greater or lesser extent Transects 5 through 29 displayed an erosional upper beach, towards high water that became accretional towards low water (Table 4.4). This is interpreted as cut and fill units, regulating the beach transects to seasonal adjustments in the near-shore energy budgets. Further to this beach face sediment movement, profiles 11, 14, 18 and 19 showed 1-2m accretion towards the top of the dune. This accretion is the expected response to sediment captured at the dune crest by the most vigorous dune grasses, as sediment is freed on the dune face and upper beach and recycled landward.

Although Transect 13 shows little change within the dune the results for Transects 12 and 13 could not be substantiated as the transects were slightly mis-placed; therefore changes in the transect positions (and heights) are displayed rather that the changes at one location.

Profile number	Height change (m) at ~ HW	Height change (m) at ~LW
5	-0.5	+0.5
9	-0.6	+0.5
15	-1.0	+0.6
17	-0.8	+0.5
19	-1.2	+0.4
23	-0.8	+0.8
28	-0.4	+0.5

Table 4.4 Cut and fill units for a selection of profiles 5-29

Towards Transect 20 the tombolo narrowed and increased in height about 19m AOD. This was the most dynamic section of the beach with significant (>2m) changes to the dunes. Frontal erosion removed up to 2m of sand over the time period, however a considerable gain occurred on the landward/intertidal side of the dunes. Unfortunately due to the highly varied topography and slightly mis-placed transects, the changes recorded at Transect 20 cannot be fully quantified. However, given the erosional trend evident on adjacent profiles and the absence of vegetation on the dune face at this location, it is likely that the section was erosional too. Transect 21 is located between two sections which experienced frontal erosion and it responded by accretion landwards, with the dune migrating onto the intertidal sand flat of Cata Sand.

Towards the southern limit of the tombolo, where it joins the island (Transect 27) the changes were more subtle, reflecting the underlying topography (presence of a till capped headland rather than an intertidal sand flat) and aspect which reduced wave energy. The simple trends of intertidal changes were still present, with accretion at low water and a related loss at high water (approximately less than 0.5m change for each). At the dune crest little change was observed. Transects 25 and 26 indicate the problems of mis-locating transects, after survey posts are lost due to erosion/accretion/vegetation growth. Although this is frustrating as it limits understanding, it is a problem associated with working in such a dynamic environment.

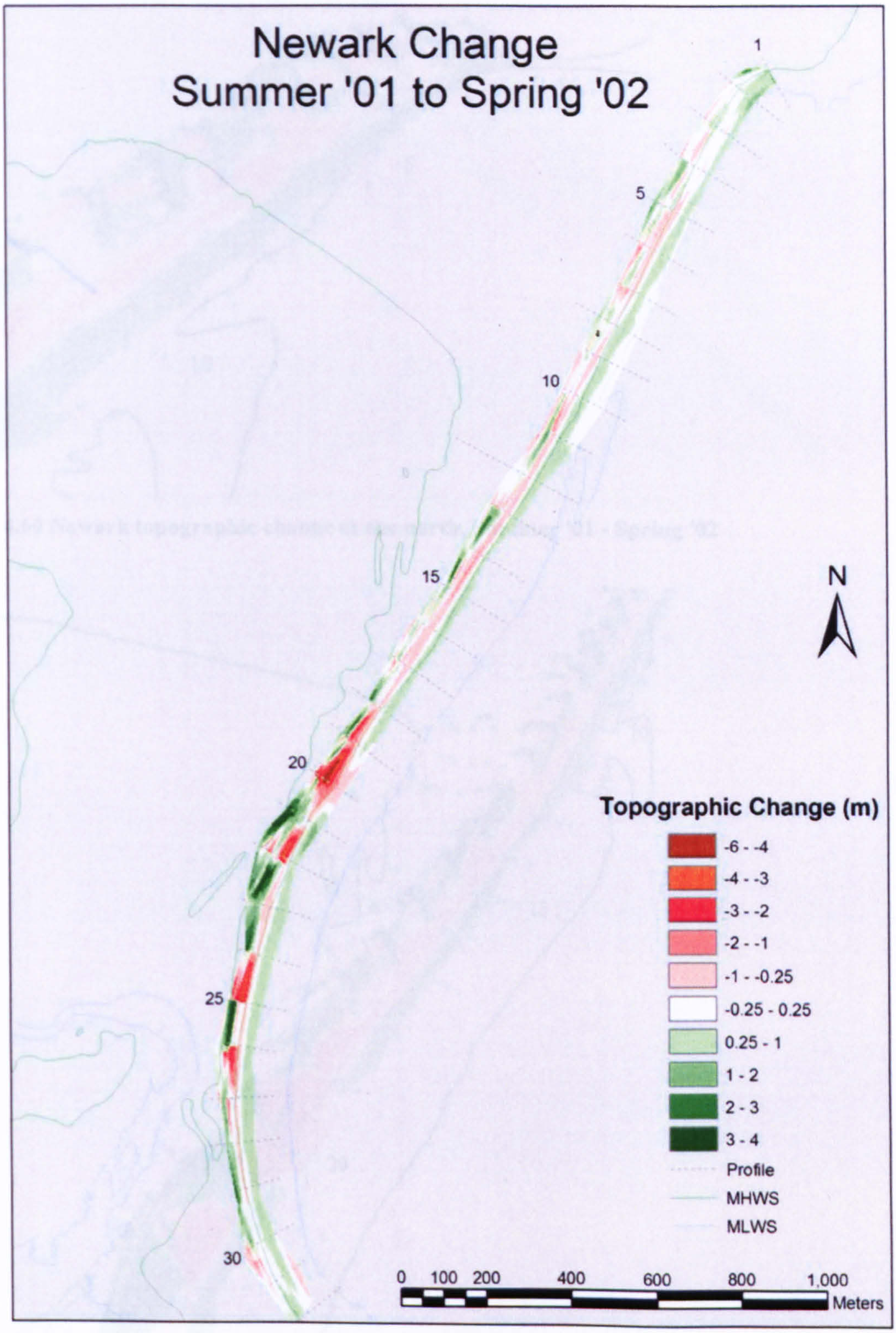


Figure 4.59 Newark Topographic Change, Summer '01 - Spring '02

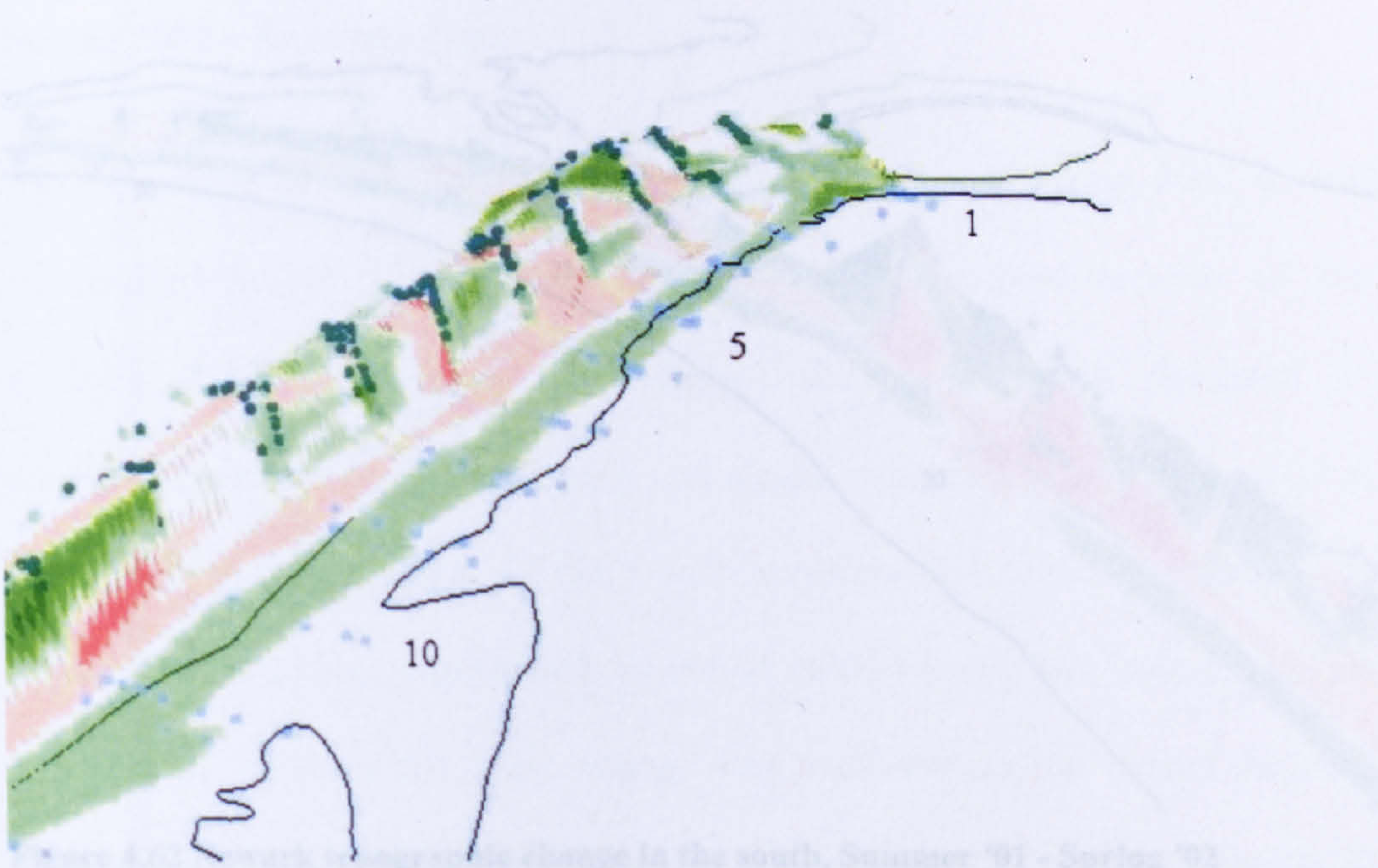


Figure 4.60 Newark topographic change in the north, Summer '01 - Spring '02

Figure 4.61 Newark topographic change in the centre of the bay, Summer '01 - Spring '02

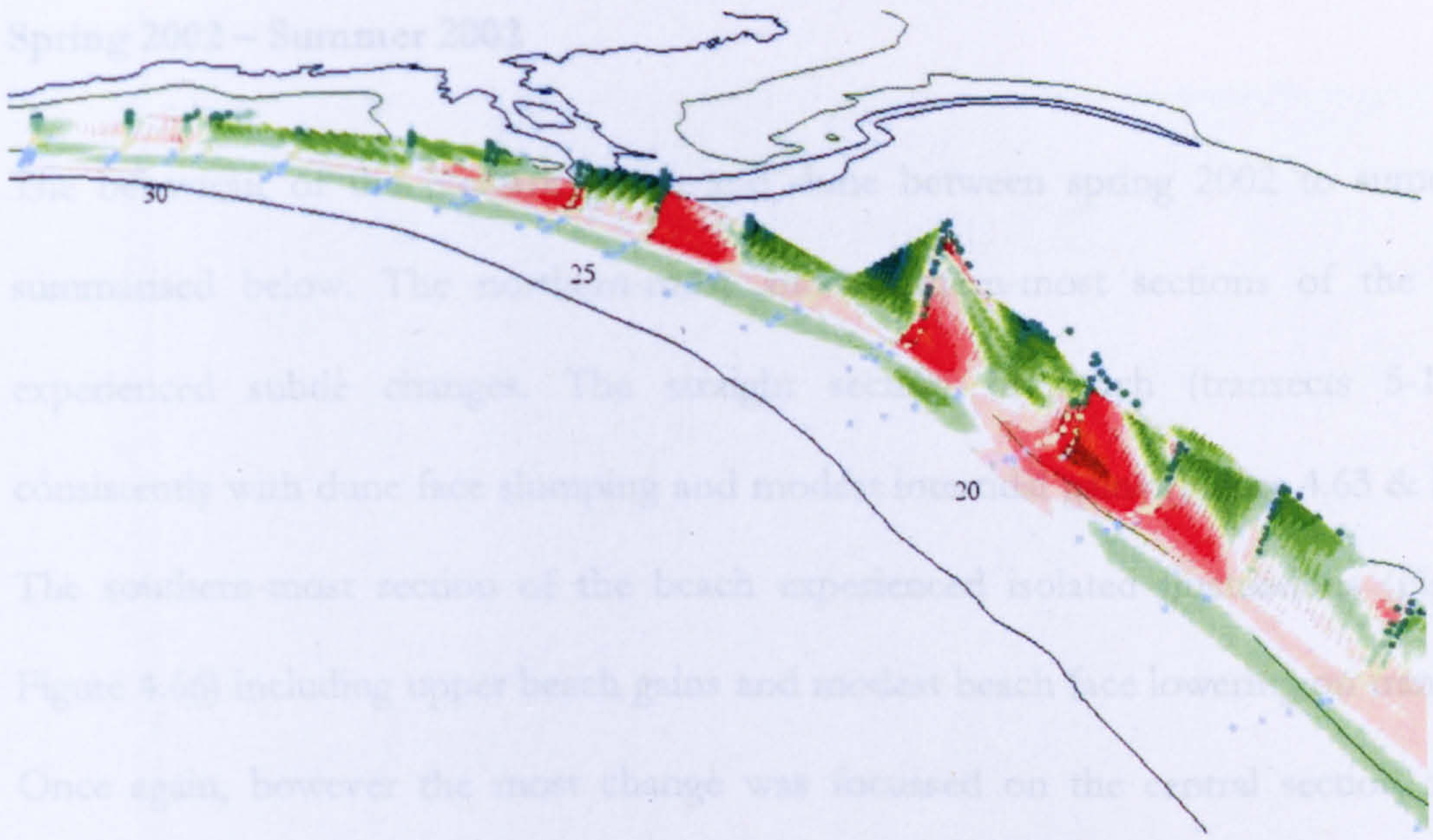


Figure 4.62 Newark topographic change in the south, Summer '01 - Spring '02

Spring 2002 – Summer 2002

The behaviour of the Newark beach and dune between spring 2002 to summer 2002 is summarised below. The northern-most and southern-most sections of the beach have experienced subtle changes. The straight section of beach (transects 5-18) behaved consistently with dune face slumping and modest intertidal gains (Figure 4.63 & Figure 4.64). The southern-most section of the beach experienced isolated fluctuations (Figure 4.63 & Figure 4.66) including upper beach gains and modest beach face lowering on transect 30 &31. Once again, however the most change was focussed on the central section of the beach (Figure 4.65) with large changes occurring in the vicinity of the gaps (transects 20-23).

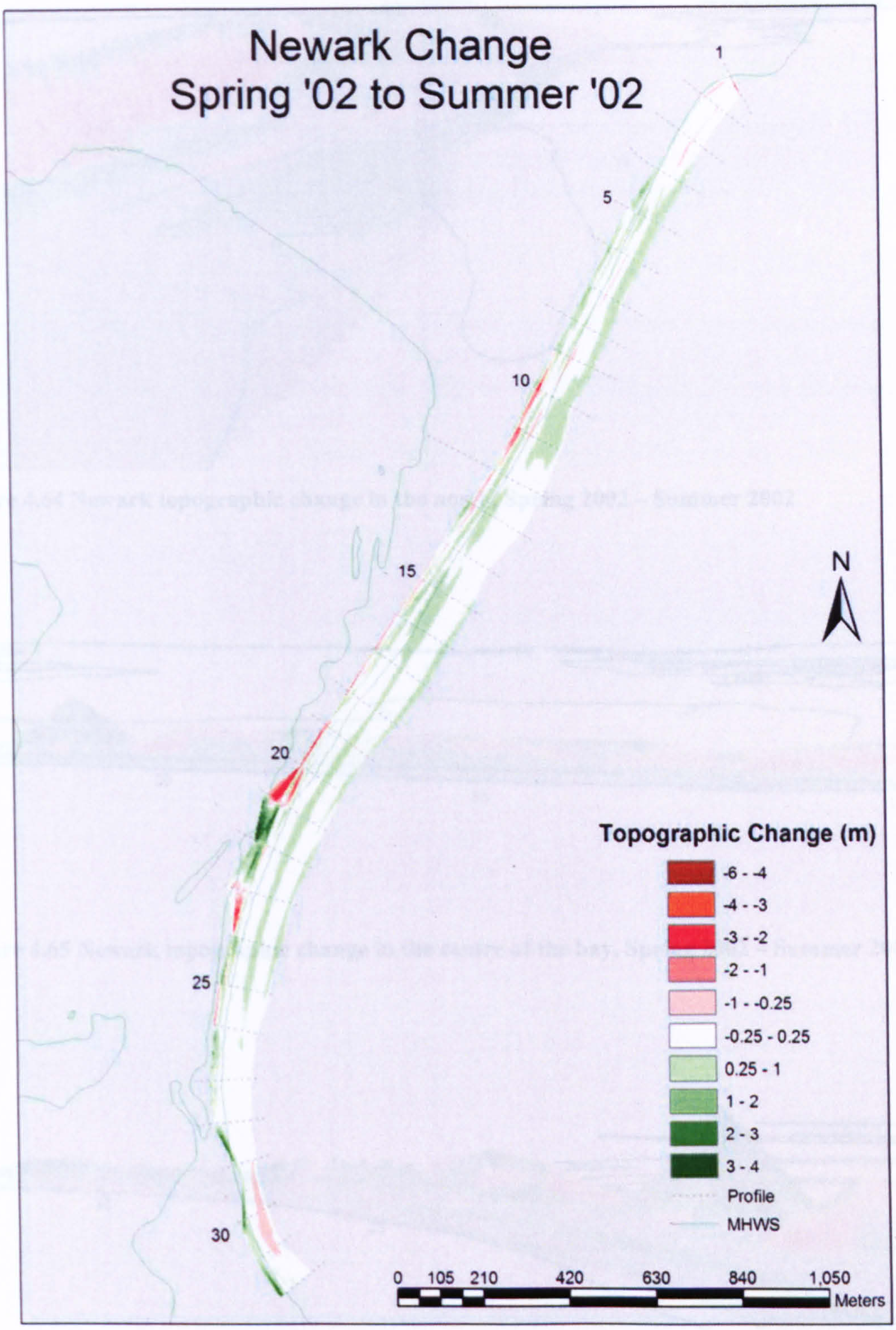


Figure 4.63 Newark Topographic change, Spring 2002 – Summer 2002

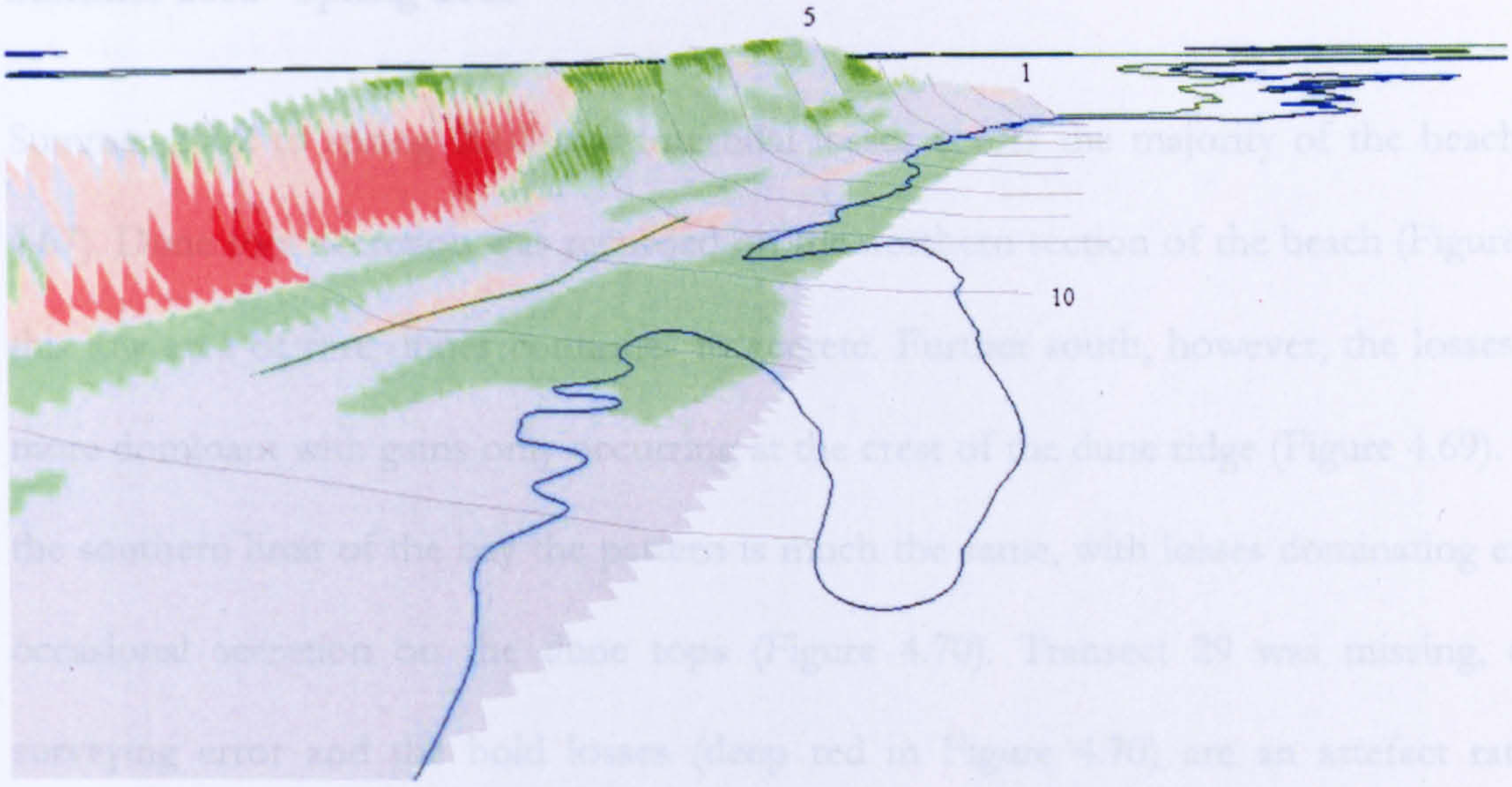


Figure 4.64 Newark topographic change in the north, Spring 2002 – Summer 2002

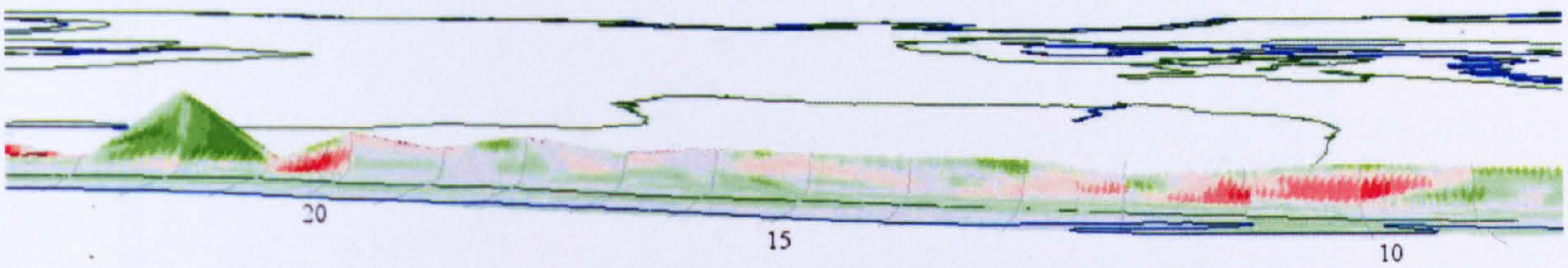


Figure 4.65 Newark topographic change in the centre of the bay, Spring 2002 – Summer 2002

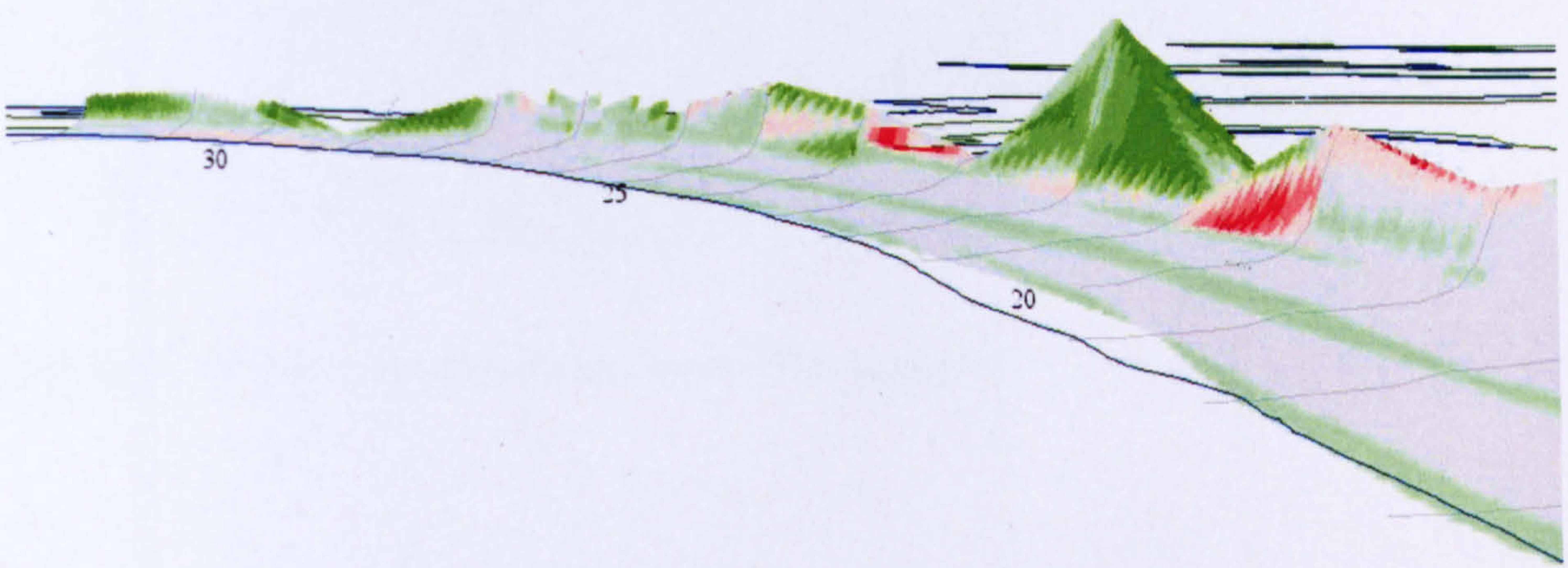


Figure 4.66 Newark topographic change in the south, Spring 2002 – Summer 2002

Summer 2002– Spring 2003

Summer 2002 to spring 2003 saw intertidal losses across the majority of the beach (Figure 4.67). Dune foot accretion was recorded on the northern section of the beach (Figure 4.68) as this low area of fore dunes continues to accrete. Further south, however, the losses become more dominant with gains only occurring at the crest of the dune ridge (Figure 4.69). Towards the southern limit of the bay the pattern is much the same, with losses dominating except for occasional accretion on the dune tops (Figure 4.70). Transect 29 was missing, due to a surveying error and the bold losses (deep red in Figure 4.70) are an artefact rather than observed trends.

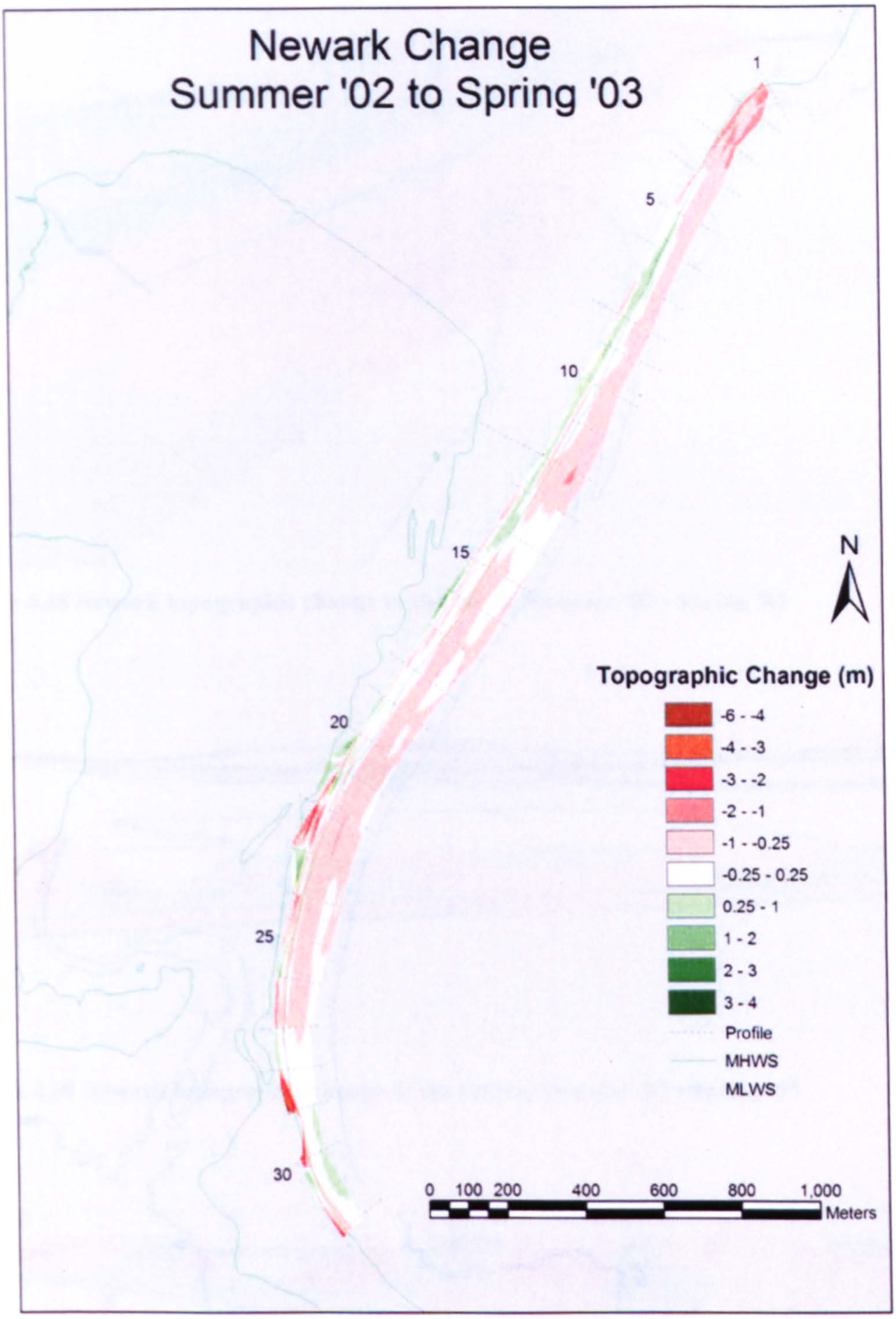


Figure 4.67 Newark topographic change, Summer '02 - Spring '03

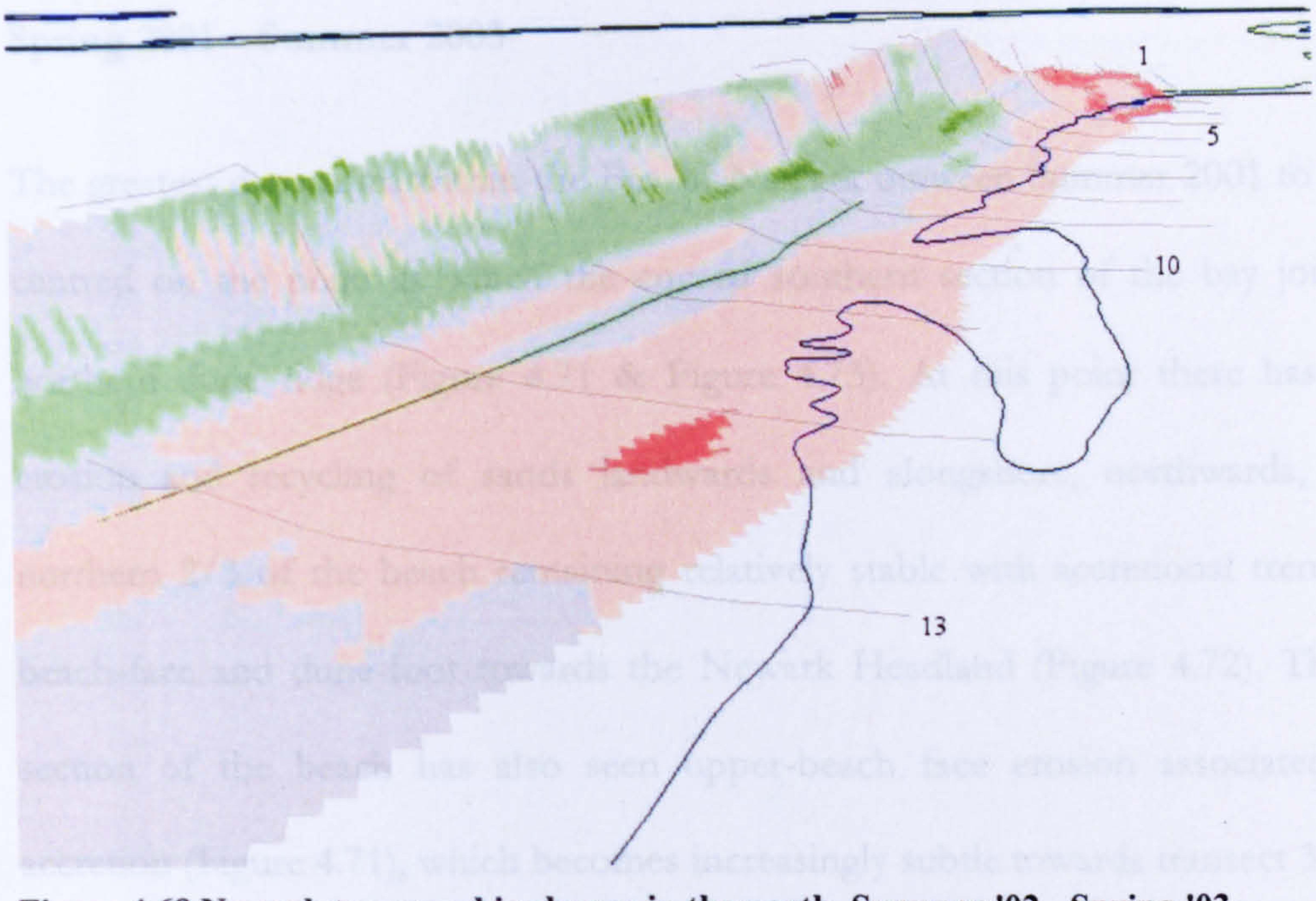


Figure 4.68 Newark topographic change in the north, Summer '02 - Spring '03

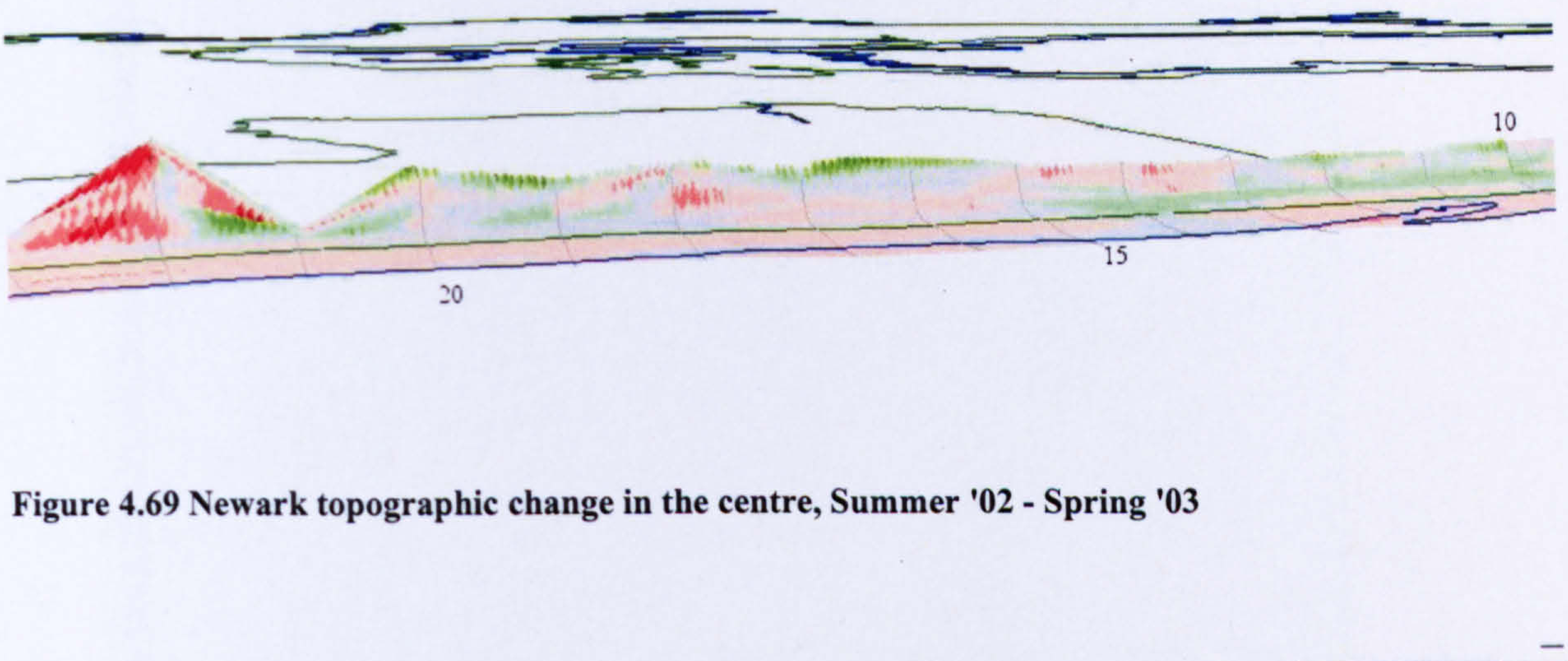


Figure 4.69 Newark topographic change in the centre, Summer '02 - Spring '03

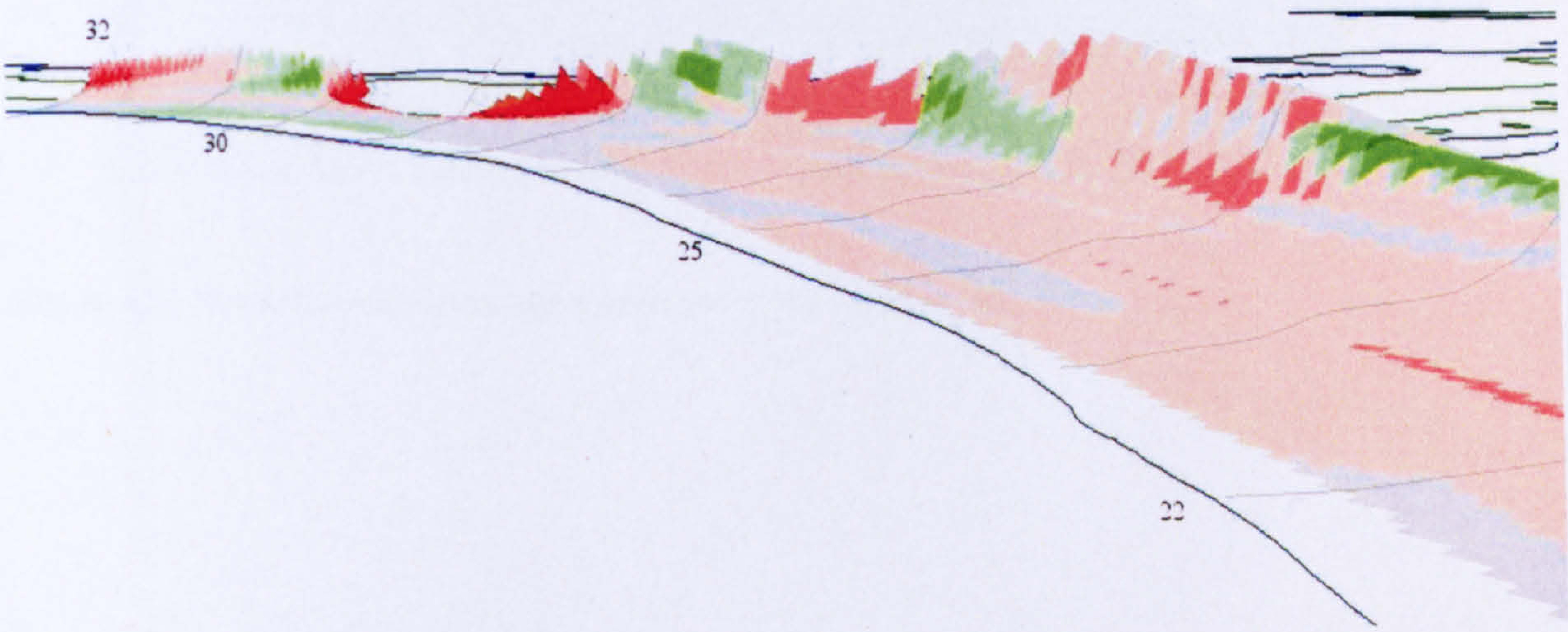


Figure 4.70 Newark topographic change in the south, Summer '02 - Spring '03

Spring 2001 – Summer 2003

The greatest dynamism within the Bay of Newark between Summer 2001 to Spring 2003 was centred on the point at which the curved southern section of the bay joins the straighter northern dune ridge (Figure 4.71 & Figure 4.73). At this point there has been dune face erosion and recycling of sands landwards and alongshore, northwards, resulting in the northern 2/3 of the beach remaining relatively stable with accretional trends visible on the beach-face and dune-foot towards the Newark Headland (Figure 4.72). The southern-most section of the beach has also seen upper-beach face erosion associated with dune top accretion (Figure 4.71), which becomes increasingly subtle towards transect 32 (Figure 4.74).

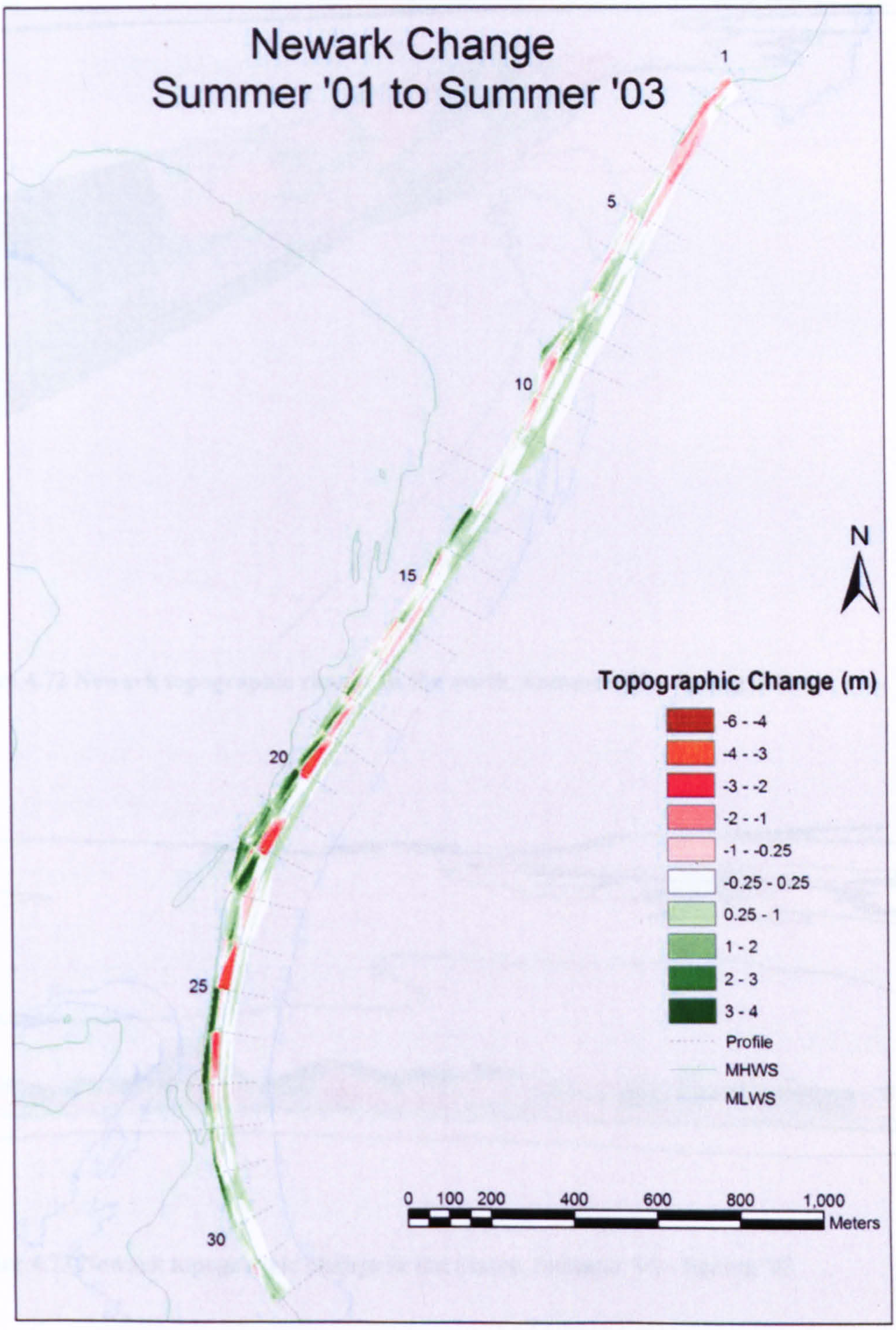


Figure 4.71 Newark topographic change, Summer '01 - Spring '03

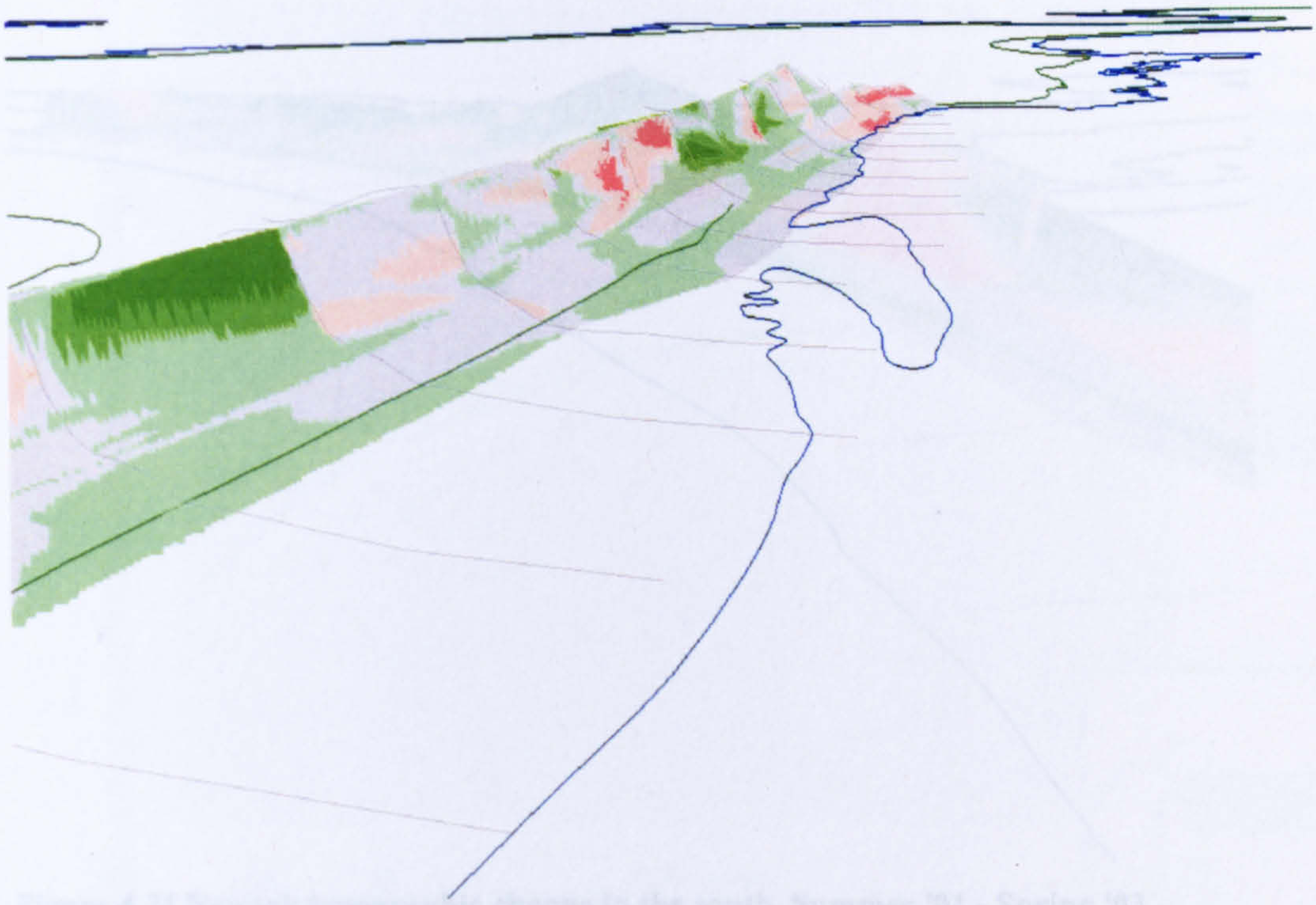


Figure 4.72 Newark topographic change in the north, Summer '01 - Spring '03

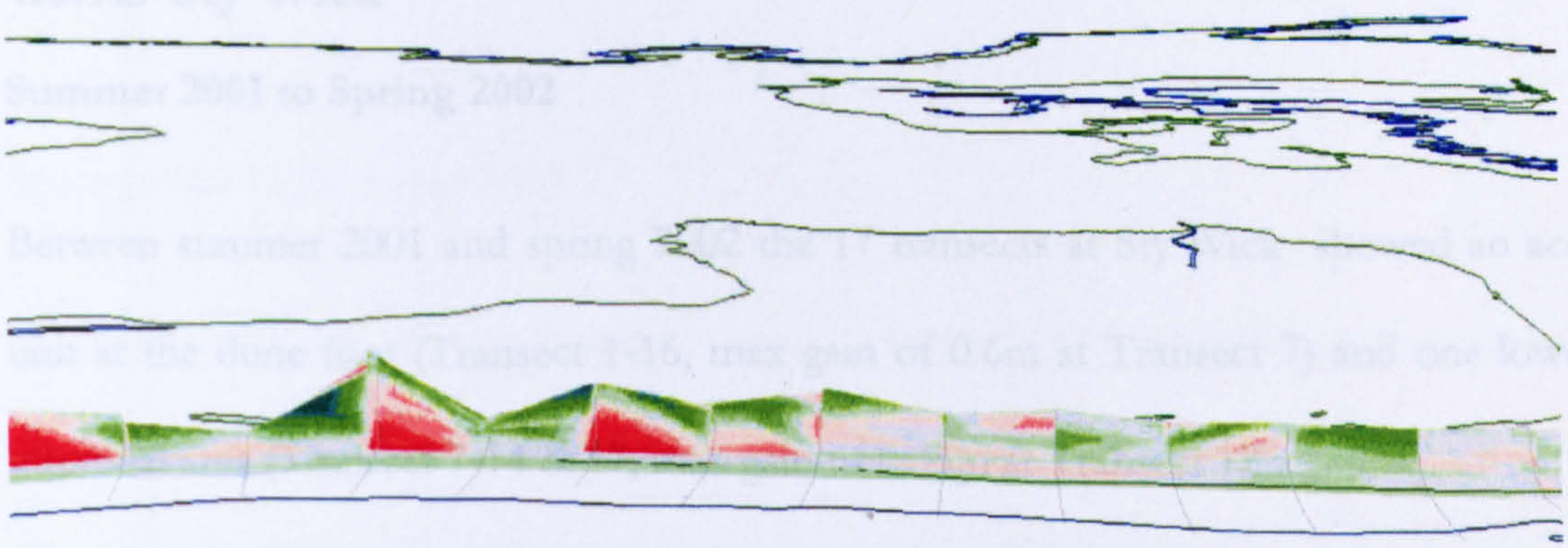


Figure 4.73 Newark topographic change in the centre, Summer '01 - Spring '03

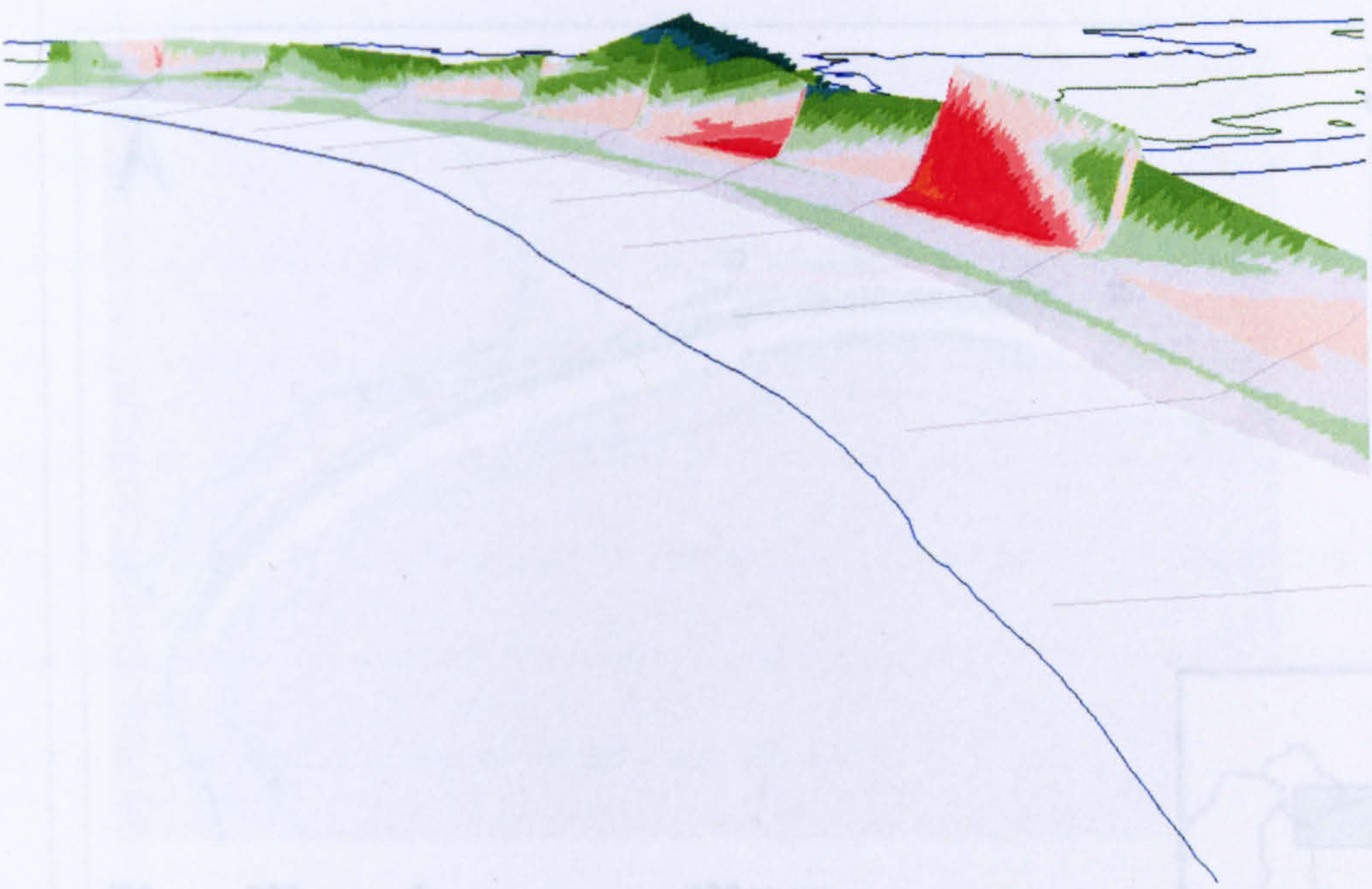


Figure 4.74 Newark topographic change in the south, Summer '01 - Spring '03

4.6.1.3 Sty Wick

Summer 2001 to Spring 2002

Between summer 2001 and spring 2002 the 17 transects at Sty Wick showed an accretional unit at the dune foot (Transect 1-16, max gain of 0.6m at Transect 7) and one lower in the intertidal area (Transect 7-14 & 17, max gain of 0.35m at Transect 12).

Further beach level changes were found towards the dunes, seen in Transect 2-7 around the MHWS line (max -0.4m, Transect 4). In addition to these changes Transect 7 & 9 were also lowered (by -0.8m & -0.3m, respectively), however Figure 4.75 displays a greater loss between the transects, which should be ignored as it has no supporting data points and thus was a product of the interpolation. Mis-locating profile 12, during one of the surveys lead to the loss area between Transects 11 & 12. The general trends experienced between summer 2001 and spring 2002 are evident, namely the accretion of intertidal bars and the clipping of the dune foot around the MHWS.

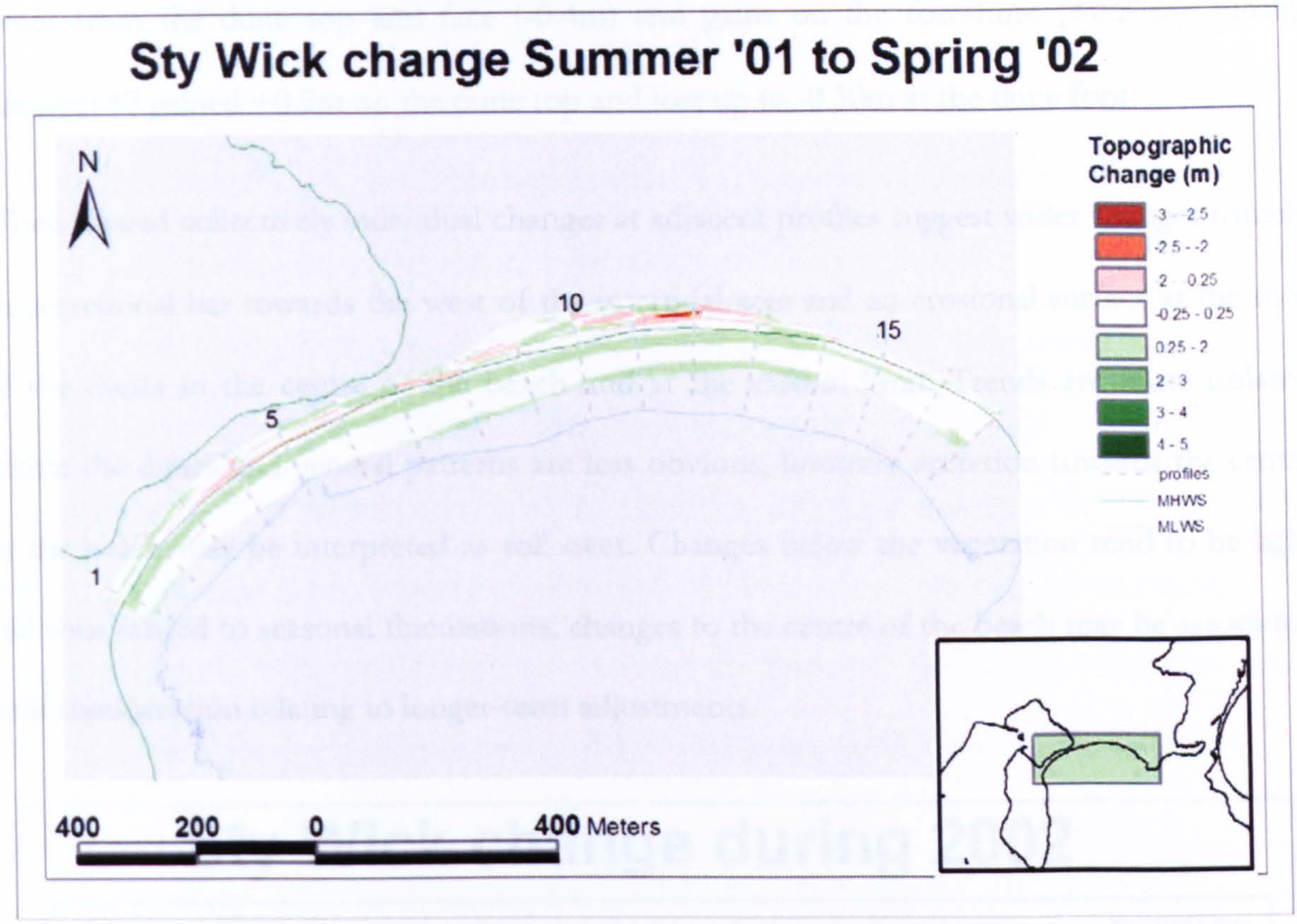


Figure 4.75 Sty Wick topographic changes, Summer '01 to Spring '02

Spring 2002 to Summer 2002

Figure 4.76 depicts the topographic changes recorded between spring and summer profiles during 2002 on Sty Wick beach (Figure 4.76). Transects 1-6 display an accretional trend within the intertidal area, reflecting an increase in height up to +0.4m. Transect 1 has a red area above MHWS. This is attributed to the differences of positions between subsequent surveys and should be discounted. Transects 7 to 11 display a pink area towards the dune foot, indicating a loss of sand no more than +0.4m (Figure 4.76). Transects 12 and 13 did not experience significant changes (i.e. less than +/- 0.25m) within the beach; however, changes were present at the top of the transects within the dunes, due to subtle differences within the location of the transect. Transect 14 recorded gains on the foreshore (up to +0.29m) and dune crest (up to +0.76m), in addition to a loss (-0.28m) at the dune foot. Transect 15 shows subtle gains at the dune crest and intertidal (both +0.27m). The penultimate transect (16) displays losses from the dune top and face (-0.4m) and gains on the foreshore (+0.27m). Finally Transect 17 gained +0.5m on the dune top and lost up to -0.30m at the dune foot.

When viewed collectively individual changes at adjacent profiles suggest wider changes namely an accretional bar towards the west of the intertidal area and an erosional surface at the foot of the dunes in the centre of the beach and at the eastern limit. Trends are more isolated within the dunes and general patterns are less obvious, however accretion towards the centre of the beach may be interpreted as roll over. Changes below the vegetation tend to be light and thus related to seasonal fluctuations; changes to the centre of the beach may be associated with transgression relating to longer-term adjustments.

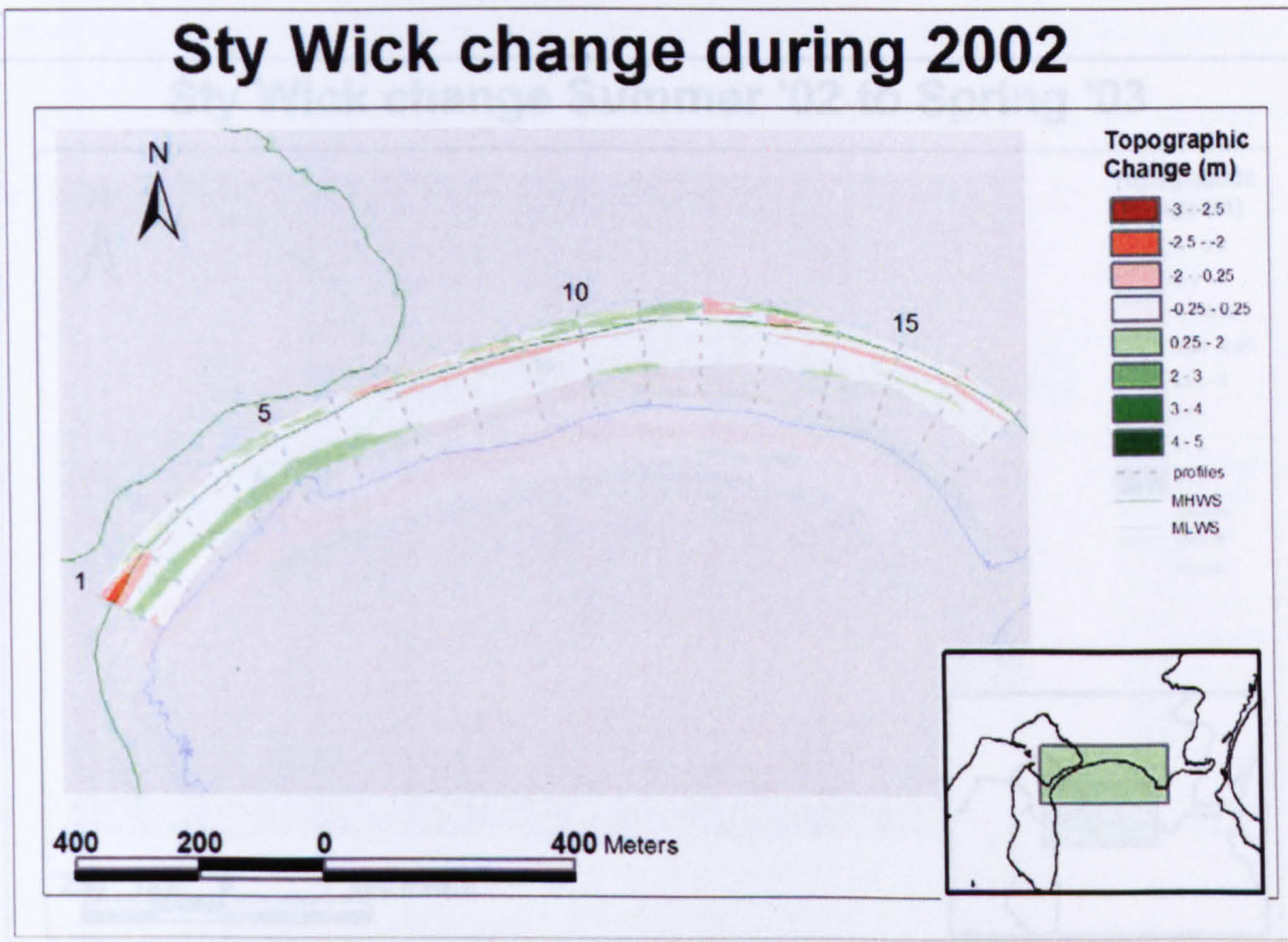


Figure 4.76 Sty Wick topographic changes, Spring '02 to Summer '02

Summer 2002 to Spring 2003

The reader may note that the profiles for '02-'03 seem to extend further into the intertidal, this is related to combination of the tidal heights (monthly and daily variations in tidal range) encountered during each survey. The strips presented are the combined footprint of both surveys, i.e. if one survey extends further than the other, only the overlap is presented. Figure 4.77 depicts the transect changes recorded between summer 2002 and spring 2003 on Sty Wick beach. All transects (1-17) showed a reduction in height within the intertidal zone. The loss was at its maximum in transect 2, reflecting a reduction in height of 0.64m. This is likely to be related to the inter-seasonal cut and fill cycle associated with winter and summer transects and this will be confirmed or rejected by analysis of the changes within 2003 and comparisons over the entire period (i.e. spring '02 vs. spring '03 and summer '01 vs. summer '03). Intertidal gains were found on Transects 4 - 6 (with up to 1.2m of gain) and more subtle increases of up to 0.3m were measured on Transects 13 & 14. The eastern end of the beach (Transects 14-17) showed accretion around the MHWS line, with a maximum gain of 0.4m.

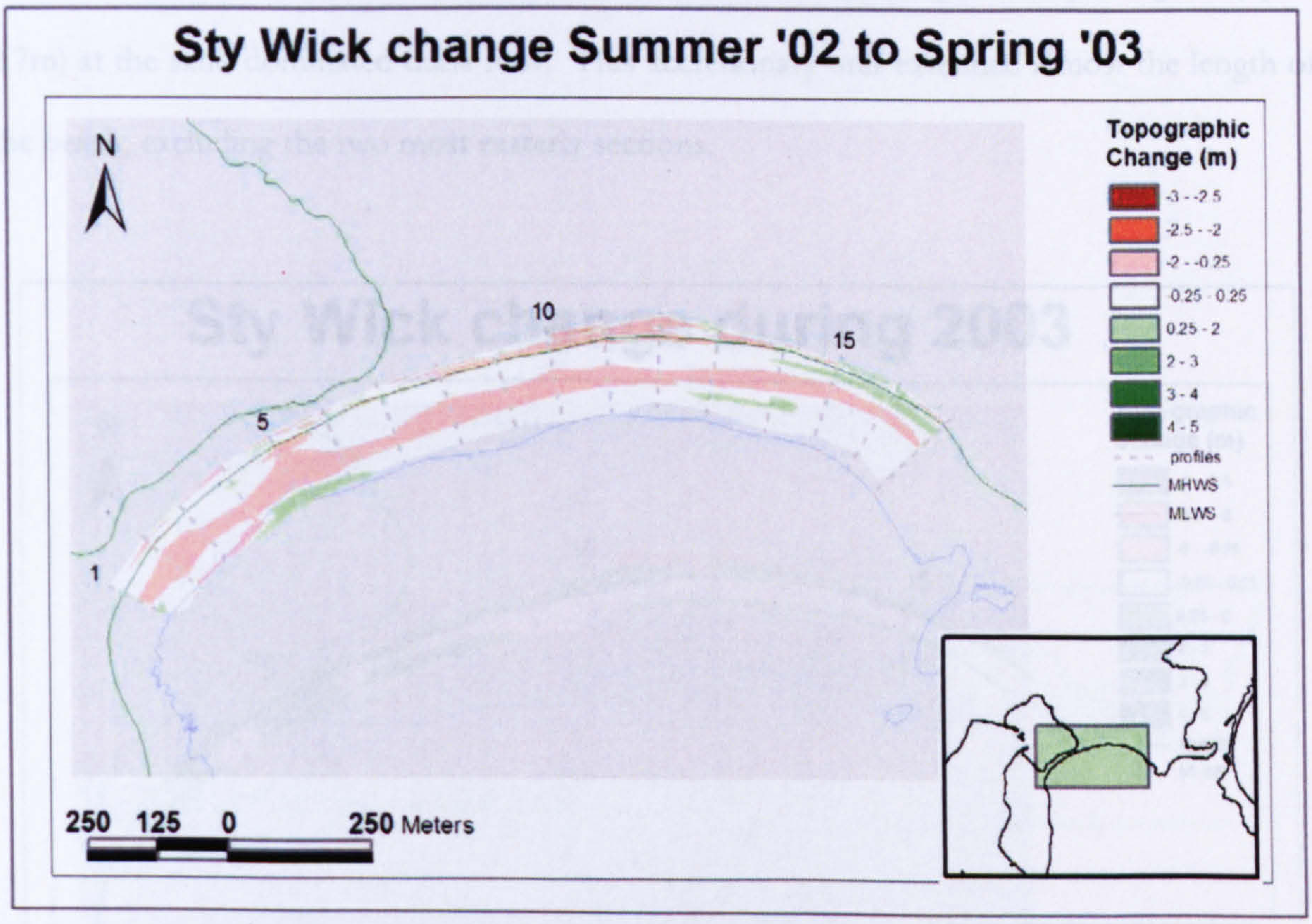


Figure 4.77 Sty Wick topographic changes, Summer '02 to Spring '03

Spring 2003 to Summer 2003

Figure 4.78 displays the changes recorded between spring 2003 and summer 2003. Accretional areas were apparent from west to east and from the foreshore and in the dune face. One area of loss was recorded in the back beach area around Transect 11&12.

The first 5 transects displayed gains on the foreshore and towards the dune foot. The foreshore gains were a maximum of 0.6m, however the gains towards the dune foot were more substantial, being up to 1m of vertical change. Changes to a gravel unit at the dune foot (Transects 1-3) could be interpreted as a winter to summer cut and fill cycle. Transect 5 had gains of up to 0.5m on the foreshore, which reduced landwards. Transect 6 showed more subtle changes, where as Transects 7 and 8 had an intertidal gain (up to 0.5m) and gains (up to 0.7m) at the sand dominated dune foot. This accretionary unit extended almost the length of the beach, excluding the two most easterly sections.

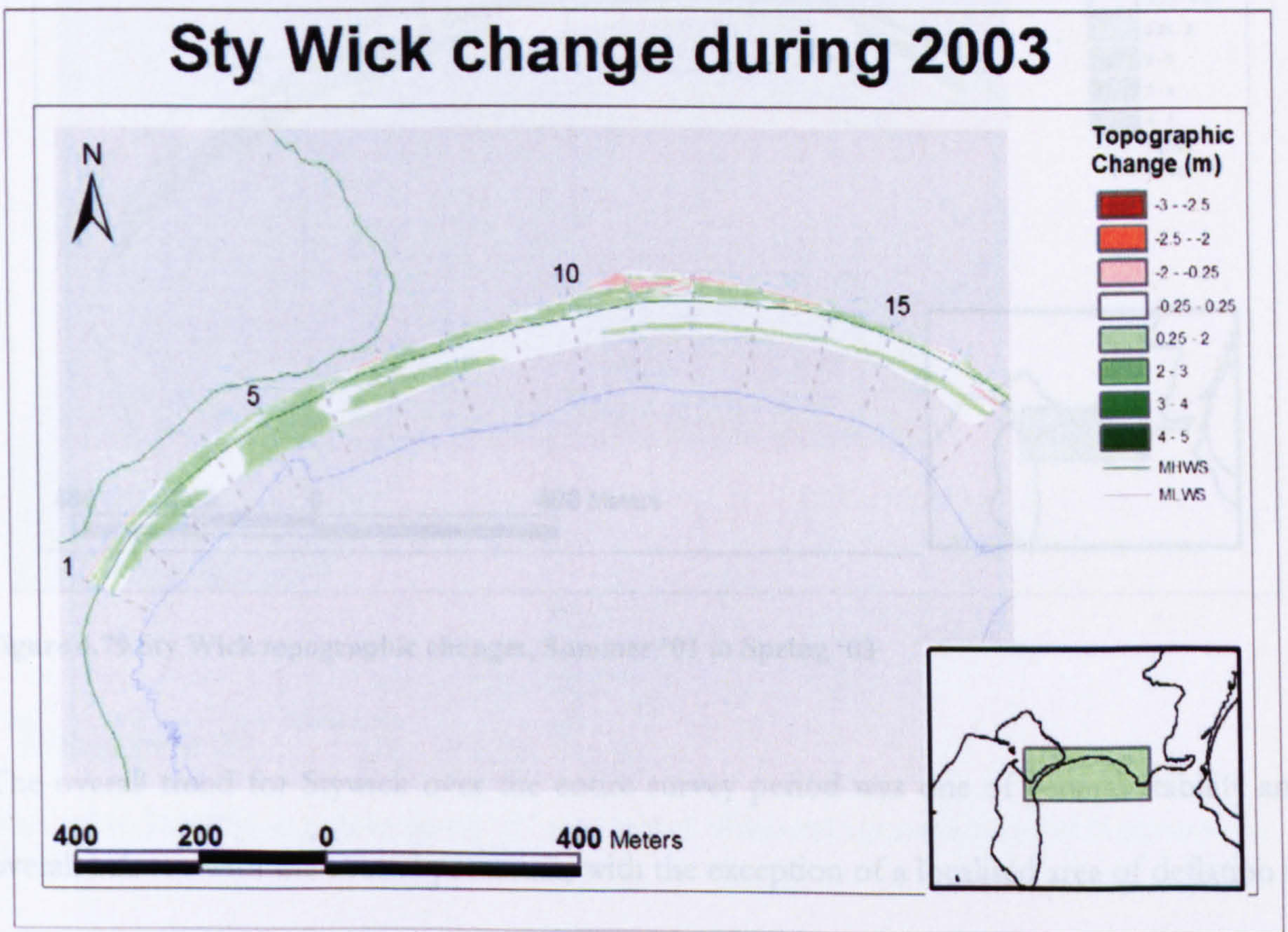


Figure 4.78 Sty Wick topographic changes, Spring '03 to Summer '03

Summer 2001 to Summer 2003

Figure 4.79 is a comparison between the 2001 and 2003 summer profiles. The overall fluctuations were relatively subtle with most changes under 2 meters, but with one exception at the back beach at Transect 12. This large loss is positioned in the back beach (and is related to subtle difference in the position of the transect within the dunes). Two accretional areas found in the intertidal area (Transect 1-8 and 10-17) had a gain of <0.6m and <0.5m, respectively. The accretionary area at MHWS was one of the most dynamic components of the beach, with gains of up to 1.8m at Transect 9.

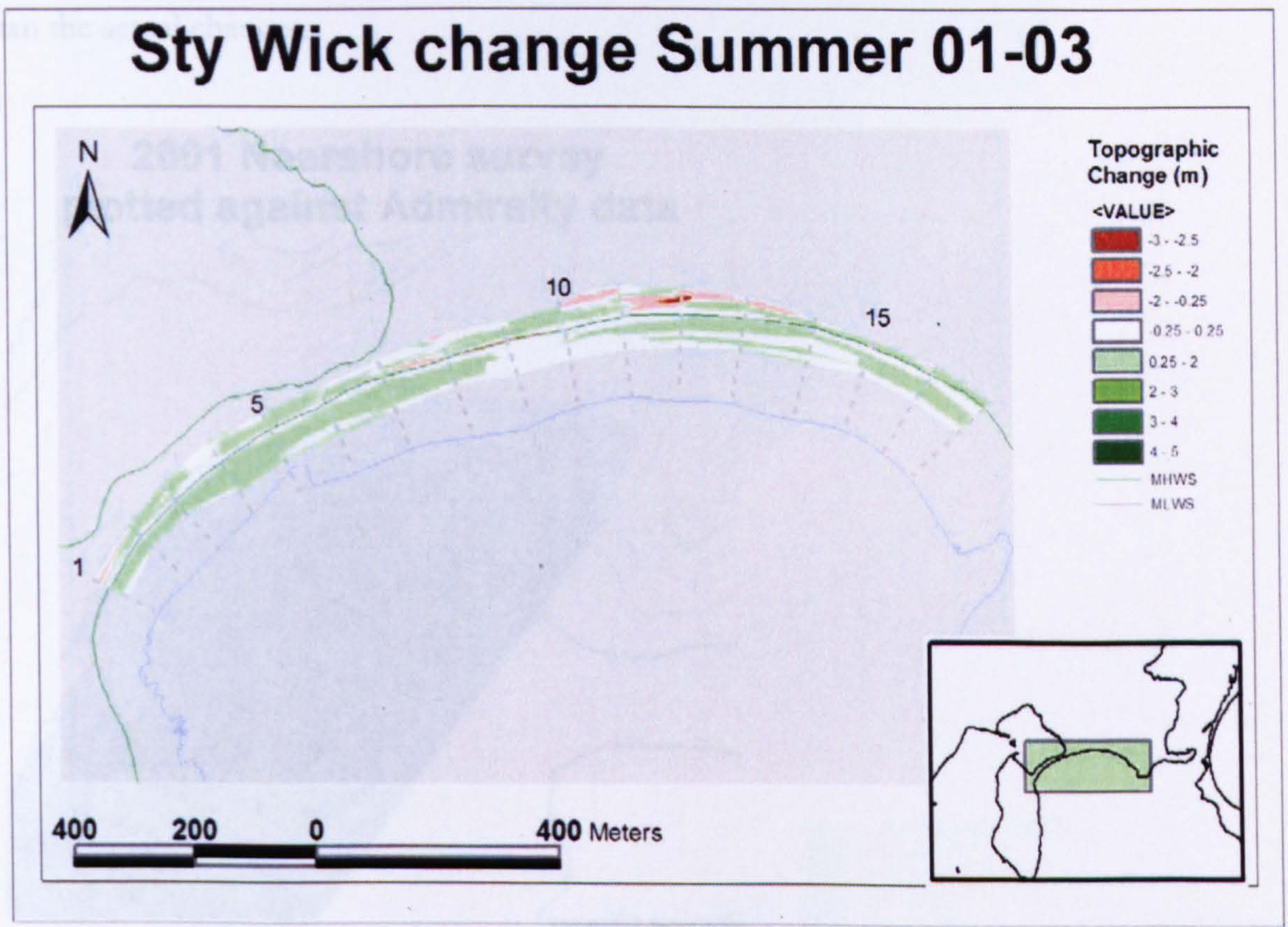


Figure 4.79 Sty Wick topographic changes, Summer '01 to Spring '03

The overall trend for Stywick over the entire survey period was one of general stability and overall balance with the coastal processes, with the exception of a localised area of deflation in the centre of the beach (Transect 12).

4.6.2 Nearshore bathymetric changes

The following section outlines results from the 2001 nearshore survey of Lopness, Newark and Sty Wick. The nearshore survey is plotted in 5m intervals from 0mOD(K) and compared against [1]the Admiralty Survey, which is based on the 1850 Beaches survey. The difference between Chart Datum and Ordnance Datum (Kirkwall) is -1.9m.

4.6.2.1 Bay of Lopness

Figure 4.80 shows a general deepening in the nearshore since 1850, in fact the -10m OD (2001 surveyed depth) are comparable in places with the 5mCD line, a height change of ~3.1m. The square eastern-edged of the 2001 survey data is likely to reflect the plotting method rather than the actual changes.

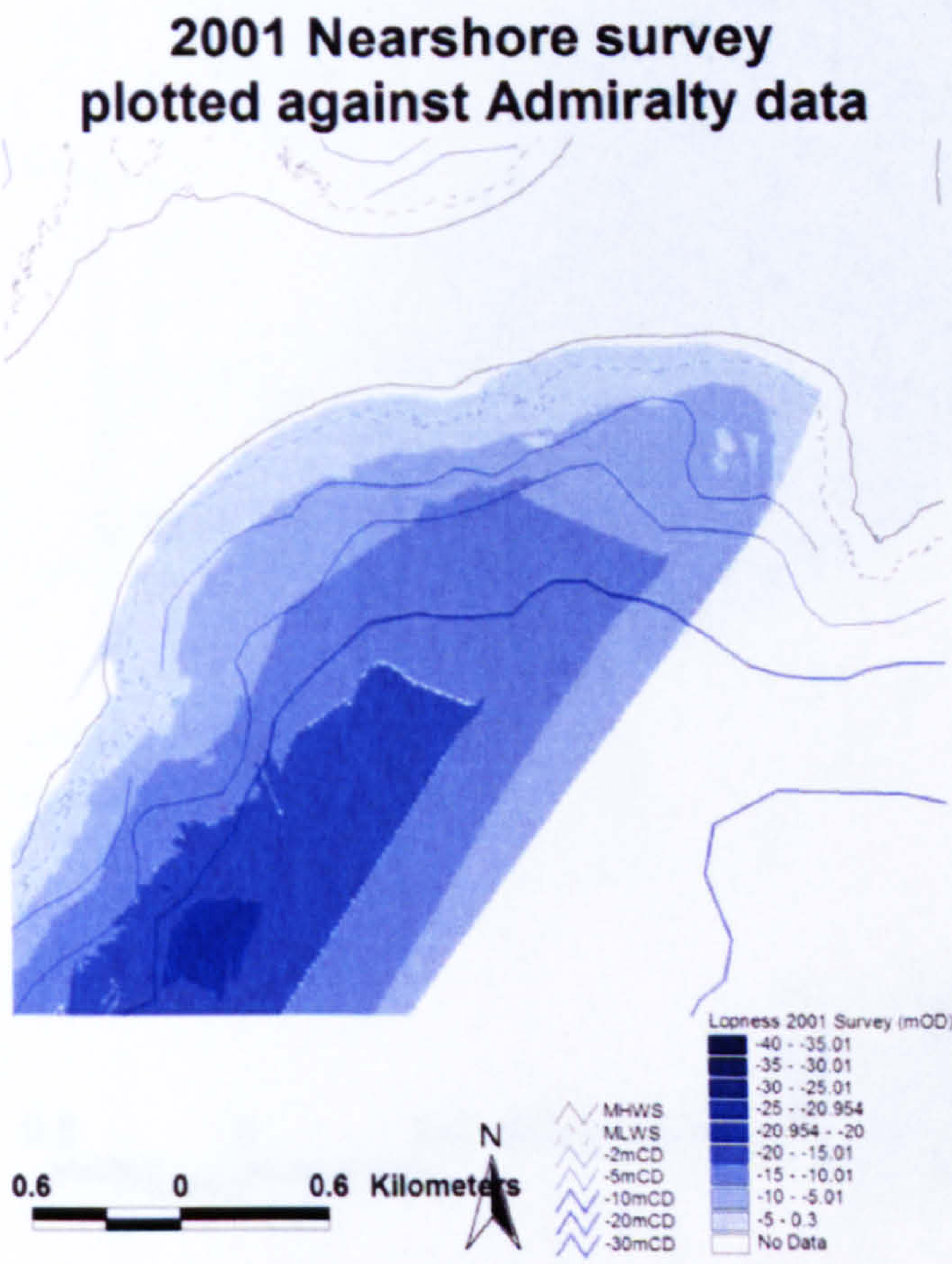


Figure 4.80 The 2001 nearshore survey of Lopness Bay, compared against Admiralty data, based on the Becher 1850 Survey.

[1] Due to the technical problems the 2002 Nearshore survey is unavailable. For that reason the 2001 nearshore survey is compared with Admiralty Survey which is less rigorous that the author would like.

4.6.2.2 Bay of Newark

Figure 4.81 displays the 2001 nearshore survey for Newark and also shows a nearshore steepening in areas up to -10mCD. The deeper waters off Newark are thought to be representative, although the south-eastward facing edge of the 2001 plot reflects the plotting method, rather than actual change.

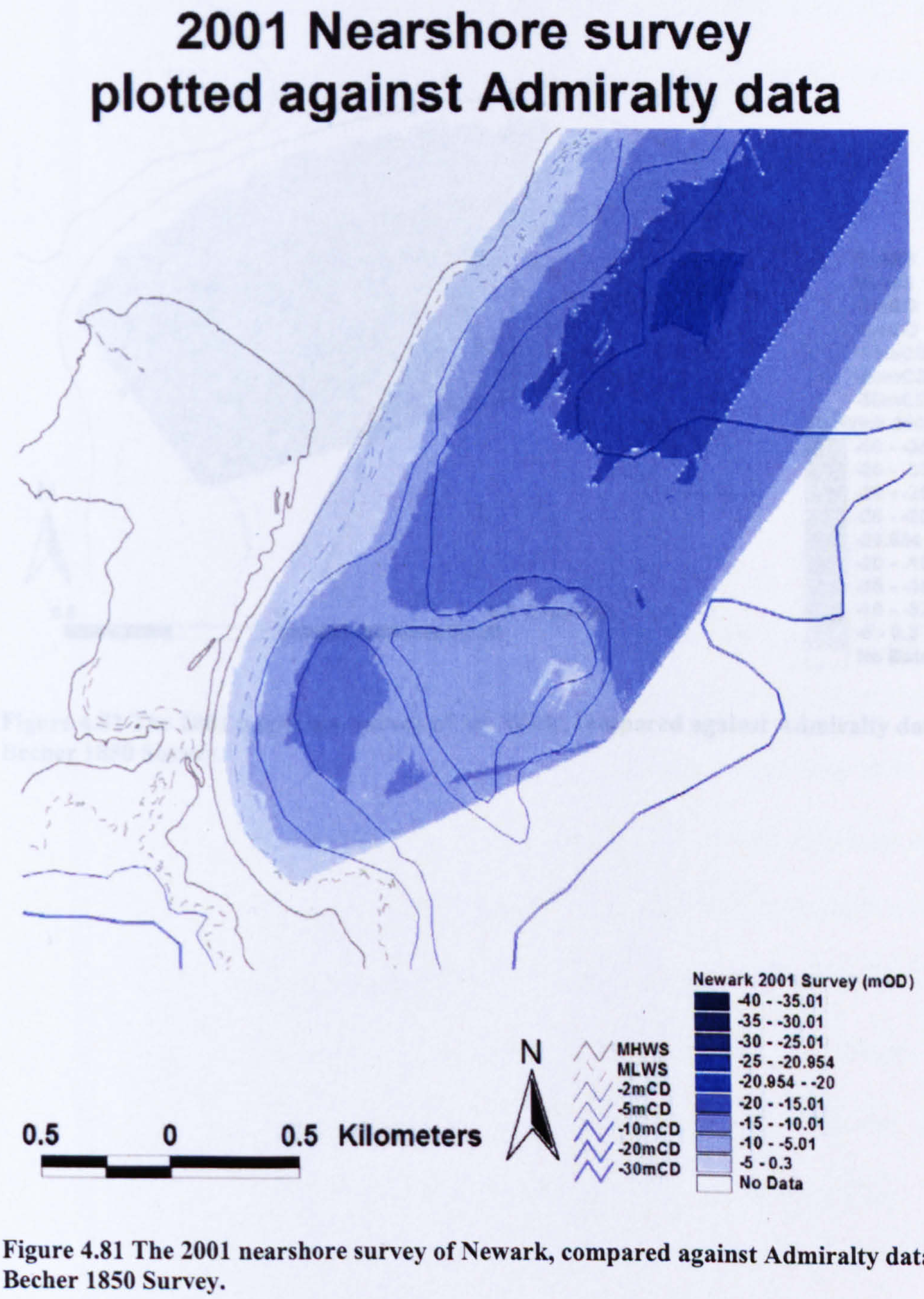


Figure 4.81 The 2001 nearshore survey of Newark, compared against Admiralty data, based on the Becher 1850 Survey.

4.6.2.3 Sty Wick

Figure 4.82 shows the 2001 nearshore survey of Sty Wick, plotted against the Admiralty data. Once again, there is a deepening in the nearshore between the two surveys.

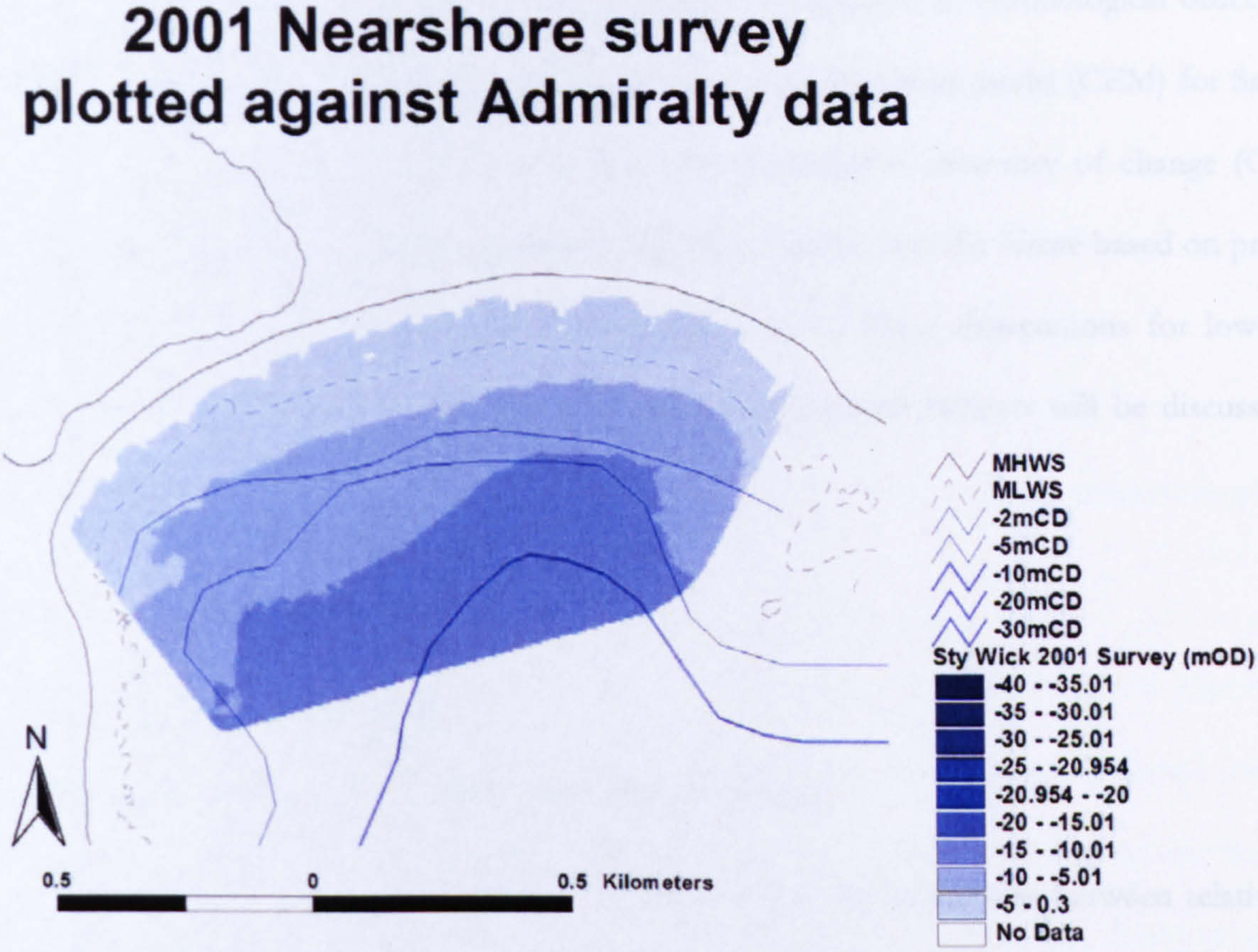


Figure 4.82 The 2001 nearshore survey of Sty Wick, compared against Admiralty data, based on the Becher 1850 Survey.

5 Discussion

This chapter discusses the results and collates the individual strands of evidence related to the role of sediment supply and sea level change on submerging shorelines; it also outlines the wider implications of this research. The discussion is organised in chronological order, and attempts to integrate the available evidence into a coastal evolution model (CEM) for Sanday from the Late Holocene to the present day. The geomorphic inventory of change (CEM) associated with adjusting forcing conditions, will be extended into the future based on present and future climate change scenarios. The implications of these expectations for low-lying submerging shorelines, for future planning and for designated habitats will be discussed in Chapter 6.

5.1 A chronological base

5.1.1 The sea level curve

Rates of RSL change and modes of coastal evolution

Fundamental to the behaviour of soft coastal systems is the interaction between relative sea level and the stability of coastal landforms, and the sediment abundance/scarcity, which can result in either progradation counteracting transgression or erosion, even when sea level is falling (Figure 5.1). The implications of this relationship are that sediment supply is crucial for understanding the behaviour of soft coasts. Thus a beach will be poised to react by prograding when sediment supply is abundant and reorganisation under sediment scarcity and under dynamic equilibrium where geomorphic growth balances sea levels. Obviously these conceptually clinical circumstances are rarely met in an open system such as the coast, especially over the length of time under consideration in this investigation.

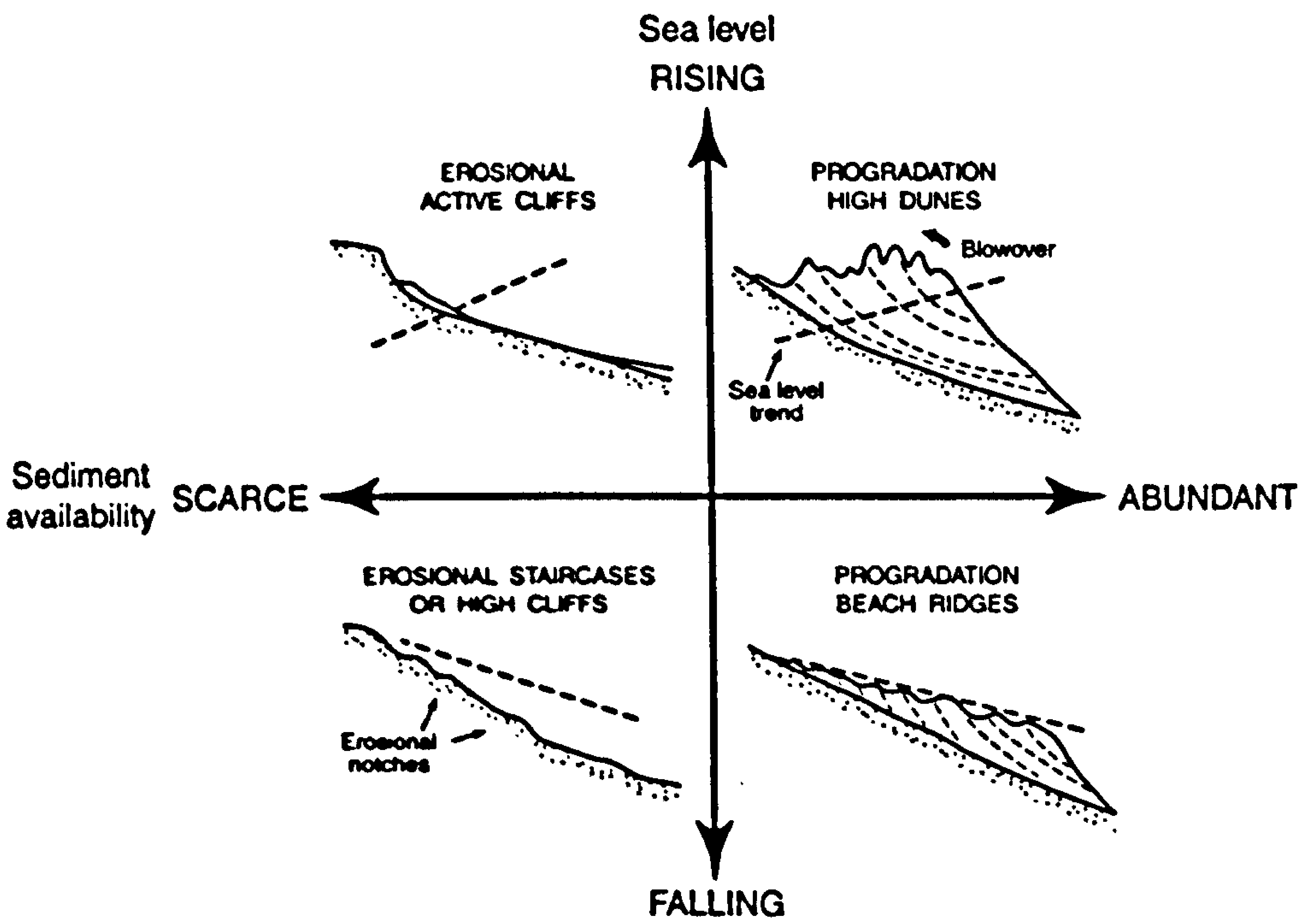


Figure 5.1 The morphological consequences of the interaction of sea level rise and sediment supply, modified after Carter (1989).

The rate of sea level rise plays a crucial role in the mode of coastal evolution (Carter *et al* 1989): under high rates of sea level rise (for example, such as experienced around much of Scotland in the period before 6.5kaBP, Figure 5.2) coastal landforms left behind by the rising sea level as coastlines transgressed with little shoreface modification and therefore limited beach building (Hansom, 1988).

Under the lessening rate of sea level rise (from around 6.5kaBP for most of Scotland, Figure 5.2) large-scale modification of sediments occurred (Firth *et al* 1995). This was manifested around the Scottish coast with the arrival of gravels and sands. A modern analogy of this phase of development is the gravel barriers of Nova Scotia (Carter *et al* 1989) where relative sea level rise rates greater than 3mm/yr feed the coastal system by accessing local sediment stores, in this case the erosion of a local drumlin field.

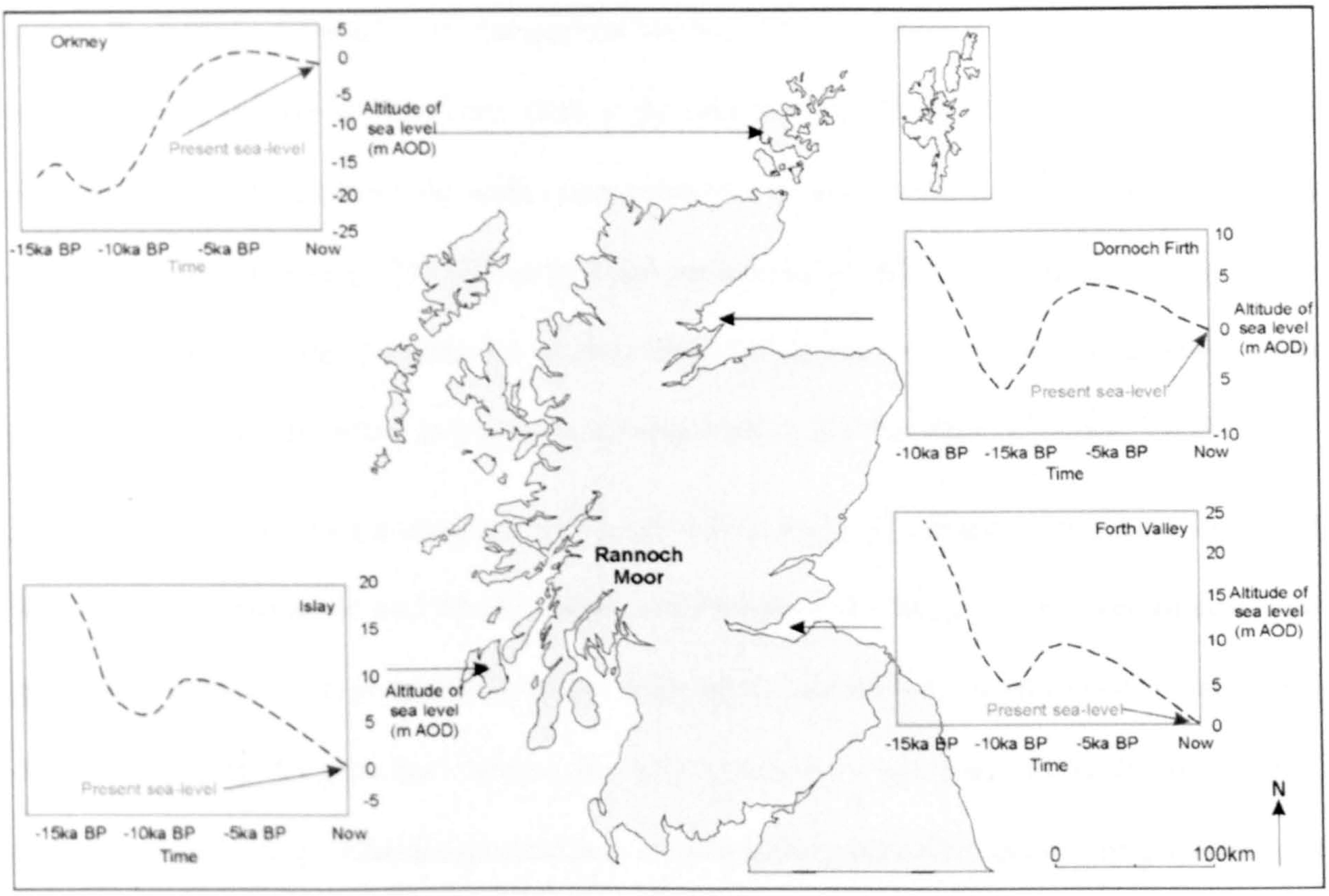


Figure 5.2 Orkney sea level curve after Shennan *et al* (2002) including rates of relative sea level change.

From ~5kaBP the sea level rise slowed dramatically (<1.4mm/yr) and although offshore contributions became increasingly limited through time terrestrial contributions became very scarce indeed as new coastal and non-coastal sediments were not being accessed at the same rate. On Sanday the low-lying topography would have further reduced the potential terrestrial sediment supply, as archipelagos tend not to have significant catchments to form meaningful rivers. Carter *et al* (1989) contrasted the dynamic Canadian example, above, and the generally stable (<1mm/yr) east coast of Ireland where the relative deficit in sediment supply increases the dominance of local basement control and cross shore drainage. This reduction in relative sea level rise, together with a finite offshore sediment inventory led to a widespread switch in the coastal sediment economy from abundance to scarcity, the timing of which was dependant on the relative position of the coastline to the centre of glaci-isostatic uplift (Hansom 2001). Areas towards the periphery of the former Scottish icecap (Figure 5.3) not only experienced submergence for longer but also experienced longer periods of transgression (landward retreat due to sea level rise) and/or the earlier onset of retrogradation (landward retreat due to sediment scarcity). Examples of this general landward re-organisation of coastal assemblages exacerbated by relative sea level rise include the coastlines of the Northern and Western Isles of Scotland and is manifest by wide-scale erosion of sandy beaches in the Highlands and Islands region where only 7% of beaches are accretional (Mather and Ritchie, 1984). These 'peripheral' submerging coastlines are characterised by numerous sites where submerged peats and the remains of terrestrial archaeology are exposed on the foreshore (Dawson, 2005).

Historically this has been contrasted with areas within the zerô-isobase, which have benefited from isostatic emergence and where coastal assemblages have been draped over an emergent geological surface, via processes such as regression (shorelines advance due to sea level changes) and/or progradation (shorelines advance due to increases in sediment supply). However, this isostatic inheritance is subject to progressive reduction and recent investigations (Pethick, 2000; Graff, 1998) suggest that the area of isostatic recovery is becoming smaller. The implications of this are discussed further in Section 5.6.

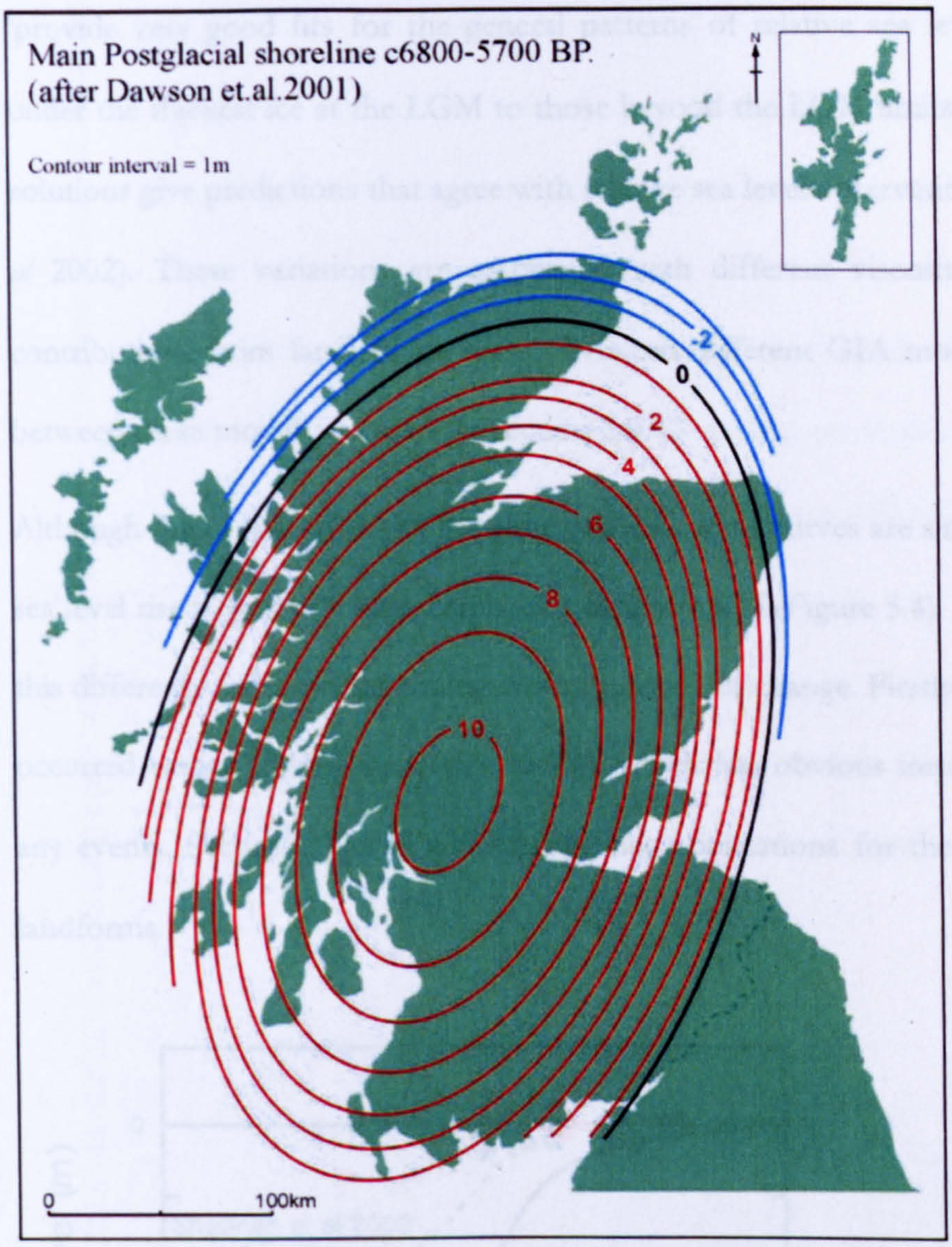


Figure 5.3 The Holocene Main Post-Glacial Shoreline after Dawson *et al* 2001

The above interpretation assumes that the Shennan *et al* (2002) sea level curve, used to constrain the phases of development is accurate. An earlier alternative was Lambeck's reconstructions of the Holocene development of the British Isles (1993, 1995). The main differences between the two models are due to different rheological assumptions for the Earth's crust, the use of a larger number of sites available to Shennan *et al* (2002) to constrain their model and developments regarding the behaviour and demise of the Devensian ice cap. As stated in chapter 2, 'significant disagreements remain between Glacial Isostatic Adjustment models (GIA models). Other than Shennan *et al* (2002) current analyses are Lambeck (1995) and Peltier (1998) which, 'provide very good fits for the general patterns of relative sea level change between areas under the thickest ice at the LGM to those beyond the LGM limits, but none of these model solutions give predictions that agree with relative sea level observations at all sites" (Shennan *et al* 2002). These variations are associated with different viscosity profiles and meltwater contributions from far-field ice sheets between different GIA models. Further comparisons between these models are made in section 2.9.4.'

Although the overall forms of the alternative sea level curves are similar, the magnitude of the sea level rise is greater within Lambeck's earlier model (Figure 5.4). Two direct implications of this difference, relate to the timing and magnitude of change. Firstly, a previous lower sea level occurred earlier within Lambeck's model, which has obvious implications for the timing of any events. Secondly, the rate of change has implications for the behaviour of submerging landforms.

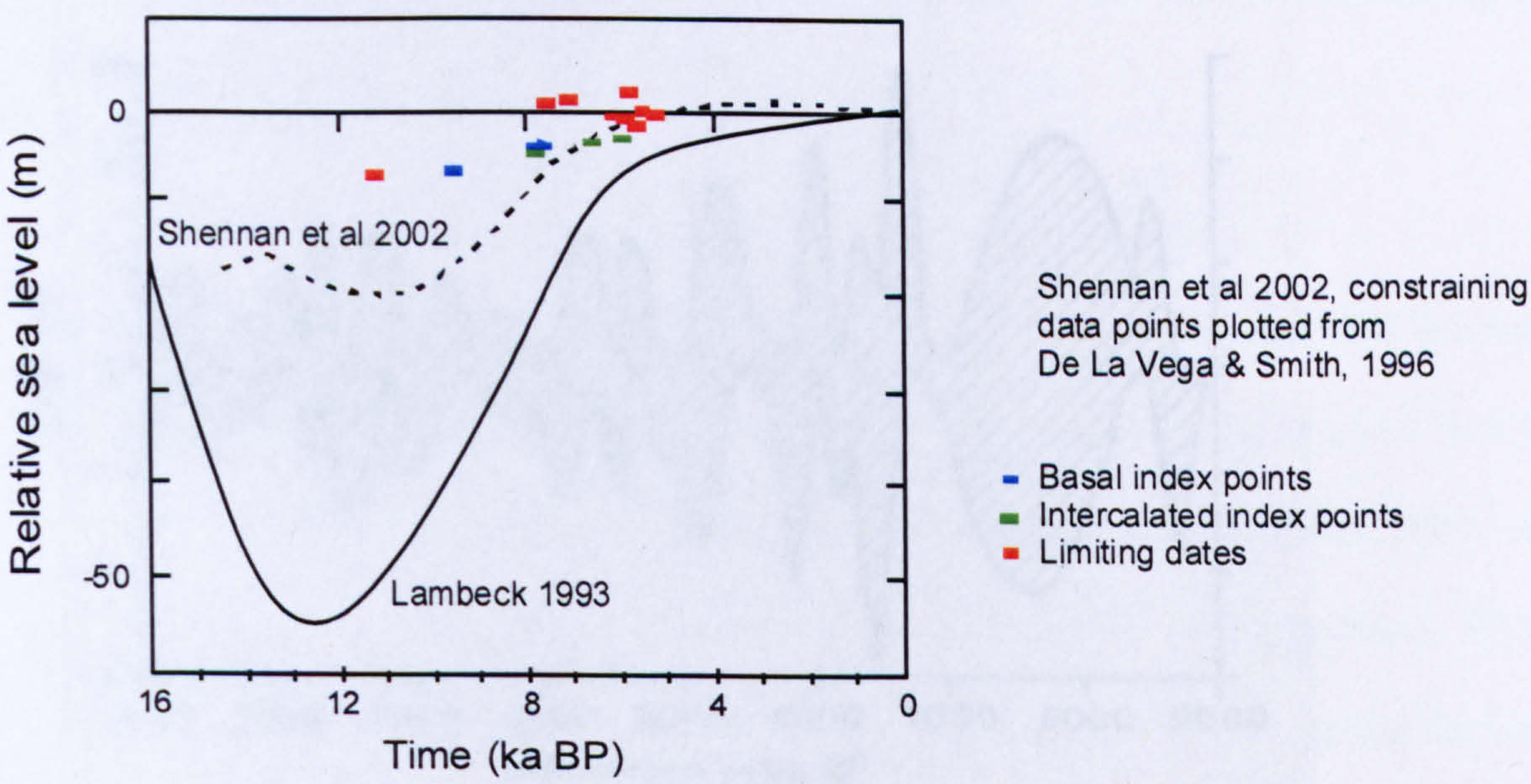


Figure 5.4 Comparison of Shennan *et al* (2002) and Lambeck's (1993) Orkney sea level curves.

The more rapid and greater magnitude changes of Lambeck's earlier model are problematic when the rates of relative sea level rise are compared with the phases of behaviour expected at different relative sea level rise rates (Carter 1989) and the juxtaposition of the resultant morphology of Sanday. Although the position of the Otterswick buried forest is better fitted to the Lambeck Sea level curve, being a only little above that part of the Lambeck (1993) relative sea level curve, the remaining geomorphology of central Sanday is then confined to within the last 4ka. This is problematic because the rates of submergence may not be significant enough to deposit a spit of this size at a time when the literature expects cannibalisation and reorganisation of existing sediments in-situ. In addition to this the Lambeck sea level curve demands much accretion at a time and space when one would expect erosion.

Another source of error was acknowledged by Shennan *et al* (2002): the modelled eustatic component of global sea level changes in the Holocene (Figure 5.5). This illustrates how much we still have yet to establish as far as GIA models and their implications on individual areas of coast.

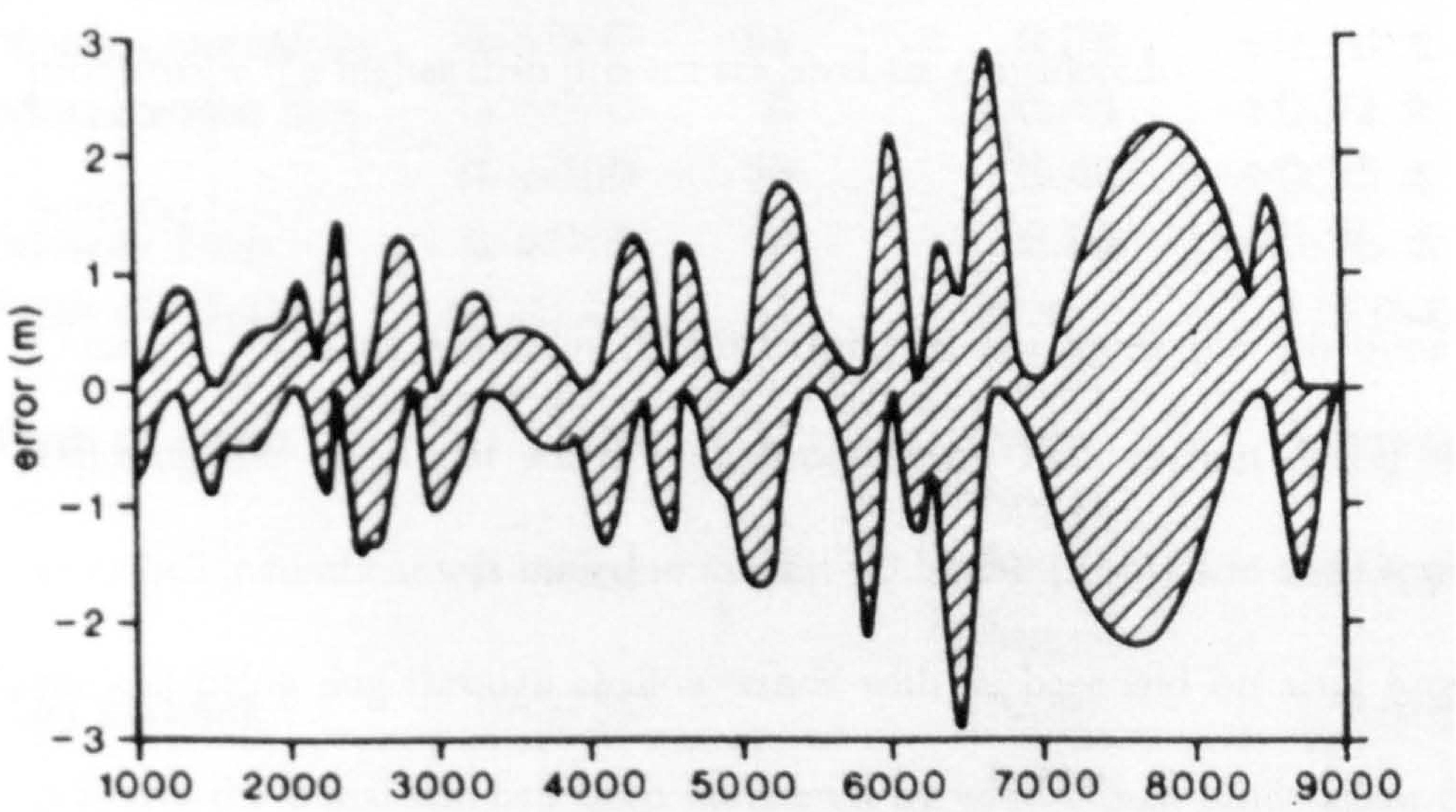


Figure 5.5 Maximum errors in the estimation of eustasy, assuming an error in the age of the samples up to ± 200yrs and a eustatic curve with oscillations (Shennan *et al* 2002).

Higher than present Holocene sea levels

There is no direct evidence within the literature for the higher than present sea levels shown in Shennan *et al* (2002) for Orkney during the Holocene, which places the sea level curve above current sea level for the last 5kaBP, peaking at +1.5m above present levels at 2.5kaBP. The modelled higher than present sea level reflects rheological assumptions and the adjacent GIA model rather than any specific geomorphological evidence within the Orkney archipelago (Shennan *et al* 2000). There are a number of alternative strands of evidence which make the possibility of higher than present sea levels for the last 5kaBP, as described by Shennan *et al* (2002) less likely:

- The 1-3mm/yr relative sea level fall depicted in Shennan *et al* (2000) curve for the last 2ka is not reflected anywhere within coastal geomorphology of either Sanday or neighbouring islands. This emergence should have been manifest across the archipelago, since accretional units would have been superimposed on a recessional landform. The accretional sections that are present are too low to be indicative of 2 thousand years of emergence.
- The juxtaposition of the Lopness Bronze Age cist (Figure 4.35) and its surroundings are problematic if a higher than present sea level are considered:

  Scenario 1:

  During a southerly storm in AD2000 (present sea level) the 3m dune cliff retreated, exposing the burial cist and it's till foundations. Radiocarbon dating showed that the crouched incumbent was buried in the cist ~3.5kaBP (Robertson and Downes, 2000), with the cist being dug through shallow sands with its base laid on a till foundation. Within ~500yrs the burial site had been inundated by wind blown sands again during the Little Ice Age. It is likely that there was sand deposition at the site during the intervening period – evidence of which was subsequently removed prior to the deposition of Little Ice Age deposits (Sommerville 2003).

  Scenario 2:

If higher sea levels are considered then at the time of burial the high tide level was 1-2m above present position (assuming the tidal range was unchanged). Given the relative altitude to high tide the cist site was likely to be a low marshy location – not appropriate for a burial site. There must also have been a large dune system seaward of the cist, which although likely, its wide-scale erosion must have occurred as relative sea levels fell over the last 3kaBP. Therefore Scenario 2 is less likely than Scenario 1.

- The youngest gravel ridges located within the Plain of Fidge require a sea level slightly above present levels. If considered in association with the Comber (1993) conversion of 3.2m above MSL, the ridges require a MSL 1.4m above present levels. However, if Combers error term is incorporated (±0.9m), then sea levels only need to be 0.5m above present levels. This can be incorporated within the period 5 - 4.5kaBP of the Shennan *et al* (2002) sea level curve.
- Finally, the location of the second peat sample found to the north of Cata Sand is explained more simply through a rising-to-present sea level. This is explained further in section 5.1.3.

There is a gap in the literature over the last 5kaBP regarding relative sea level change in the Northern Isles of Scotland. Recent GPS investigations at tidal stations within the UK suggest that the peripheral coastal areas are presently experiencing relative sea level rise (Bingley *et al* 2001). The rate of RSLR and implications of this are discussed in Chapter 6.

All of these considerations, above, indicate that the pattern of sea level change over the last 5kaBP may be more varied than the gently changing curve that Shennan *et al* (2000) propose in the absence of any specific information. The juxtaposition of the youngest ridges and the wider recessional signature within Sanday and its neighbouring islands, may suggest that sea levels did rise above present levels a little after 5kaBP, before returning to their present position more quickly than the proposed by Shennan *et al* (2000). However, there remains no other independent geomorphic evidence of a higher than present sea level to verify its presence. This would provide the conditions which have led to an increasing cannibalisation of terrestrial deposits during the last 2kaBP, reflecting global sea level rise and dwindling new sediment supply contributions. In spite of this the Shennan *et al* (2002) sea level curve is used for discussion purposes.

5.1.2 Preserved gravel ridges and the relative sea level curve

As Sanday became submerged by rising sea levels over the Late Holocene many of the former deposits were eroded, recycled and re-deposited as younger landforms at different locations, heights and orientations all reflecting more recent sea levels and sediment supply conditions. Fortunately in Central Sanday, several fragments of these former beaches are preserved as surface gravel ridges indicating past shorelines whose orientations do not conform to present. These represent earlier time-steps and are located towards the middle and southern end of Cata Sand. Furthermore, the subsurface GPR investigations identified that the suite of ridges were more extensive than suggested by their surface exposures and that the direction of extension was towards the northeast so that the most recently deposited ridges lie to the northeast, below the Plain of Fidge (See Chapter 4, Section 4.3.1).

Establishing the approximate position of the earliest coastline is problematic, since no geomorphological features survive from this time. It is nevertheless possible to approximate the location of the coast based upon the altitudes derived from the sea level curve (Figure 5.2) and mapping these with landform height, orientation and altitude derived from the coastal bathymetry. Where sea level impinges upon bedrock surfaces, reconstruction of the former coastline can proceed with a reasonable degree of confidence. A lesser degree of confidence is attached to soft sections of the coastline, since these undergo significant fluctuations in volume. In spite of this constraint, and working backwards in time, it is possible to sequentially construct shorelines based upon the orientation of surviving geomorphology, sea level curve derived altitudes and existing bathymetry.

However, matching the altitude of gravel ridges to any sea level is fraught with uncertainty and assumptions. For example an assumption here is that the intertidal altitudes of the ridges in Cata Sand and under the Plain of Fidge have not undergone significant winnowing and settling. Comber (1993) used the altitude of gravel ridges in association with sea level curves to approximate an age for gravel ridge deposition on straight sections of gravel ridges. He used a conversion factor between mean sea level and gravel ridge altitude of ca. 3.2m ± 0.9m for the active straight ridges on a part-buried gravel spit system at Culbin on the Moray Firth coast of the Scottish mainland. The part-buried gravel ridges in Sanday are similar to the Culbin situation and following Comber (1993), ridge altitudes are assumed to be ca. 3.2m above the mean sea level of the time. Independently, the maximum gravel ridge altitude in Sanday is within the Plain of Fidge at 4.6mOD.

The oldest preserved gravel ridges are currently located within the southern part of Cata Sand, with only their distal ends being preserved as they curve inland from underneath the present dune capped tombolo. Although little remains of the straight section of the ridges, given the orientation of the distal ends the arms of the ridges must have extended seawards of the present tombolo. Given their altitude and using Combers (1993) conversion factor these oldest preserved ridges are plotted on Shennan *et al* (2000) sea level curve in Figure 5.6.

Given the only remaining sections of the earliest preserved ridges are their distal ends, their altitude may be lower than the straight section of the ridges, which have previously been removed. This is likely to result in an over-estimation of the age of these earliest features.

The same procedure has been carried out for the youngest preserved ridges within the Plain of Fidge, whose altitude of the straight section of the ridge is at 4.6mOD. This relates to a mean sea level 1.4m above present (or a minimum of 0.5m above MSL if the Comber 0.9m error term is utilised). These altitudes and resultant dates are plotted onto Figure 5.7.

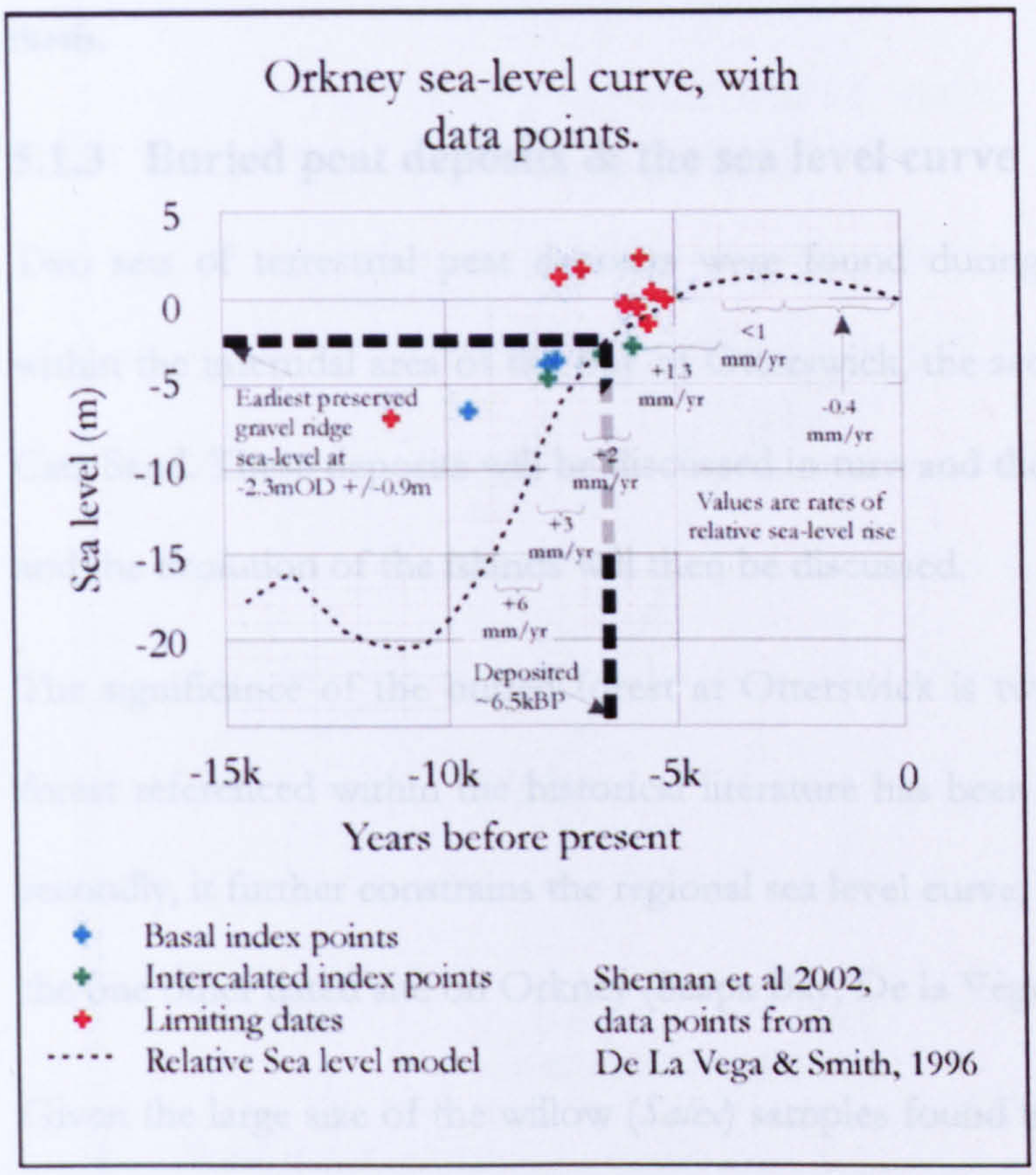


Figure 5.6 Orkney sea level curve (Shennan et al 2002) with the oldest preserved gravel ridge (dashed line) on Sanday. Note the error term from Comber (1993) is ±0.9m. Note an alternative sea level curve is introduced in Section 5.1.3, which will be used for the remainder of the thesis.

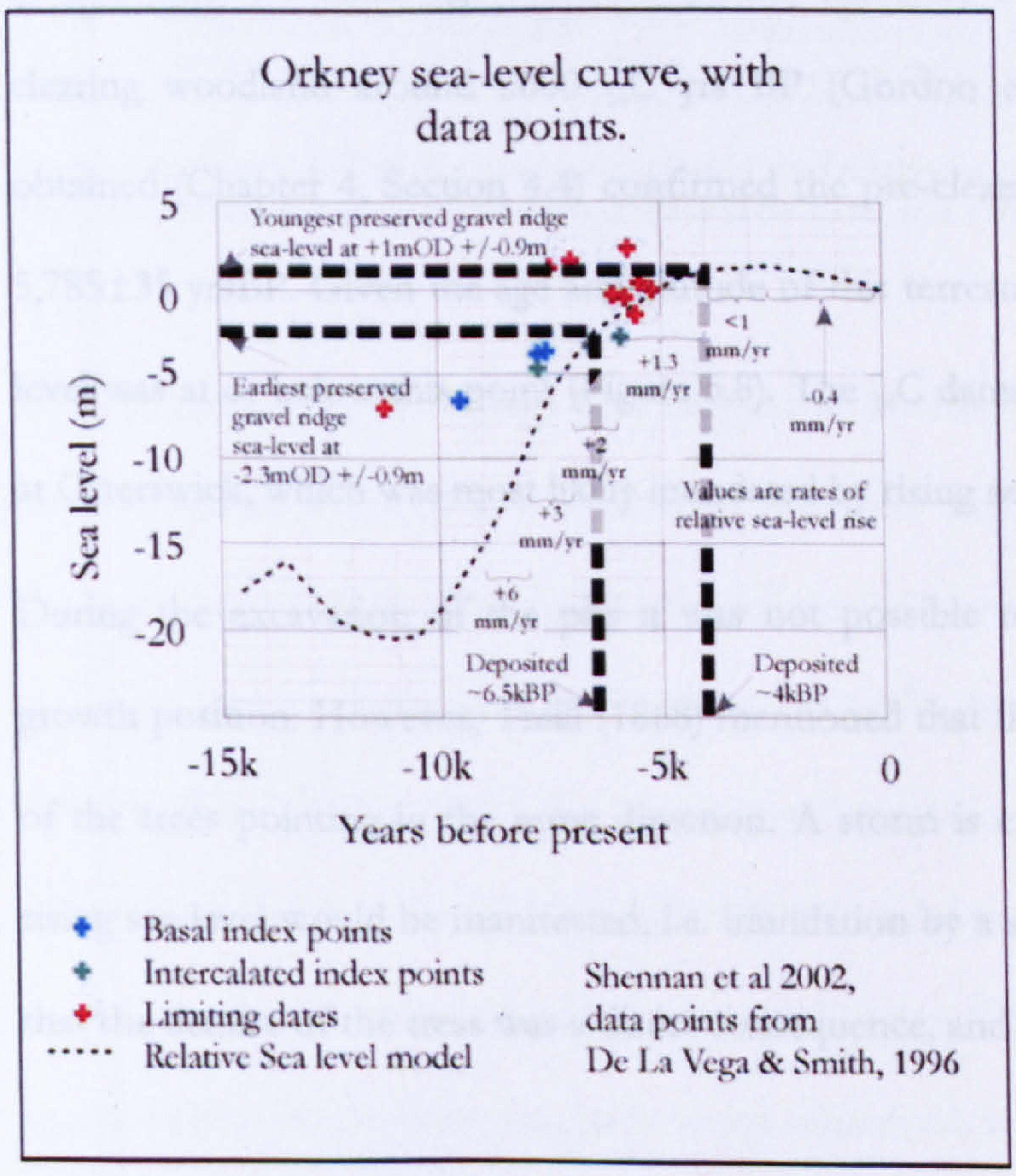


Figure 5.7 Orkney sea level curve (Shennan et al 2002) with both the oldest and youngest preserved gravel ridges (dashed line) on Sanday plotted. Note the error term from Comber (1993) is ±0.9m. Note an alternative sea level curve is introduced in Section 5.1.3, which will be used for the remainder of the

thesis.

5.1.3 Buried peat deposits & the sea level curve

Two sets of terrestrial peat deposits were found during the fieldwork campaign, the first within the intertidal area of the Bay of Otterswick, the second beneath a field to the north of Cata Sand. These deposits will be discussed in turn and their significance to the sea level curve and the evolution of the islands will then be discussed.

The significance of the buried forest at Otterswick is twofold; firstly it is the first time this forest referenced within the historical literature has been sampled, dated and identified. And secondly, it further constrains the regional sea level curve, which is supported by samples from the one other dated site on Orkney (Scapa Bay, De la Vega & Smith 1996).

Given the large size of the willow (*Salix*) samples found in the Bay of Otterswick, the original trees would have been valuable as fuel wood for early inhabitants had inhabitants been present at that time. So initial age estimates placed the trees before the local populations began clearing woodland around 3000 $_{14}$C yrs BP (Gordon et al 2002). The radiocarbon ages obtained (Chapter 4, Section 4.4) confirmed the pre-clearance age with dates of 5,590±40 & 5,785±35 yrsBP. Given the age and altitude of this terrestrial peat we can assume that the sea level was at or below this point (Figure 5.8). The $_{14}$C dates give a minimum age for the forest at Otterswick, which was most likely inundated by rising sea levels.

During the excavation of the pits it was not possible to verify whether the trees were in growth position. However, Traill (1868) mentioned that the forest was 'laid prostrate' with all of the trees pointing in the same direction. A storm is exactly the mechanism with which a rising sea level would be manifested, i.e. inundation by a storm contingent on sea level rise so that the demise of the tress was a direct consequence, and indicator of, a sea level rise.

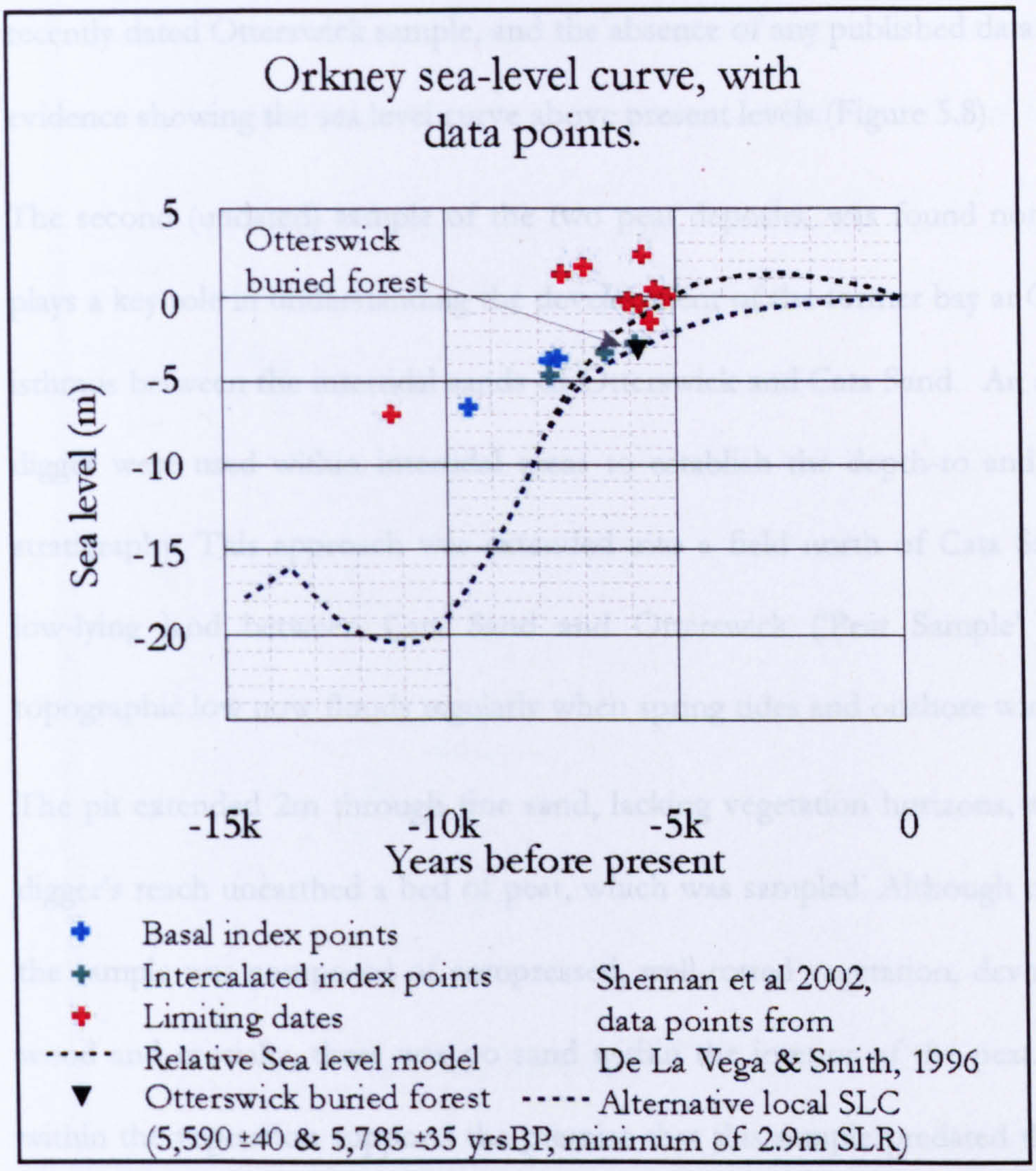


Figure 5.8 Buried forest of Otterswick plotted on Orkney sea level curve, Shennan *et al* (2002). The blue (lower) relative sea level curve is drawn in by hand and reflects the Orkney data.

The inclusion of the terrestrial peat samples at Otterswick raises questions about the exact track on the sea level curve, which lies ~1.5m above the Otterswick dates (Figure 5.8). Given the limited error terms of the radiocarbon dating and surveying, the presence of other points below the line (De La Vega & Smith 1996) and regional effects of the modelling, it is possible that the Shennan *et al* (2000) sea level curve has over-estimated the altitude around 6kaBP. Such a miscalculation would result in landforms associated with this misplaced-part of the sea level curve being overestimated in terms of their age. This means that the earliest preserved gravel ridges which were originally being estimated at ~6.5kaBP, could be as young as ~5.5kaBP, if the sea level curve is too high. An alternative curve is drawn, which reflects the recently dated Otterswick sample, and the absence of any published data or geomorphological evidence showing the sea level curve above present levels (Figure 5.8).

The second (undated) sample of the two peat deposits, was found north of Cata Sand, and plays a key role in understanding the development of the former bay at Cata Sand but also the isthmus between the intertidal sands of Otterswick and Cata Sand. An augur and mechanical digger were used within intertidal areas to establish the depth-to and nature-of underlying stratigraphy. This approach was extended into a field north of Cata Sand along the narrow low-lying land between Cata Sand and Otterswick ('Peat Sample' in Figure 5.9). This topographic low now floods regularly when spring tides and onshore winds combine.

The pit extended 2m through fine sand, lacking vegetation horizons, and at the limit of the digger's reach unearthed a bed of peat, which was sampled. Although not formally identified, the sample was composed of compressed, well-rotted vegetation, devoid of any branches of wood and crucially, there was no sand within the interior of the peat. The absence of sand within the vegetation supports the premise that this sample predated the arrival of marine or dune sand at Cata Sand. It's juxtaposition beneath a single sand layer (absent of remains of vegetation horizons) indicates two possible forms of development.

The first explanation is that the capping-sands are of marine origin and were deposited at 1.5 to 3.5mOD; conditions that matched the postulated high Holocene sea level of Shennan *et al* (2002) model. The second explanation is that the sands may also have been delivered via aeolian means, and vegetation had little time to establish. This is considered more likely given the altitude of the deposits and the deposition of other comparable deep homogenous sand deposits (machair) elsewhere on the island.

The presence of rock out crops between Cata Sand and the Bay of Otterswick does indicate that there has always been a very shallow narrow rock isthmus between the two intertidal water bodies, thus limiting the amount of island building during submergence to the areas of Cata Sand and the Plain of Fidge, rather than the whole central section of the island (Figure

5.9). This land, was very low-lying rocky and therefore prone to flooding and unsuitable for occupation. As a result it remains devoid of archaeological sites (Figure 4.34).

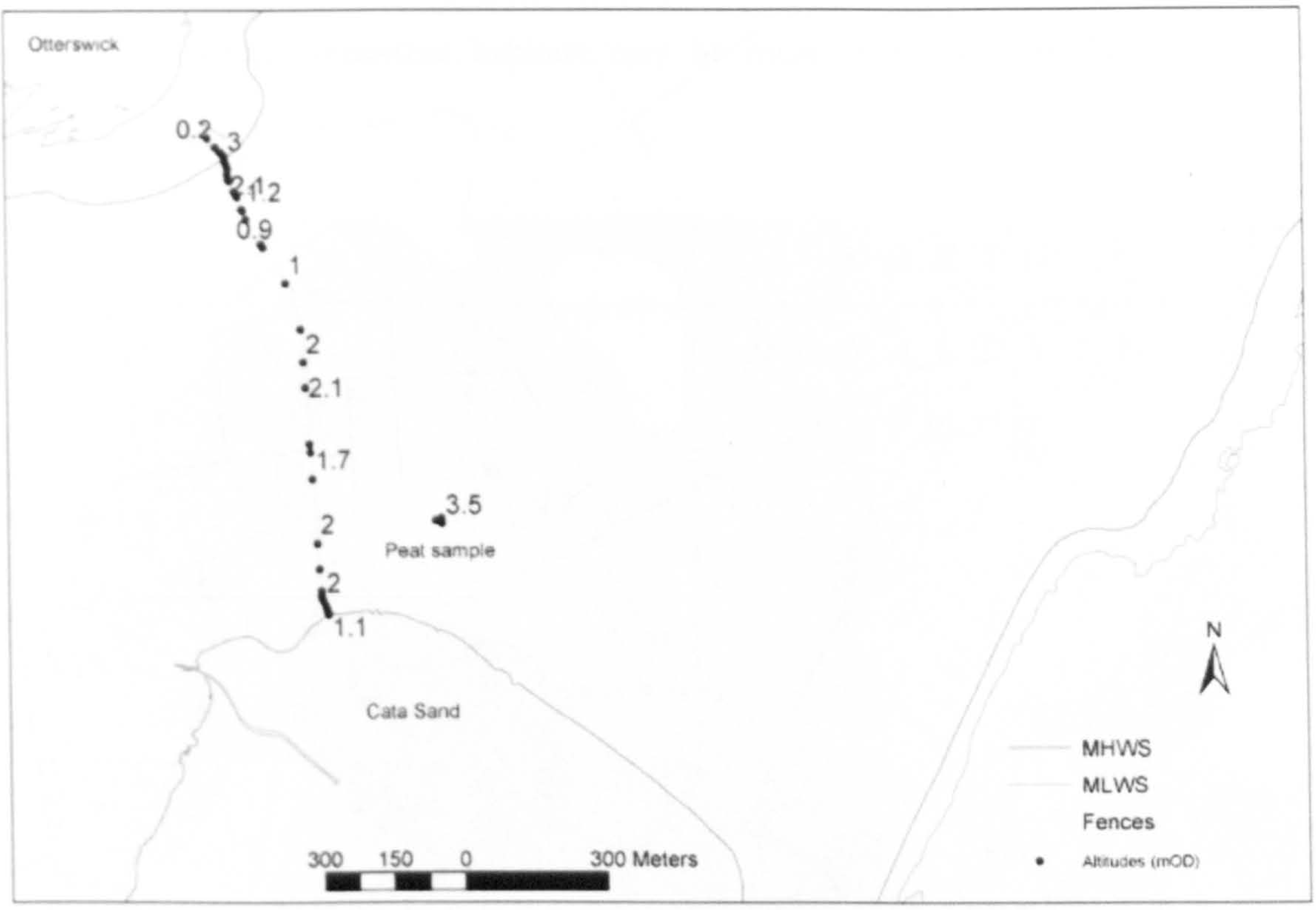


Figure 5.9 A map of surface altitudes of the low-lying isthmus between Cata Sand and Otterswick and the position of the second peat sample found 2m below ground level of 3.5mOD. Note, MHWS = 3.2mCD, CD is 1.9m below OD Kettlefoft, therefore MHWS = 1.3mOD.

Although increasing availability of sand on the east coast of Sanday is thought to have initiated around 3kaBP, the investigations within the Bay of Otterswick suggests an earlier date for the north facing coast. Radiocarbon dates for the buried forest of Otterswick places their demise around 5.6kaBP (5,590±40 & 5,785±35 yrsBP, SUERC) however the degree of preservation suggests that the samples were protected from wave energy and remained in an anoxic environment since their death. The simplest explanation is that they were submerged by rising sea levels and buried with marine sands. Historical sources suggest that forest peat covered much of the Bay of Otterswick (Traill, 1868) indicating that the degree of preservation occurred over a wide area in a short period of time, before the trees could be washed away. Inspection of consolidated blocks of peat did not show any sand grains, which is consistent with a near-instantaneous marine inundation shortly after the demise of the trees. The present bathymetry of the outer section of the Bay of Otterswick (Figure 5.10) does not contain any rock lips, comparable to that of Cata Sand or Little Sea, so the rate of inundation and distribution of former terrestrial habitats may be more complex than the island's other intertidal sand flats.

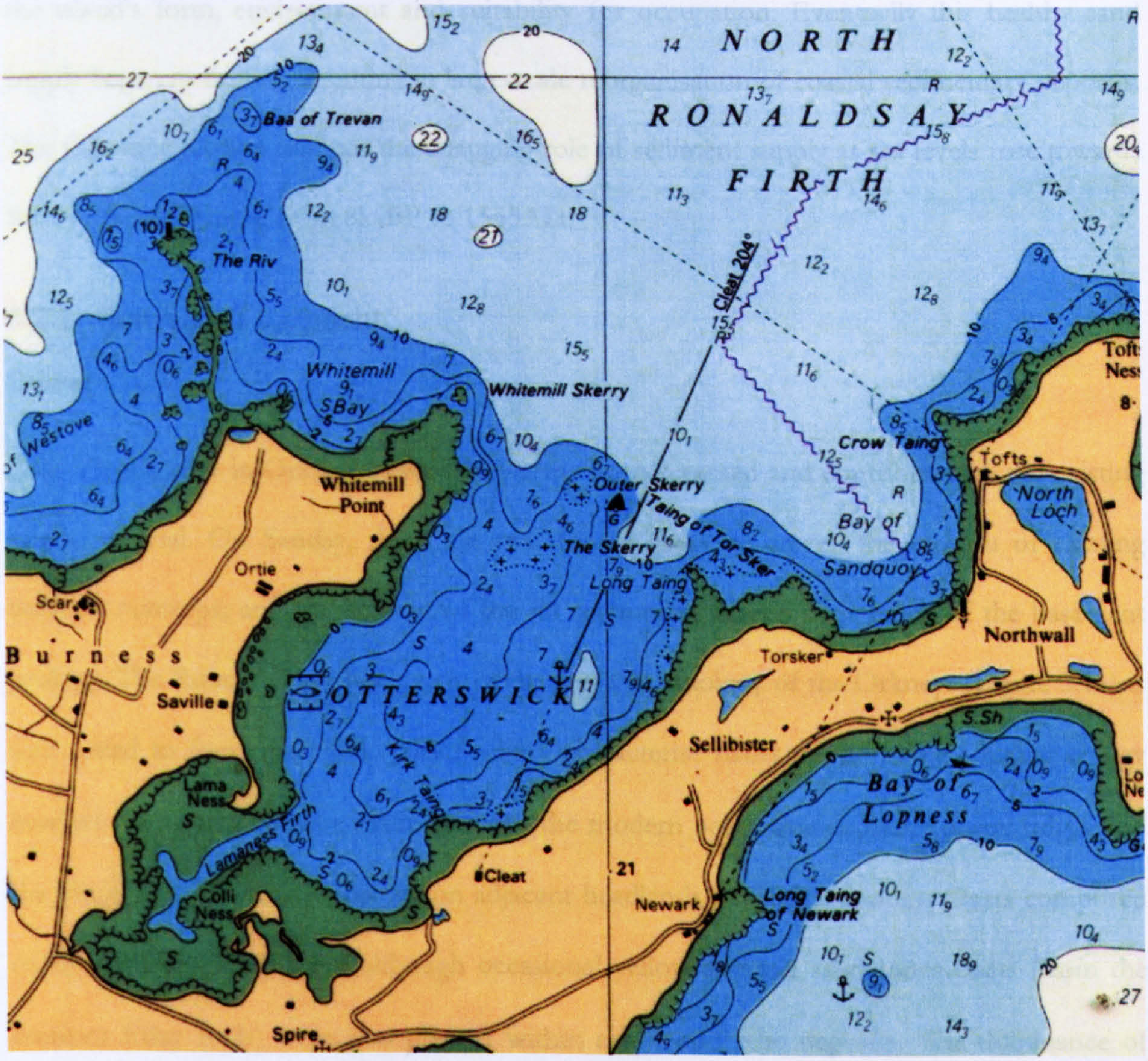


Figure 5.10 Bathymetry of the Bay of Otterswick (Admiralty Chart 2250)

5.2 Late Holocene geomorphological changes

The land-forming processes operating in Sanday over the late Holocene are comparable to those recorded elsewhere in the UK. Both sea level and sediment supply changed over the last 8ka, with earliest landforms dominated by accretional gravel units, which then became increasingly recycled, before the increasing dominance of sand led to large-scale changes to the island's form, environment and suitability for occupation. Eventually this healthy sand supply began to decline, resulting in large-scale reorganisation of coastal sedimentary deposits. The following section outlines the changing role of sediment supply as sea levels rose towards their present position, from 8kaBP to 1555AD.

5.2.1 Sources of sediment

Gravel

As sea levels rose in Orkney, new source areas were accessed and contributed to the existing beach material. On Sanday, there are two source areas of gravel: the erosion of existing bedrock outcrops; and the erosion of the till sediments, draped over much of the basement geology. The Rousay Flags, like much of the regional lithology of the Orkneys (Figure 5.11) is well suited to form the blocky clasts which characterise many of the island's higher energy beaches. Comparisons were made between the modern beach gravels, relict gravel ridges and the lithology of basement geology on adjacent headlands in Central Sanday. Clasts composed of Rousay Flags dominated although occasional yellow and red sandstones clasts (from the adjacent Eday Beds) were also present within active and relic deposits. The dominance of Rousay flags indicates a strong local control on the sourcing of gravel sized material.

A second source of material is principally from drift veneer: till and other surface sediments. Orkney has a poorly developed till, which in most part is thin, highly angular and not much more developed than weathered-fractured bedrock. The fines within the till will provide both clasts and sands to the coastal sediment budget and the latter will be retained in calmer locations of the sediment cell leaving the larger clasts on more exposed beaches.

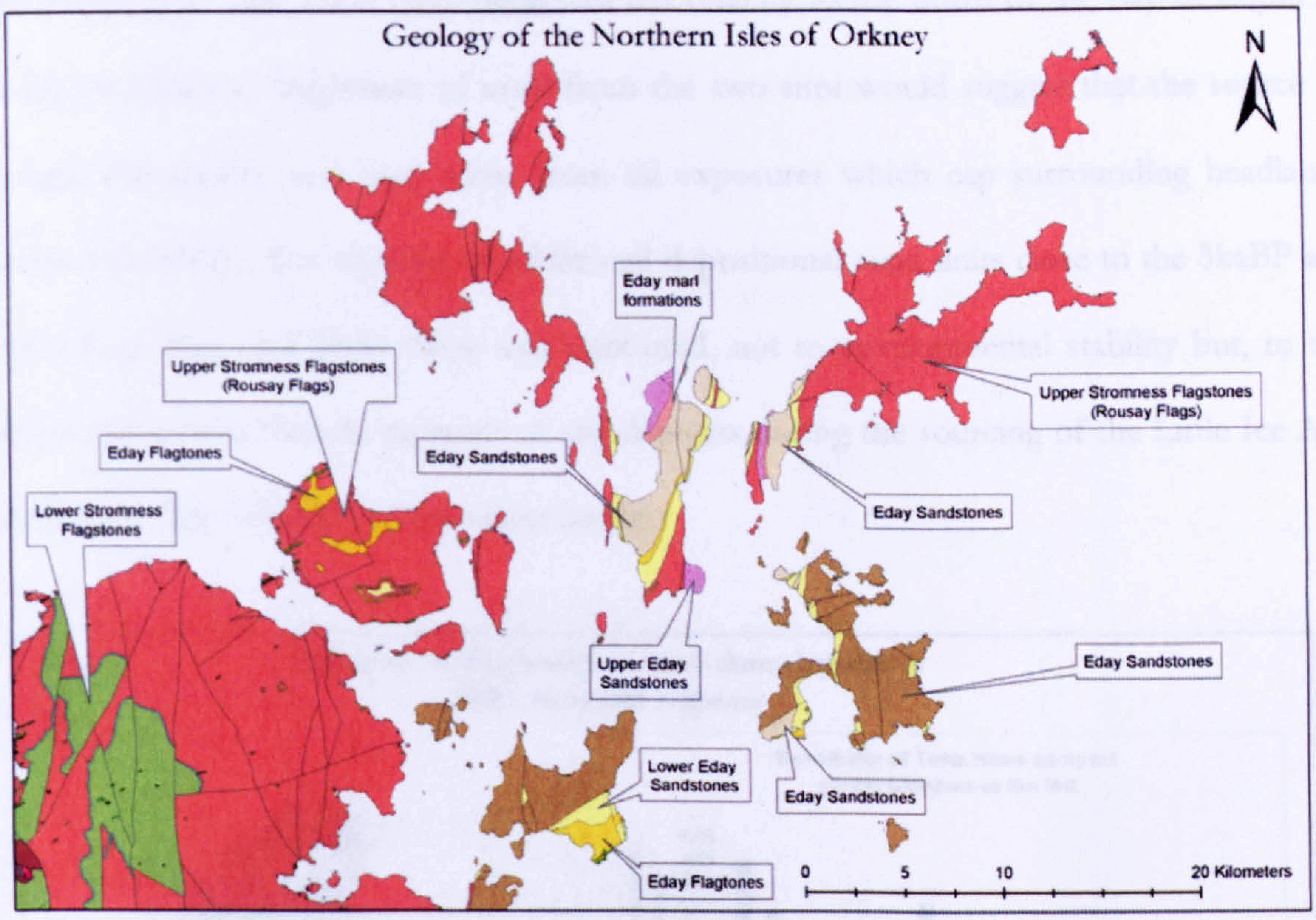


Figure 5.11 Map of basement geology for northern isles of Orkney,

Sand

Sommerville (2003) used Optically Stimulated Luminescence (OSL) dating to establish the age of sand deposits within archaeological sites in the Orkney Islands including Sanday. Her work established phases of increased wind blow in Sanday and other adjacent islands, which may have caused the abandonment of some prehistoric settlements. She also highlighted the utility of OSL to establish the provenance of sand via their 'brightness'. This reflects their source and so can be used to compare the possible sources of the sands. The brightness of a sample is a measure of the energy returned from quartz grains after being exposed to a standard amount of radiation administered in the laboratory (Sommerville 2003).

Two of the sites investigated by Sommerville (2003), Lop Ness and Tofts Ness, are discussed here to clarify the sourcing and sediment pathways of sand over at least the last 3.5kaBP. Both sites show at least two phases of sand deposition (Figure 5.12). Although the technique uses a few hundred grains of quartz, it is assumed that these are broadly representative of the depositional unit. The Tofts Ness peninsula lies directly to the north of the Bay of Lopness, and any similarity in brightness of sand from the two sites would suggest that the source of the sand was similar, and may come from till exposures which cap surrounding headlands (Sommerville 2003). The absence of additional depositional sand units close to the 3kaBP age at both Lop Ness and Tofts Ness was attributed, not to environmental stability but, to the likely recycling (and thereby erosion) of any deposits during the sourcing of the Little Ice Age deposition (1200-1800AD) of the upper sands.

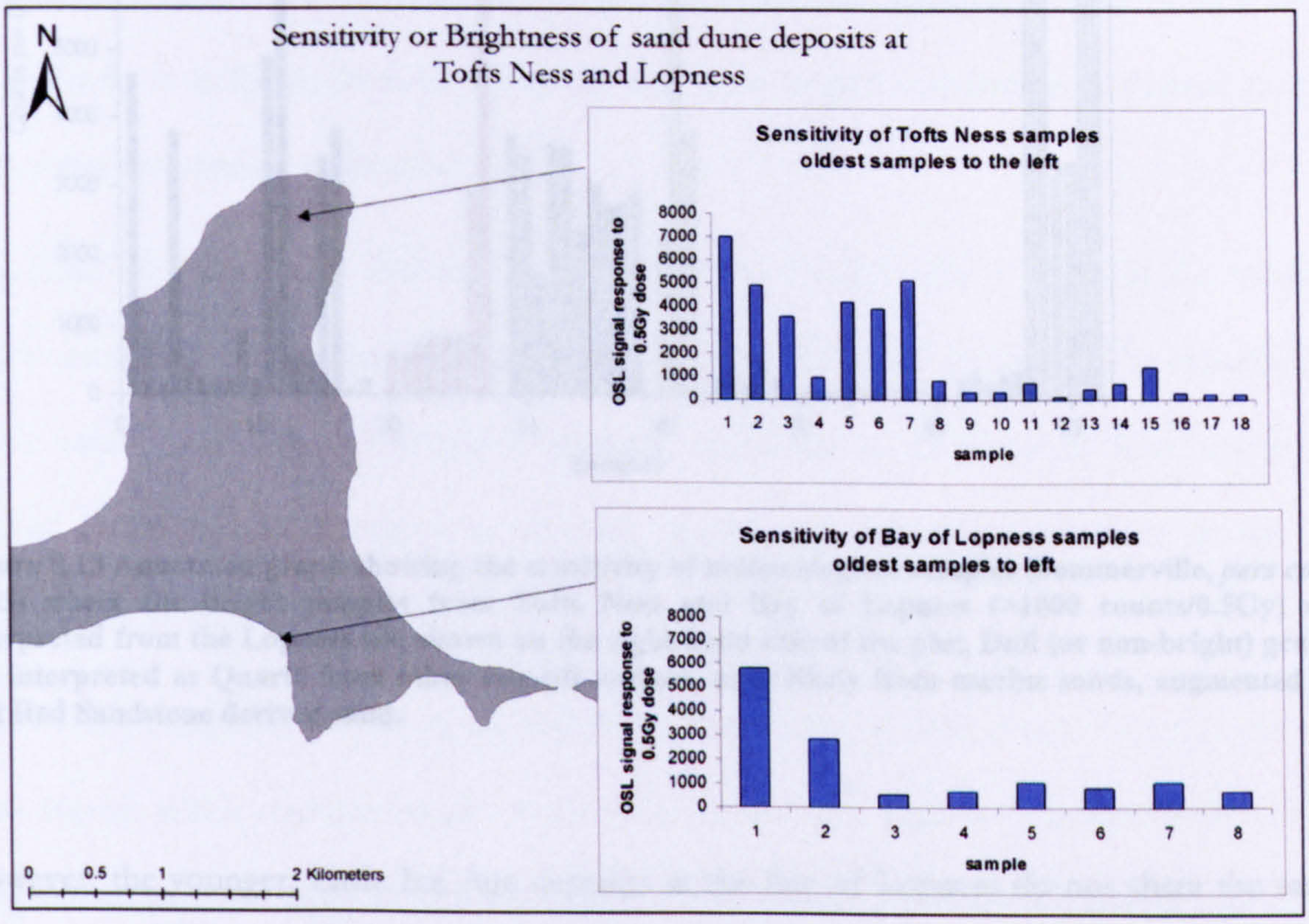


Figure 5.12 Periods of increased wind blow in the Northern Isles of Orkney, based on OSL dates from archaeological and geomorphological sites. Sommerville (2003).

Figure 5.13 Shows the sensitivity of archaeological samples at Tofts Ness, Lop Ness and Lopness Till under 0.5Gy of illumination. Analysis of the till outcrop, which underlies the burial cist at the northern limit of the Bay of Lopness, has established that it shares the sensitivity characteristics of some of the lower (~3kaBP) sand deposits at both Lop Ness and Tofts Ness (indicated by higher responses to the 0.5Gy, Figure 5.13). The variation of sensitivity within the sites highlights the adjusting source areas with older deposits reflecting till-sourced sand associated with the frontal erosion associated with changes in sea level conditions.

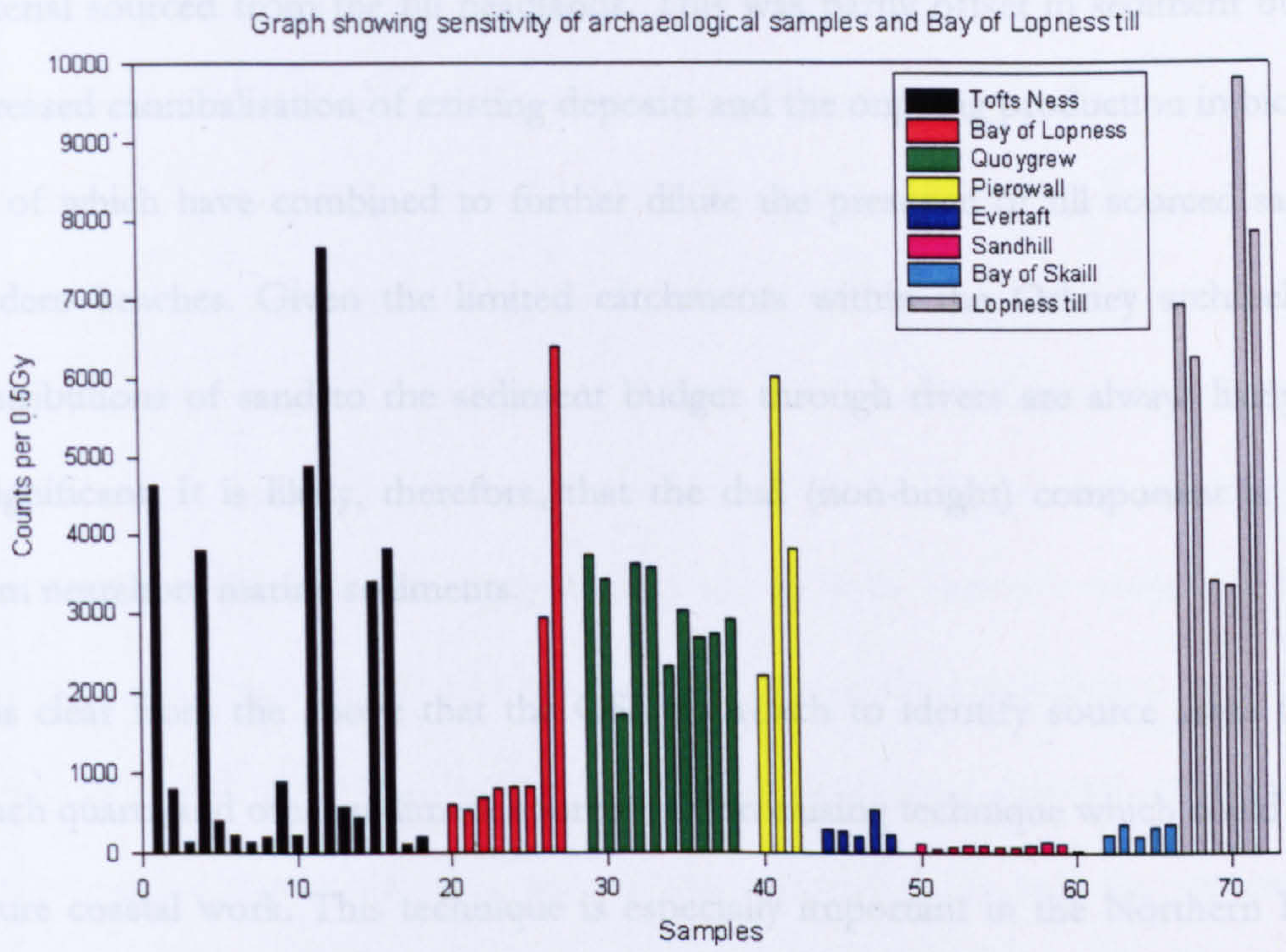


Figure 5.13 Annotated graph showing the sensitivity of archaeological samples (Sommerville, *pers com*, 2003) where the bright samples from Tofts Ness and Bay of Lopness (>1000 counts/0.5Gy) are interpreted from the Lopness till, shown on the right hand side of the plot. Dull (or non-bright) grains are interpreted as Quartz from other non-till sources, most likely from marine sands, augmented by Old Red Sandstone derived sand.

However, the younger, Little Ice Age deposits at the Bay of Lopness do not share the same brightness characteristics (i.e. less than 1000counts/Gy) and suggests that their source was unlikely to be directly from the till deposits and more likely from recycled sediment derived from deposits elsewhere. The change in source is likely to be associated with the dwindling supply of new till-sourced material into the coastal cell as sea levels rise more slowly, leading to an overall reduction in sediment supply (See Figure 4.24, Bathymetric Analysis). This trend extends to the modern beach sands which are relatively less sensitive than those early sands; reflecting sources other than the till capped headlands. This is again attributed to the slowing relative sea level rise, reworking of existing deposits and dilution of directly sourced 'bright' individual grains.

The reduction in rate of relative sea level rise caused a decrease in the production of new material sourced from the till headlands. This was partly offset in sediment budget terms by increased cannibalisation of existing deposits and the ongoing production in biogenic material. All of which have combined to further dilute the presence of till sourced sands within the modern beaches. Given the limited catchments within the Orkney archipelago, terrestrial contributions of sand to the sediment budget through rivers are always likely to have been insignificant. It is likely, therefore, that the dull (non-bright) component is derived mainly from nearshore marine sediments.

It is clear from the above that the OSL approach to identify source areas for the modern beach quartz and other sediment sources is a promising technique which could be expanded in future coastal work. This technique is especially important in the Northern Isles, where the current knowledge of glaciation is relatively incomplete and where questions remain on constraining sediment provenance.

These interpretations have led to the following developmental chronology at Lop Ness. The sand deposit which stratigraphically overlies the burial cist at Lop Ness postdates the cist by approximately 500yrs. The cist was constructed onto a till layer (~3.5kaBP) and then probably inundated by wind blown sands (~3kaBP). The site then was occupied, with a midden layer deposited during the Iron Age and inundated much later by blown sands during the Little Ice Age. Subsequent submergence and coastal erosion exposed this terrestrial archaeological site on the foreshore during a southerly storm in 2000. Such storms, with northward travelling waves, are likely to be the most damaging to a south facing section of coast (like that at the Lopness headland); crucially, however the associated winds are able to transport any available material northwards to inundate the land to the north, namely Tofts Ness. This process is likely to have happened in the past, linking the 'bright' till deposits in the source area on the southern section of the Lopness headland to the north via wind-blow, thereby delivering 'bright' deposits to Tofts Ness (i.e. a northerly movement of older sediments from Lopness to Tofts Ness, Figure 5.13).

Another important component of establishing sediment provenance concerns the production of biogenic sands. During the OSL sample preparation all non-quartz components of the sand sample were removed (Sommerville 2003). Comparisons of the samples from the modern beach with those of the archaeological deposits show that they are not significantly different in their biogenic / mineral components (Figure 5.14) and indicates that over the preceding ~3kaBP, there has been no significant change in the dominance of biogenic / mineral component of the sediment budget. This agrees with Farrow's work, which suggests that biogenic sand production is and has been actively producing sediment over the last ~4ka. It should be noted, however, that the variation of biogenic / mineral components of modern beaches and offshore deposits are complex (Figure 5.15) and the understanding of the variation is incomplete.

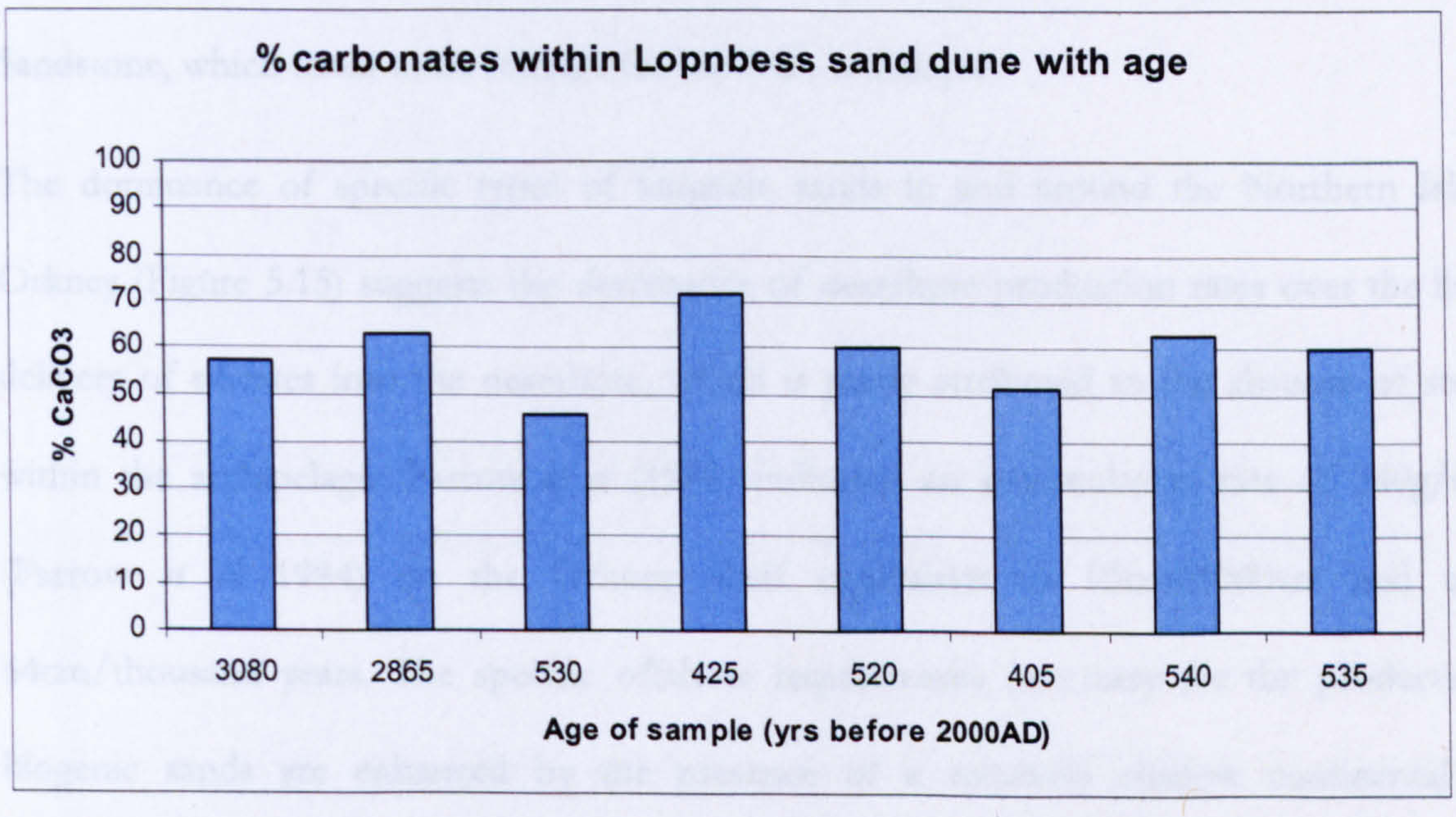


Figure 5.14 Comparison between the biogenic and mineral component of archaeological and modern beach samples. Sommerville (2001)

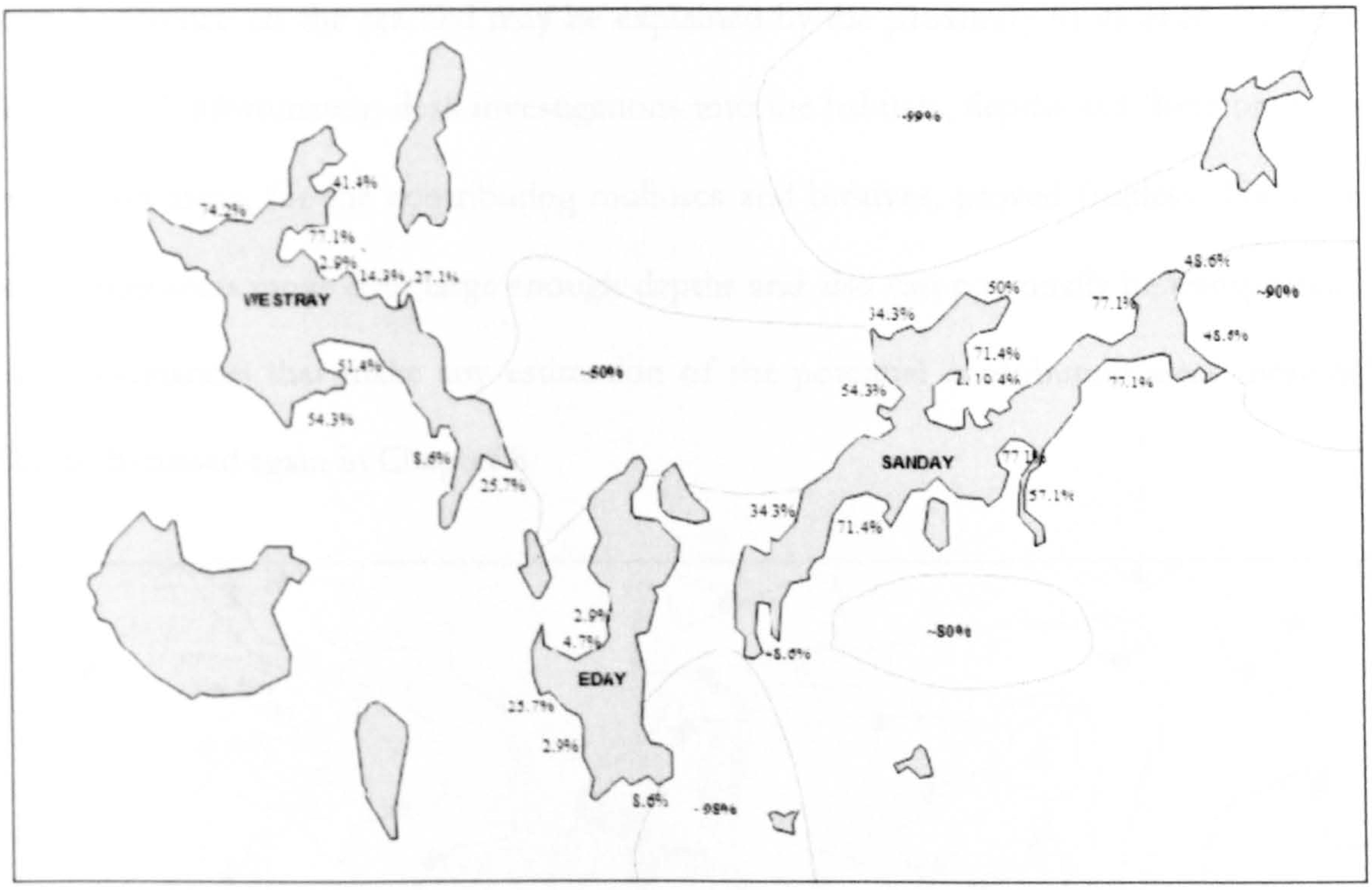


Figure 5.15 Comparison between the biogenic contribution of modern beach and offshore deposits Sommerville (2001) and Farrow (1977)

It is also fortunate that the Northern Isles are mainly composed of Old Red Sandstone (Figure 5.11) and the poorly developed Orkney till has a strong dominance from the Old Red Sandstone, which tends to be suitable for the OSL technique.

The dominance of specific types of biogenic sands in and around the Northern Isles of Orkney (Figure 5.15) suggests the dominance of nearshore production rates over the limited delivery of silicates into the nearshore, which is partly attributed to the absence of streams within the archipelago. Farrow *et al* (1984) indicated an accumulation rate of 540g/m^2/yr (Farrow *et al* 1984) on the Orkney shelf equivalent to 10cm/1000yrs and up to 64cm/thousand years. The specific offshore requirements necessary for the production of biogenic sands are enhanced by the presence of a relatively shallow continental shelf surrounding the Northern Isles of Orkney (Figure 5.16). Interestingly, samples from Westray's modern beaches were analysed and showed evidence of secondary boring, consistent with spending no more than a century on the sea bed after death (Braithwaite, *pers.coms* 2001). This limited presence on the sea bed may be explained by the proximity to its eventual terrestrial deposition. Unfortunately, desk investigations into the habitats, depths and therefore potential production areas, for the contributing molluscs and bivalves, proved fruitless. The potential production areas range over large enough depths and also can potentially be transported large enough distances that make any estimation of the potential contributing areas meaningless. This is discussed again in Chapter 8.

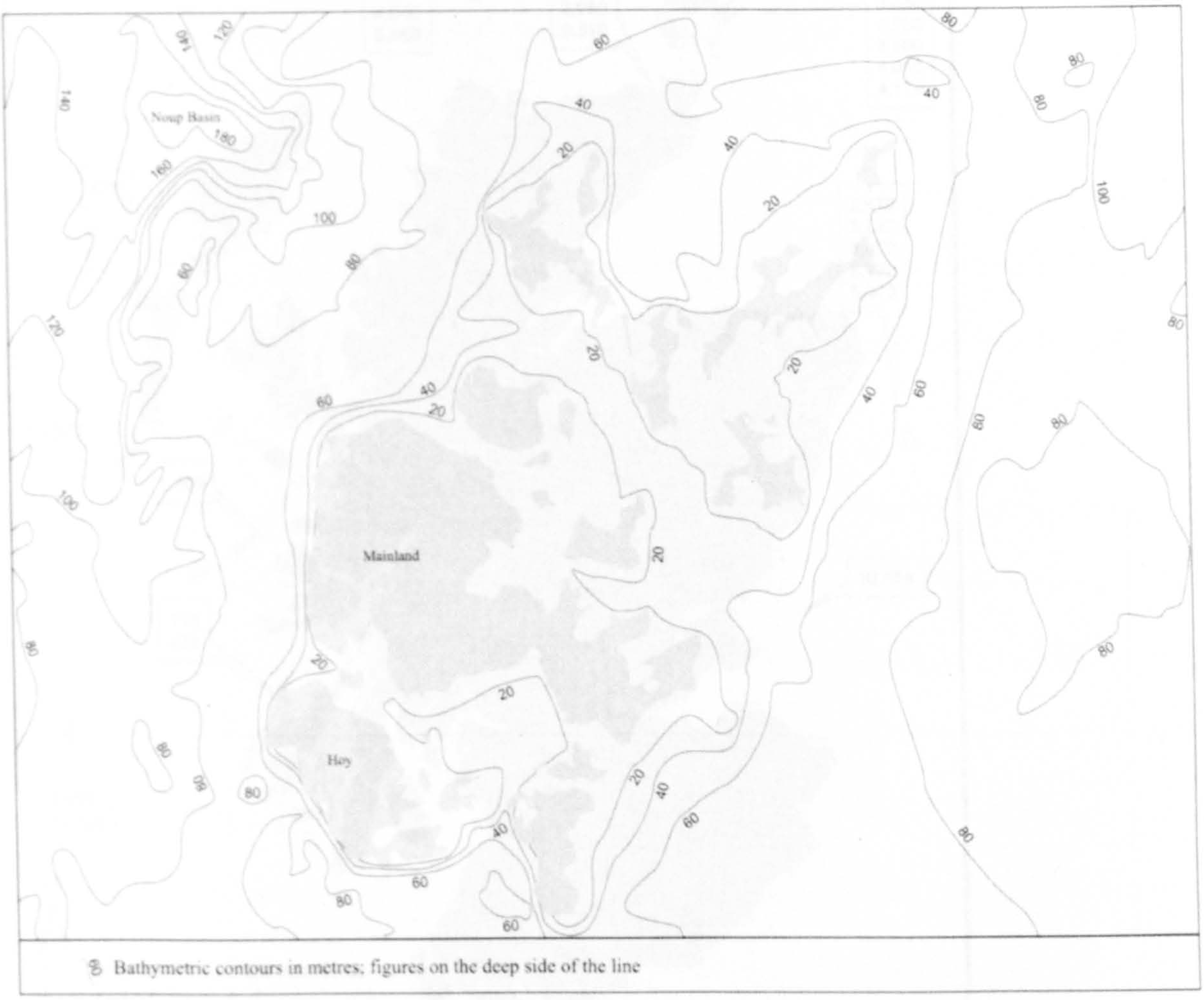


Figure 5.16 The shallow continental shelf surrounding many of the Northern Isles of Orkney (BGS 1987)

Stride *et al* (1999) compared 51 radiocarbon dates from surface carbonate sand deposits surrounding the continental shelf of northern Scotland (Figure 5.17). They concluded that:

- o the wide range in biogenic sands is accumulating faster than it can be destroyed via bioerosion, winnowing away of fines by currents and frequent disturbance by waves.

- The ages of biogenic sands are in keeping with conclusions that their location and grain sizes have been determined by late Holocene water movement.

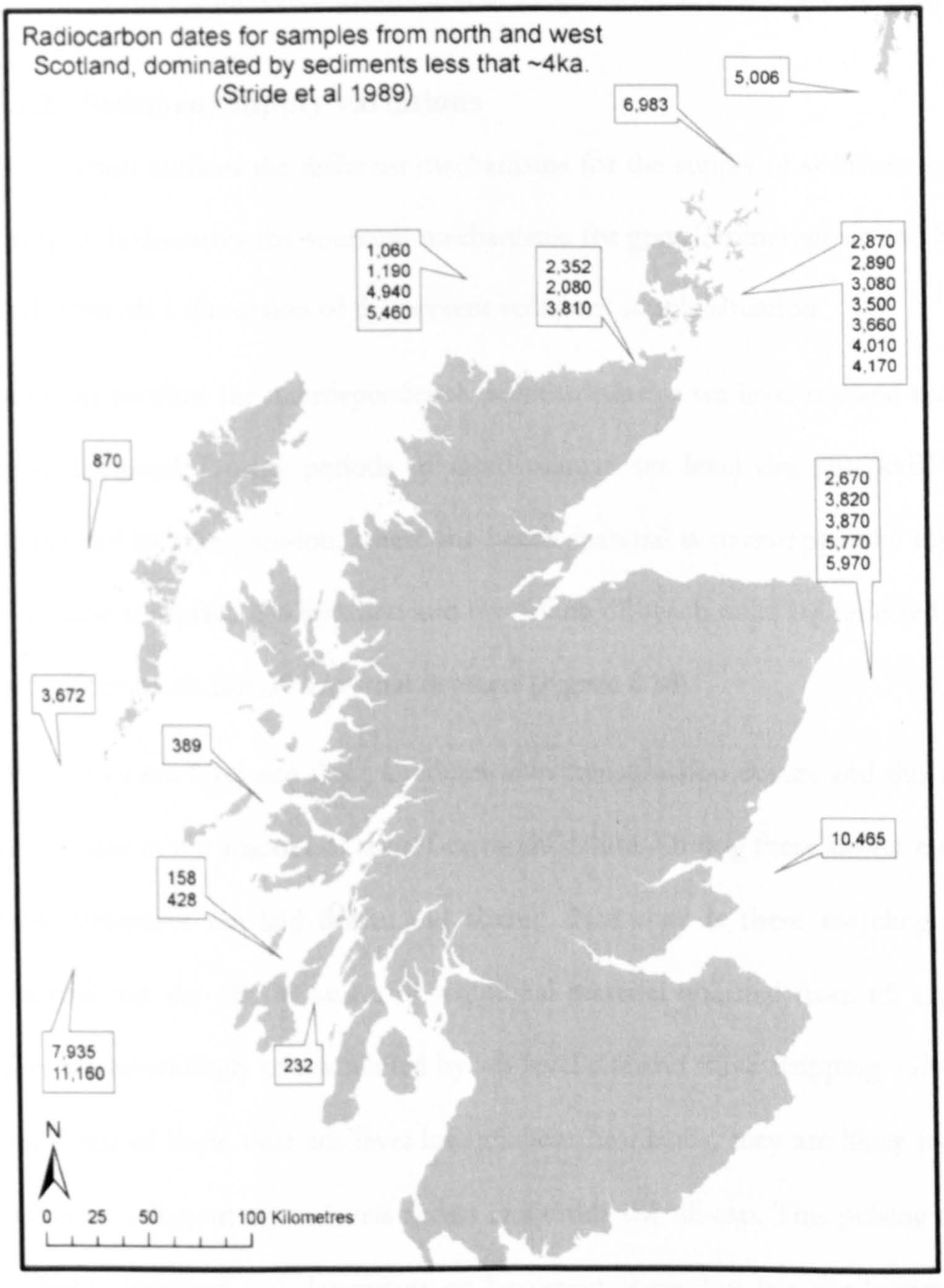


Figure 5.17 Radiocarbon dates for samples from the north & west coast of Scotland dominated by sediments less than ~4ka. (Stride *et al* 1999)

The literature suggests that the biogenic production is ongoing and influenced by the presence of shallow phototropic waters. If this is the case then since 6kaBP we should expect production to increase given the recent occupation of shallow waters. This on a backdrop of a constant reduction based on age, will be manifested as an increase in preserved deposits with ages less than 6kaBP. The subsequent slowing of sea level rise with its reduction in the contribution of till into the sediment budget may have been reflected in the improved conditions for the increased production of biogenic sands in the last 4ka (Figure 5.18).

5.2.2 Sediment supply variations

This section outlines the different mechanisms for the supply of sediment and how they have changed. It discusses the sourcing mechanisms for gravel, minerogenic and biogenic sand and leads towards a discussion of the present sediment supply situation.

In earlier sections the interdependence between relative sea level rise and sediment supply has been discussed. During periods of rapid relative sea level rise (10-7kaBP) shorelines have dominated by transgression, where the beach material is overstepped by the rising sea levels. Very little shoreface modification and reworking of beach units are reflected by a transgressive unconformity on top of terrestrial deposits (Figure 5.18).

As rates of sea level rise slow, a reduction in transgression occurs and this is concurrent with an increase in the amount of shoreface modification. During these slower rates of sea level rise large structures are laid down and altered. Not only is there recycling of existing beach material but also the inclusion of additional material quarried from till capped headlands as they are increasingly overwhelmed by sea level rise and wave stripping. Given the topography and form of these near sea level low-gradient headlands, they are likely to deliver a pulse or pulses of sediment as sea levels access and erode the till-cap. This pulsing of sediment supply is highly localised and dependant on basement form, but has similarities to the large river dominated sections of coast (River Spey for example), where pulses of sediment, derived from fluvial events, dominate the behaviour of the coastal sub-cell (Gemmell 1999).

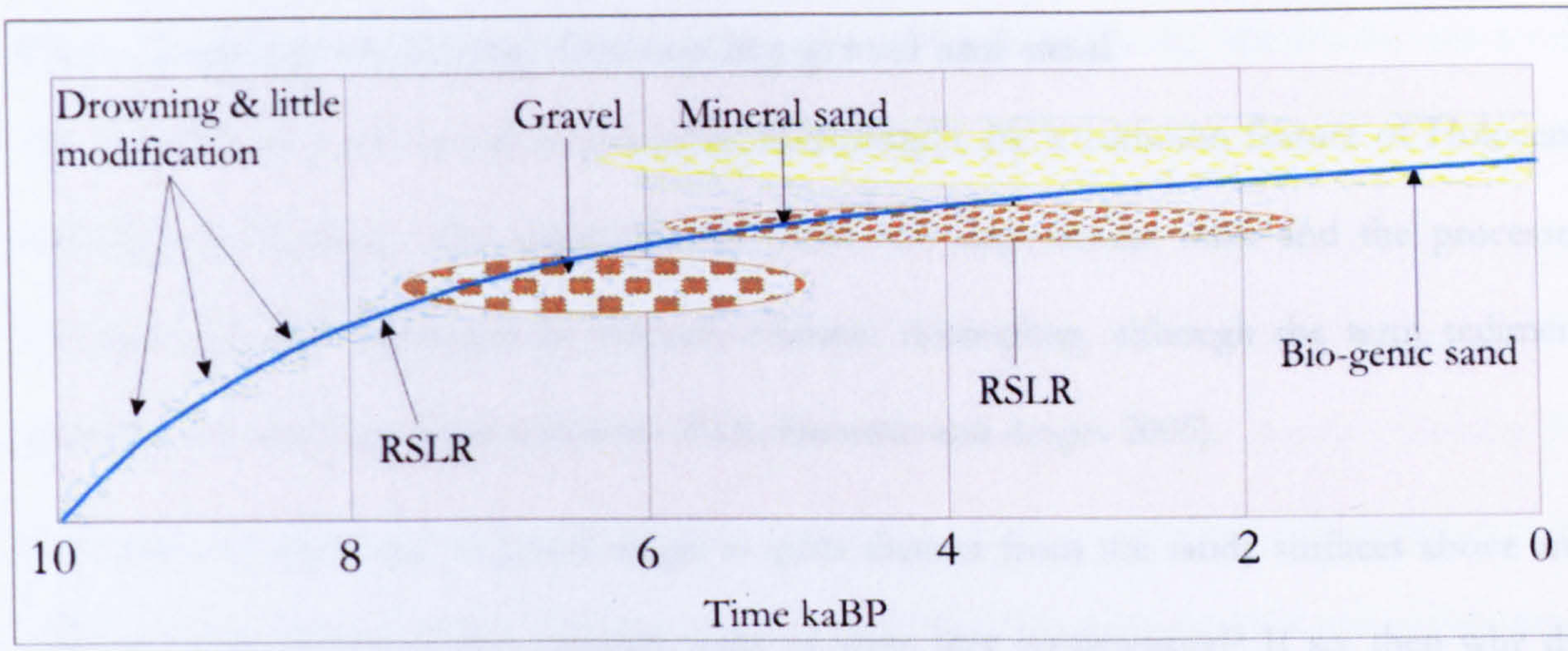


Figure 5.18 Sketch of phasing of sediment supply with relative sea level rise.

5.2.3 The role of geology, bathymetry and sea level: theoretical considerations from machair evolution

The following section develops theoretical arguments made by Hansom & Angus (2001 & 2005) regarding the changes to sediment supply driven by a reduction in sea level rise within Machair coastlines. As Holocene sea level rise slowed (6,500yrs BP) there was a reduction in sediment supply released into the coastal zone. However this concept is biased towards the role of sea level, however when topography is considered many varied scenarios can be generated. If a simple linear shoreline is considered the primacy of sea level is maintained, however if one considers a small archipelago or a multi-headland section of coast (each at different altitudes close to sea level) then the role of altitude, topography and sediment sources becomes increasingly important (Hansom & Angus, 2005). Thus the more varied the coastline's plan-form is, composed of near-sea-level headlands, will introduce a more complex sediment supply history and therefore a more complex set of assemblages to be formed. This increasingly complex set of circumstances exists on the Sanday coast as well as other large dune and machair coasts within the Western Isles, where on which most of the relevant literature was based.

5.2.4 Sediment switching: Decoupling gravel and sand

The presence of gravel-cored sand-capped assemblages are a common feature of Holocene shorelines in Scotland. The separation of these two depositional units and the processes necessary for their formation is termed sediment decoupling, although the term sediment switching has also been used (Hansom 2001, Hansom and Angus 2005).

In Sanday the basement of gravel ridges is quite distinct from the sandy surfaces above and adjacent. Why did they form separate units or were they co-deposited? If so, then why did they become separated at a later date?

Under any energy situation a mix of gravel and sand will result in gravels isolated at maximum altitudes and sand will temporarily sit at the foot of the gravels or on adjacent sections which reflect lower energy conditions. Gravels then remain untouched until the next high energy event and sands are removed. The cycle will repeat until gravels are no longer available to move onshore, or when overstepped by rising sea levels. If relative sea level falls then offshore sand will be accessed progressively in addition to the other nearshore sediments (i.e. gravel lag and fines). Gravels will also have been stripped from terrestrial deposits as sea levels rose, being placed at maximum altitudes by the largest event. As such many gravel ridge features can be considered relict.

The above switch from sand to gravel is operated by the energy levels and the availability of sediment mixtures. The implications of this switch, however, can be greatly affected by the nature of the underlying geology and the magnitude and sense of relative sea level change. If these changes occur in a shallow firth for example, with fluctuations in relative sea level, then the different phases of evolution can be separated. The Dornoch Firth is a classic example of this (Figure 5.19), where the inner firth is dominated by gravel landforms (Ardjachie Point, Ness of Portnaculter and Cuthill Links), which are associated with higher sea levels and wave energies (reflecting higher wave energy in the wider firth, prior to the development of the outer firth)(Hansom & Leaf 1990). Although sands were likely to be within the coastal cell, the highly energetic situation meant that the sands were not deposited. As relative sea levels continued to fall, sands dominated and the outer firth continued to develop, thereby closing the wave window within the inner firth. This stage was associated with the constriction of Morrich More and Dornoch Points, the change in relative wave energies resulted in the creation of Ardjachie Point, a smaller lower spit composed of smaller gravels reflecting the dominance of waves from the west. The varied sea level and shallow underlying geology allows these separate phases of development result in deposits being spread over a wide area.

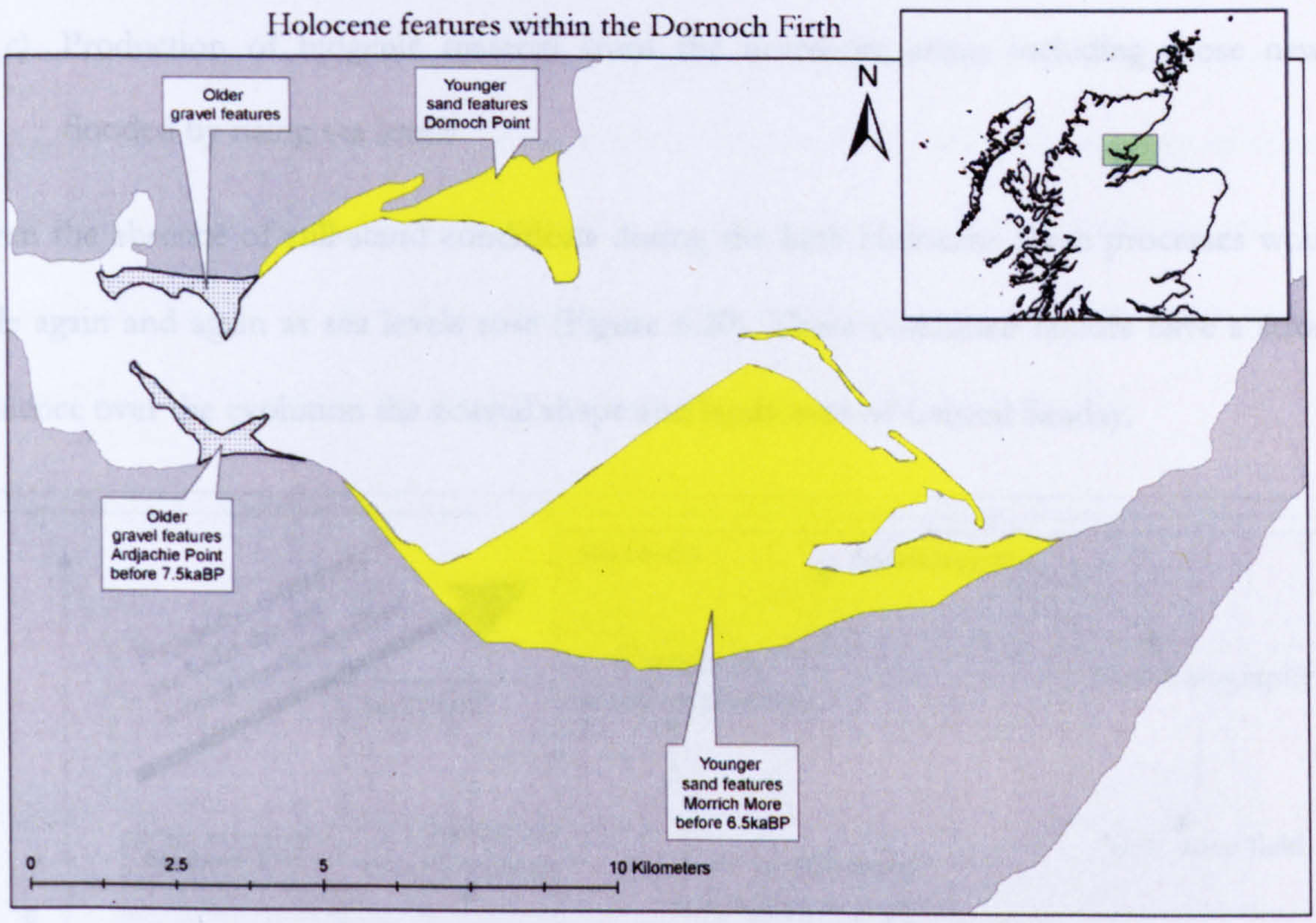


Figure 5.19 A sketch of the gravel features in the inner Dornoch Firth (before 7.5kaBP) and the sand features which formed more recently (before 6.5kaBP) at the mouth of the Firth.

Earlier sections (Section 2.3.2 & 5.2.3) have discussed the depositional phases and their controlling mechanisms. This section seeks to outline the influence of bathymetry on the emerging coastal outline and sediment supply and thus the subsequent evolution of Central Sanday.

1. As sea levels rise a new littoral zone is created as the hinterland is accessed by marine processes whilst the previous shoreline is submerged under increasingly deeper water.

2. New material is released within the coastal cell, and is derived from three key sources, which vary spatially and temporally:

   a) Former glacial deposits & weathered rock outcrops providing mineral contributions via sand and gravel;

   b) Re-organisation of existing material within the nearshore and onshore areas and

   c) Production of biogenic material from the nearshore areas; including those newly flooded by rising sea levels.

Given the absence of still-stand conditions during the Late Holocene these processes would cycle again and again as sea levels rose (Figure 5.20). These combined factors have a strong influence over the evolution the coastal shape and landforms of Central Sanday.

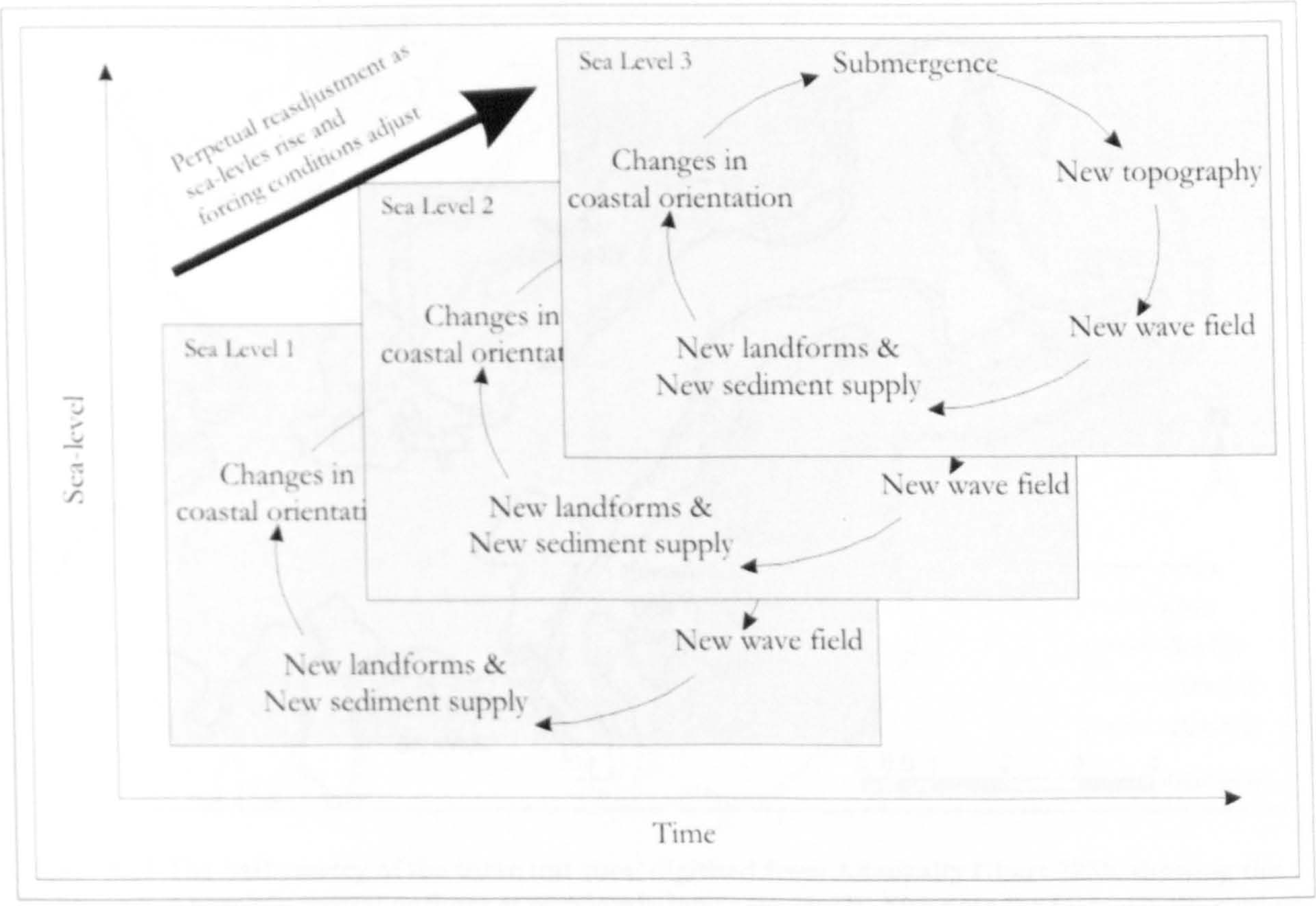


Figure 5.20 Flow diagram of changing role of bathymetry and sediment sources as rising sea levels accesses new sediments and underlying geological containers.

In Sanday, headlands have a dual role in the development of accretional features which flank them. In sedimentary terms, they not only provide material sourced through frontal erosion via sea level rise, but crucially when they are finally submerged erosion of the till-capped flat-topped morphology delivers a pulse of gravel and sand into the system. Once the cap is removed, the bedrock remains to absorb wave energy as a shoal or skerry. In addition, in terms of wave energy and orientation, headlands provide a crucial role in diffraction and reflection of the wave field, which interacts with the soft landforms and shaped the remainder of the bay. This changing role is highly site specific and is strongly related to antecedent conditions and basement form. Thus the configuration of the gently undulating basement geology of Sanday has a fundamental control on the creation of the earliest stages of coastal development, reflected in the juxtaposition of the earliest preserved gravel ridges. The presence of a former till-capped headland and present submerged island in the study areas is confirmed as Baa Gruna on the Admiralty Chart (Figure 2.11 and Figure 5.21).

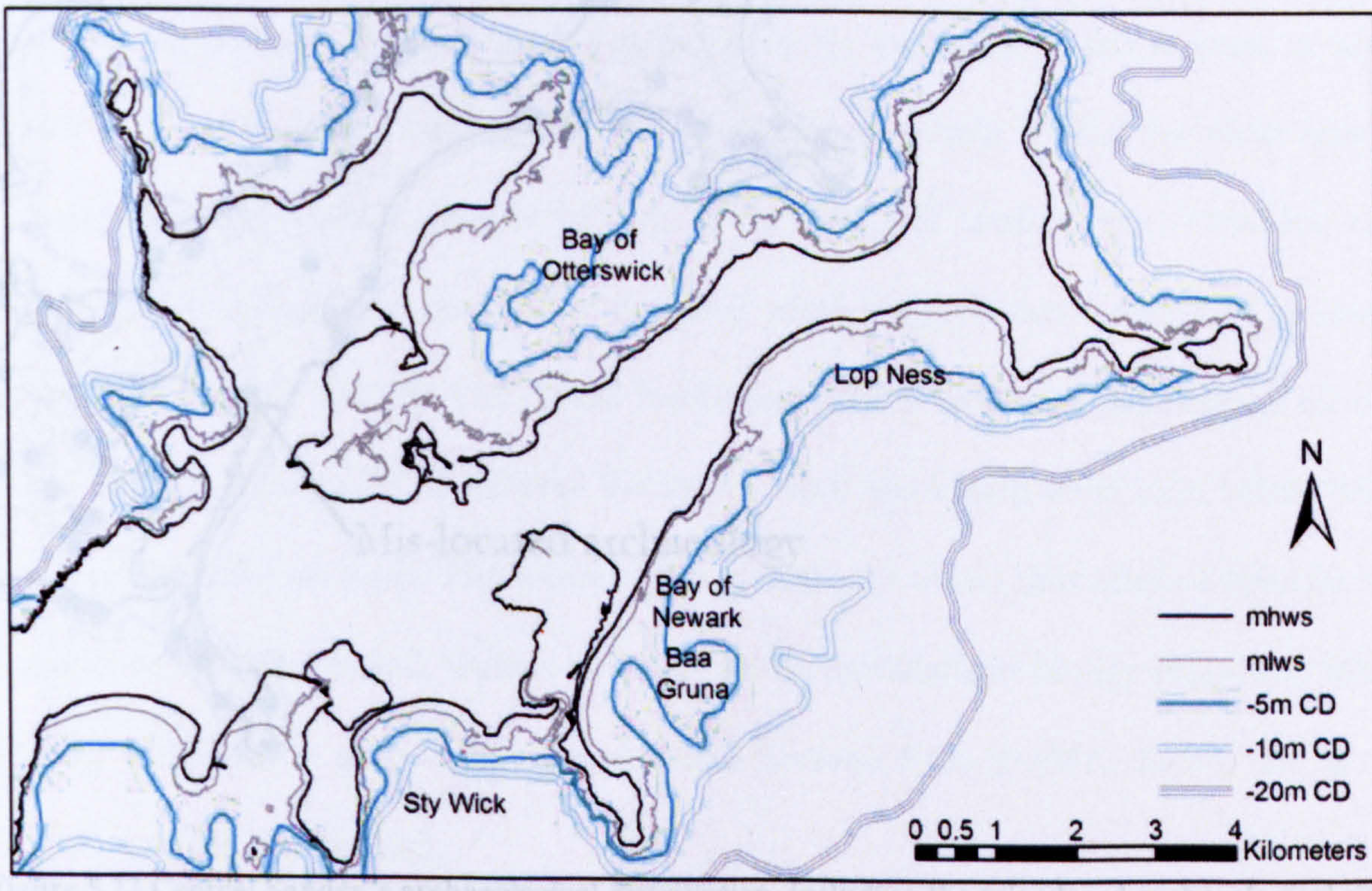


Figure 5.21 The bathymetry of the three test sites, digitised from Admiralty Chart 2250, showing the highly varied possible coastal outlines at previously lower sea levels. Also note the formerly till-capped headland and presently submerged island of Baa Gruna, within the Bay of Newark.

5.2.5 Distribution of archaeological sites

The pattern of archaeological remains indicate that particular areas (generally higher areas dominated by bedrock) were most commonly used by the islands prehistoric residents. Other areas where archaeological evidence was less common, appear to be those lower areas dominated by surfaces characterised by marine and aeolian deposits. This pattern suggests significant coastal changes in the island's last 6,000 years. Of particular interest is the central area of the east coast, presently composed of the Plain of Fidge and Cata Sand. Within the archaeological records of Lamb (1974) a stone built structure of unknown age allegedly built on a till base was given a grid reference in the centre of the Plain of Fidge. This position does not match Lambs (1974) description (Figure 5.22). After consulting Lamb, it became obvious that the archaeology was misplaced during its reporting and was not within the Plain of Fidge but on the Newark Headland to the north (*pers comm*) this has now been accepted by RHCAMS and the data base has been modified.

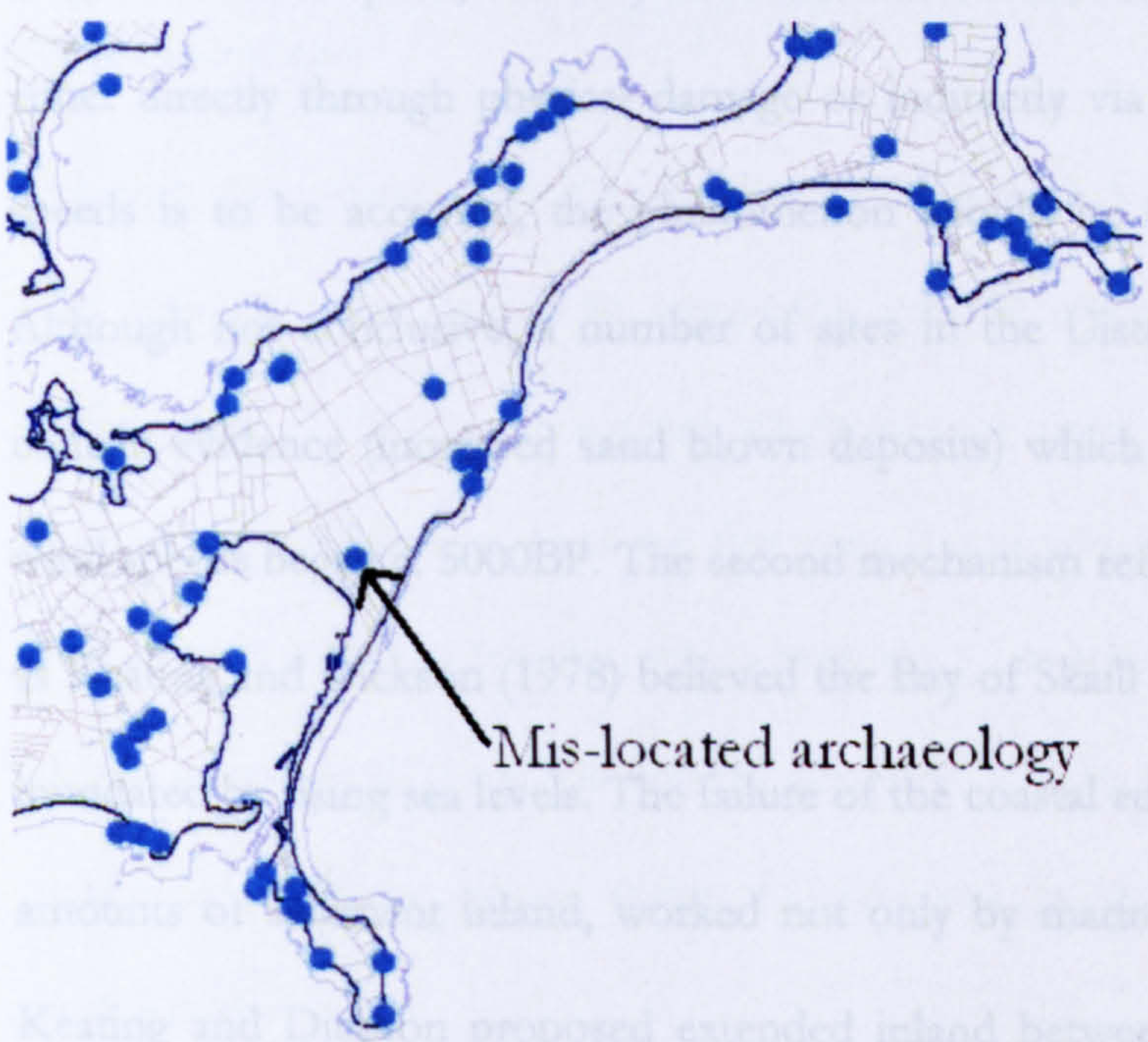


Figure 5.22 Central Sanday's archaeological distribution, including the mis-placed archaeological site within the Plain of Fidge (Lamb 1974).

This pattern of prehistoric human occupation centred on topographic high areas and avoiding those dominated by more recent (Holocene) landforms is striking and adds further support to the island's developmental narrative proposed here.

5.2.6 Demise of woodland

Two detailed historical accounts exist for submerged forests within the Orkney Isles; the first is at the Bay of Skaill, Mainland and the other at Otterswick, Sanday. This section of the discussion will outline the environmental changes which have been proposed to explain the demise of woodland on the Orkney Isles. Keating and Dickson (1978) investigated the changes in the vegetation during the mid-Holocene and associated these changes at the Bay of Skaill with wider geomorphological adjustments of the bay and broarder sand blow events.

The first of two mechanisms introduced to explain the decline of the trees near the Bay of Skaill, was deterioration in air temperatures between 5700 and 5000BP. If accompanied with increase in wind speed, this may have affected crucial stages of development of tree species, either directly through physical damage or indirectly via salt spray. If this increase in wind speeds is to be accepted, the phenomenon should be detectable within the wider region. Although not conclusive, a number of sites in the Uists and Harris (Outer Hebrides) also contain evidence (increased sand blown deposits) which suggests that a period of increased wind speeds began c. 5000BP. The second mechanism reflects local geomorphological factors, as Keating and Dickson (1978) believed the Bay of Skaill was a fresh water loch, before being inundated by rising sea levels. The failure of the coastal edge would have released considerable amounts of sediment inland, worked not only by marine but also aeolian processes, which Keating and Dickson proposed extended inland between 5700-5000BP, thereby dating the formation of the Bay of Skaill.

The transformation of an inland loch (or a topographic depression) into a marine inlet is expected and repeated in numerous locations in the submerging archipelagos towards the periphery of the Devensian Ice Sheet. There are similarities with the formation of Cata Sand (discussed in Section 5.5.2) and that of the Bay of Skaill, where the coastal edge was compromised, allowing marine processes to access terrestrial areas. However the combination of intertidal rock outcrops and the relatively sheltered nature of the breach point, in the case of Cata Sand and Little Sea, have led to the formation of intertidal sand flats, which can be compared to the open coast of the Mainland west coast and the resultant crenulate bay formed at Skaill. Once again the altitude of rock outcrops plays a significant control on other land-forming processes.

5.3 Historical changes to geomorphology

5.3.1 Historical maps and representations of Sanday's shape since AD1555

This section discusses the wealth of historical secondary datasets including early maps of the archipelago and written accounts of the island and its changing shape from the 16th Century.

Historical Maps

Although the earliest cartographic representations of the Orkney Isles date from the 1550s their value is quite limited in comparing specific changes to the islands form. However, Collin's map (1691) is the earliest which can be used and linked with other accounts, to illustrate coastal changes. It is the first map found which mentions 'Runnabreck', a formerly productive island (Figure 5.23), which now sits 5.5m below CD. The demise of these offshore islands is expected given the general sea level rise in the area, however the memory and persistence of these events within folklore acts as additional checks to any evolutionary expectations.

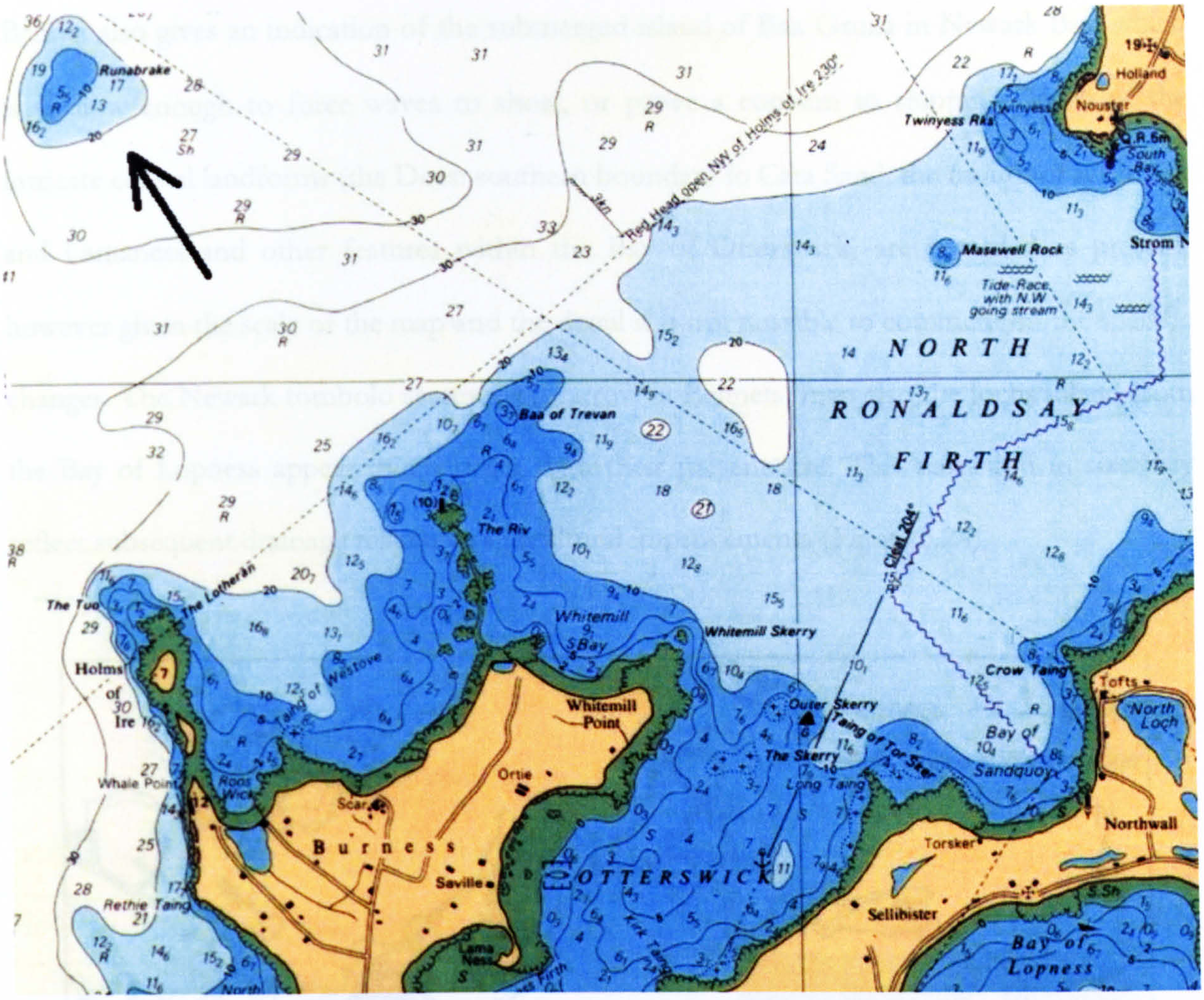


Figure 5.23 Admiralty chart of Orkney's Northern Isles, showing the offshore island of Runnabreck, north west of the skerry named the Riv.

By the 18th century cartography had improved significantly and this allows more useful comparisons to be made. Bennets' (1781) map includes the 'Holms of Ire' and the 'Rive' (the Riv) as northerly extensions to the Burness peninsula (east of Otterswick). The Riv is discussed below, however Walter Traill Dennison tells of…

"A lady who died in 1851 told me that when she was a child girl she heard an old man, Olie Scot, tell that his grandfather used to drive horses on to the Holms if Riv. The Holms were then accessible at ebb-tide, and during flood the horses were confined by water on the Holms." (Muir 1995, Page 176)

Another argument for their former size is the shoal called 'the Holms' indicating that at one point in time much of it was above MHWS. As 'Holm' is a Scots term for a small island.

Bennet also gives an indication of the submerged island of Baa Gruna in Newark Bay, which is shallow enough to force waves to shoal, or prove a concern to shipping. Much of the intricate coastal landforms (the Dees: southern boundary to Cata Sand, the mouth of Little Sea and Lamaness and other features within the Bay of Otterswick) are recorded as present, however given the scale of the map and the detail it is not possible to comment on the specific changes. The Newark tombolo seems very narrow in Bennets' map also the lochs inland from the Bay of Lopness appear much larger than their present size. This reduction in size may reflect subsequent drainage related to agricultural improvements (Figure 5.24).

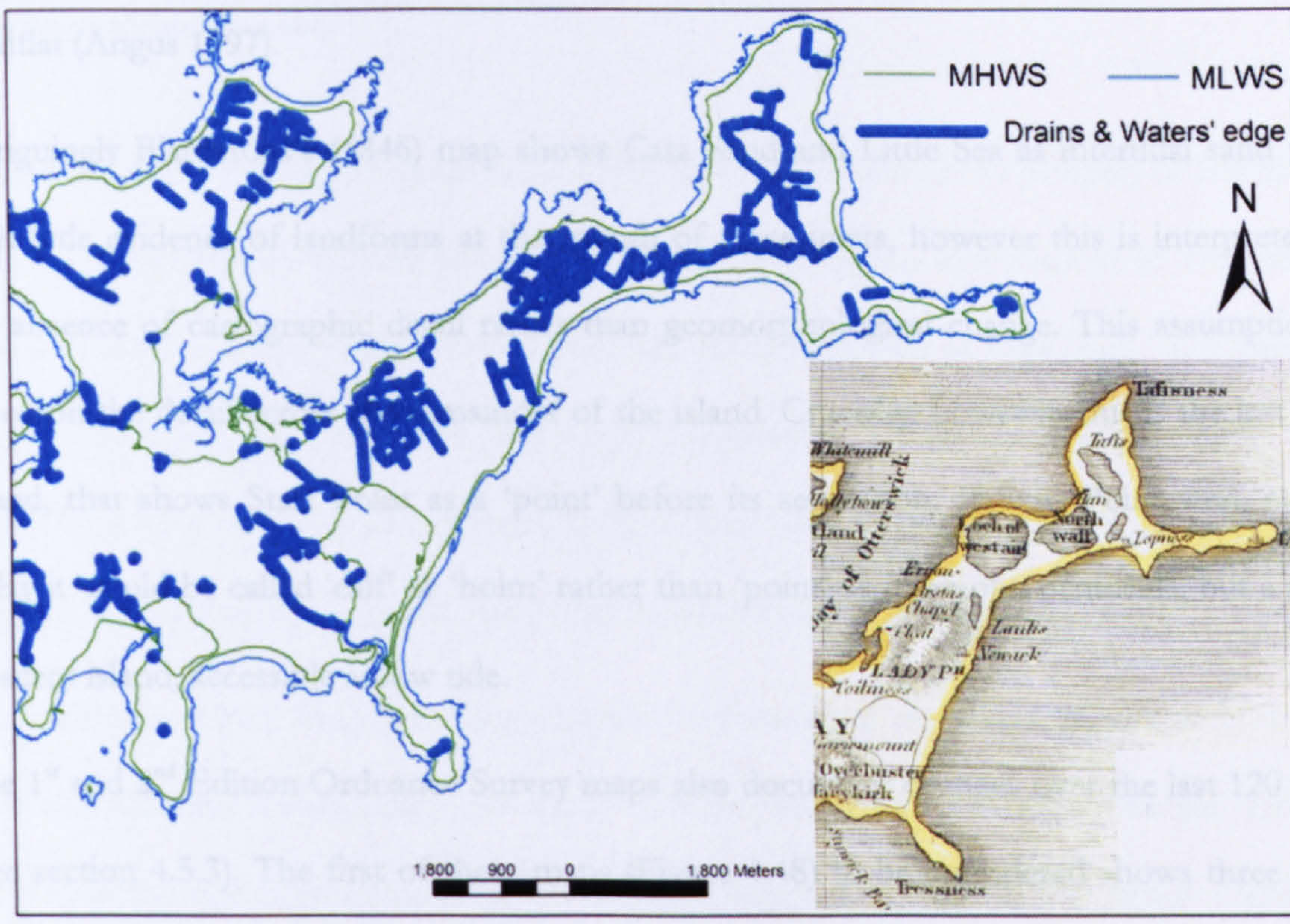


Figure 5.24 Comparison of the extent of former lochs (Thomson 1822) and the position of modern drains (based on OS data) Note, the width of the drains have been magnified for visual effect.

The Thompson (1822) map of Sanday is the first of two maps (the other being Groome 1896) which show notable changes to the saline and freshwater bodies on the island. Both Cata Sand and Little Sea are characterised not as intertidal sand flats, as they are today, but as a terrestrial depression and a freshwater loch, respectively. Given the detail of the map and the impression of accuracy for the remainder of the island, it raises the question of either significant geomorphic changes or a cartographic error. A Sanday resident (Jimmy Walls, *pers comm.* 2001) talked of areas of Cata Sand once being productive fields and owned by local farmers. This folk memory would support a former terrestrial Cata Sand or at least a much smaller intertidal area. It also raises the possibility that the low-lying fields, which would probably become flooded by 'winter lochs' (an elevated water table associated with winter conditions), being drained by resident farmers. Although there is no direct evidence of this, the same scenario occurred at Loch Paible, North Uists, when a farmer attempted to drain a winter loch, and the area was inundated with marine water and the former fields now make up an inter tidal sandflat (Angus 1997).

Intriguingly Blatchford's (1846) map shows Cata Sand and Little Sea as intertidal sand flats, with little evidence of landforms at the mouth of these inlets, however this is interpreted as the absence of cartographic detail rather than geomorphological change. This assumption is based on the detail across the remainder of the island. Crucially, however, this is the last map found, that shows Start Point as a 'point' before its separation. If Start Point were named today it would be called 'calf' or 'holm' rather than 'point' as it is not a peninsula, but a small adjacent island, accessible at low tide.

The 1st and 2nd Edition Ordnance Survey maps also document changes over the last 120 years (See section 4.5.3). The first of these maps (Figure 4.48) to be considered shows three fresh water lochans (small lakes) in the vicinity of the surface ridges within the southern Plain of Fidge. The largest is in the current position of the isotopic field mentioned in the GPR profiles, and overlies which overlays subsurface gravel ridges. An explanation for this change is that the lochan has infilled with wind-blown sand since 1882, up to the water table, resulting in the flat surface and slightly different plant species found in this area (Figure 5.25).

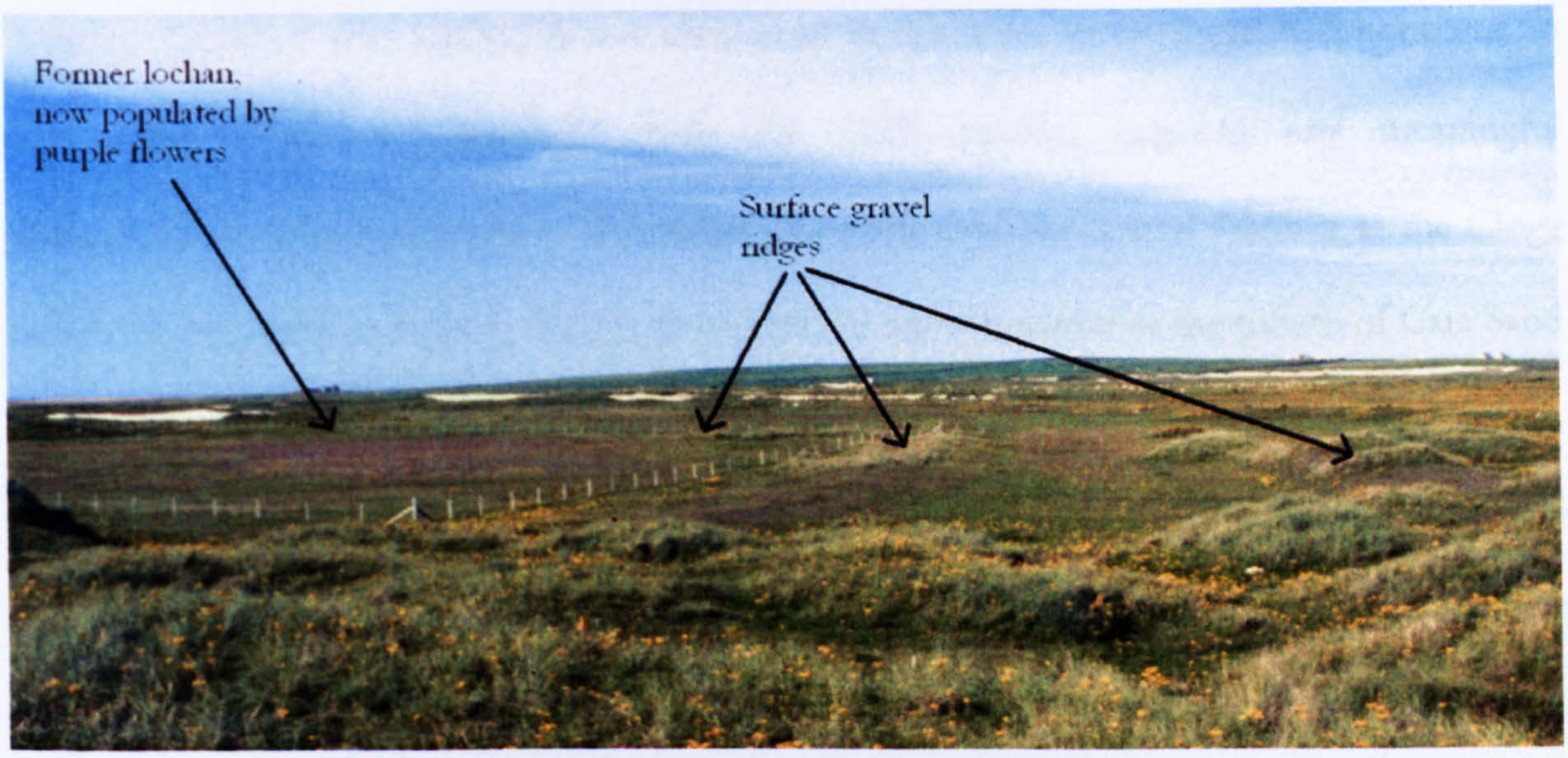


Figure 5.25 Southern Plain of Fidge, showing area of former lochan shown on the 1st Edition OS map, which is now a flat sandy field populated by purple flowers. The surface gravel ridges acted as the boundaries of these lochans.

In addition to the infilling of these lochans, Figure 4.44 also shows the position of HWMOST further inland from the present position of MHWS. This occurs in a number of locations on the open coast and also along much of the sand-based boundary of Cata Sand. Although this suggests accretion associated with vegetation colonisation, the picture may be more varied. Fence lines have been lost and replaced further inland due to frontal erosion (D. Drever, *pers comm.* 2001) particularly along the inner edge of the Newark Tombolo.

The landforms which fringe the Clogg (mouth of Cata Sand) and Ouse (mouth of Little Sea) have also changed significantly since the 1st Edition (1882) survey (Figure 4.51 and 4.52). In each case the drainage channel hasn't adjusted significantly but the adjacent supra-tidal features have. In the case of the southern boundary of Cata Sand the rock outcrop at East Sands (see Figure 4.46) has provided basement control in this area, irrespective of the more transient nature of the gravel and sand features present. The 1882 map has a much smaller sand feature extending eastwards from The Dees (the seaward extension of Conninghole, Figure 4.51). These sand deposits are superimposed on gravels which extend northwards past Ossamy (an Old Norse word indicating a river dammed by gravels) and align themselves with the Girthes which continue north and join up with the remaining gravel ridges underlying the

Newark tombolo. Although GPR was attempted in this area, an overhead telephone line to Tres Ness farmhouse interfered with the GPR profile, negating any meaningful interpretations. The realisation of the earlier orientation of the coastal features at the Clogg raises two important questions. Firstly, the historical representation of the mouth of Cata Sand may have reflected the rock outcrop – rather than the more recent Late Holocene deposits. Secondly, the Ossamy gravels may be the extension of the Girthes so that the former gravel shoreline was, prior to separation possibly during the inundation of Cata Sand, much further west than the present southern section of the Bay of Newark.

All of these mapped changes indicate that the last few hundred years have seen significant coastal adjustment, in the same sense as the earlier trends suggested by the pre-OS maps. All of these data sets illustrate the relative youth of some of these coastal features and their dynamism, in addition to the possibility of an artificial cut at the Clogg.

Map names and their significance

Although the earliest mapped form of the island dates from the 16th century a lot of the place names are from Old Norse. As such they represent a language and description of an island which may date back as far as the 9th – 13th Century (period of Norse/Viking presence in the parts of the Orkney Islands). As such these annotations and place names contribute to understanding the former shape of islands. Lamb's (1992) entomological summary of the place names of Sanday was insightful, some examples of particular relevance to this investigation are listed below:

Ayre Old Norse (O.N.) for *eyrr* → gravel ridge,
Balyer O.N. for ball or rounded; *garor* → O.N. for a wall → a rounded wall west of the Riv
Cata Sand *Keyta* → O.N. for foul water
Clay Brae A clay slope on the southern side of Start Point, indicating a till-capped headland
Clogg Old Scots (O.S.) for ravine. The clogg is the drainage channel for Cata Sand.
Conninghole → Conning is O.N. for rabbit, therefore a derogatory term for an area rabbit infested area.

Elsness first recorded as Helsness, *ness* → O.N. for a point of land, Hels → possibly Eldr → related to the large number of burnt mounds on the peninsula

Foskey Reef *Fosse* → Norwegian for foam, Foskey reef is the skerry south off Els Ness

Girthes O.N. *grjot* → stony or rocky ground, these are the south-westerly orientated gravel ridges within Cata Sand.

Kru O.N. *Kro* → pen or enclosure → presently part of the skerry at the Riv.

Lambs Cots east of Maiser, Conning hole, now on Cata Sand, may relate to an eroded house

Peat Banks name of a field, containing a shallow basin of peat alluvium 600m north of Newark Farm House.

Riv O.N. *Rif,* → a reef, obviously named as a skerry during times when Norse was spoken, however, previously it has had other uses.

Stromness Road old pathway to Tres Ness originally along the Cata Sand side of the Newark dunes, which now is exposed within the dune, as evidence of the Newark tombolo translating into Cata Sand.

Tres Ness is genitive of O.N. *tre* → tree, possibly indicates the submerged peats, or drift wood.

Historical written accounts

Marwick (1951) tells of how some Orcadians who were visiting Norway came across an old Sanday resident. Legend has it, she asked about:

"the woods o' Otterswick, the Ba Green of o' Rinnabreck, the rabbit links of Catasand and the Horse Buils o' Riv." (Marwick 1951, p235)

All of these features are presently underwater or intertidal. Interestingly, however, the Rabbit links of Cata Sand, have obviously experienced significant changes over the life time of this story. Rabbits inhabit sand dunes, but do not burrow near the water table especially if it is saline. In addition, rabbits were introduced to the Northern Isles some time before 1500AD as 'a rental book of the Earldom dated 1497-1503, formed part of the rental in kind paid to the Earl the links of Derness, Burra, North Sandwick, Pappa prope Westray, and Sanday, combining to supply 114 cunnings (rabbits) and 1274 cunning skinis (pelts)' (Ritchie 1920, p250).

The list of former-terrestrial now-intertidal features mentioned by the old Sanday resident has strikingly similarities to an undated local poem:

The Ba' Green o' Runnabreck,

The Horse Buils o' Riv,

If it wasna for the woods o' Otterswcik,

What wey wid we liv?

Modern day Orcadians would associate a 'Ba Green' as a pitch for 'The Ba': a local game between two teams, totalling a few hundred players, which is traditionally held during Christmas and New Year festivities. Although this interpretation of a local 'football pitch' (i.e. a substantial area of grassland) succumbing to coastal erosion fits an interpretation of coastal submergence, and was also mentioned in the Statistical Accounts of Orkney (1845), an alternative interpretation is also possible. 'Green' may be an altered form of the Old Norse word for a Shoal or a Grunyie (i.e. Baa Gruna, a submerged island within the Bay of Newark). 'Ba' is also an old Orkney word for a breaking wave. So the first line of the poem may suggest a lost area of grassland or a shoal which is now an offshore island some 5m below LAT, and some 5km north of Sanday (Figure 5.23).

The 'Horse Buils' are horse pens or overnight quarters, and were located on the Riv, which is now a skerry (a line of rock outcrops near high water mark) extending northwards from the Burness peninsula (Figure 5.23). The final reference in the poem is to the woods of Otterswick, which if were alive when the old Sanday resident had seen them, dates her along with the woods to between five and six thousand years old. An alternative interpretation is that the poem refers to tree-stumps, rather than living forests. Given either analysis, the poem should be read as an account of the folk-memories of the residents of the time. The changing shape of their island associated with submergence has been witnessed by a generation of Sanday residents and has been reflected in their experiences and folk-memory.

The Statistical Accounts (1845) the coastal changes were summarised, so: 'In many places the sea gains upon the land; and, in a few places, the land gains on the sea, by throwing up banks of stones and sand, which serves as ramparts or dykes against its future attacks.'

Traill (1868) quoted a letter in his paper to the Botanical Society of Edinburgh on Submarine Forests:

"In the winter of 1838 there was a long-continued gale of north east wind, which entirely cleared away the shell sand from about 50 acres of the flat surface usually left dry at low water. Going down one day at low tide, I was astonished to see, instead of the white sand, what appeared a wide stretch of black moss covered with fallen trees, lying with their roots sticking up, exactly as I saw trees afterwards in Canada laid prostrate by a hurricane......All were lying in the same direction, from SW to NE. On taking to a boat, I found the same moss surface, mostly denuded with sand, showing itself under the deep clear water, with trees lying across its surface, quite across the bay to Tuftsness, four miles off, where are rapture of the peat had taken place – as all over that ness, under 9 or 10 feet of blowing shifting sand, the same peat moss and tree remains are to be found as under the waters of the bay, although raised above high-water mark some 10-12 feet. In digging in the moss at Otterswick I did not find any deer's horns or other animals remains; but I am told that at Skaill Bay several deer's horns were found, and are still in the possession of Mr Watt of Skaill."

This explicit account of the buried forest of Otterswick is of great interest and highlights not only some of the first accounts of relative sea level change investigations but also raises the possibility of a wide expanse of peat deposit which could be sampled to extract more sea level index points.

All of these written accounts support the historical map evidence and geomorphology demonstrate substantial areas of the island have been lost to submergence. This submergence has been witnessed by a generation of Sanday residents and these expressions have been captured in the folk-memory of rhyme and poem.

5.4 Recent morphological changes (2001-2003)

This section will discuss the recent changes to the three beaches, starting with Lopness, then Newark before discussing the changes at Sty Wick and will bring this review of all of the available data up to date. Previous sections discussed changes during the Late Holocene, through archaeological times and those recorded by historical sources. Although the results were derived from the topographic surveys, they are here augmented by geomorphological evidence within the three beaches.

5.4.1 Recent changes to Lopness beach and dunes

The period from spring 2002 to summer 2003 has seen relatively modest changes to Lopness beach. The subtle changes summarised in Figure 5.26 can be grouped into three categories, which will be discussed in order from west to east. The first kilometre (1st 10 transects) of the bay has been generally stable with subtle foreshore gains. This may be associated with the presence of the rocky foreshore extending from Newark Farm. The central section of the beach overlying the rocky foreshore has seen losses below and gains above MHWS, which is interpreted as roll over. Given the sandy substrate in this area and the vegetation (dominated by marram) some of the eroded sediment has been caught at the top of the dunes (particularly between transects 17-23 and 27-30). The third section of beach including the majority of the eastern bay (transects 32-41) is dominated by cliff losses. This has been attributed to two processes, slumping and subsequent wind-blow. However in this area the fields used for cattle grazing come to the edge of the dune cliff, in many cases without a buffer of marram grasses and therefore any sand that is transported landwards (i.e. north) is unlikely to be retained at the coastal edge but distributed across the machair surface.

Between spring 2002 and summer 2003 Lopness beach can be described as being slightly erosional, with sediment being reorganised landwards and dependant on the hinterland land-use being kept at the coastal edge. The most westerly end of the beach has bucked this trend remaining relatively stable throughout the survey period.

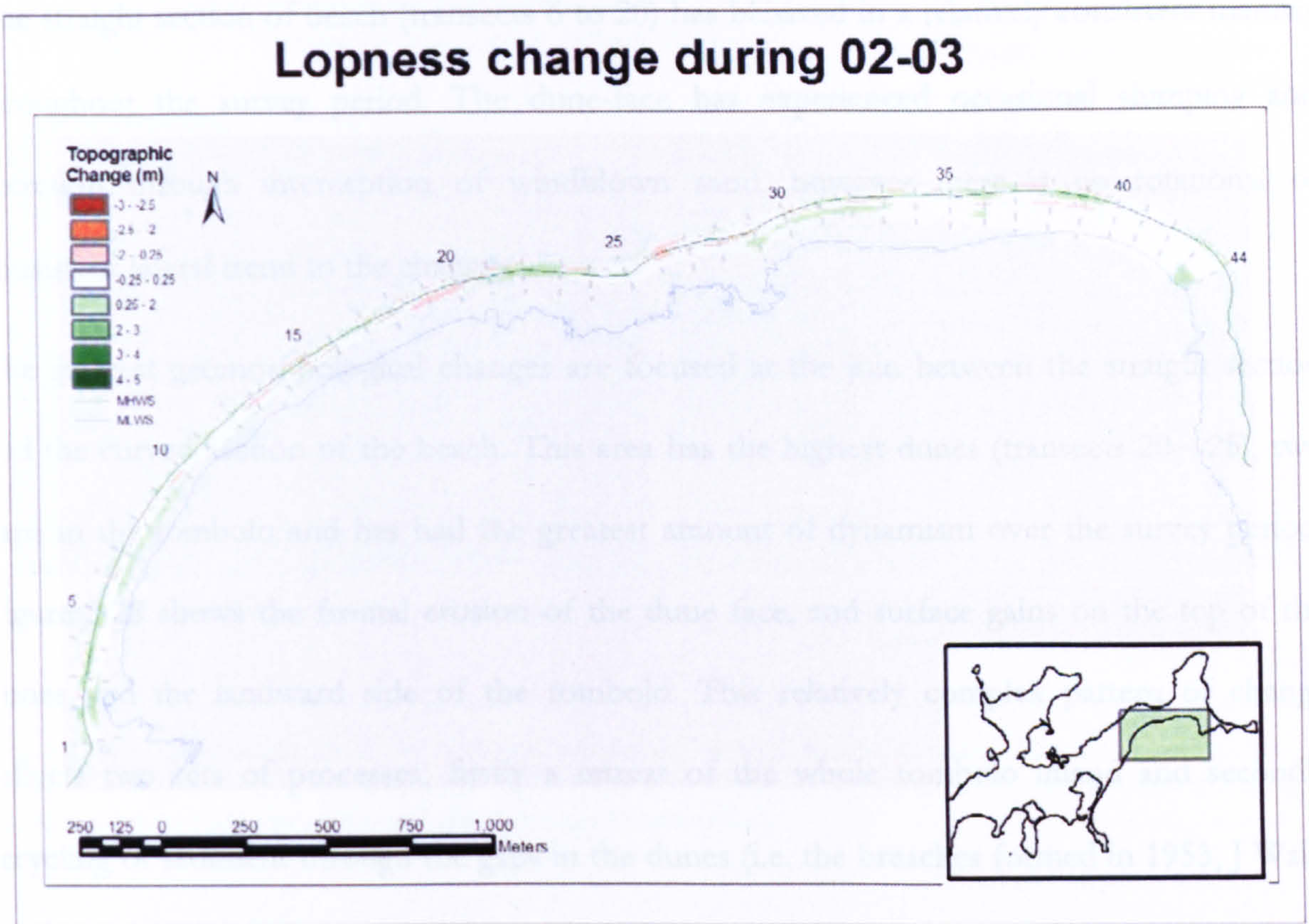


Figure 5.26 Summary plot of geomorphic changes to Lopness between spring 2002 & summer 2003

5.4.2 Recent changes to Newark beach and dunes

The overall behaviour of the Newark beach and dune between summer 2001 to summer 2003 will be summarised in four sections below (original figures are in section 4.6.1). The northern and southern sections of the beach have experienced subtle changes, the straight section of beach (transects 5-20) behaved consistently and finally the curved section of the bay (transects 20-25) experienced the most changes.

If the recent behaviour of the northern and southernmost sections of the beach are considered, shoreface losses in the north and subtle accretion in the south seem uncharacteristic when compared with the wider geomorphology of these areas. However the losses in the northerly section of Newark are mostly associated with beach face lowering and frontal erosion of the young ramp of dunes in the northernmost 200m of the beach. This apparent contradiction is clarified in Figure 5.27. Meanwhile the general stability and occasional accretion at the south of the bay reflect subtle gains on the dune cliff.

The straight section of beach (transects 6 to 20) has behaved in a relatively consistent manner throughout the survey period. The dune-face has experienced occasional slumping and accretion through interception of windblown sand, however there is no rotational or consistent lateral trend to the changes.

The greatest geomorphological changes are focused at the join between the straight section and the curved section of the beach. This area has the highest dunes (transects 20 - 25), two gaps in the tombolo and has had the greatest amount of dynamism over the survey period. Figure 5.28 shows the frontal erosion of the dune face, and surface gains on the top of the dunes and the landward side of the tombolo. This relatively complex pattern of change reflects two sets of processes, firstly a retreat of the whole tombolo inland and secondly recycling of sediment through the gaps in the dunes (i.e. the breaches formed in 1953, J Walls *pers comm.* 2001).

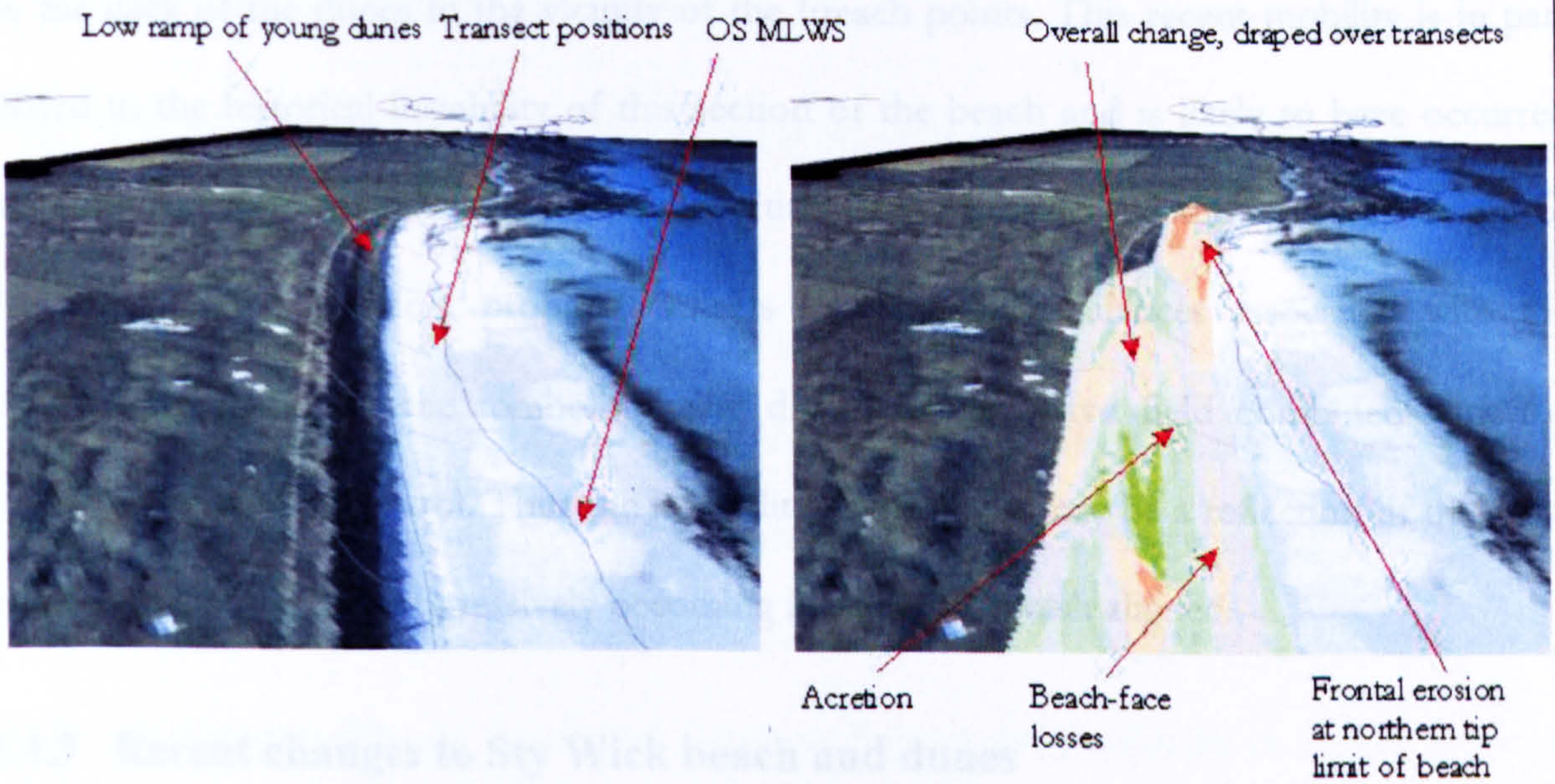


Figure 5.27 Oblique images of the northernmost section of Newark beach, showing an aerial photograph (2004, © SNH) and the overall change surface (Summer 2001 to Summer 2003) with surface lowering in reds, surface gains in green and little change in unshaded.

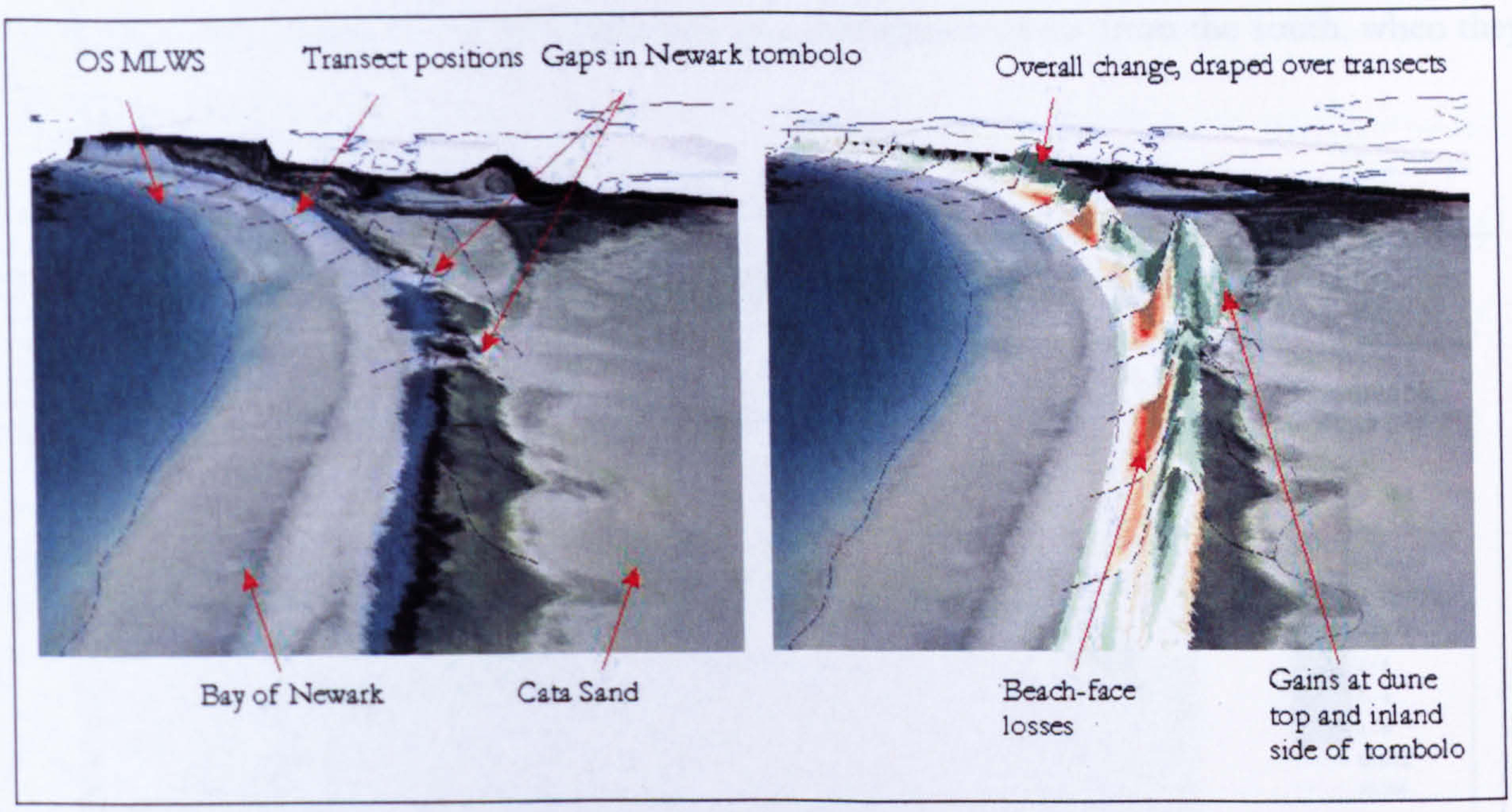


Figure 5.28 Oblique images of the southern section of Newark beach, showing an aerial photograph (2004, © SNH) and the overall change surface (Summer 2001 to Summer 2003) with surface lowering in reds, surface gains in green and little change in unshaded.

These changes are characterised by beach face losses, large changes on the dune cliff top and on the back of the dunes in the vicinity of the breach points. This recent mobility is in part related to the historical instability of this section of the beach and is likely to have occurred since the breaches in 1953. However the location of the breach, and the increased height of the dunes at this location, probably reflects longer-term imbalances associated with the transgressive nature of the tombolo, being driven by the wave field combined with the absence of basement control. Thus the instability at this point may be a reflection of the gross morphology of the bay progressively becoming increasingly swash aligned.

5.4.3 Recent changes to Sty Wick beach and dunes

The beach and dunes at Sty Wick have experienced modest changes over the survey period (Figure 5.29). The Bay has lateral stability with only seasonal variations in the intertidal and occasional fluctuations around MHWS. This stable situation has been attributed to this bay-head beach being broadly in balance with its forcing processes, which have been favourable over the survey period and notably without a storm from the south. In addition, the beach is well sheltered by the long peninsulas at each end of the bay. These not only serve to protect the beach from all but southerly storms but also will refract waves from the south, when they do occur.

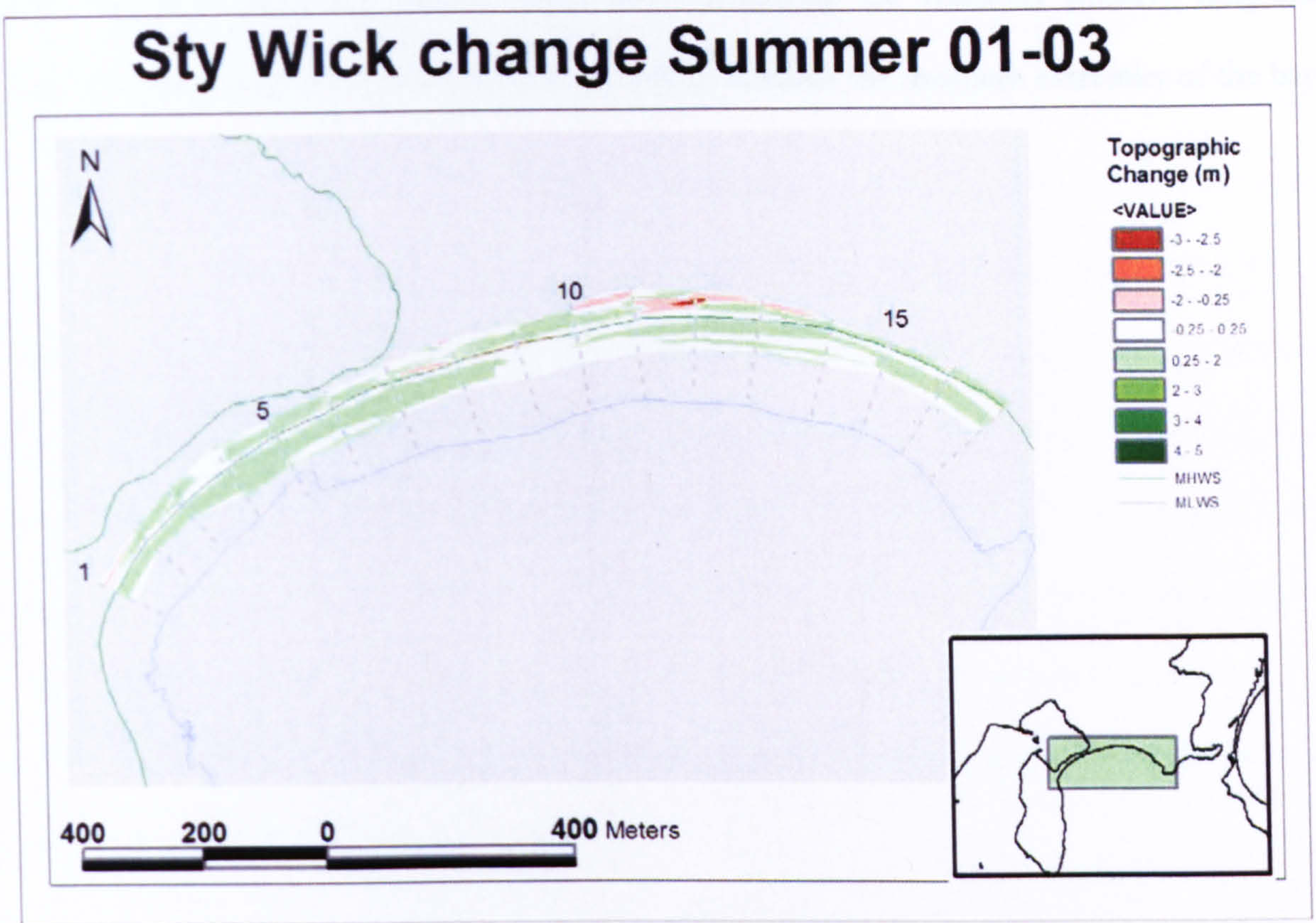


Figure 5.29 . Summary plot of geomorphic changes to Sty Wick between summer 2001 & summer 2003

5.4.4 Summary of changes to all three beaches

Both the beaches of Lopness and Stywick have experienced modest changes throughout the survey period. These beaches are in broad balance with their forcing mechanisms (i.e. wave field and sea level) however they have experienced landward transgression over the survey period. Contrasting this, the beach and dunes at Newark have adjusted in a more complex manner, which can be separated into three geomorphic units. The southern extremity of beach (i.e. the curved section) has changed little, most likely due to the presence of the rock headland of Tres Ness dominating wave refraction. However the join between the curved and straight section of the dunes has adjusted the most. This has been interpreted as the transition zone between the swash aligned southernmost section with the drift aligned section of the northern half of the bay. The presence of the highest dunes, most dynamic landforms and historical breaching in 1953 identify this as the dynamic area of the beach and dune system. The remaining straight section to the north of the gaps in the dunes has not experienced large scale changes over survey period, most likely reflecting the relatively positive longshore sediment supply, which has fed a modest accretion towards the northern extremity of the bay.

5.5 *Coastal Evolutionary Model (CEM): 10kaBP-0BP*

5.5.1 Development of the CEM

Integrating the subsurface GPR investigations with past and present geomorphology, bathymetry and sea level history together with map, chart and documentary evidence allows a model of the coastal evolution of Central Sanday to be produced. The time-steps of the model are approximate but provide insights into coastal change at different time periods. The presence of rocky headlands (basement control) is the basis of the model – the template on which the different landforms are constructed, recycled and re-constructed. The CEM below is conducted in two sections. Part 1, (shown in Steps 4-8, Section 5.5.2) relies on preserved evidence of beach ridges together with bathymetry and the sea level curve (Shennan *et al* 2002). Part 2 (shown in Steps 1-3, Section 5.5.3) relies solely on reconstruction based on bathymetry and the sea level curve (Shennan *et al* 2002) and the coastal landforms that have been recycled in their entirety.

5.5.2 The CEM, a step-by-step discussion of the evolution of Central Sanday based on preserved evidence

The first phase for which geomorphic evidence exists is gravel dominated and described in Step 4. The earliest preserved gravel ridges are located at the southern end of Cata Sand and are at an altitude of 1.2mOD. If the modelled sea level curve is considered these features are estimated to be 6500yrs old, given their present altitude and the likely height above sea level at time of formation (Comber 1993, Shennan *et al* 2002, Figure 5.30). However, if Shennan *et al* (2002) sea level curve was adjusted to reflect the forest at Otterswick and some of the data points from De La Vega and Smith (1996), the earliest preserved ridges could date from 5.5kaBP. Given the previous discussions, outlining to the absence of evidence of higher than present sea levels, the 'adjusted local sea level curve' has been used, which is a hand-drawn line reflecting the presence of Orkney peats and does not rise above the present sea level.

From 5.5kaBP the rate of sea level rise starts to slow as the gravel spits recurve into the former bay of Cata Sand. The evolutionary phases for which direct evidence remains (Steps 4-8) are discussed below before the preceding stages of development (Step 1-3) which can be inferred from the juxtaposition of the geomorphology and surrounding rock outcrops.

Step 4: ca. 5.5kyr BP

The oldest preserved gravel ridges are currently located within the southern part of Cata Sand, with only their distal ends being preserved as they curve inland from underneath the present dune capped tombolo (Figure 5.30A). Although little remains of the straight section of the ridge, given the orientation of the distal ends, the arms of the ridge must have extended seawards of the present tombolo. Given the 1.2mOD altitude of the earliest preserved ridges they are likely to have been laid down around 6.5kaBP if the Shennan *et al* (2002) sea level curve is considered (Figure 5.30B). However this is revised to 5.5kaBP when local peat and other dating evidence is more strongly regarded (see section 5.5.2). At this hindcast[1] sea level the nearshore island of Baa Gruna would have been above sea level and its till cap is likely to have been providing additional material through quarrying and also providing a wave shadow which is partly responsible for the orientation of the ridges (Figure 5.30C). For these ridges to form, a northward longshore drift would have been required feeding sediment from Tres Ness northwards towards the headland at Newark. The deposition area (the tip of the gravel spit) extended north into Newark Bay, fed by the removal of earlier gravel ridges laid down towards the southern end of the beach and augmented by quarrying of material from low-gradient till-capped headlands. The position of these feeder ridges is hindcast from Step 3 to Step 1 given their likely geomorphological development.

The east coast is not alone in experiencing significant change at this time; as the forest at Otterswick, dies at this time. The proposed scenario is a harsh storm which blew the trees

[1] Hindcast: used here as the opposite of forecast, i.e. predicting earlier stages of development.

over in the same direction (Traill 1868), and inundate the shallow hinterland surrounding the Bay of Otterswick.

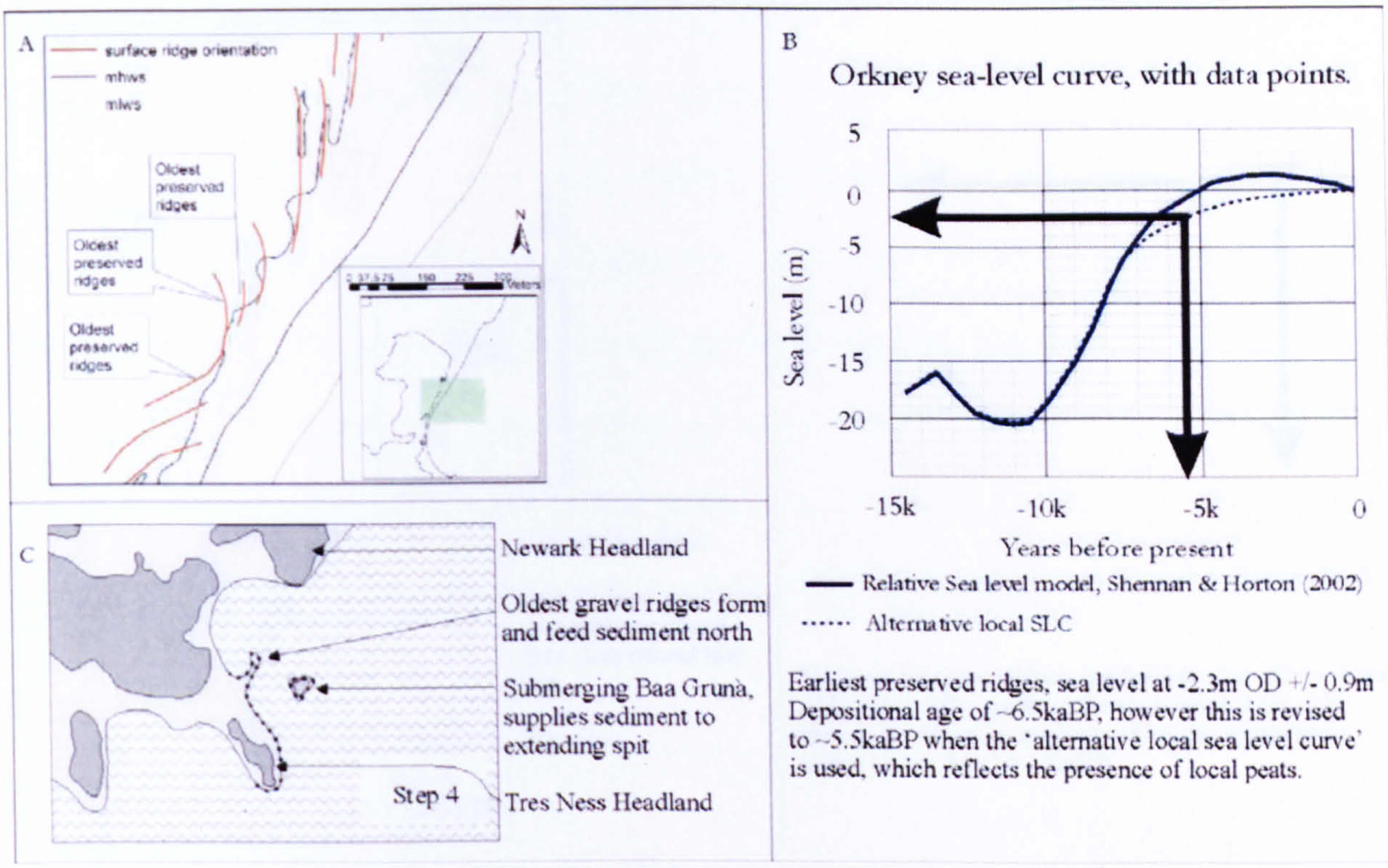


Figure 5.30 Step 4 of the CEM, (A) The supporting evidence: the oldest preserved ridges lying at the midpoint of the Newark tombolo. (B) Orkney sea level curve: with the earliest preserved gravel ridges on Sanday plotted. (C) The proposed coastal configuration: The spit of which the distal ends are preserved, extends northwards, possibly partially benefiting from the wave shadow in the lee of the island of Baa Gruna. Note, dark grey: rocky headlands, pale grey: low-lying land, dotted line: gravels, wavy lines: the sea.

Step 5: ~3kaBP

The northward extension of gravel ridges continues into Step 5 when they extend into the area presently occupied by the Plain of Fidge (Figure 5.31A). For the youngest and northernmost of these ridges, if the Comber (1993) conversion factor is strictly applied, then these ridges would be very recent (i.e. they are at an altitude comparable to present sea level), however a similar sea level has been present for the last 3 to 2.5kaBP. The implications of this are discussed further in Chapter 8. Given the altitude of these ridges the spit was largely in place by approximated 3-2.5kaBP (Figure 5.31B). In addition the island of Baa Gruna had become submerged by rising sea levels and it's till cap provides a pulse of gravels into the northerly extending gravel ridges. Erosion of the source areas in the south to feed deposition areas in the north started a clockwise rotation of the gravel beach (Figure 5.31C), which has continued to the present day.

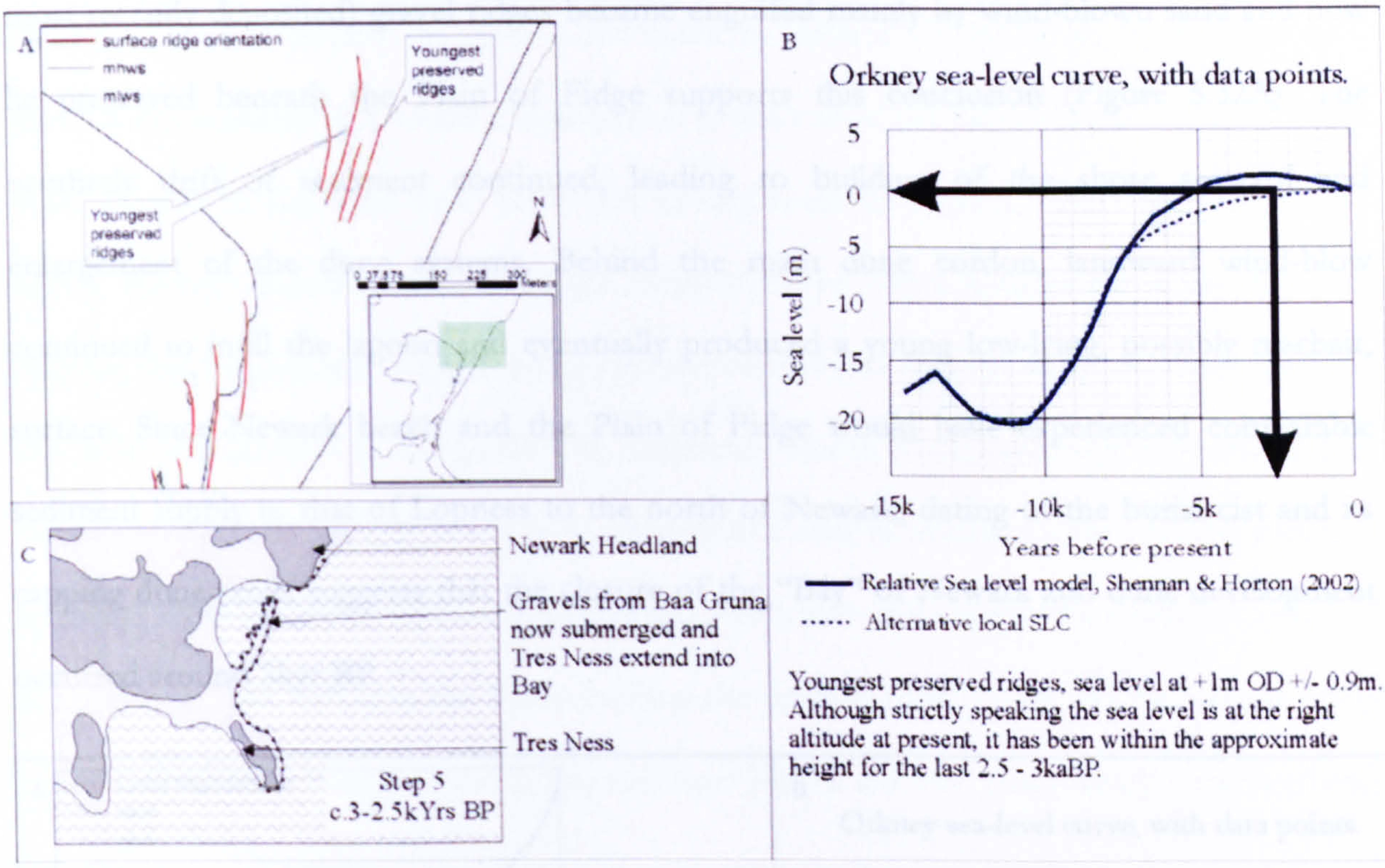


Figure 5.31 Step 5 of the CEM. (A) The Supporting evidence: Dominance of sands in the north rather than gravels (supported by GPR). (B) Orkney sea level curve: wide scale arrival of sand by 3kaBP, derived from aeolian deposits above Lopness cist. (C) The proposed coastal configuration: CEM shows the northerly limit of gravel ridge extension into the area presently occupied by the centre of the Plain of Fidge. Note that the island of Baa Gruna has been submerged by rising sea levels.

Step 6: ~ 3kaBP

The northward drift of gravels from the southern section of the beach towards the north has eventually closed off the entrance to Newark Bay forming a lagoon. However, since the supply of gravel-sized sediments appears to have been reducing (the GPR showed that no new ridges were being developed and sand had become more prevalent), the final sealing of the inland Newark "Bay" was not achieved by gravel ridge extension but by sand infill of a narrowing and shallowing tidal channel. The deposition of the final recurves of the gravel spit within the Plain of Fidge probably coincided with the wide scale arrival of sand on the east coast of Sanday. Associated with this change to sand deposition, the sedimentation rates behind the northward extending spit may also have been favoured by progressively lower energy wave conditions, perhaps augmented by aeolian deposition of sands blown from the developing dune systems. The fact that the GPR transects show that the northernmost (and most recently deposited) gravel ridges became engulfed mainly by wind-blown sand and now lie preserved beneath the Plain of Fidge supports this conclusion (Figure 5.32A). The northerly drift of sediment continued, leading to building of the shore seaward and enlargement of the dune systems. Behind the main dune cordon, landward wind-blow continued to infill the lagoon and eventually produced a young low-lying, possibly machair, surface. Since Newark beach and the Plain of Fidge would have experienced comparable sediment supply to that of Lopness to the north of Newark, dating of the burial cist and its capping dune sands suggests that the closure of the "Bay" of Newark and dune development occurred around 3kyr BP.

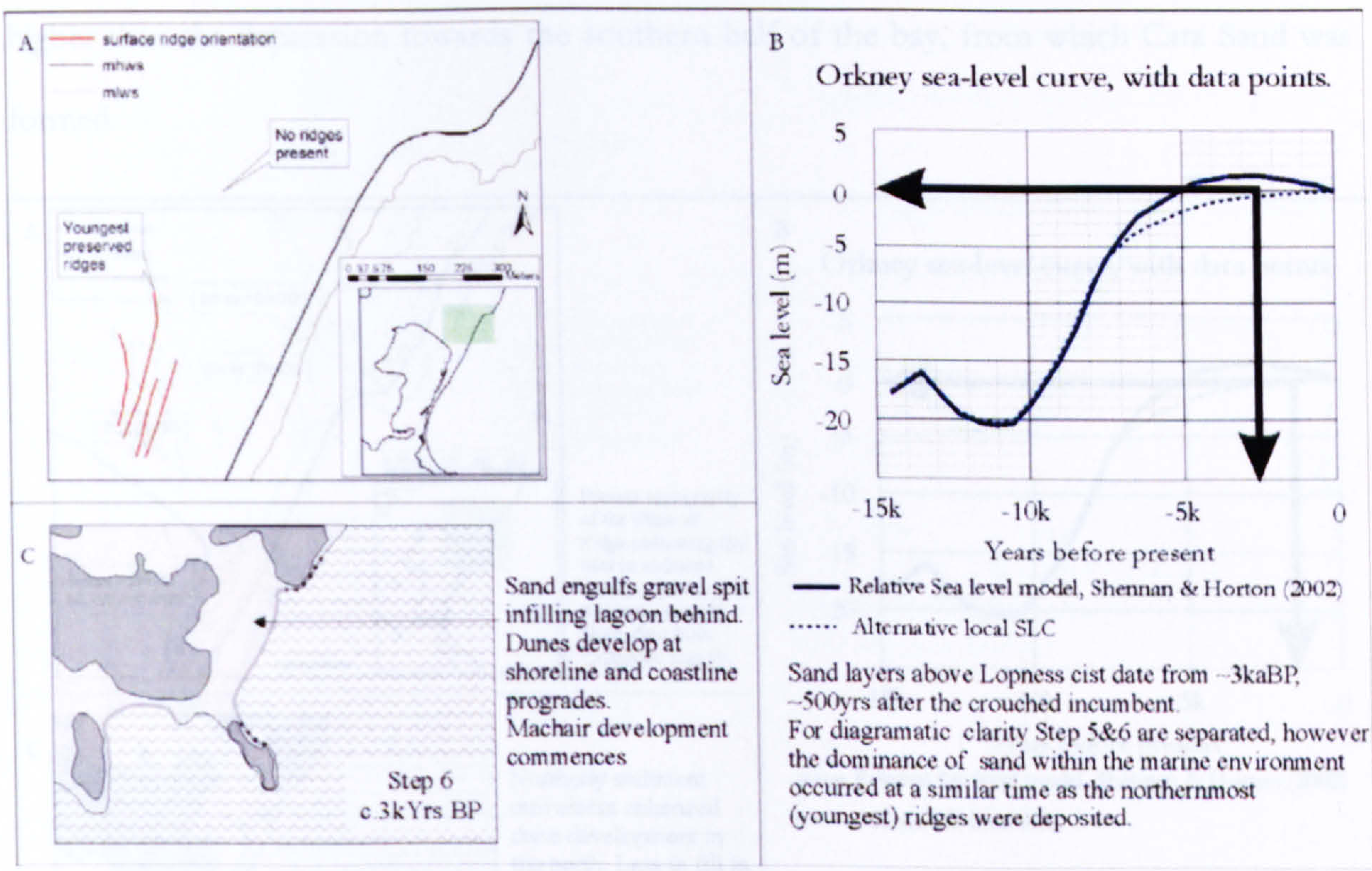


Figure 5.32 Step 6 of the CEM. (A) The Supporting evidence: Dominance of sands in the northern Plain of Fidge rather than gravels (supported by GPR). (B) Orkney sea level curve: wide scale arrival of sand by 3kaBP, derived from aeolian deposits above Lopness cist. (C) The proposed coastal configuration: CEM shows the northerly limit of gravel ridge extension into the area presently occupied by the centre of the Plain of Fidge. Progradation of the shoreline seawards and the inundation of terrestrial areas of the island by large volumes of sand. Note that the island of Baa Gruna has been submerged by rising sea levels.

Step 7: ca. 3kyr BP to Historical

The closure of the "Bay" produced a shoreline resembling that of today (Figure 5.33). The direction of net sediment movement continued by erosion in the south feeding sediment towards the northeast and resulted in accretion at this end of the bay. Accretion of sand at this point resulted in landward wind-blow and was reflected in a much wider dune system and higher, thicker machair landforms in the Plain of Fidge. There appears to be no reason to suppose that the machair surface did not extend southwards into the Cata Sand area although at a lower altitude than in the north. The northward bias in coastal sediment movement from the southern end of the bay would have resulted in a relative imbalance between the potential sediment supplies able to be blown landwards, which was restricted in the south and plentiful in the north. This results in the dunes backing the northern half of the Bay of Newark being higher than the depression towards the southern half of the bay, from which Cata Sand was formed.

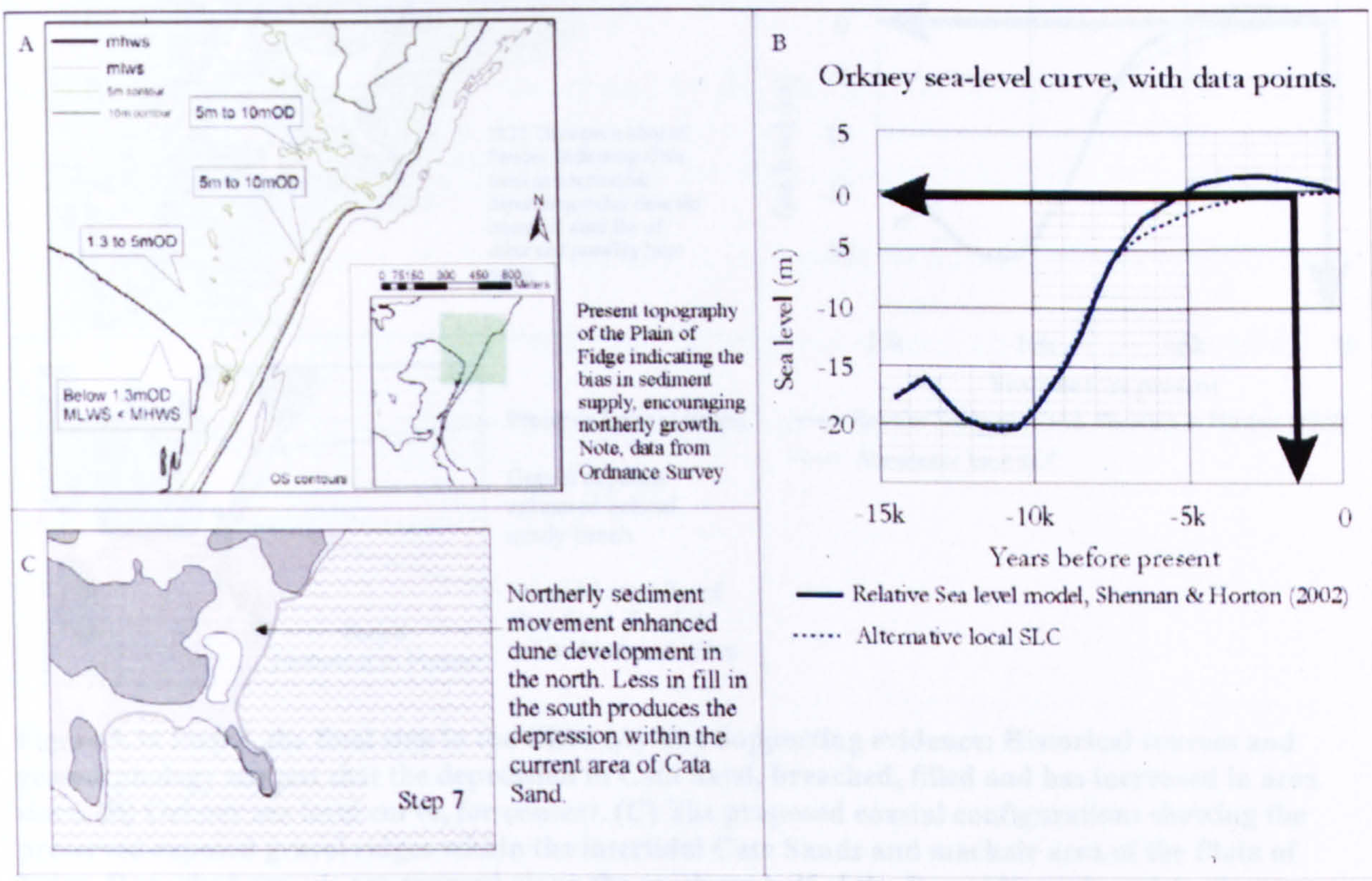


Figure 5.33 Step 7 of the CEM. (A) The supporting evidence: the landforms in the Plain of Fidge increase in height and sand dominance. (B) Orkney sea level curve: where relative sea levels are broadly comparable to present levels. (C) The proposed coastal configuration: The northerly bias in longshore drift resulted in higher dunes being deposited in the northern end of the bay in comparison to the source area in the south.

Step 8: Historical to Present

Continued northerly movement of sediment produced erosion in the south and deposition in the north and so a clockwise rotation of the beach orientation continued (Figure 5.34). During this time the sea breached through the topographic low area west of Tres Ness, where sediment supply was hitherto very restricted, resulting in marine inundation of the depression behind the main beach to form the intertidal sand flat of Cata Sand (Historical maps within Section 4.5). The 1st Edition maps indicate the low-lying nature of this section of coast until the recent accumulation of sands on top of the gravel and basement geology, to the west of Tres Ness. These early maps also show the breach crossing the gravel ridge (the Girthes and Ossamy). The north-south breach was more likely than the west-east breach, given the progradation of the Newark dunes.

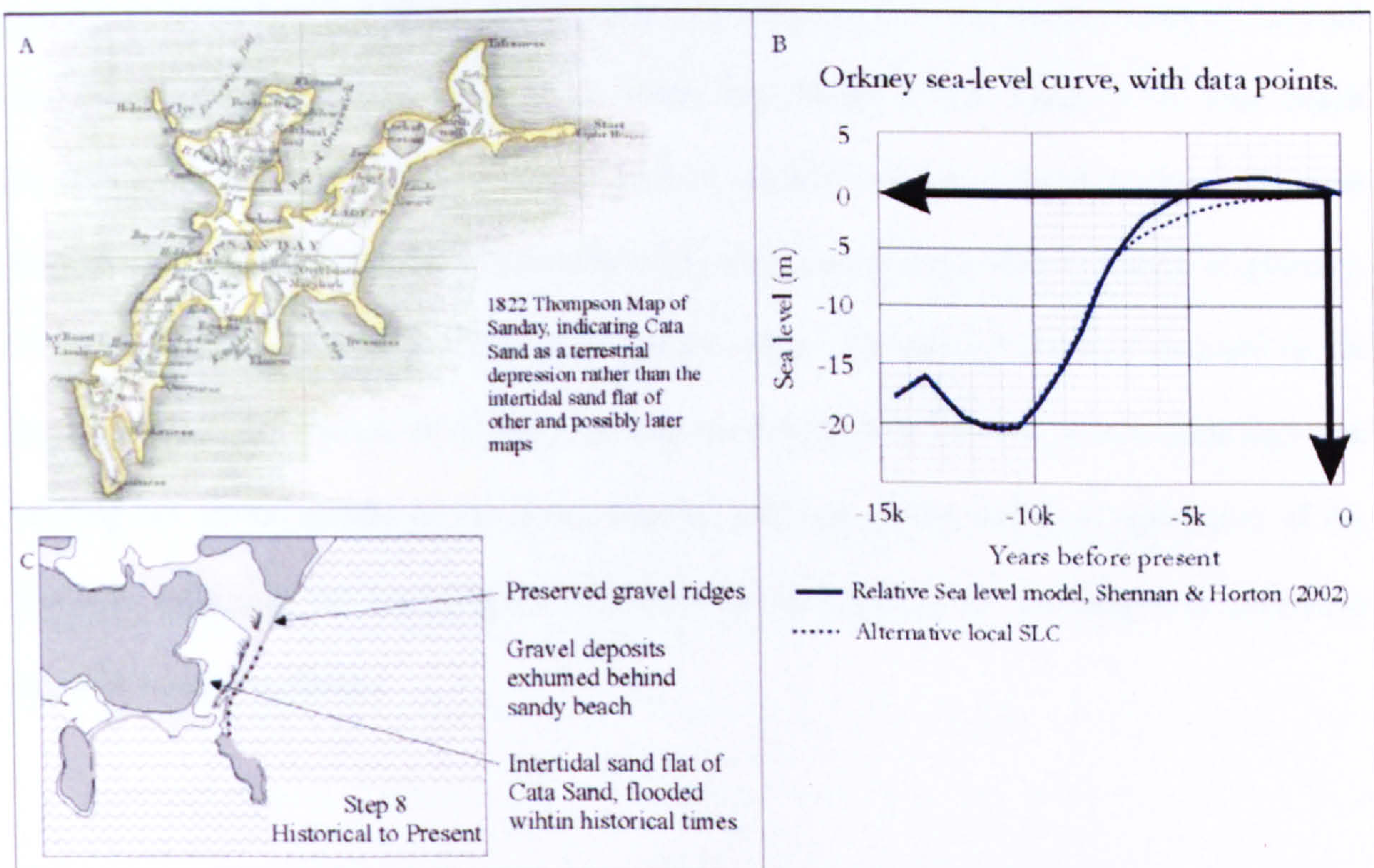


Figure 5.34 Step 8, the final step in the CEM (A) The Supporting evidence: Historical sources and geomorphology suggest that the depression in Cata Sand, breached, filled and has increased in area since. (B) Orkney sea level curve, for context. (C) The proposed coastal configuration: showing the preserved exposed gravel ridges within the intertidal Cata Sands and machair area of the Plain of Fidge. Reworked gravels are exposed along the southern half of the Bay of Newark under winter conditions reflecting the long-term erosional bias of the south relative to the northern half of the bay.

The inundation of Cata Sand would have started sporadically; perhaps during storm conditions at high tide, but became more frequent as relative sea level rise dominated. The transformation of the area behind the main beach has been captured on historical maps: the low area (Cata Sand) is shown on the Thompson map of 1822 as a low-lying, possibly cultivated area, unconnected to the sea (May & Hansom, 2003), yet within a few decades subsequent maps show an arm of the sea known by the new name of Cata Sand. The transformation of a low-lying, possibly cultivated machair into an intertidal Cata Sand, may serve as an analogue for other similarly situated locations across the island. This is similar to the proposed scenario that lead to the destruction of the buried forest of Otterswick.

The re-organisation of soft deposits has continued to date and the Bay of Newark is now transgressing landwards whilst rotating normal to the dominant wave direction, as outlined previously in Section 5.4. Beach and dune erosion is greatest in the southern Bay of Newark and dune building continues in the north of the bay (Figure 5.28 & Figure 5.35). Such beach and dune erosion due to frontal erosion may eventually result in a break in the connection between Newark and Tres Ness (exacerbated by the very limited sediment supply at present). The exhumation of buried gravel deposits on the upper shoreface at the southern end of the beach and the exhumation of an old path way, once located at the west of the dune and now eroding out of the middle of the dune, may be evidence of the landward translation of the tombolo reflecting the recycling of sediments in the absence of contemporary nearshore contributions of sediment.

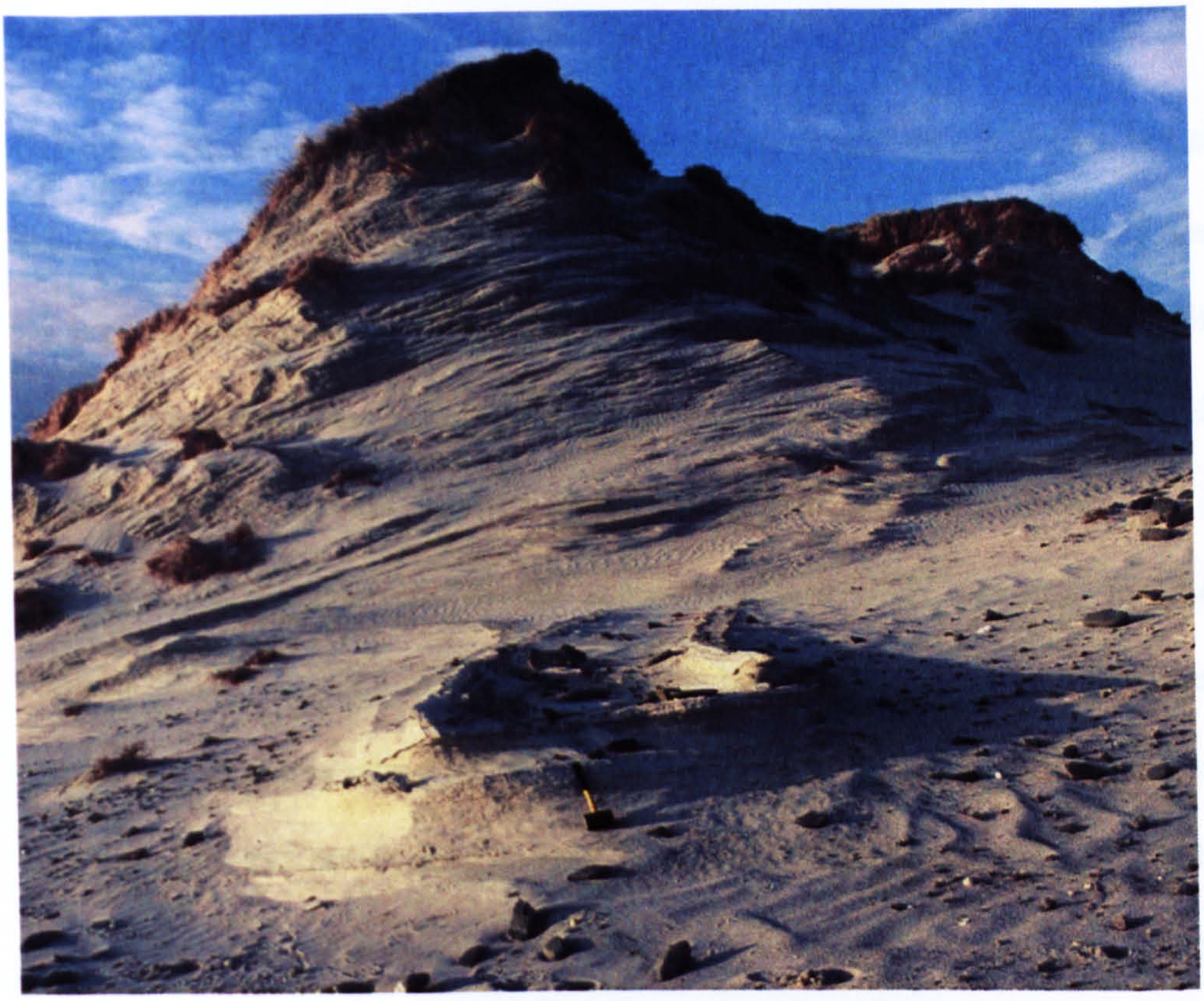


Figure 5.35 The 'Stromness Road' a former carriage-way servicing Tres Ness farm, which used to run along the inside of the tombolo, was subsequently covered over by the retreating sand dunes and is now exposed at the northern gap in the Newark Dunes. Note hammer for scale.

5.5.3 The CEM, a step-by-step discussion of the evolution of Central Sanday: Hindcast from 8kaBP to 6.5kaBP

The juxtaposition of altitudes of basement geology and the orientation of the earliest preserved ridges hints towards an earlier number of evolutionary steps involving erosion of the island of Baa Gruna, which allowed the earliest preserved ridges to be formed. These steps have been arranged in chronological order, like the earlier sections, but it should be noted that no geomorphological evidence remains for these steps. However, they provide a simple progression towards the earliest preserved ridges, whose orientation and initiation is hard to explain otherwise.

Step 1: ca. 8kyr BP.

The time series for the hindcast steps commences with the coastline position at the current –10m contour (Figure 5.36). According to the relative sea level curve of Shennan *et al* (2002), sea level would have impinged on the shore at this altitude at ca. 8kyr BP. However, this position likely underestimates the land area on headlands like Tres Ness, due to subsequent erosion of any till cap. It may also overestimate the soft sections of coast due to the deposition of littoral units in the intervening years. To account for these factors, those sections of the coastline most affected have been transgressed in subsequent steps. At 8kaBP relative sea level was rising relatively fast and so the dominant process was rapid submergence and transgression rather than coastal reworking. This is reflected on shallow sloped coastal sections by rapid translation of the shoreline into the developing 'Bay' of Newark (Step 2).

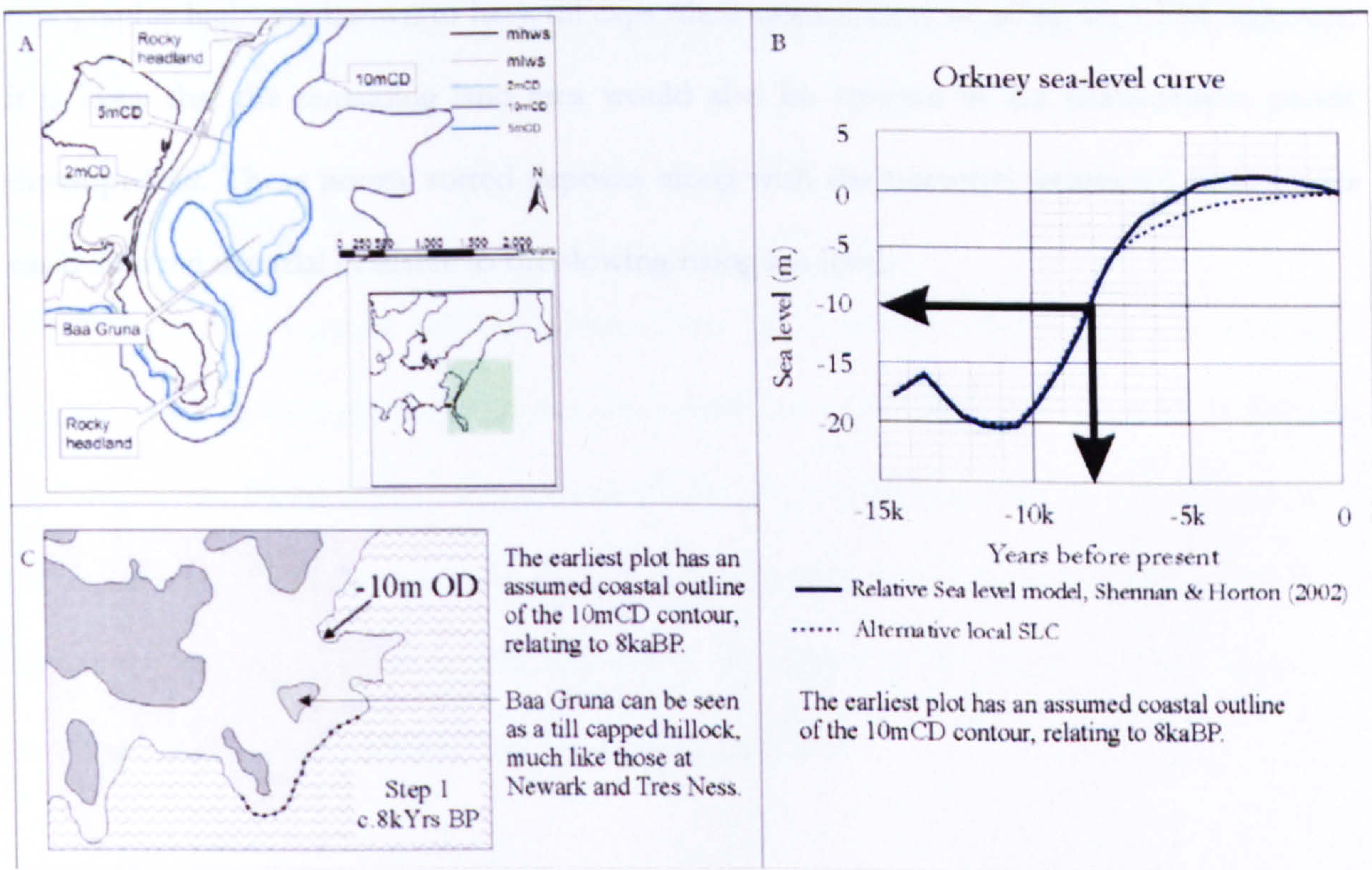


Figure 5.36 Step 1 of the CEM. (A) The Supporting evidence: based on the present bathymetry of the east coast of Sanday. (B) Orkney sea level curve: MSL was 10m below present 8kaBP (C) The proposed coastal configuration: A low-lying coastal plain extends well beyond Baa Gruna and the other main headlands, which would dominate the skyline as the visible hills. Note the confidence is at its lowest given the arguments within the text above.

Step 2:

Submergence continued to dominate with relatively little transgression around the headlands and more considerable areas of inundation south of the Newark headland (Figure 5.37A). Subsurface investigations (including GPR and ground truthing) have shown this area to be composed of sand deposits rather than gravels at depth. The orientation and extension of gravel ridges from the south indicates that the area south of Newark headland was likely inundated and had become a 'deepwater' bay (Figure 5.37C). At step two the remainder of the shoreline was pinned by till-covered rock at Newark, Tres Ness, Els Ness and Baa Gruna (now a submerged rocky islet) at -2mOD. Gravel (eroded from the till-covered rock pinning points) began to fill the trough between Tres Ness and Baa Gruna and experienced reworking and translation. As sea levels continued to rise, the isthmus narrowed. Although the topographic highs are known to have till caps (dark shaded areas on all of the CEM diagrams) it is likely that the remaining land area would also be covered in the characteristic poorly developed till. These poorly sorted deposits along with the fractured weathered bedrock are easily sourced material available to the slowing rising sea level.

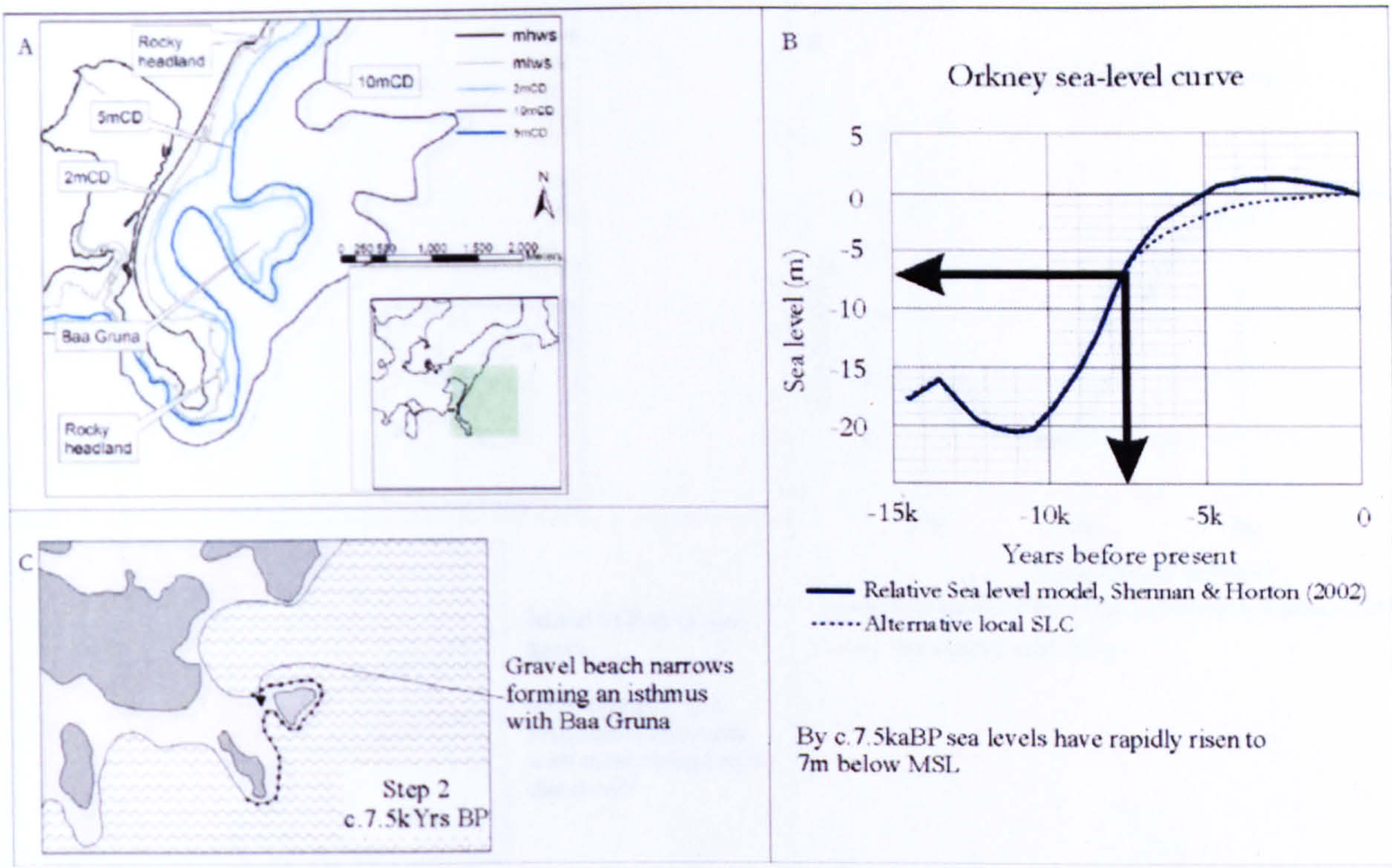


Figure 5.37 Step 2 of the CEM. (A) The Supporting evidence: no accretional units have been preserved, so this is based on the bathymetry. (B) Orkney sea level curve: at 7.5kaBP the sea level was 7m below present levels. (C) The proposed coastal configuration: a narrowing isthmus was being affected by rising sea levels continuing to rise, also additional sediments were being provided from the low-angled till-capped headlands.

Step 3: After 7.5 kyr BP

The thinning of the gravel isthmus between Tres Ness and Baa Gruna eventually resulted in the sea breaking through to produce a spit, which then experienced considerable reworking and dynamism (Figure 5.38). Judging from the elevation of offshore Baa Gruna, this may have occurred at ca. 7.5kyr BP. Not only did Baa Gruna provide a considerable wave shadow to the gravel spit at Step 3, which is reflected in the orientation of the spit, but it also acted as a sediment source area to the beaches developing landwards.

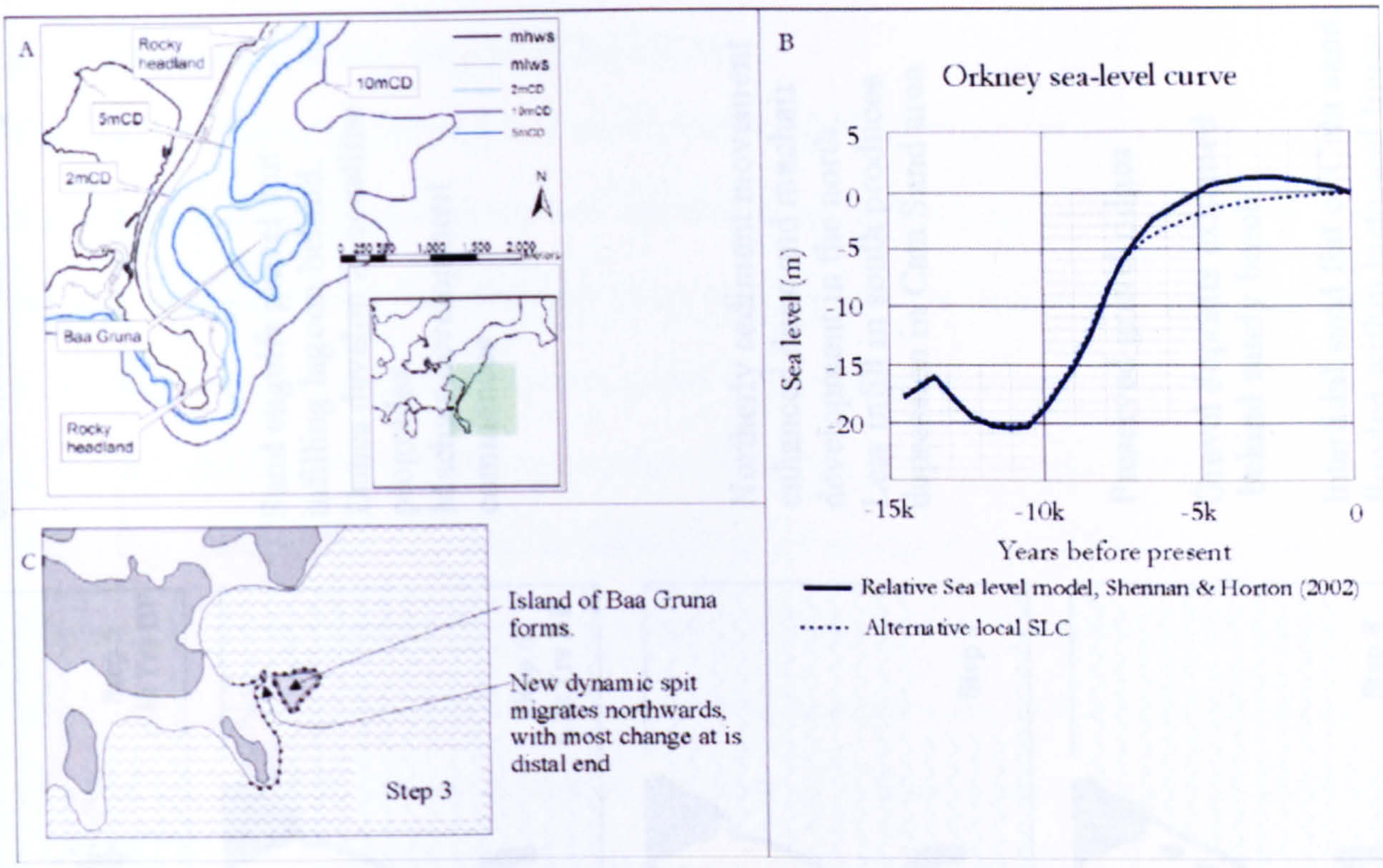


Figure 5.38 Step 3 of the CEM. (A) The Supporting evidence: based on bathymetry and the existing coastal configuration (Step 4) for which the evidence was preserved. (B) Orkney sea level curve: for context. (C) The proposed coastal configuration: the isthmus broke free from the till-capped island of Baa Gruna and formed a spit, which accreted northwards as the predecessor of the earliest preserved gravel ridge.

Figure 5.39 provides a summary of the 8 steps of the Coastal Evolutionary Model.

Coastal evolutionary model, Central Sanday, Orkney Islands

5.5.4 Summary of key stages in the CEM

The earliest preserved gravel ridge is at an altitude of 1.2mOD, which has been compared with the Shennan *et al* (2002) sea level curve to establish an approximate age of deposition (sea level was approximately 3.5m below the ridge crest, resulting in a sea level of 2.1m below present 6.5ka BP). The most northerly exposed gravel ridge within Cata Sand is at an altitude of 1.6mOD (6.2kaBP) and is ~800m to the north. Given the position and the gradient of the sea level curve a rate of spit extension is estimated at an average rate of 2.6m/yr (i.e. 800m in 300yrs). The youngest ridges are located within the Plain of Fidge at an altitude of 4.6mOD, which if the same conversion is used (Comber 1993) requires a sea level comparable to levels over the last 3kaBP to the present day (if the error of ± 0.9m is used). An age of 3kaBP is derived from the sea level curve for these northern ridges (Table 5.1).

Gravel ridges in...	Ridge altitude (mOD)	Age (kaBP)	Distance (m)	Rate (m/yr)
Southern Cata Sand i.e. earliest preserved ridges	1.2	6.5	-	-
Northern Cata Sand	1.6	6.2	800	2.6
The Plain of Fidge	4.6	3	+400	0.12

Table 5.1 Showing the age and accretion rates of gravel ridges extending from earliest preserved ridges (presently located within Cata Sand) northwards to the most recently deposited (exposed ridges within the Plain of Fidge).

The rapid reduction in the rates of spit extension is expected when the rate of sea level rise and the increasingly scarce gravel supply are considered. Before 6kaBP the rate of RSLR was greater than 2mm/yr, rates which Carter *et al* (1989) established through contemporary analogies and associated with wide-scale reorganisation of gravel systems. The literature associates this period with the greatest amount of reorganisation of coastal landform assemblages (May and Hansom 2003). As the rates of RSLR fell, so too did the vigour of the reorganisation of gravel units and sand became increasingly dominant within the coastal system (Table 5.2).

Approximate Period (kaBP)	Rate of RSLR (mm/yr)	Sediment	Geomorphological activity
8 – 7	4	Rapid transgression of gravel units	Submergence of till capped headlands, rapid morphological changes.
7 – 6	2		
6 – 5	1	Moderate transgression and increased recycling of gravels	Spit extension northwards, quarrying old proximal spits as rates of spit extension reduce. Also inundation of Otterswick forest ~5.7kaBP
5 – 4	1		
4 - 2	1	Influx of sand, contributions from local till sources and biogenic material	Dune and machair formation initiated. Transgression during submergence, converting marine into terrestrial areas.
2 – 0	0.25	Little new sediment other than biogenic material	Frontal erosion and retreat of coastal edge inland encroaching on terrestrial vegetation and archaeological sites.

Table 5.2 Summarising the timing of and rates of RSLR change derived from the adjusted local sea level curve (based on Shennan *et al* (2002) but reflecting local peats (Figure 5.8)) and the evolutionary phases on the Central Sanday coast.

5.6 Summary of main results

The various subsurface investigations have highlighted that the changing phases of coastal evolution in Central Sanday, have been dominated by variations in sediment supply that have been accessed at different altitudes as sea level inundated a low lying undulating geological basin. Initially gravel dominated during the earliest phase (for which evidence remains) and it appears that the role of underlying geology was crucial, providing anchor points from which the gravels could be reworked. The dominance of these control points varied as the sea level rose. Initially within the Bay of Newark, the Baa Gruna dominated coastal development in its lea, followed by the two headlands at Tres Ness and Newark. The absence of headlands within the centre of the Bays of Lopness and Sty Wick, led to a much simpler landward recession.

The initiation of Sanday's dunes and machair development (between 5 & 3kaBP) postdates that from other machair areas, for instance within the Western Isles, however it does agree more closely with other local sand dominated coastal systems within the region.

More recent behaviour of the three beaches indicates Sty Wick and Lopness are generally in balance with present wave climates and the Bay of Newark has a recent (<100yrs) northerly tendency, fuelled by dune instability where the tombolo is at its narrowest. The instability appears to be initiated by the gales of 1953 where the single dune cordon was punctured to produce two major gaps through the dunes. These gaps remain, although partly sealed by low dunes.

Climate change scenarios suggest that the forcing processes are likely to get increasingly harsh, on top of a rising sea level which is affecting an increasing amount of Scotland. Unfortunately, further to this the rates of sea level rise towards the second half of the century may increase to levels comparable to the Holocene transgression, with radical implications for the coastal geomorphology.

6 Implications of the CEM for the management of submerging shorelines

The CEM outlined the coastal development to the present in 8 steps, but questions remain as to the future ways in which the future development of the coast may progress and what the management implications will be both for Sanday and for other shorelines.

6.1.1 Climate change

Although historical rates of relative sea level rise for peripheral areas of the UK may be only few millimetres per year, an order of magnitude smaller than some of the other changes discussed below, it is the base-level on which all other processes operate and a baseline set to accelerate. Therefore, like-for-like events will be increasingly hard felt as relative sea level rise acts to compound other processes. Given Graphs (1998) investigations into the annual tidal maximum at a number of Scotland's ports, it appears that the isostatic inheritance is not keeping pace with eustatic increase in sea level, this resulting in migration of the zero isobase inland towards uplift centre of Scotland. This implies that our post-glacial isostatic inheritance is almost spent. Thus increasing areas of Scotland will become threatened as relative sea levels rise and accelerate and our coastal assemblages, which have enjoyed emergence or recent stability, may then start to rework to reflect renewed submergence (Pethick, 2000).

Given the time elapsed since the last glacial period, sediment supply is now restricted, Also the temperate nature of our climate and the increasing anthropogenic stabilisation of terrestrial landforms have further limited any fluvial contribution to the coastal cells. In the inner firths much of the shoreline has been impacted, via land claim, structures, dredging and other coastal protection measures. This reduction in sediment entering the coastal cell has led to drift aligned systems becoming increasingly rare, and the general trend of erosion and reorganisation of beaches towards a swash aligned equilibrium position.

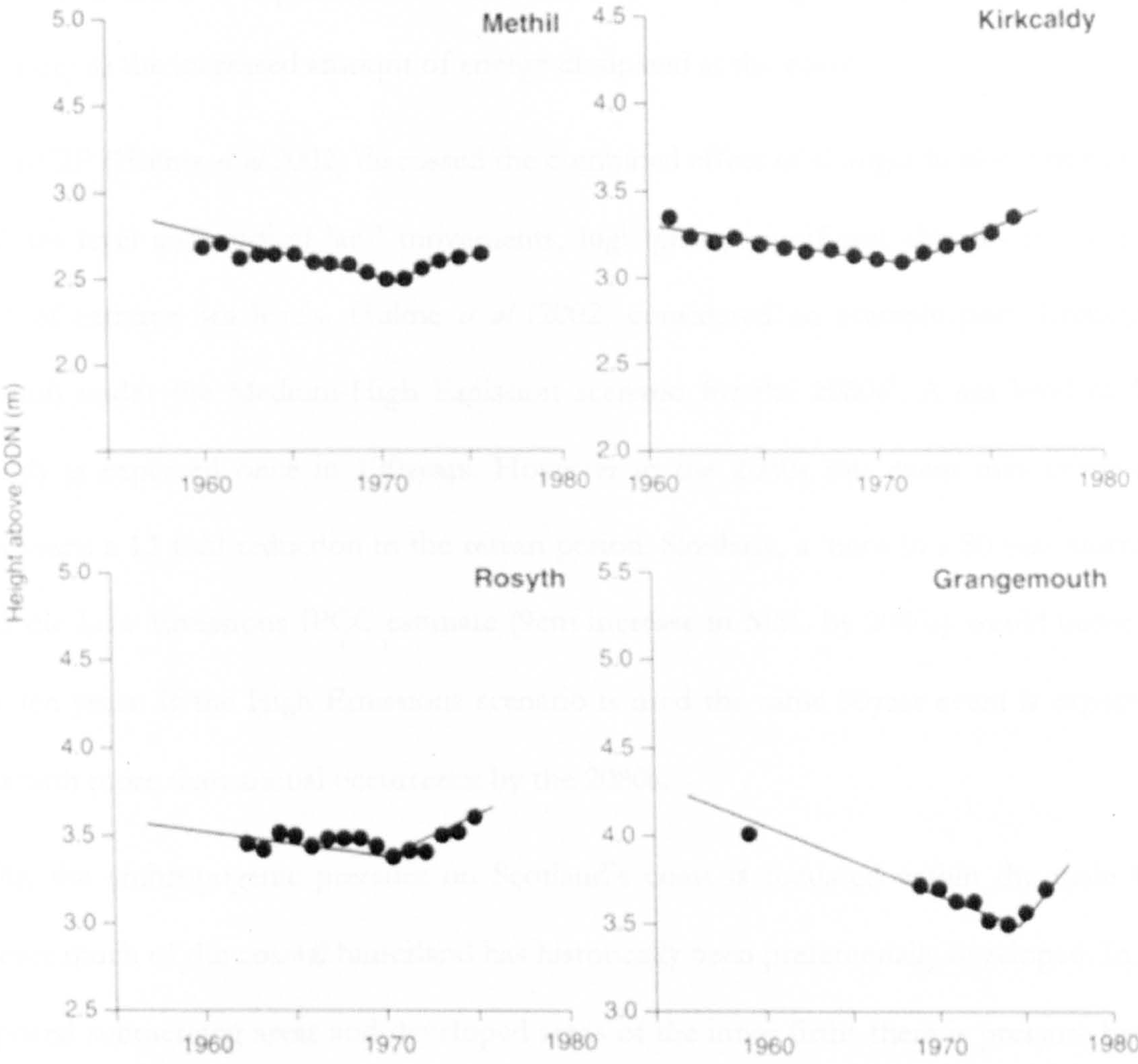


Figure 6.1 Annual tidal maxima from four tide gauging stations on the Firth of Forth, showing a falling trend followed by an rising trend (Graph et al 1989). The timing of the inflection reflects the position of the gauging station with respect to the zero-isobase line. This pattern has been interpreted as the up-firth progression of the zero-isobase line as the area experiencing relative sea level rise reduces with time.

Changes have not been limited to the sea level and sediment supply because climate is, and has always been, changing. For example, the pattern and changing frequency of storms has been traced using the NAO since the 17th century and although the pattern is variable, there has been an increasing trend over the last thirty years of increasingly stormy winters (Dawson *et al* 2002). This fluctuation in the NAO may be partly responsible for the 10-15% increase in significant storm wave heights within the North Atlantic since the 1950s (Gunther *et al* 1989). Such changes in storminess and associated significant wave heights will energise the nearshore environment, and it is expected that there will be a morphological response (erosion of the beach face) to the increased amount of energy dissipated at the coast.

The UKCIP (Hulme *et al* 2002) discussed the combined effect of changes in storminess, rise in global sea level and vertical land movements, highlighting significant changes to the return period of extreme sea levels. Hulme *et al* (2002) considered an example port, Immingham (England) under the Medium-High Emission scenario for the 2080s[1]. A sea level of 1.5m, currently is expected once in 120years. However in the 2080s this event may occur every seven years: a 13 fold reduction in the return period. Similarly, a 'once in a 50 year storm' the under the Low Emissions IPCC estimate (9cm increase in MSL by 2080s) would occur once every ten years. If the High Emissions scenario is used the same 50year event is expected to occur with more than annual occurrence by the 2080s.

Finally, the anthropogenic pressure on Scotland's coast is focussed within the main firths, however much of the coastal hinterland has historically been preferentially developed. In some peripheral submerging areas and developed areas of the inner firths there is pressure between land use and coastal processes. Although land claim has become increasingly rare, development within inappropriate areas continues. In the coming years it will be interesting to see how Local Authorities police development in flood-prone areas, particularly after the publication of the Second Generation Flood maps (SEPA, expected Spring 2006) and LiDAR surveys (Firth of Forth SE and Western Isles, SNH).

All of these processes will continue to occur at a time where the area of Scotland affected by relative sea level rise is increasing, where sediment supply is at an all time low and when storminess seems set to become increasingly severe and unpredictable. As much of Scotland's coast is undeveloped it is likely to continue to respond naturally. It is crucial, therefore, to understand the natural patterns of change that have already occurred. Given the highly varied

[1] The term 2080's is used here, and in the remainder of the thesis, to describe the period from 2070 to 2100.

nature of the Scotland's coastal response to glacial unloading, recent behaviour at certain peripheral locations may be representative of other more central location in the future.

6.1.2 Step 9 of the CEM – the near future

Step 7 and 8 of the CEM provide a context of change within which the recent morphological changes can be placed. Amalgamating these clues allows the future development of the island to be postulated. These scenarios are presented below (Figure 6.2 - Figure 6.4), and their local and wider-scale implications are discussed in the remainder of this section.

Lopness and Sty Wick, which in varying degrees, have been moving towards swash-alignment are likely to continue slowly retreating landwards with rising relative sea levels. Given their swash alignment the change will not be focused in any particular area, however given the varied morphology and land-use of the back beach areas the retreat may be greater in some places. This would include the tombolo at Sty Wick retreating faster than the eastern end of the bay which benefits from a back beach and dune sediment store and increases in height landwards. It also has a till and geological foundation in places (Figure 5.29). However, at present the integrity of the tombolo at Sty Wick makes the likelihood of a breach relatively unlikely. The slow recession of the coast at Lopness is likely to continue, however as discussed previously the hinterland land-use may have a differing effect on the integrity of the coastal edge. However, the coastal edge is backed by low lying machair so what if erosion breaches the flooding will occur over a wide inland low-lying area.

The Bay of Newark has been subject to the most geomorphic change of the three test sites since summer 2001. This dynamism has been focussed at the point in the beach's planform where the curving southern limit of the bay joins the straighter section that extends northwards (Figure 5.27). Although it is likely that there is a historical component to this dynamism, and this has been evident since the breach in 1953, there is wider geomorphological evidence for this. The northerly bias in sediment flux is evident at Newark in the form of the preserved gravel ridges and the height increase of the Plain of Fidge northwards. This continues today and is reflected in the recessional dunes in the south and the accretionary general dune form towards the Newark headland. Given the general reduction of sediment supply and the negligible additional new sediment supply from Tres Ness headland, the beach will attempt to rotate increasingly to the west so that it recedes at the Tres end and accretes at the Newark end to become increasingly swash aligned. The locus of change is the point at which the bay ceases to be swash aligned, i.e. the southern limit of the straight section of the bay (Figure 5.28). The result of focussing the wave energy at this point is frontal erosion, which frees up sediment that becomes available for wind blow or longshore transport. This results in an increase in the height of some of the dunes, but it also has led to the dunes being breached where instability dominates. Since the storm surge of January 1953 which formed the gap in the Newark dunes they have not been compromised (J. Walls *pers comm.* 2001). The favourable attribute of the tombolo is its' gravel core, composed of reworked Late Holocene ridges. This relatively resilient core will continue to resist marine breaches in the near future.

The interior of the island is also at continued risk from submergence. This is focussed in two locations, firstly between Cata Sand and Otterswick and also between the south-western limit of Otterswick and the North Bay. The low-lying land separating Cata Sand and Otterswick is already submerged under storm surge conditions and this is likely to continue with increasing frequency (UK trend from Hulme et al 2002). In fact the northern side of the Otterswick/Cata Sand isthmus is already affected by marine inundation and in this regard it may be analogous to an earlier stage in the evolution of Cata Sand.

The distribution of buildings and infrastructure have been compared against Figure 6.3 to highlight the areas at greatest risk from future coastal change. Although the majority of the buildings remain above the 5m contour, which provides some security, the three main roads cross the both of the low lying isthmuses, which may cause problems increasingly in the future.

The distribution habitats of natural heritage interests are shown in Figure 6.4 which are likely to experience coastal change in the near future. Although the changes considered here would be interpreted as 'natural change' there are likely to be changes from one habitat type to another. The sand dunes on the Newark tombolo (shaded yellow in Figure 6.4) are likely to continue narrow and translate landwards, however the habitats of adjacent sides of the tombolo are sandflats are likely to translate with them. The salt marsh area on the south side of the Bay of Otterswick is likely to continue to move southwards, narrowing the isthmus as it goes. From a conservation perspective, rather than attempting to preserve these habitats in their present state, allowing the natural processes to operate will provide areas of differing stability and therefore a range of habitats in their continued state of evolution.

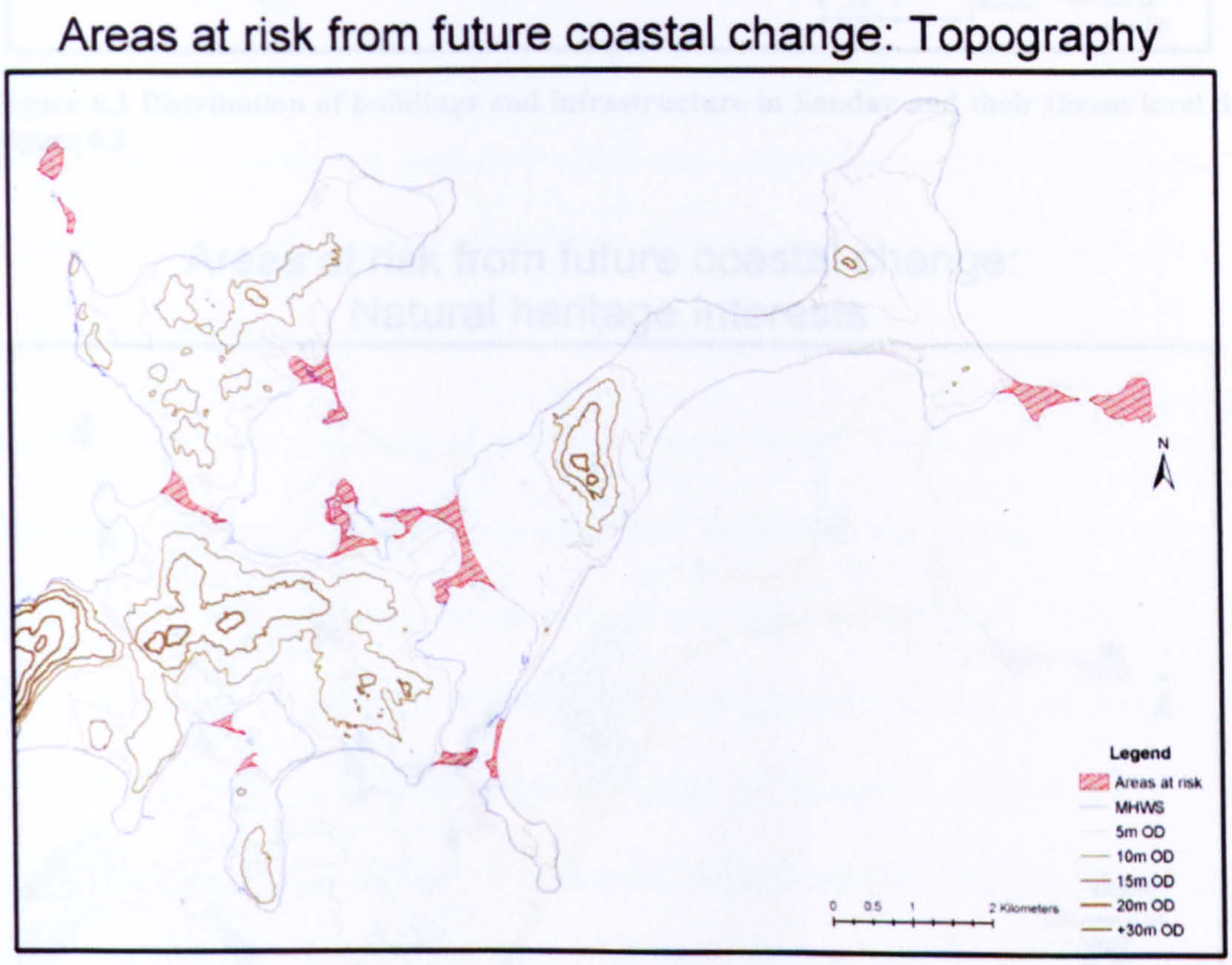


Figure 6.2 Coastal Evolutionary Model forecasting the areas at most risk from future climate change within Sanday. High risk areas are shaded in red.

Areas at risk from future coastal change: Buildings & Infrastructure

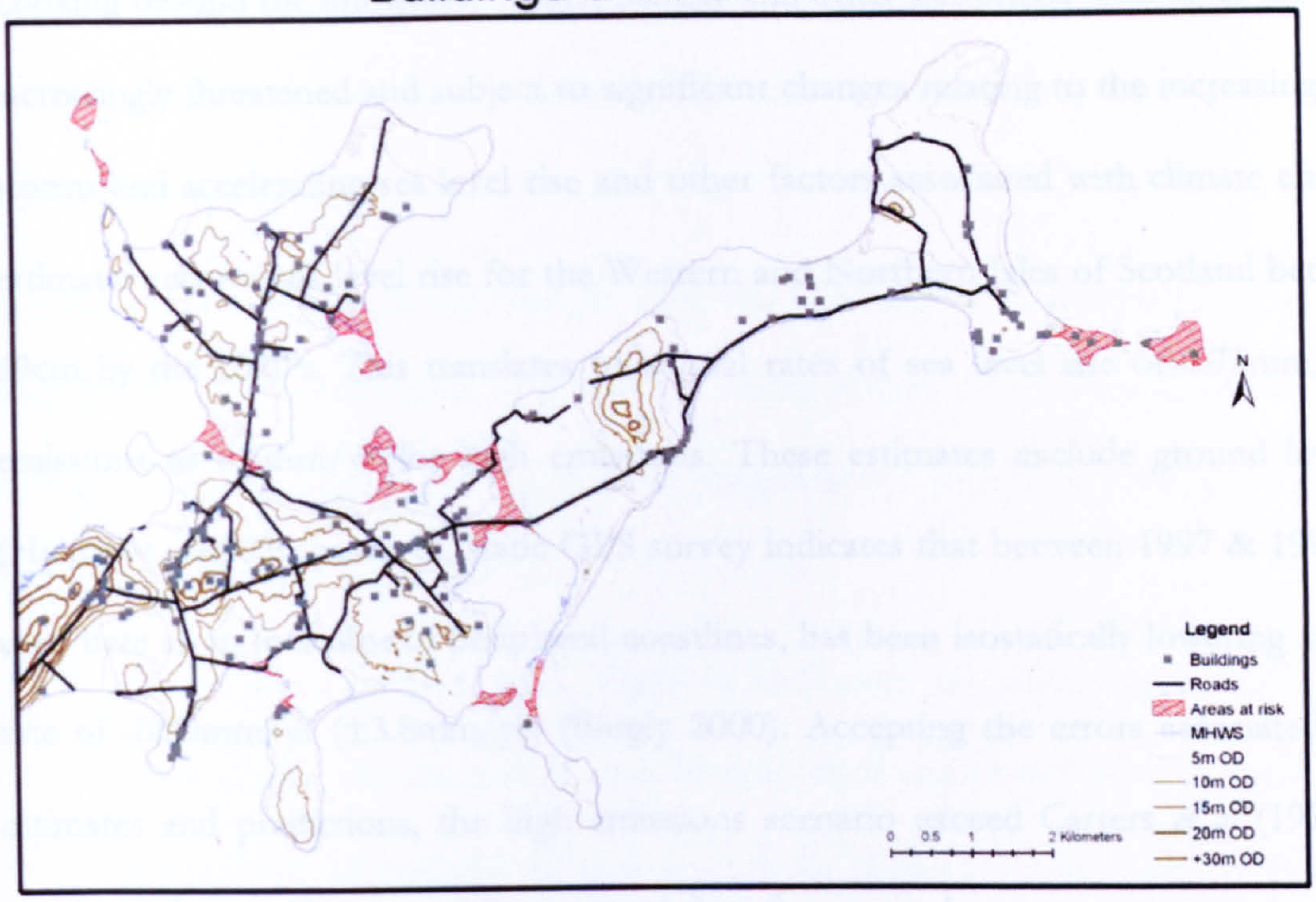


Figure 6.3 Distribution of buildings and infrastructure in Sanday and their threat level derived from Figure 6.2

Areas at risk from future coastal change: Natural heritage interests

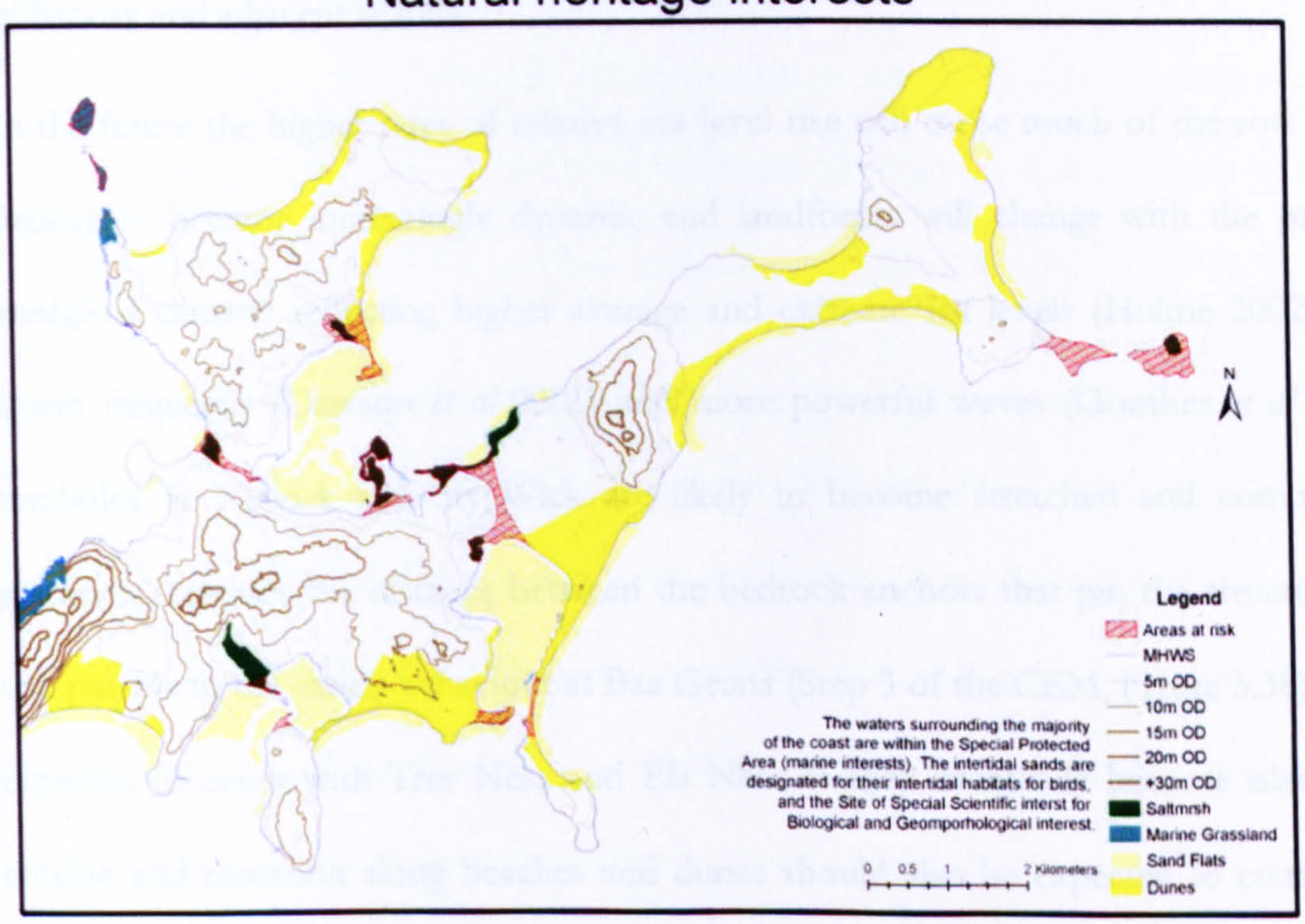


Figure 6.4 Distribution of natural heritage interests in Sanday and their threat level derived from Figure 6.2.

6.1.3 Step 10, 11, 12 of the CEM – the longer term future

Looking beyond the immediate future, Sanday and other peripheral[2] coastlines are likely to be increasingly threatened and subject to significant changes relating to the increasing severity of storms and accelerating sea level rise and other factors associated with climate change. IPCC estimates relative sea level rise for the Western and Northern Isles of Scotland between 6 and 69cm by the 2080's. This translates to annual rates of sea level rise of 0.75mm/yr for low emissions to 8.6mm/yr for high emissions. These estimates exclude ground level changes (Hulme *et al* 2002), however, static GPS survey indicates that between 1997 & 1999 Shetland, used here as an indicator of peripheral coastlines, has been isostatically lowering at an average rate of -0.89mm/yr (±3.8mm/yr) (Bingly 2000). Accepting the errors associated with these estimates and predictions, the high emissions scenario exceed Carters *et al* (1989) 3mm/yr threshold for significant modification and therefore coastal systems may start to reinvigorate. These rates of relative sea level rise, which are comparable to those experienced between 8-6kaBP in Orkney (Shennan *et al* 2002), are likely to cause reorganisation of the soft coastline of Sanday and adjacent islands.

In the future the higher rates of relative sea level rise will cause much of the soft sections of Sanday to become increasingly dynamic and landforms will change with the progressively energised climate: reflecting higher average and extreme sea levels (Hulme 2002), changing storm frequency (Dawson *et al* 2001) and more powerful waves (Gunther *et al* 1989). The tombolos at Newark and Sty Wick are likely to become stretched and compromised as recession increases the distance between the bedrock anchors that pin the structures. This is comparable to the earlier behaviour at Baa Gruna (Step 3 of the CEM, Figure 5.38) and can be expected to occur with Tres Ness and Els Ness as they eventually become islands. Frontal erosion and recession along beaches and dunes should also be expected to continue, as the beaches' attempt to adjust to the higher sea level and increased wave energy. The Cata Sand to

[2] 'Peripheral' is used here to reflect its limited glaci-isostatic inheritance, i.e. that it is far away from the centre of the Scottish ice cap during the Devensian glaciation.

Otterswick and Otterswick to North Bay isthmuses are likely to be increasingly inundated, possibly leading to deterioration of the vegetation and habitats as they become brackish and saline. In addition to this instability associated with vegetation stress may cause wind-blow to become a wider problem.

Combining the severity of the changes expected from the UKCIP report (Hulme *et al* 2002), and the coastal modifications of a test site under similar rates of sea level rise (i.e. Sanday during the late Holocene) the longer term prognosis for peripheral coastlines is stark. Given this, two changes are called for:

- Firstly, monitoring a wide range of indicators (including geomorphic, geological, oceanic and environmental) must be continued and extended so that rates of change, for example of isostatic adjustments and/or eustatic sea level rise are re-appraised, in an iterative manner, in order that our climate change scenarios are continually informed with data that is fit for purpose.
- Secondly, our approach to planning for future change must incorporate these expectations. It is essential that planning at the coast and on adjacent low-lying-hinterland areas, from Central Government, through Local and Structural Plans reflect the severity of even the low and medium emissions scenarios.

6.1.4 Comparisons with other low-lying submerging coastlines

Given the increasing geographic spread of areas which are experiencing sea level rise (Graph, 1998); understanding the behaviour of submerging shorelines in peripheral areas may provide a proxy of future change for other areas. Low-lying submerging areas are likely to be affected the greatest. In this regard some of the climate change implications for the Northern and Western Isles of Scotland are comparable.

The dune and machair systems of the Western and Northern Isles can be conceptualised in a broad evolutionary tract, starting 6kaBP and extending beyond the present day into the future.

The geomorphology of the machair system was at its healthiest 4-3kaBP when there it is likely that there were large dune systems, fed by the buoyant sediment supply from moderate rates of sea level rise accessing and redistributing both mineral (derived from glacial and fluvi-glacial sediments) and biogenic sand production (from marine species colonising the newly claimed phototropic shelves provided by previous sea level rise) (Hansom & Angus 2000). The subsequent reduction in sea level rise led to a stagnation of sediment supply, resulting in an increase in the cannibalisation of existing coastal deposits (May and Hansom 2003). This is the general evolutionary position of Scottish machair.

The next section will consider the wider implications of the future changes to sea levels. IPCC estimates of future sea level rise for the 2080's range from 6 to 69cm. Alternative, more conservative estimates of global sea level change within UKCIP (Table 6.1) raise concerns for medium and high emissions scenarios (Hulme *et al* 2002). For areas which do not benefit from isostatic emergence, the coming decades will be marked by increasing coastal erosion and reorganisation of soft sediments across much of the world.

	Sea level rise (cm)			Change (mm/yr)		
Date	Low Emissions	Med Emissions	High Emission	Low Emissions	Med Emissions	High Emission
1975	0	0	0	-	-	-
2040	9.5	10	10	1.5	1.5	1.5
2060	15	17	17	2.7	3.5	3.5
2080	22	25	32	3.5	4.0	7.5
2100	27	35	46	2.5	5.0	7.0

Table 6.1 Global sea level change with respect to 1961-1990 average, derived from the HadCM3 climate model. Source: UKCIP (Hulme et al 2002). Note these values are 'somewhat less than the quoted IPPC values for the 2100 since we are averaging over the period 2071-2100' (Hulme *et al* 2002).

The wider implications of Table 6.1 are the annual rates of sea level change, which in the second half of the century are comparable to that of the Holocene transgression, were the coastline experienced significant changes in plan-form and structure. This expectation of wide scale-changes to the coastline is rarely discussed (by planners or conservation bodies for example), however if the effects of climate change are to be managed, then these discussions need to be aired with wider audiences, Local Authorities, National Government and beyond. These discussions need to encourage a longer-term perspective and improve the awareness of the geomorphic, climatic and oceanic[3] processes. The improvements in estuarine management over the last decade, creating managed realignment sites, need to be extended into higher energy environments. Similar principles should be employed: managing sediments and allowing processes to continue to move sediment freely, all within an understanding of the next evolutionary-step for the landforms. In addition the norm should include setting back new development, only permitting soft & movable land-uses in flood prone areas and accommodating environmental instability. This should be seen within the wider context of working with processes, much like the principles of sustainable catchment management, as part of a range of sustainable initiatives within a context of Integrated Coastal Management.

[3] Oceanic factors would include the effect of storm surges and their behaviour as they change from deep-water to shallow-water waves.

7 Conclusions

This thesis set out to address the following aims (from Chapter 1):

Aim	Outcome
Reconstruct local sea level history from published data and modelling, supplemented with new datable material.	Otterswick Forest found, sampled and dated which refines local sea level curve.
Map subsurface former shoreline positions using subsurface techniques.	GPR established the subsurface architecture of freshwater dominated areas and coring techniques extended this into saline areas.
Account for historical and present change of shorelines	Historical maps and topographic surveys have established the context of change and it's contemporary component.
Collate juxtaposed active and relict landforms and datasets into a conceptual model of coastal evolution; thus tracing the late Holocene, historical and present morphological expressions of variations in sea level and sediment supply.	CEM constructed integrating the stages of development from 8kaBP to the present day. Future sea level rise has been used to forecast future change.
Finally reflect on the generality (or otherwise) of these balances and outcomes, and outline the main management implications.	The critical role of sediment supply has been emphasised and the implications of this are increasingly applicable given the increased areas experiencing relative sea level rise.

In Sanday, sediment supply is the key factor which has negated the conventional effects of relative sea level rise. The delicate balance between sediment supply and sea level on a low lying undulating geological surface has preserved some of the geomorphological features which once extended into a marine bay and transformed sea into land, *whilst* relative sea levels were rising. These developmental landforms have not only survived the subsequent submergence but have been reflected in the archaeological record of this island. This *island building* has occurred during a period when submergence would have otherwise lead to further fragmentation of the archipelago and can be contrasted sharply with the conventional transgression and erosion on beach units elsewhere.

The positive sediment supply was fuelled from three sources, including:

- delivery of existing adjacent terrestrial deposits consumed by more rapid rates of relative sea level rise, in excess of 3mm/yr. These provided minerogenic sands and gravels (but whose volume has reduced as relative sea level rise slowed towards present rates);
- reorganisation of existing marine minerogenic sands and gravels which once existed at lower, earlier sea levels, but that have remained within the sediment cell;
- augmented by biogenic sediment production that phased to supply the nearshore at a time when the volume of terrestrial contributions started to fall.

The initiation of wide-scale dominance of sand within the coastal zone dates from at least 3kaBP, which is comparable with other locations within the Orkney archipelago. However, this date is later than the dune and machair systems in the Western Isles. The sourcing and route-ways of the till-based component, although now small, has been traced using the OSL signal from sand from the source outcrop, to an initial sand deposit and on to a secondary deposit.

Implications of the locally affluent sediment supply conditions experienced in the Bay of Newark between 8-3kaBP, was not only contrasted by the neighbouring beach units, but during the last 3kaBP reflected transgressional modes of coastal change, with all three beach units adjusting towards swash-aligned bay-head beaches. This was a response to dwindling sediment supply conditions and limited relative sea level rise rates, reflecting the increasing dominance of a wave field, which relates to the recently submerged bathymetry and therefore geological basement control.

Lateral and transgressional reorganisation has been reflected, not only within the geomorphology but also in the place names, folk memory and the earliest to most recent maps. The recent behaviour of the three test sites reflects the longer-term balance of the landforms, their forcing mechanisms (sediment supply, sea level and inherited basement geology) and the absence of more significant storm events during the survey period. Although the 2001-2003 topographic surveys demonstrate little more than seasonal fluctuations, the geomorphology reflects changes over longer periods, which indicate:

- A gravel core foundation, which will resist larger magnitude events.
- Biogenically dominated sands which are largely stable apart from their coastal fringe, which is periodically clipped back, by occasional storms.
- Low-lying intertidal areas, some of which have been inundated, will become increasingly submerged by 2mm/yr relative sea level rise and storm surges, which will increasingly become a management problem.

The combination of landform evolution and the ongoing changes in forcing mechanisms will increasingly threaten these low-lying islands, their population, infrastructure and habitats. From a Nature Conservation perspective, periodic frontal erosion and inundation by storm surges are one part of the range of natural forcing processes, which have always operated and which are responsible for the evolution of the island. Thus, the natural free reorganisation of sediment is the very essence of these habitats, which in some locations are responsible for self healing (i.e. the gap in the Newark dunes). As such they do not present a direct concern to the Earth Science interests of the island. However, this may not be said for the other ecological and ornithological interests in the island, which may be viewed (by others) as being threatened. Therefore all management options must reflect the underlying primacy of geomorphological processes in the long-term health of low lying habitats. Any management approaches which resist the long-term changes in evolution of the island may start to divorce the habitat from the processes which were responsible for their creation and future survival. As a result these dune and machair on the periphery of the UK are a wasting asset and should be conserved as such, rather than being preserved in their present state. This perception is being realised on the (submerging) south coast of England, where a principle of no net-loss for designated habitat is increasingly becoming realised as unachievable and counter productive to the longer term objectives of nature conservation (Orford, 2004).

8 Appraisal of methodology & Future work

Improvements of methodology

One shortfall of this research is the limited confidence associated with the dating of individual sets of gravel ridges. At present relative ages are the best we can employ, as have been here. However, it is possible that more datable materials may emerge that allow the age of gravel features to be dated, which would confirm the time line presented here. OSL dating of the sands that were intercalated with the gravels would allow this or $_{14}C$ materials found in association with the ridges. A second issue experienced within the project was the mislocation of transects during beach surveying. These occurred due to two reasons, firstly the dynamism of the habitat resulted in areas being significantly alterations between surveys, secondly, however was our limited experience with the GPS system and always learning more with time. To address this limitation, if the surveys were repeated a greater number of survey pegs would have been used, possibly with metallic targets so that a metal detector could be employed in hard-to-find-areas, also the employing a technique where previous (years) surveys are loaded into the GPS unit and the survey route is traced over again.

An alternative approach, which would be utilised, would be Digital Phototgrammetry. More data sets area available now, and the computing power is more readily available than at the start of the research period. This would allow the 3D analysis of DTMs derived from sets of present and historical aerial photos. This technology is even more suitable given it's compatibility with other remotely sensed data sources, including LiDAR, MicroSAR and the forthcoming NanoSAR for example.

Future research directions

- o Biogenic production, volumes, dates, residency times, mixing rates, sources, pathways etc. Further interpretation of benthic surveys (incl SNH data sets) of nearshore, this would allow the rout-ways from the source areas to the initial and present temporary stores to be investigated. This would also establish whether this source of additional sediment supply is set to continue, and whether our management of the seas could be improved, in this regard.

- o The extension of the sensitivity (OSL brightness) investigations of the till source areas, thereby establishing the other part of the sediment route-ways. The further development of OSL in this *unexpected* direction could prove useful in improving our understanding of how landscape and coastal changes occur especially given the start climate change scenarios predicted for the second half of this century.

- o Additional detail to constrain sea level curve – expand the search for the rest of the buried forests of Otterswick and Orkney.

- o Further constrain the flooding of Cata Sand and comparable assemblages elsewhere

- o Shallow seismic investigations extending the tomographic interpretation of the islands core.

- o Date the gravel ridges more accurately, than their relative ages established within this investigation.

In addition to this there are some more specific research questions which could also be asked:

- Timing of the flooding of Cata Sand. – possibly look a the altitude of The Clogg and estimate the age via the sea level curve.
- Also get an understanding of the velocities within The Clogg during flood tide and see if Cata Sand is filling with or emptying of sediment.

PAGE

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