The Geomorphology of Viking and Medieval Harbours in the North Atlantic

John Preston

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Declaration

The work presented in this thesis is original and my own, except where work which has been part of jointly-authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been to the work of others. No part of the thesis has been submitted for any other award or professional qualification.

Chapter 4

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Abstract

The aim of this thesis is to understand the role of geomorphological change in the abandonment of Norse harbours in the North Atlantic. Nodes of maritime activities that were established by Norse settlers during the Scandinavian Viking Age often developed into important towns and cities. Some of these, however, disappeared for unknown reasons. Norse harbours in the North Atlantic varied in scale. They ranged from small landing beaches used by small boats for local use through to much larger anchorages handling considerable trade and being important nodes on the transatlantic trading network.

Changes in coastal geomorphology necessitated a response from seafarers. In this thesis, a conceptual framework for the formation, recovery and stability of headland-dominated sandy beaches in high-energy environments is established, based on empirical observation and on the use of the MIKE21 numerical sediment transport model. Under persistent calm climatic conditions, nearshore seabed gradient is a weak control on beach formation and persistence in embayments. However, under persistent stormy conditions, nearshore sea bed gradient becomes the prominent control. Embayments with nearshore gradients of > 0.025 m/m inhibit beach recovery on a sub-annual timescale, while gradients < 0.025 m/m promote beach recovery.

These ideas are assessed in the Shetland Islands, using numerical modelling, geomorphology and OSL dating on sand blow deposits. In the late Norse era beach landing sites in Unst became prone to depletion and destruction because of increased storminess. Numerical modelling (MIKE21) supports the idea that the recovery time of different sandy beaches on Unst is dependent on average nearshore slope. The beach at Sandwick has shallow nearshore gradients and recovers quickly in the face of storminess, but beach stability at Lunda Wick is more uncertain, and thus Lunda Wick represents a more problematic landing place.

The Norse harbour of The Bishop's seat at Garðar in the Eastern Settlement of Greenland is assessed to evaluate the impacts of gradual long term geomorphological change on coastlines that lack soft-sediment. A high resolution, near shore bathymetric survey shows that, due to relative sea level rise of 1 m/500 years, the landing site became more difficult to access during the later period of Norse settlement and key onshore infrastructure was disrupted.

The possible role of terrestrial supplies of sediment in changing the viability of landing places is assessed through an evaluation of the Norse trading centre of Gásir in northern Iceland. Geomorphological mapping and analysis of fluvial connectivity indicate that the delta on which Gásir is located is prone to aggradation from large, irregular pulses of sediment derived from landslides in the catchment. Written sources and geomorphological mapping indicate geomorphological changes around the same time that trade was shifting to the use of boats with a deeper draft. Cultural change and environmental changes would have reinforced each other in rendering the harbour site nonviable.

Geomorphological forces acting on varying spatial and temporal scales have the potential to disrupt the use of landing sites. Whether environmental changes led to the abandonment of a landing site was strongly influenced by the seafarers' *competence* and available *technology*. Higher levels of competence would enable more problematic landing sites to be used, but there are limits to this adaptation. Technological changes, such as the use of larger and deeper draft boats, would have changed the geomorphic requirements for harbour sites, and thus may have led to a *passive* abandonment of the site over time rather than *active* abandonment such as that in the face of a catastrophic change of the shoreline. Coastal geomorphology was a critical factor affecting the use of Norse harbours, as it interacted with the wider cultural and economic developments in the North Atlantic realm. This thesis demonstrates that numerical sediment transport analysis is a powerful tool in coastal archaeological research as it can illuminate processes driving observable changes in the empirical record.

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Table of Contents

Appendices

Appendix A – Luminescence dating of sediments from Underhoull and Lund, Unst, Shetland.

Appendix B – Geomorphological maps.

- **B1 – Lunda Wick, Unst, Shetland**
- **B2 – Sandwick, Unst, Shetland**
- **B3 – Hvalsey, Greenland**
- **B4 – Igaliku Kujalleq, Greenland**
- **B5 – Qassiarsuk, Greenland**
- **B6 – Igaliku, Greenland**

Appendix C – Soil core photographs.

- **C1 – Burra Firth**
- **C2 – Wick of Skaw**
- **C3 – Sandwick**

Appendix D – Model sensitivity runs

List of Figures

List of Tables

1 Introduction

1.1 Overview

> *"As for me, I am tormented with an everlasting itch for things remote. I love to sail forbidden seas, and land on barbarous coasts." – Herman Melville,* Moby Dick, or, the Whale (*1851, page 29*)

The overall aim of this thesis is to understand the key drivers of coastline evolution over a range of spatial and temporal scales and their significance for the development, continuity and/or decline of Norse and Medieval harbours.

There is perhaps no more evocative an image of adventure in the collective imagination of Northern European cultures than that of the Viking sailor, ploughing the vast and tempestuous seas of the North Atlantic in search of honour and riches in far off lands.

The Norse diaspora, during which large parts of northern Europe and the North Atlantic landmasses were colonised by successive waves of peoples originating from Scandinavia (~800AD – ~1000AD), had a profound and lasting impact on many Northern Hemisphere cultures beyond mere imagination. Indeed, the populations of Iceland and the Faroe Islands and partially those of Scotland, Ireland and northern England all share a common language root, and common traditions (e.g. Dahl, 1970; Birks, 1988; McGovern, 1990, Roesdahl, 1998; Ross, 1998; Wilson et al., 2001; Hadley, 2006; Hall, 2007).

What is perhaps unique to the Norse, amongst the great civilisations against whom they are often compared, is that there was never a Norse *empire*. When we think of the Romans, the Byzantines, the Carolingians, the Ottomans, the Spanish, and many other powerful historical civilisations, they operated under a centralised political structure. They often had a capital city as the seat of emperors or kings that administered the lands which lay under their influence, however successfully or unsuccessfully. Yet there was never any centralised political power of the Norse as an entire people (Barrett, 2008; Laxness, 2009; Winroth, 2014). They existed instead as a *culture*, sharing a common language, common traditions and a common mythology (e.g. Davison, 1962; Gordon, 1981; Fitzhugh & Ward; Lindow, 2002; Townend, 2002; Kendall, 2015, Krzewińska et al., 2015). Each Norse settlement was essentially independent. Many hypotheses have been considered for the drivers of the diaspora and motivation behind the colonisation efforts, with none entirely agreed upon. One notable work evaluating the various 'determinisms' for Norse expansion is by Barrett (2008), who suggests a 'youth bulge' as one of the most likely causes, with young Norsemen primarily concerned with seeking treasure (Barrett, 2008). However, another common explanation of the origin of the Norse diaspora was the desire to flee from increasingly centralised power being felt in Norway in the 8th century (e.g. Imsen, 2010; Sigurdsson, 2013). Figure 1.1 is an idealised map of the routes Norse raiders, traders and settlers took throughout Europe and the North Atlantic in the early Norse period.

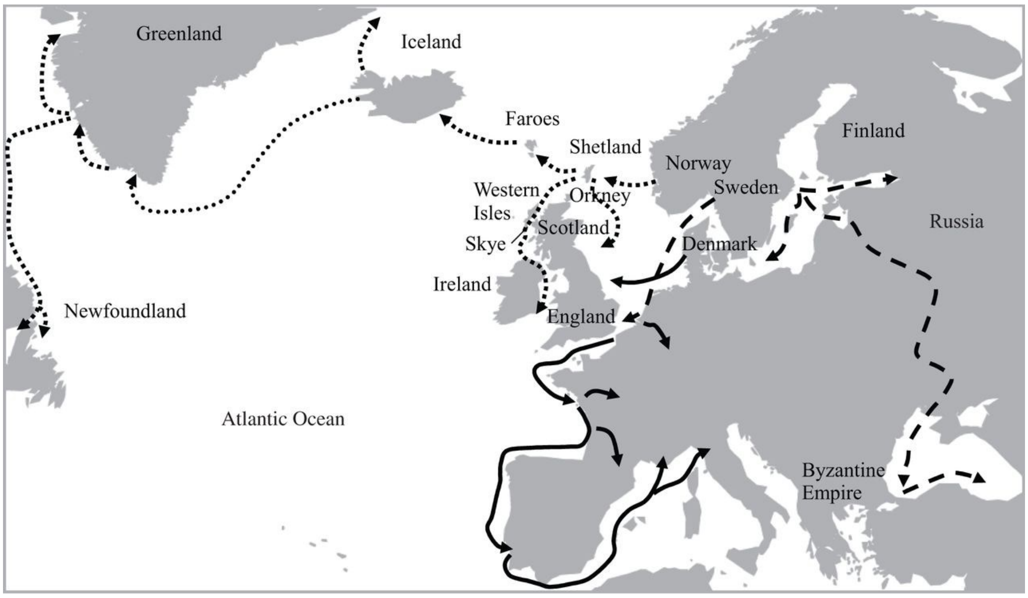


Figure 1.1 – Routes of the Norse Diaspora from Scandinavia (source: Krzewińska et al., 2015). Different coloured lined represent migrations of different populations.

The Norse Diaspora did not proceed solely in a westerly direction. Norse influence was felt throughout Europe (Jones, 1985; Thaden, 2001; Dachowski, 2006; Barrett, 2008). The city states of Novgorod, Muscovy and Kiev (now modern day Russia and Ukraine) suffered regular Norse raids in the 8th and 9th centuries, and were eventually founded by descendants of these raiders (e.g. Birnbaum, 1987; Melin, 2005). They even reached as far south as Constantinople and beyond. Indeed, the Varangian Guard of the Byzantine Empire was typically composed of hardened Norse warriors (Dawkins, 1947; Hutter, 1985). However, the Norse had perhaps the most lasting historical impact in their journeys west.

1.2 The Westward Expansion

The Norse benefitted from their skills as seafarers and navigators to exploit the seas to the west of Norway (e.g. Haine, 2007). They were also excellent shipwrights, with clinker-built ships, such as the famous longship, being the workhorse of early Norse voyages. The clinker design (hull planks overlapping) had been in use for several centuries before the beginning of the Viking Age, with the Nydam boat being perhaps the most famous early example of this design. The Nydam boat was excavated from a site in Denmark, and is dated to approximately 320. The addition of rectangular sails and keels to clinker-built boats in Scandinavia allowed greater range and stability than oar-powered ships. The Norse therefore had a long tradition of shipbuilding, which they exploited to its fullest when it came to the opening of the Viking Age (Christensen, 1982; Crumlin-Pedersen, 1991; Heath, 2005; Crumlin-Pedersen, 2009; McGrail, 2014).

The first recorded Viking raid in Britain famously occurred in 793 CE at the Lindisfarne monastery on the north east coast of Northumbria. This opened an era of increasing raiding and settlement of the British Isles by the Norse primarily from Denmark and Norway, and marked the ‘traditional’ start of the Viking expansion period (e.g. Sawyer, 1971).

This settlement extended west across the North Atlantic through the 9th century. The northern British Isles, the Faroe Islands, Iceland and eventually Greenland were all colonised by the Norse between 800 – 1000 CE (e.g. Jones & Sasada, 1984; Sines, 2015). Once long thought to be simply a legend from the Norse Sagas, the remains of a small Norse settlement were found at L'Anse aux Meadows on the north-east tip of Newfoundland in 1960, proving that the Norse even reached as far as Canada representing the first (recorded) Europeans to have made landfall North America (Ingstad, 1962; Ingstad, 1977).

As with all settlers throughout history, the Norse lived off the land as they extended their culture throughout the North Atlantic. The Norse were expert farmers, and introduced animal husbandry throughout their colonies, raising cows, pigs, horses and sheep. In some areas (i.e. Faroes, northern British Isles, and parts of Iceland) they grew cereal crops such as barley, flax seed and oats but also they relied upon wild resources to supplement their subsistence diets. They would trap birds, and regularly take to sea to gather fish and marine mammals. These practices formed the basis for trading networks, and over time low-bulk but high-value goods such as walrus ivory, steatite items, pottery or falcons began to give way in the mid-13th century to high-bulk items such as stockfish (dried cod for the most part, but haddock and other species also) and wool. (Hansen, 1991; Amorosi et al., 1996; Perdikaris & McGovern, 2007; Dugmore et al., 2012; Harrison, 2013; Kendall, 2014; Marttila, 2016). Fish in particular became a major source of economic value, with evidence from contemporary Norwegian sources suggesting a significant increase in fishing in Norwegian and British waters by no later than the 12th century, and a significant increase occurring in Iceland from the 13th century (Marttila, 2016). This was accompanied by changes in ship technology towards larger, deeper draft ships such as cogs which were capable of carrying far more cargo than earlier, shallower draft boats such as knarrs (McGrail, 1998; …2014).

1.3 Harbours in the North Atlantic

The Norse were very reliant on the sea. Many aspect of their lives, from food supplies to trading to transport, relied upon it. Over successive generations, the Norse built up an unrivalled knowledge of seafaring which they exploited to its fullest in their adventures west of their homelands in Scandinavia.

There are no ships without harbours, and no harbours without ships. The Norse seafarers relied upon a network of anchorages, landing sites and harbours and needed an intimate knowledge of find, approach and use these sites (Marcus, 1955; Marcus, 1960; Zilmer, 2005). These could range from small landing beaches used on a daily basis for local travel, foraging and nearshore fishing, to major harbours with associated infrastructure handling considerable international trade (e.g. Morrison, 1978; Hansen, 2000; Smith, 2007; Arneborg, 2006; Harrison, 2013).

The knowledge of safely navigating from place to place could become outdated, due the changing weather patterns, currents and coastal geomorphology. This was perhaps less critical if the harbour was visited frequently and thus knowledge was kept up to date. However for less frequently used or visited places, environmental change could present a major risk. As way of example, the Great Candlemas Storm of 1602 destroyed seven beaches overnight at Kirkjubøur, Faroe Islands (Guttensen, 1992), which never reformed. This was a significant loss of safe landing beaches in the area and would have both immediately disrupted the local ability to access the sea, as well as being problematic for infrequent visitors to the landing place who would be relying on the stability of this coastline. Thus the rapid change in coastline immediately impacts harbour users on a short-term, but also long-term timescale when landing sites do not recover.

1.4 Geomorphology of North Atlantic coastlines

The North Atlantic coasts travelled and settled by the Norse were very varied. From the deep rocky fjords of Norway, to sandy pocket beaches of Shetland and the extensive volcanic beaches of Iceland, the Norse found themselves in many different geomorphological settings, and thus also exposed to some very different trajectories of geomorphological change.

Geomorphological processes can act upon coastlines on a varying temporal and spatial scales (e.g. Wolman & Miller, 1960; Lippmann & Holman, 1990; Masselink et al., 2014). On a decadal to centennial timescale, changes in relative sea level can alter coastline morphology (e.g. Dean & Dalrymple, 2004, pp. 36). On more immediate timescales, storm action can cause significant change to a coastline through removal of beaches, or erosion of cliffs (e.g. Cooper et al., 2004; Mastapaud et al., 2009, Limber & Murray, 2011). Conversely, a storm can deposit material on a coastline and create beaches, and progradation of estuaries can significantly alter the morphology of a coastline (e.g. Dalrymple et al., 1992; Woodroffe et al., 1992).

The North Atlantic is characteristically subject to frequent storms and has a complex history of relative sea level change. Sediment can be brought to the coastline from both offshore and onshore sources, and both input and removal of sediment can be both gradual or abrupt (e.g. Rogers, 1997; Bond et al., 1997; Clarke & Rendell, 2009; Trouet et al., 2012; Gehrels et al., 2006; Brader, 2015). This has profound inplications for the utilisation of coastlines by seafarers if the geomorphological conditions of a harbour changed dramatically, a once useful anchorage or landing place could become unviable, even dangerous. Depending on the nature, scale and speed of geomorphological change, there was scope for adaptation, however, storms could render a previously useful landing place unviable overnight, thus requiring the area to be abandoned. The concepts of *active* and *passive abandonment* are useful here to consider Norse adaptation to a changing coastline (Dawson, 2013). If a landing place is destroyed by storm action in a single event, it would be *actively* abandoned, with the conscious intention of never using it again, or at least never using it in its present form. If a harbour, over years or decades, becomes slowly unviable either by relative sea level rise, progressive siltation or erosion, the landing place may be *passively* abandoned, that is to say, used less and less over a period of time, but with no conscious intention by the users to ever actually abandon the place.

1.5 The Little Ice Age

As mentioned above, the North Atlantic is subject to frequent storms. Climatic conditions and their impact on coastal geomorphology is an major theme of this thesis, as the Norse settlement period and the transition towards the early modern period occurred coincident with major changes in the climatic conditions in the Northern Hemisphere, the transition from the Medieval Climate Anomaly (MCA) to the Little Ice Age (LIA). Mann (2009) reconstructed surface temperatures to show that the MCA began around 850 and is characterised by a period of relatively calm climatic conditions. Storms would still have occurred, but fewer and more predictable. This came to an end in 1250, and storminess began to increase until a clear signal of a decreasing average surface temperature is seen from approximately 1400 (Figure 1.2).

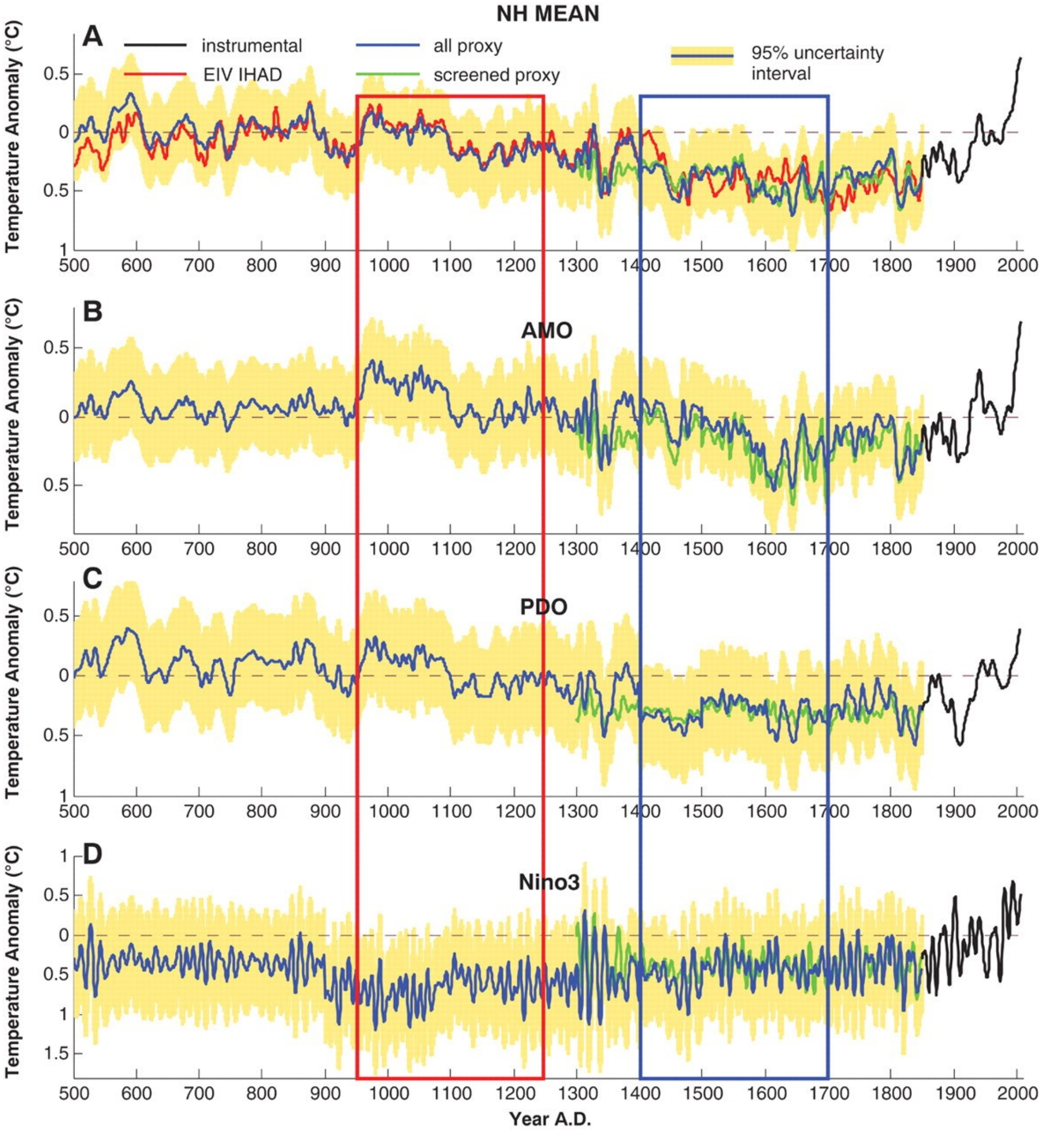


Figure 1.2 - Decadal surface temperature reconstructions (reproduced from Mann, 2009). Surface temperature reconstructions have been averaged over (A) **the entire Northern Hemisphere (NH),** (B) **North Atlantic AMO region [sea surface temperature (SST) averaged over the North Atlantic ocean as defined by (*30*)],** (C) **North Pacific PDO (Pacific Decadal Oscillation) region (SST averaged over the central North Pacific region 22.5°N–57.5°N, 152.5°E–132.5°W as defined by (*31*)], and** (D) **Niño3 region (2.5°S–2.5°N, 92.5°W–147.5°W). Shading indicates 95% confidence intervals, based on uncertainty estimates discussed in the text. The intervals best defining the MCA and LIA based on the NH hemispheric mean series are shown by red and blue boxes, respectively.**

These time periods are critical to the understanding of how the Norse were impacted by changes in the coastlines they exploited as harbours and landing sites on a variety of temporal and spatial scales.

1.6 Scientific context

In this section I will present an overview of coastal geomorphological processes, concentrating on those found in high-energy environments such as the North Atlantic. I will also present an overview of Norse settlement and seafaring in the North Atlantic. Detailed, field-site specific historical and archaeological context will be presented in the respective thesis chapters.

1.6.1 Coastal geomorphology

Coastal erosion is a well-studied phenomenon, and is caused by a variety of processes, such as change in sea level, variation in sediment supply, waves, storm surges, longshore removal of sediment and transport, and sediment sorting on beaches under wave action (Zhang et al., 2011; Meyer et al., 2008; Sunamura, 1992). Each of these processes vary in their contribution to coastal erosion dependent on the location and characteristics of the coastal reach being studied, and it also stands to reason that these processes can be altered by changes in climate (Viles & Goudie, 2002).

The dominant controls on coastal evolution are dependent on the particular location being studied. The vulnerability of coastal areas to erosion is determined by its topographical and geomorphological setting (Aunan & Romstad, 2008). Yet common to all coastlines are two controls that act continuously: wave action and sediment transport. Data on wave action can be sourced from various places, most commonly from wave buoys and gauges in the study reach (Ashton & Murray, 2001). Wave action is a critical mechanism for the evolution of coastlines as it removes and reworks sediment, and even small changes in the fetch, angle and approach of waves can have a significant effect on shoreline evolution. Ashton and Murray (2006a, 2006b) showed how the deep water angle of wave approach can have a significant effect on shoreline evolution. Waves approaching the shoreline at a low-angle (~45° or less) tend to lead to ‘flattened’ planform shoreline shapes, with the opposite response from high-angle waves, forming embayments and headlands.

The availability of soft sediments along a coastline is one of the key drivers in coastal evolution. Understanding and quantifying sediment transport can be problematic, as it relies on identifying and quantifying the sediment budget relevant to the coastline under study. A sediment budget can in theory be calculated using the continuity equation (Dietrich & Perron, 2006), however in practice this is not sufficient for accurate modelling due to the lack of empirical evidence being used in this technique. Sediment budgets can be quantified in a number of ways. Traditional techniques, such as sediment cores or boreholes (Berendsen & Stouthamer, 2001) can be used to estimate the composition and volume of sediment in a fluvial catchment (which can be a large contributor to coastal sediments) but can be labour intensive and has the potential to be unrepresentative of a catchment if core sample locations are inappropriate. This could be particularly problematic in a coastal setting, where the source of sediment is less clear. Remote sensing techniques such as aerial photography or LIDAR can offer a comprehensive view of all sources and sinks of sediment in a catchment. Areas of low elevation are identified by LIDAR, which can give indications of sediment sinks. Aerial photography can be used to delineate sediment sources, for example large gravel bars or glacial till in a catchment. However it cannot identify precise composition of sediments (Brown et al., 2009, Meyer et al., 2008). Ground penetrating radar can be used to determine composition and depositional patterns in sediments, however it can be problematic depending on the depth of sediment and the interpretation of results, which is not straightforward (Neal, 2004). Physical techniques such as bore hole sampling, and other remote sensing such as resistivity and seismic surveys can also give indications of subsurface structure (e.g. Wunderlich et al.; 2015; Wilken et al., 2015). A study by Bluck (1998) looked at the actual structures present upon gravel beaches. The conclusion was that gravel beach structures are determined by wave/beach interaction, and that the clast assemblages found on gravel beaches – discrete units of clasts of certain textures and distributions – are often separated by planes of discontinuity. These structures can give indications of the depositional environment. For example, a regressive gravel barrier tends to form a series of gravel ridges separated by lagoonal deposits. Conversely, a prograding gravel structure can form as a response to a continuous supply of sediment to the beach surface (Bluck, 1998; Buscombe & Masselink, 2006).

Previous research into modelling coastal erosion has focused on a variety of scales, from large scale modelling of coastlines 100 km+ (Meyer et al., 2008; Zhang et al., 2011), to medium scale coastlines 20 km+ (Makiaho, 2007), to smaller scale coastlines ~1 km in length (Murray & Limber, 2006a). These models are of variable complexity. For example, the Zhang et al. (2011) model contains several modules which take into account ocean circulation, wind-induced waves, sediment transport, cliff erosion, bathymetry, and nearshore storms. In contrast, the Murray & Limber (2011) model of beach evolution contains only three equations to control the evolution of beaches in front of rocky cliffs. The complexity of models does not necessarily correlate with the scale of coastline being modelled. Cowell et al. (1994) modelled large scale coastal behaviour using simple principles of sediment mass balance, applied to the evolution of the south Australian coast. Conversely, the complex model of Zhang et al (2011) mentioned above was for a study area of comparable size.

Modelling must necessarily be tested/validated by observation. While short-term coastal evolution has been observed and recorded (Lazarus & Murray, 2007; Rosser et al, 2013; Lim et al, 2010), yielding important empirical evidence to refine short-term coastal modelling, the modelling of coastal evolution over longer timescales is more problematic. For modelling of processes over the last approximately 200 years, it is possible that mapping is available that will allow models to be partially calibrated (Mäkiaho, 2007), however the accuracy of such maps cannot always be relied upon without an understanding of the cartographic techniques used at the time. Therefore, often the only option available for model calibration is to create models that reproduce those features of observed coastal erosion (Cowell et al., 1994; Ashton & Murray, 2006).

Analysis and prediction of coastal evolution beyond the short-term must also address relative change in sea level. The level of the sea along the coast is a major control on the deposition and erosion of sediment, and has fluctuated throughout history. Sea level change is either eustatic (net changes in the volume of water, driven primarily by changes in global ice coverage), isostatic (changes in land elevation relative to a fixed point, driven by glacial rebound or tectonics), or a combination of both. Long-term sea level change can be calculated by observing such features as raised beaches, ancient shorelines and isolation basins (e.g. Sanjaume & Tolgensbakk, 2009; Long et al., 2011; Mercier et al., 2013), however reconstructing past sea level change on centennial timescales is not a straightforward process. For particular models of coastline evolution, analysis of foraminifera in sediment samples from isolation basins can help calibrate models for sea level change (Norðdahl & Pétursson, 2005; Lloyd et al., 2009). If the presence of certain species of foraminifera and diatoms (that are more tolerant to certain conditions, such as brackish water, open ocean, etc.) correlate to the model's predicted changes in coastline when the basin became isolated from the sea (e.g. Marriner & Morhange, 2007; Lloyd et al., 2009; Mueller et al., 2013), then it is possible to reconstruct the rates of relative sea level change. Lloyd et al. (2013) applied this technique to reconstructing sea level from North West England, which has comparatively limited past sea level data available.

Seal level does not necessarily follow a simple curvilinear line throughout time (i.e. linear increase) on a coastline, whether rising or falling. Eustatic and isostatic forcing, from the response of land to the loss of ice sheets after the last glaciation, plays a major role in this. In terms of the Scottish Ice Sheet, it can be seen that different loading forces equals different responses from the landscape. For example, those areas that were at the margins of the Scottish Ice Sheet, such as the northern isles and particularly Shetland, have a very minor isostatic response compared to those closer to the centre of the Ice Sheet, such as the Western Isles of Scotland and the West Coast of Scotland (e.g, Lambeck, 1995; Shennan & Horton, 2002; Hubbard et al., 2009; Clark et al., 2012).

In areas of variable ice loading such as the Greenland Ice Sheet, relative sea level change can be very different in a relatively small spatial area. For example, sea level change estimates in southern Greenland can vary up to 1 m/1000 years in as little as 25km (Sparrenbom et al., 2006; Kjuipers et al., 2008). This can potentially make drawing conclusions on large-scale geomorphological change in these areas problematic.

Coastal erosion processes in polar regions have arguable more complex controls than those towards the equator. Polar climates are more sensitive to climate change. This is caused by a process known as Arctic amplification, where the loss of sea ice exposes darker albedo surfaces and ocean, which absorbs solar radiation more readily than ice/snow, thus temperatures tend to rise faster than those further south (Serreze et al., 2006; Screen & Simmonds, 2010). This exposes Arctic coastlines to more rapid variation in erosion and deposition rates and is particularly true for permafrost coastlines. These ice-rich coasts are subject not only to erosion mechanisms impacting lower latitude coastlines, but also to thermo-erosion. Higher water temperatures can lead to rapid erosion of permafrost coastlines (Mueller et al., 2013), coupled with higher water temperatures leading to the loss of ice armouring the coastlines in these areas. This has implications for coastal archaeological sites in Arctic regions, which may be subjected to much more rapid degradation than those further towards the equator. (e.g. O'Rourke, 2017).

In non-permafrost coasts in the North Atlantic, rapid coastal evolution, whether erosional or depositional in nature, has implications for coastal archaeology, particularly the identification of former landing places and abandoned harbour sites. It is only relatively recently that research has been turned to the identification and understanding of ancient harbour evolution (e.g., Marriner & Morhange, 2007, Marriner et al., 2008). Many archaeological sites are under threat from coastal erosion (e.g., NORDEN, 2011, Aunan & Romstad, 2008; Dawson et al., 2017), and have only recently been focused on in areas such as Norway (Knitter et al., 2012). Therefore research into understanding coastal evolution in these areas is increasingly urgent to understand and potentially protect these unique places.

1.6.2 Archaeological context

The word ‘harbour’ in this thesis is used to denote any number of permutations of locations that boats can dock. The Oxford English Dictionary defines harbour as “A place on the coast where ships may moor in shelter, especially one protected from rough water by piers, jetties, and other artificial structures.”

Based on this definition, harbours can range from simple landing places, where shallow-draft boats can run up onto beaches, to infrastructure-backed locations, composed of jetties and other structures (e.g. warehouses, storehouses). Nitter et al. (2012) offer that a ‘harbour’ should offer protection from currents, winds and waves, and have an easy seaward approach under a wide range of conditions that should be free of skerries and sunken rocks, the sea-floor should be favourable for anchoring, and fresh water must be available. Nitter et al. also makes a distinction between landing places and harbours, and suggest that what makes a ‘good’ landing place does not necessarily make a ‘good’ harbour. That is, landing places where small boats could run up onto shore (for example beaches, inlets or creeks) were not necessarily able to support more extensive harbour infrastructure for deeper draft boats. Harbours, in contrast, may be identified because of their infrastructure - especially if this is constructed from masonry.

For the purposes of this thesis, the word ‘harbour’ will encompass all these definitions. Except where specific definitions related to landing places, harbours and anchorages, as mentioned above, are required for discussion purposes.

The intended use of harbours could lead to them having very different characteristics. For example, most harbours may be used as centres of trade in which can access needs to be easy and straight forwards. Solli (2014) noted, however that harbours may be used as safe havens from attacks or raids. In this case, a harbour that is actually complex to navigate, with shoals and skerries as natural defensive lines, would be favourable. Only by local knowledge of the navigation of these places would these be ‘safe’ to use.

The changing nature of ship technology is an important control on the use of harbours in this time period. In in the 9th century the long ships, *faerings* and *knarrs* (figure 1.1) were used for marine voyages. These were robust clinker built, shallow-draft keeled boats, allowing them to be beached wherever a suitable soft sediment shoreline could be located on a beach, inlet or creek. In the North Atlantic seaway these began to give way to larger and deeper draft vessels, such as the cog, the development of which was driven by the needs to move low-value but high-bulk commodities (e.g. Unger, 1980; McGovern, 1990, Crumlin-Pedersen, 1991; Feeley, 2012). which had different mooring needs from the earlier ship designs (Crumlin-Pedersen, 1991; …, 2002; Cunliffe, 2001; McGrail, 1998).

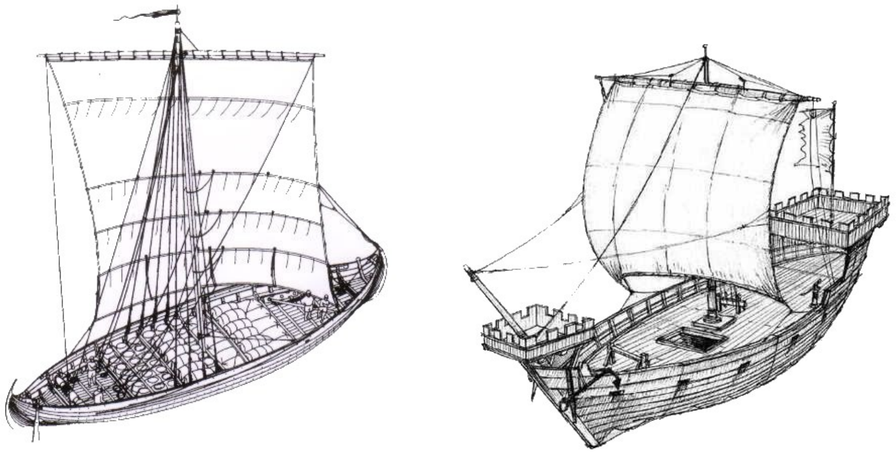


Figure 1.3 - Illustrative examples of a knarr (left), approximately 20 m in length, and a cog (right), approximately 30 m in length (figures on deck for scale). The draft of a cog was over twice as deep as a knarr (source: Løset, 2004).

During the early middle ages, certain harbours in the North Atlantic islands became important centres of trade and economic power. Contemporary sources and archaeological investigations have established several of their abandoned harbour sites. A well-known example is Gásir, on the eastern coast of Eyjafjorður, northern Iceland. This was a major trading harbour in the summer months, and was mentioned several times in contemporary Icelandic sources between the 11th and 14th century (Pétursson, 1999; Roberts, 2002; Harrison et al., 2008; Harrison, 2013). Archaeological investigations have revealed Gásir to be a large, well established harbour with a network of booths (temporary structures used by harbour workers) and even a church, which underlines its significance. The last mention of Gásir in literature is in 1391 and is believed to have been abandoned very soon afterwards. Extensive archaeological excavations carried out on this site revealed an extensive network of trading booths and the remains of non-local pottery (Roberts, 2002; Harrison et al., 2008).

In Greenland, the most important harbour in the Eastern Settlement (in southwest Greenland) was Garðar (the modern settlement of Igaliku) (Arneborg, 2003; … 2006; Madsen, 2014). This was already an important trade site when the bishopric of Greenland was established. The first bishop to take his seat there did so in 1126, and it became a cultural and economic hub and remained so for most of the Norse period (Arneborg, 2006). The last recorded bishop to sit at Garðar did so until 1378. As the 14th century drew to a close less and less shipping from the east visited Greenland, and the last recorded European contact was in the early 15th century (Barlow et al, 1997; Dugmore et al., 2012).

Both Gásir and Garðar show evidence of significant geomorphological change (sedimentation and sea level rise respectively), and began to fall out of use in roughly the same time period as changing boat technology and shifting patterns of trade. This suggests that not just one harbour, but several locations across the North Atlantic around the 14th/early 15th century suffered from increasing external pressures which contributed to their abandonment.

1.7 Project - Harbours in the North Atlantic 800 – 1300 (HaNOA)

This thesis has its roots in the HaNOA project, a multi-national multi-year interdisciplinary project funded by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG, Grant #: CA 146/17-1). The core aims of the HaNOA project, split into six sub-projects (SP), is:

- to investigate possible port facilities and their functions by studying medieval written sources (SP1);
- to examine the topography of ports in relation to navigational aids (e.g. landmarks), ballast fields, the seabed and the locations of landing-places and port facilities on land (SP2);
- to refine and consolidate the so-called fetch method to localise and evaluate ports or landing-places (SP4);
- to analyse ballast as an archaeological source for the first time, in order to gain an understanding of the origins of trading vessels and the volume of maritime trade,

- **to understand the role of geomorphology in the function and abandonment of harbour sites (SP5)**;

- and to ascertain the most reliable indicators for the elusive ports of the Viking period and the Middle Ages in the North Atlantic. (source: http://www.spp-haefen.de/en/projects/hanoa-harbours-in-the-north-atlantic/)

This thesis is designed to fulfil, but not be constrained by, the aims of SP5 of the HaNOA project as listed above.

1.8 Thesis Aims

The overall aims of this thesis are to understand the key geomorphological drivers of coastline evolution over a range of spatial and temporal scales, focused on the North Atlantic, and how these affect the ways in which seafarers utilise the coast.

This overall aim is tackled by addressing four key research questions that will structure the dissertation:

1) What are the conditions necessary for a soft sediment coastline (e.g. beaches, deltas, estuaries) to remain stable over decadal to centennial timescales?

Soft sediment coastlines are the focus as they are the most favourable landing places for small boats, as rocky coastlines would have led to ships being damaged in anything other than flat calm conditions (which was rare in the North Atlantic). However, it is important to define what is meant by ‘stable’ in this question. Two types of stability are proposed: Locational continuity, and landform continuity.

Landform continuity is where a particular landform retains the same morphology and location over centennial timescales. Locational continuity is where a particular landform is present in the same spatial location over centennial timescales, however is subject to morphological change over these timescales. Examples of this would be a delta, saltmarshes and mudflats, as the location would persist however the specific morphology would change over time with variation in sediment supply and wave energy.

These definitions are important as they have implications in identifying coastlines which may be suitable for different utilisation by seafarers. A beach that has landform continuity could be a reliable place to establish a landing place that would endure over time. A beach that has locational continuity would still be useable as a landing place, but morphological instability would limit seafaring activities, as shoreline infrastructure would be undermined by changes in morphology (for example, shifts in sand locations, or blown sands)

This question will be assessed using empirical field data and morphodynamic models.

2) What are the drivers of instability of exposed, soft sediment coastlines?

This question is a necessary follow-on from question 1. If a coastline exhibits a lack of continuity or stability, it is important to identify and quantify the environment processes causing the instability. It is also important to understand whether these rates of change are gradual or sudden. Sudden changes in coastline morphology would suggest a particular environmental threshold may been passed, with profound implications for adaptive responses by people. Identifying thresholds of change would valuable insights for both past changes in coastline morphology, and also the potential future changes

3) How does the geomorphological context affect the structural equilibrium of coastlines utilised by seafarers along relatively sheltered coastlines?

The evolution of coastlines depends both upon their composition and the forces acting upon them. Therefore the geomorphological setting of a site is key to understanding the different drivers of coastline change or stability. For example, environmental processes acting on the coastline of a small island in the open ocean would necessarily be different from the processes that are acting on coastlines within a sheltered fjord, due to the potential for exposure to changing patterns of wind and waves. The terrestrial hinterland is a major potential supplier of soft sediments to the coastline, which may also derive sediment from offshore sources. The answers to this question will give insights into how the utilisation of the coast was impacted by/responded to different geomorphological factors and help answer question 4, below.

4) What is the relationship between coastline stability and harbours and landing sites?

The answers to questions 1 to 3 will reveal relationships between different geomorphological factors and the histories of landing sites and harbours in contrasting settings. It will reveal whether certain geomorphic criteria were necessary for a landing site or harbour to become established, how it influenced their growth, and how utilisation by seafarers responded to any changes in coastline morphology. It may be that certain types of use were extremely resilient to geomorphic changes, while others were sensitive to particular types of change. The ability for seafarers to adapt their competence or technology to these changes is also important to consider.

1.9 Thesis Structure

This thesis will present an overview of the approaches and methods used in the thesis. This will be followed by a field report to identify sites that required detailed study. Four data chapters are then presented as semi-independent case studies. These chapters then feed into the discussion chapter, followed by the thesis conclusions. Figure 1.4 illustrates this structure in a flow chart. Chapters 4 and 5 are interlinked as the theories developed in Chapter 4 are applied to Chapter 5, with field sites in Chapter 5 used as empirical data in Chapter 4.

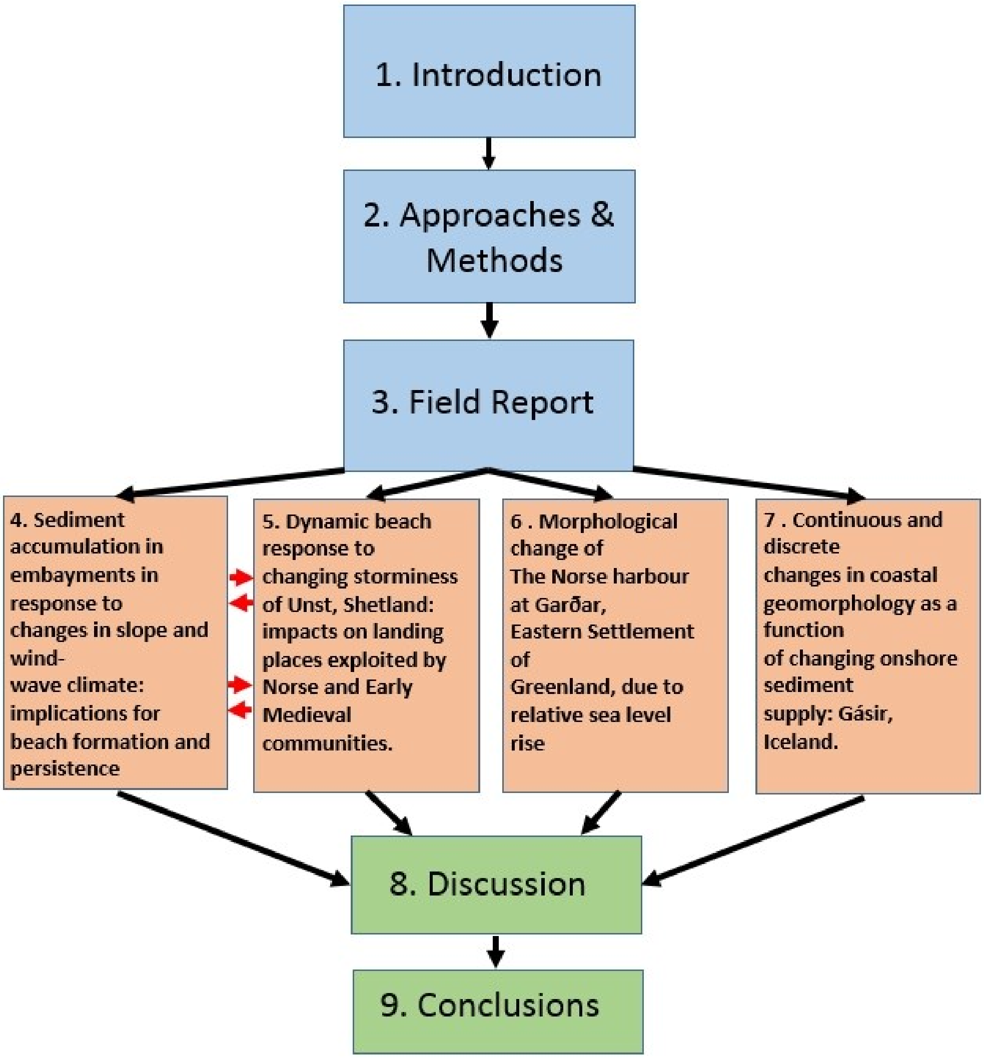


Figure 1.4 - Thesis structure flowchart.

2 Approaches and Methods

The focus of this dissertation is on the Norse and Medieval period and the North Atlantic islands of Shetland, Iceland and Greenland. In mainland Europe, almost every important early medieval harbour developed into a town or city, but the situation in the far North Atlantic is very different. In the Viking era the nodes of maritime activity in Iceland, Greenland, and Shetland were mostly simple landing places used during the summer months. Some of these places (but not all) grew to handle trade of considerable value and importance which gives them a special role in the economic history of Northern Europe and the development of the proto economic system that extends into the North Atlantic in the High Middle Ages. Guided by the HaNOA project, the overall strategy is to select a range of known Norse and Medieval harbours across the North Atlantic islands that developed in different ways and assess geomorphological contributions to these outcomes. In particular, the criteria for sites chosen were that they have settlement continuity and some do not; they occupy a range of different types of coastal environment, and all failed to become towns or cities.

Guided by the research questions set out in Chapter 1.8 two methodological approaches are used: 1) fieldwork and empirical observation, and 2) computational analysis. This chapter will give an overview of the specific fieldwork methods undertaken for field data collection and analysis. It will also give an overview of the theory and operation of the computational modelling undertaken in the thesis. Specific model experiments pertaining to studies in the data chapters shall be presented in-situ in the respective data chapters.

2.1 Fieldwork

As stated above, the HaNOA project covers a wide range of study sites in an equally wide range of geomorphological settings across the North Atlantic. I present a thorough field investigation of each site in Chapter 3, describing and quantifying where possible the specific geomorphic features of these sites and their likely trajectories of change. In particular, the geomorphic stability of each site will be considered with the research questions in mind. Initial methods and field experiments carried out at the field sites are included in this report.

Those that showed both evidence of geomorphic change (whether rapid or gradual) as well as the mechanism of geomorphic change being different than other sites (to explore the range of forces impacting Norse seafarers and their ability to adapt to such changes) were chosen for a more in-depth analysis. Repeat visits to these sites were undertaken to collect data specific to the experimental design required to answer the research questions, the methodologies of which are presented below.

2.1.1 Fieldwork - bathymetry data collection and analysis

For the study undertaken at the site of the Norse harbour of Garðar, I undertook a bathymetry survey of the nearshore area in July 2015. The bathymetry was recorded using a Garmin EchoMap 50S echo sounder unit, fitted with an internal GPS and a 200 kHz/77kHz transducer. It was attached to a sea kayak, with the control unit mounted for ease of operation while also paddling. The transducer was mounted just below the water line of the kayak, with the offset between the water surface and the transducer face being 0.07 m (Figure 2.1).

The inbuilt GPS has a maximum horizontal accuracy of 3 m. This accuracy was continuously reported by the echo sounder unit during survey and found to be consistent with at least 12 satellites in view. The survey was abandoned if accuracy fell below 4 m, which was a rare occurrence. Vertical accuracy is irrelevant in this case due to depths being recorded by the echo sounder, and calibrated against tide level recorded by the installed tide gauge in Igaliku harbour.

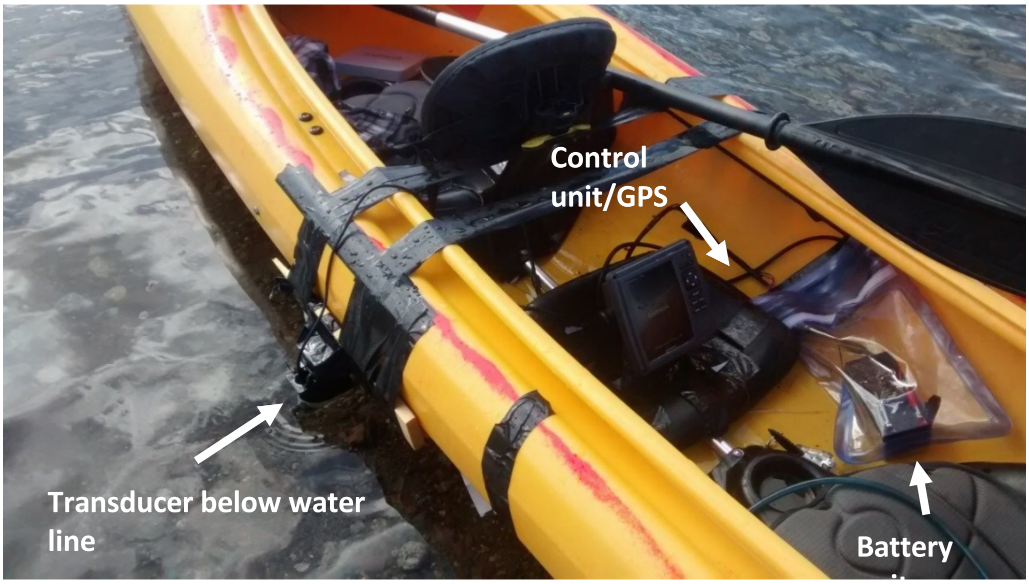


Figure 2.1 - Kayak echo sounder setup.

The echo sounder was set to record ‘tracks’ (the course of the kayak) and sonar traces, set to a 200kHz frequency, appropriate for salt water. The sonar traces were used for post processing the bathymetry (e.g. for removal of seaweed, large stones and other anomalies). The track points were set to record the GPS position and depth every 2 seconds. Transects were paddled to cover the required areas of interest. The echo sounder displayed the already paddled course, so that corrections could be made to ensure total coverage of the area of interest.

The tracks and sonar were recorded directly onto a micro-SD card, in ADM file format. An ADM file reader, GPS Utility 5.23, was used to convert the tabulated track points into CSV file format. The data was processed to remove any anomalous readings caused by fish, seaweed, duplicate points and other anomalies (automatically flagged by the echo sounder unit and recorded in metadata). The Garmin ADM file does not record specific date and time data, therefore to correct the depth data against tide levels, the start and end times of each survey period was recorded, and the time each point was recorded was interpolated every 2 seconds to allow depth correction to measured tide level. To minimise required corrections and to maximise survey area, survey was carried out on two hour slots, beginning an hour before high tide.

Once processed, the points were loaded into MapInfo 10.5 for visual display. MapInfo's raster utility, Vertical Mapper, is a simple and powerful tool that allows rapid interpolation of georeferenced depth points into a raster grid. This was used to create a bathymetry grid of the harbour via inverse distance weighting. It was then analysed in terms of relative sea level change from Kjuipers et al. (2008), who estimated a sea level rise in Igalikufjord (~10 km south of the study site) of 200cm/1000yr. This was projected linearly as 2 mm/yr., and three reconstructed coastlines were produced: 1000, around the time of the Norse Landnám in Greenland; 1250, around the time of the 'height' of the Eastern Settlement and the formal extension of Norwegian power to include the Greenland colonies (Hall, 2007); and 1500, shortly after the Eastern Settlement had been abandoned.

An accurate understanding of the tidal range at Igaliku is important. The closest tide table to Igaliku is at Qaqortoq, approximately 30 km to the south. Tide levels are dependent on the local topography of the coastline, therefore a portable Valeport 740 tide gauge was installed in the harbour for 15 days, the duration of the field campaign. This tide gauge was composed of a data logger and a pressure transducer. Data from even a relatively short time period can significantly constrain tide levels to an acceptable accuracy (Sparrenbom et al., 2006).

The tide gauge required the local datum to be added, so that the transducer level was offset below/above the datum to allow an accurate water level. As the local datum was unknown, a DGPS point was recorded at the location of the data logger, at the end of the modern harbour pier at Igaliku. This was taken as an artificial datum of 0 m, with the transducer offset set to -6.52 m, the distance between the data logger and the transducer placed in the water column. The data logger fortuitously recorded both spring and neap tides, thus allowing the full tidal range in the fjord head to be observed (Figure 2.2).

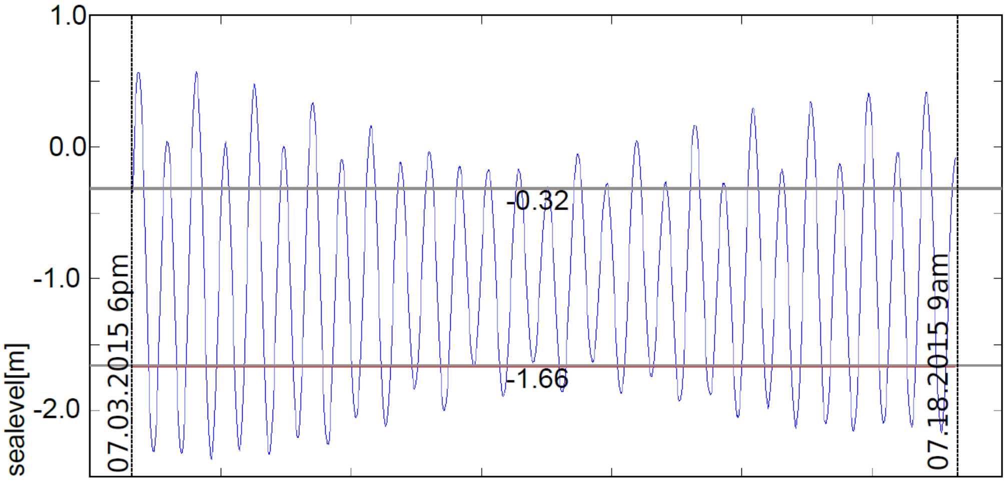


Figure 2.2 - Tide cycle measured by tide gauge, corrected to artificial datum. Black line represents mean high- and low- water level values used as reference for reconstructing past coastlines.

Depths recorded by the echo sounder either side of high tide were corrected to mean high water (MHW). The MHW and MLW (mean low water) range of approximately 1.6 m suggests, very roughly, that modern day MLW was slightly above MHW in early Norse settlement times.

2.1.2 Fieldwork - geomorphological mapping and ST:REAM analysis

This method was used for the geomorphological survey carried out in Iceland as presented in Chapter 7.

Geomorphological mapping of landslides in the valley was carried out using a combination of aerial photography and field survey. Fieldwork tablets loaded with a custom geodatabase run on ArcGIS Collector were used to record geomorphological features in the field. ArcGIS Collector (ESRI) is a dedicated field mapping package designed to run on handheld devices. It allows the recording of features directly into a geodatabase, based on preloaded shapefiles that are designed prior to the mapping exercise. Recorded features are then uploaded to the geodatabase on ArcGIS Online.

To characterise the sediment dynamics occurring in the Horgá, a modified ST:REAM (Sediment Transport: Reach Equilibrium Assessment Method) analysis (Parker, 2015) was used. This is a visual method to semi-quantitively identify the sediment dynamics within a river into six categories: erosional source; erosional exchange; balance exchange; balance transport; depositional exchange; depositional sink. These categories can quickly and simply show which parts of the river are actively eroding and depositing, as well as identifying pinch points and throttles within the river (Table 2.1). For example, for an erosional reach to be identified one would look for evidence of bank undercutting or other obvious signs of erosion. For a depositional reach, one would look for depositional features such as bars and obvious sediment accumulation. If erosions features dominate over depositional along a particular reach, it is classed as such, and vice versa. Where no features dominate, balance reaches are appropriate.

While they 'progress' from erosion to deposition in the classification list, the classifications themselves do not have to 'follow' each other throughout a river system, e.g. it is possible for a reach classified as depositional exchange to be followed downstream by a reach classified as a balance transport.

ST:REAM Classification	*Description*
1. *Erosional source*	Typically close to source, high stream power
2. *Erosional exchange*	Some small deposition features, but erosion still dominant
3. *Balance transport*	Typically fast-flowing bedrock channels, no erosion or deposition observed.
4. *Balance exchange*	Mass balance roughly equal, both depositional and erosional features observed.
5. *Depositional exchange*	Some small erosion occurring, but deposition dominant force, low stream power.
6. *Depositional sink*	No erosion, only deposition, e.g. lake, estuary.

Table 2.1 - ST:REAM Classifications. The classifications are qualitative assessments of surveyed reach properties. Continuous survey from upstream to downstream determines transition from one class to another (source: Parker, 2015).

2.2 Modelling in archaeology

Many harbours that were established by the Norse developed into large settlements that endured down the centuries and are still inhabited today (e.g. Reykjavik, Hafnarfjorður, Dublin, and Bergen). However, a network of harbours that did not survive are also present throughout the North Atlantic, and the reasons for their abandonment are as yet unclear (Mehler et al., 2015).

Gásir (Chapter 1.6.2) is an example of a well-known abandoned harbour, and will be investigated in detail later in the thesis, yet many more harbours remain ‘lost’. One of the challenges in Norse maritime archaeology (and one of the aims of the HaNOA project, Chapter 1.7) is the identification of these lost harbours. Their whereabouts can be inferred from either mentions in contemporary sources, or even preserved in place names. For example, the place name “Kaupangr” on the southern shores of Eyjafjorður translates to “Market place”, which may suggest the presence of a previous trading harbour. Nearby, the place name “Skipalon” adjacent to Gásir literally translated to “Ship lagoon”, also suggestive of maritime use. On the southern shores of Hvalfjörður in eastern Iceland, the place name “Buðasandur”, meaning literally “Booth sands”, would suggest a use for trading. Indeed, previous archaeological investigations have revealed several booths just behind the shoreline here consistent with other known booth sites by harbours (Mehler et al., 2015).

The reasons for the loss of a harbour location can vary, either the harbour was not mentioned in contemporary sources that are now accessible; the erosion of the coastline that the harbour occupied; deposition on the coastline burying harbour remains; or relative sea level rise obscuring the harbour. Coastal geomorphological research, particularly computational modelling, has the potential to play a major role in helping identify the remains of lost harbours, and charting their coastal evolution. However, computational modelling has important restrictions that must be acknowledged.

The wider understanding of geomorphological factors impacting the development and abandonment of harbour sites in the North Atlantic fits into addressing some of the shifting paradigms in archaeological research as identified by Kintigh et al. (2014). These 'grand challenges' lay out the pressing issues as identified by archaeologists in a wide ranging survey. In particular, such challenges as 'How do humans respond to abrupt environmental change?', 'How do spatial and material reconfigurations of landscapes and experiential fields affect societal development?' and 'How do humans perceive and react to changes in climate and the natural environment over short- and long-terms?' are well placed to be addressed in this thesis, and by the use of modelling in particular.

We must define at this point precisely what archaeological answers computational sediment transport modelling can provide. These *deterministic* models can simulate the short- and long-term evolution of a shoreline based on the specific input data on climate and sediment conditions given to the model. When used, in these cases, for answering archaeological questions they must be interpreted *probabilistically*, in that they can simulate the changes in shoreline and thus impacts these changes would *likely* have had on harbours and landing places. That is, models themselves cannot show definitively that a harbour site was abandoned at a specific time, but only the trajectories of geomorphic change that occur along the coastline in a given time period.

With this defined, field sites were quantitatively placed on a matrix measuring their apparent sediment volume, and their apparent exposure to climatic forcing, as these are the major inputs into a model. This helped identify which sites required modelling analysis and which were analysed using different means. Figure 2.4 shows the sediment/exposure matrix that was populated after the field campaign reported in Chapter 3.

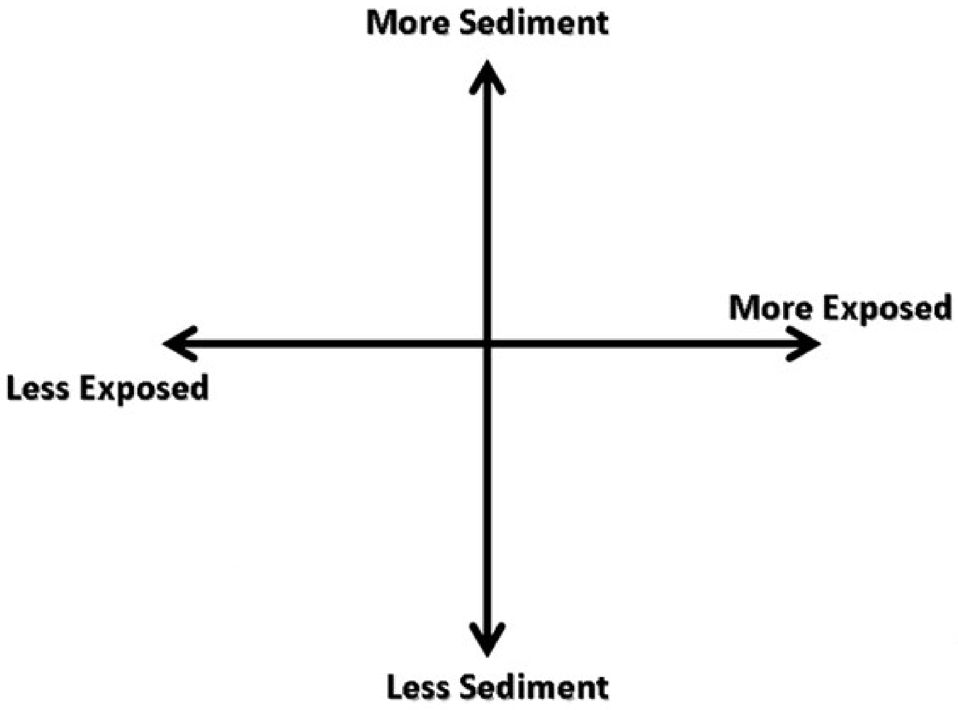


Figure 2.3 – A conceptual sediment/exposure matrix. This matrix will be qualitatively populated by field sites as a tool to understand trajectories of geomorphic change.

2.3 Computational sediment transport modelling

Sites on Unst that are composed of soft sediments with the potential for rapid geomorphic change were chosen as subjects for computational analysis using coastal sediment transport modelling.

2.3.1 MIKE21

Multiple nearshore sediment transport models exist, all with their own strengths and weaknesses, depending on their intended use. To explore the potential role of coastal sediment transport in dictating the presence or absence of sandy beaches in meso-scale embayments (both for idealised embayments and modelling embayments on Unst), I used the MIKE21 coupled hydrodynamic and morphodynamic model. This model was chosen because more than 20 years of development has produced a robust and reliable tool for coastal engineering studies (Siegle et al., 2004; Manson, 2012; Houser, 2013; Vincinanza et al., 2013; DHI, 2014). It is also suited for longer term modelling of coastal evolution, i.e. on a multi-year scale. Other modelling packages, such as Delft3D or SWAN, are generally utilised on smaller temporal and spatial scales and thus are not as appropriate for the intended modelling experiment as described below.

MIKE21 also operates on a modular basis, with computational efficiency being promoted by selecting the appropriate computational 'modules' required. For the modelling experiments in this thesis, the hydrodynamic (HD), sand transport (ST), and spectral wave (SW) module were used.

The MIKE21 ST module moves sediment in the domain by calculating the shear stress generated by water motion, using sediment transport theory in relation to both bedload and suspended load developed by Engelund & Fredsøe (1976) and Fredsøe et al. (1985). The module treats sediment as the total load (i.e. bedload + suspended load). The water motion leading to shear stress and sediment transport combines is the product of wind-generated waves, tides and currents, which are calculated by the HD and SW modules. Sediment motion is initiated when the shear stress, τ, exceeds the critical shear stress τ_{cr} required for incipient particle motion.

Dimensional shear stress τ is defined:

$$\tau = \frac{1}{2}\rho_\omega C_f {U_b}^2 \qquad (1)$$

Where ρ_ω is fluid density, C_f is the wave friction factor and U_b is the horizontal (i.e. cross-shore) wave orbital velocity at the bed. Soulsby & Clarke (2005) calculated the wave friction factor by:

$$C_f = 1.39\left(\frac{U_b T}{\left(\frac{2\pi D_{50}}{12}\right)}\right)^{-0.52} \quad (2)$$

Where T is the wave period, and D_{50} is the median grain size. The HD module does not directly output the shear stresses or wave friction factors, however these can be calculated per-time step from the horizontal wave orbital velocity outputs following these equations (Soulsby & Clarke, 2005; DHI, 2014).

The critical shear stress, τ_{cr}, is dependent on particle size and density, and is determined by:

$$\tau_{cr} = \theta_{cr}(p_s - p_w) g D_{50} \quad (3)$$

Where θ_{cr} is the nondimensional Shields parameter, p_s is particle density and g is the gravitational constant (Shields, 1936; Madsen & Grant, 1976; Paphitis, 2001). Where $\tau > \tau_{cr}$ in the domain, the ST module computes sediment transport following Engelund and Fredsøe (1976) for bed load and Fredsøe et al. (1985) for suspended load. Both bed load and suspended load transport are solved deterministically. Time-averaged bed load transport is solved based on current outputs from the HD module. Suspended load is entrained per timestep based on reference bed load conditions, and kept in motion as long as the fall velocity of the particle concentration is exceeded per timestep. The model adds both bed load and suspended load together to calculate the total sediment load per timestep.

The HD module operates on the principle of solving two-dimensional incompressible Reynolds-averaged Navier Stokes equations subject to hydrostatic pressure. This calculates per timestep fluid motion in the model domain as governed by forcing input into the model, conserving momentum between model cells. The Navier Stokes equations are too numerous and complex to present in full in this thesis, however the important local continuity equation in the HD module is:

$$\frac{\delta u}{\delta x} + \frac{\delta v}{\delta y} + \frac{\delta w}{\delta z} = S \quad (4)$$

With the two horizontal momentum equations for the x- and y- components as follows, respectively:

$$\frac{\delta u}{\delta t}+\frac{\delta u^2}{\delta x}+\frac{\delta vu}{\delta y}+\frac{\delta wu}{\delta z}=fv-g\frac{\delta \eta}{\delta x}-\frac{1}{\rho_0}\frac{\delta \rho_a}{\delta x}-\frac{g}{\rho_0}\int_z^{\eta}\frac{\delta \rho}{\delta x}\delta z-\frac{1}{\rho_0 h}\left(\frac{\delta s_{xx}}{\delta x}+\frac{\delta s_{xy}}{\delta y}\right)+F_u+\frac{\delta}{\delta z}\left(v_t\frac{\delta u}{\delta z}\right)+u_z S \qquad (5)$$

$$\frac{\delta v}{\delta t}+\frac{\delta v^2}{\delta y}+\frac{\delta uv}{\delta x}+\frac{\delta wv}{\delta z}=fu-g\frac{\delta \eta}{\delta y}-\frac{1}{\rho_0}\frac{\delta \rho_a}{\delta y}-\frac{g}{\rho_0}\int_z^{\eta}\frac{\delta \rho}{\delta y}\delta z-\frac{1}{\rho_0 h}\left(\frac{\delta s_{yx}}{\delta x}+\frac{\delta s_{yy}}{\delta y}\right)+F_v+\frac{\delta}{\delta z}\left(v_t\frac{\delta v}{\delta z}\right)+v_z S \qquad (6)$$

In which *t* is timestep; *x*, *y* and *z* are Cartesian co-ordinates; *η* is the surface elevation; *d* is the still water depth; *h* is the total water depth; *u*, *v* and *w* are the velocity components in the *x*, *y* and *z* direction; *f* is the Coriolis parameter, *g* is acceleration due to gravity, *p* is the density of water; S_{xx}, S_{xy}, S_{yx} *and* S_{yy} are components of the radiation stress tensor (important in the function of the SW module), v_t is the vertical turbulent (or eddy) viscosity; p_a is the atmospheric pressure; p_o is the reference density of water. *S* is the magnitude of the discharge due to point sources and (u_s, v_s) is the velocity by which the water is discharged into the ambient water.

These governing equations conserve mass and momentum in model cells interlinked between the HD and ST module per timestep. The radiation stress tensor is specifically output by the SW model, with the corresponding wave radiation stresses being an important component in governing motion of sediment in the ST module based on the hydrodynamics.

Another advantage of MIKE21 is that ability to create a flexible mesh (FM) model domain (Figure 2.4).

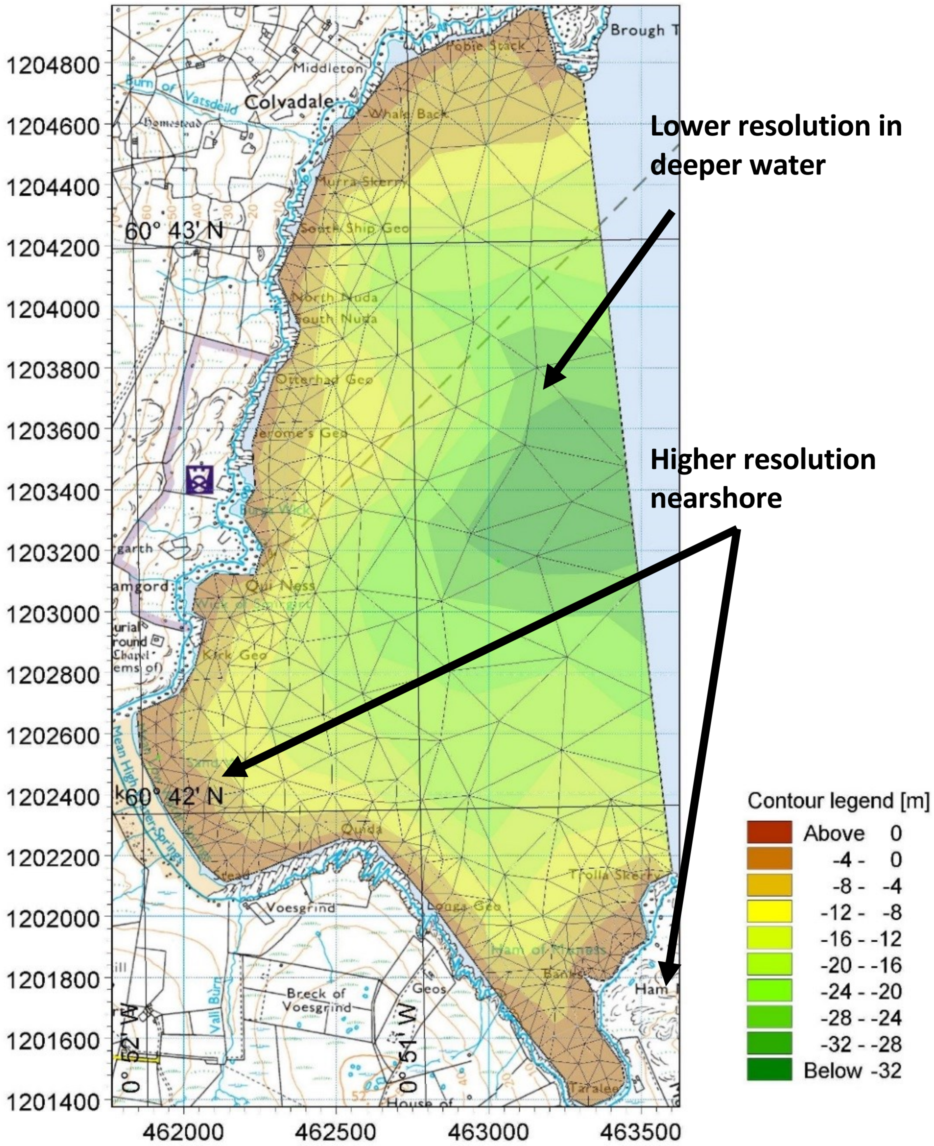


Figure 2.4 - Example of flexible mesh (FM) model setup in MIKE21 (Sandwick Bay, Unst). The FM here is set to be more detailed in nearshore areas, and less detailed in deeper water.

Rather than the model domain being composed of a grid with equal-sized cells in which calculations are carried out, a flexible mesh allows changes in resolution of certain areas of the domain. In this case, the nearshore sediment dynamics were of interest thus the resolution was set to be higher than the model domain in deeper waters further offshore. This allows model calculations to be much more computationally efficient.

2.4 Publication format

I will present each case study in the form of a publication-ready scientific journal article, with self-contained introductions, methods, results and discussions. Each publication will fit in the wider narrative of the thesis and be linked back to the research questions. The discussion chapter will place each case study into context, and discuss the wider implications of geomorphic change and the ability for Viking and medieval settlers to adapt to geomorphic changes wrought in these environments.

At date of thesis submission (November 2017), Chapters 4 and 5 were submitted to peer-reviewed journals for consideration and publication. They are lightly edited for addition into the thesis narrative.

3 Fieldwork Report

A field study of each area included in the HaNOA project was undertaken to determine which sites would be most suitable to the aims of the thesis. To this end, fieldwork was carried out between May and August 2014 in three distinct locations: Unst, Iceland and Greenland. The following reports will describe the environmental setting of the sites, along with their geomorphological context, and investigations carried out to determine their geomorphic stability and suitability for case study analysis.

3.1.1 Unst

The island of Unst is the most northerly of the Shetland Islands, located at approximately 60° 45’ N, 0° 52’ W. It is roughly rectangular in shape, approximately 20 km in length and 9 km in width. The coastline is a mixture of deep inlets (known as ‘voes’), and arcuate bays. The north of the island, particularly the north west, is composed of high cliffs while the south, particularly the south east, has comparatively low relief.

Unst has a long history of human habitation, stretching from the Neolithic to the present day. Unst is unusual within the British Isles in that it has no history of large scale arable cultivation. This means that archaeological remains are distinctly well preserved, with large ruins from all time periods still readily visible on the surface (Fojut, 2006).

Four sites were explored in detail: Lunda Wick, Sandwick, Burra Firth and Wick of Skaw. All references to archaeological dates are derived from the Royal Commission on the Ancient and Historical Monuments of Scotland (RCAHMS) websites (canmore.rcahms.gov.uk), the body responsible for cataloguing all archaeological sites in Scotland.

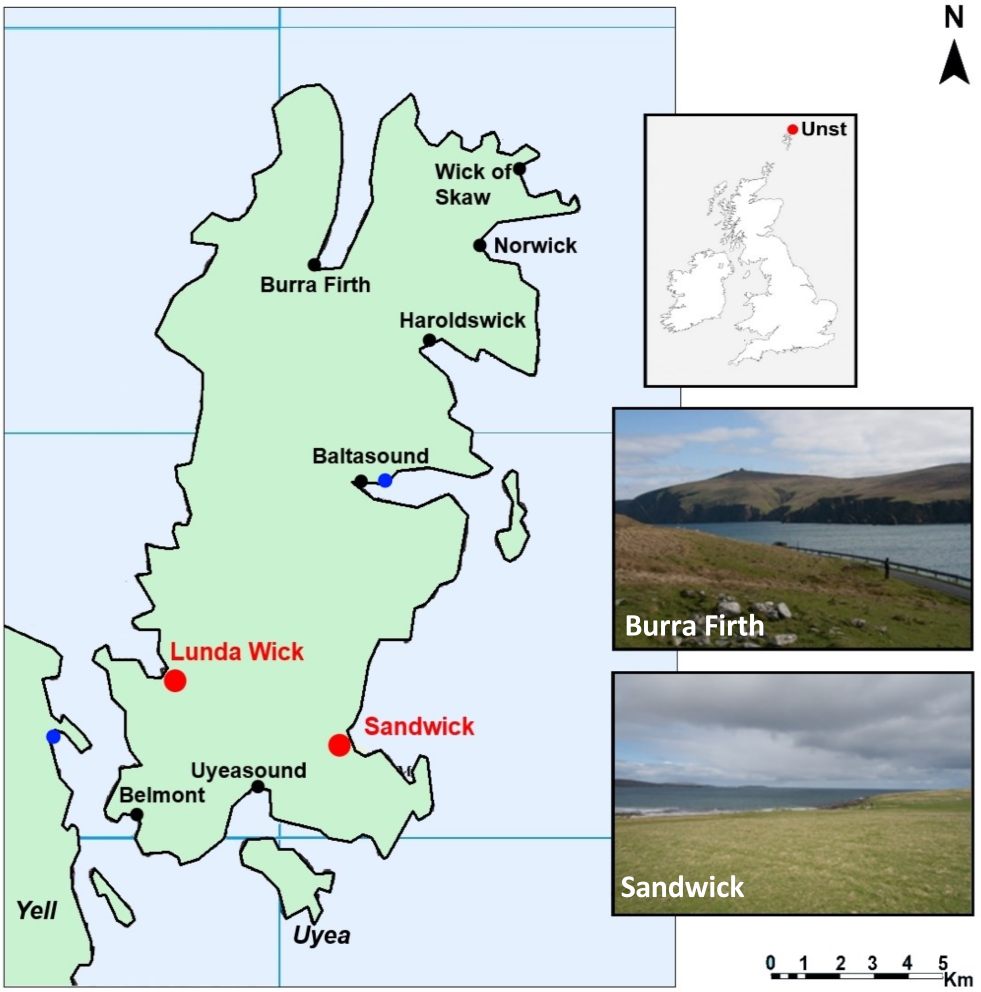


Figure 3.1 - Location of study sites on Unst. Red sites are those looked at in detail. Blue dots represent tide gauges.

3.1.2 Lunda Wick

3.1.2.1 Site description

Lunda Wick is a twin embayment on the south west coast of Unst. It faces roughly north, and is partially sheltered from the open ocean by a headland 1 km to the north, and some small skerries approximately 2 km to the north. It is split into two beaches separated by a small headland. The smaller beach to the east, Burga Wick, has the remains of two nausts (a small boat storage place) on the shore, and a Viking longhouse adjacent to the beach (Small, 1968). A 12th century Viking church and graveyard stands on the western edge of the larger beach.

Figure 3.2 illustrates the major geomorphic features observed at Lunda Wick.

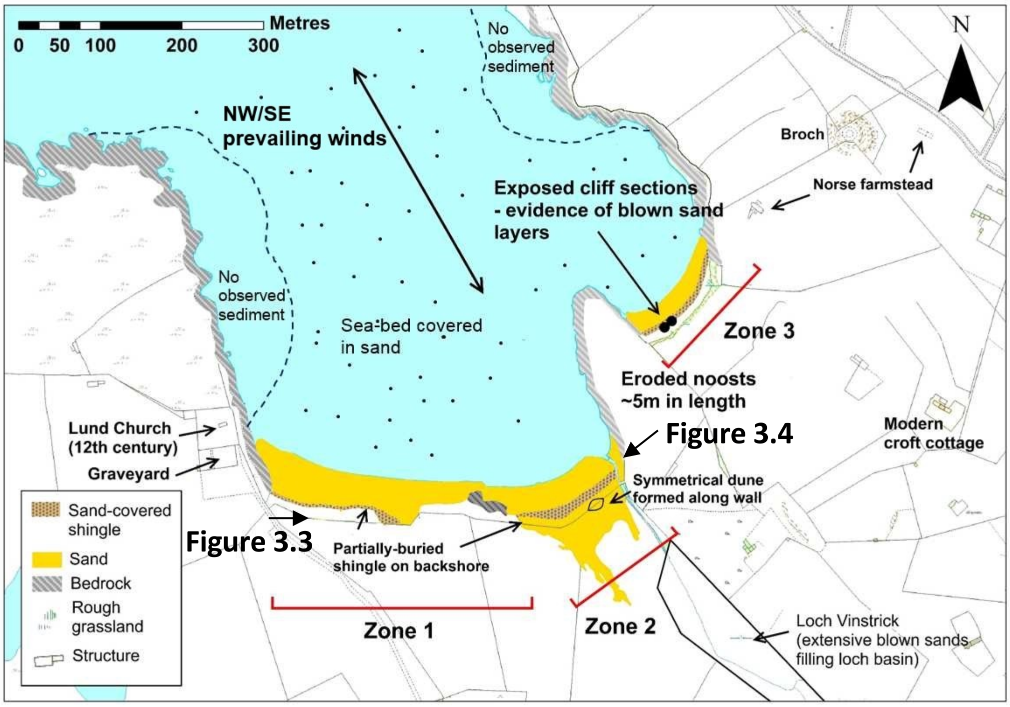


Figure 3.2 – Schematic planform map of Lunda Wick, indicating major geomorphic features and zones. (Contains OS data. Crown copyright)

3.1.2.2 Geomorphological setting

The beach at Lunda Wick is primarily composed of fine-grained sands, with larger cobbles in storm ridges higher on the beach. Evidence of blown sands stretch behind the beach zone, however the distribution of this sand indicates the relative protection that Lunda Wick offers as a potential landing place. To describe the different aspects of the bay, it was split into three zones: 1, 2 and 3 (Figure 3.2).

Zone 1, adjacent to the church, appears to be relatively sheltered. The beach shows a sharp transition between fine-grained sand at the front of the beach and the shingle storm ridge at the back. No evidence of recent blown sand is present behind the beach although small exposures on the vegetated slopes behind the beach show evidence of blown sand in the past, which has led to the formation of a partial machair (Mathers & Smith, 1973).

Figure 3.3 - View of Zone 1, looking east. Note sharp transition between backshore and vegetated land, with little evidence of blown sand on the surface.

Zone 2, in contrast to zone 1, shows significant evidence of blown sand. The shingle storm ridge in this zone is almost completely buried by this sand, with dune formation stretches behind the beach zone in a south-easterly direction. An intriguing feature present in this zone is an almost symmetrical dune that has formed on both sides of a dry stone wall at the eastern end of the beach (Figure 3.4). The SE-NW orientation of this dune, as well as the orientation of scars behind the beach suggests that these are the prevailing wind directions for Lunda Wick, and could explain why Zone 1 is more stable as it is protected from SE winds from the headland north of the church.

Figure 3.4 - Symmetrical dune in zone 2. North (and the sea) is to the right of the photograph. Note partially-buried shingles, and dune formation occurring in the background.

Historic maps of Lunda Wick mention the Loch of Vinstrick, location behind zone 2 of Lunda Wick. This is currently an area of vegetated marshland. The oldest detailed map of the area was surveyed in 1877, which indicates that the Loch was marshland then also. However, both the name and evidence of historic shoreline from aerial photography would suggest that this was an open body of water in the past.

Zone 3 of Lunda Wick is the smaller side bay separated from zone 2 by a headland called Vinstrick Ness, composed of slightly coarser sand than Zones 1 and 2. Little evidence of blown sand exists behind the beach, suggesting that this bay is well sheltered from prevailing winds. The NW prevailing winds that act upon zone 2 may be disrupted by the headland approximately 1 km north of zone 3. Evidence of cliff erosion is present, however, with the partial remains of a reportedly 12th century noost being situated on the edge of the backshore.

Lunda Wick shows evidence of past geomorphological change, both in terms of cliff erosion, and blown sand. The blown sand deposits in zone 2, and the Loch of Vinstrick, suggest that such quantities of blown sand were not always the case, thus suggesting some shift in climatic conditions.

3.1.3 Sandwick

3.1.3.1 Site description

Sandwick is a large embayment situated on the south east coast of Unst, approximately 650 m in width. It faces north east, constrained on each side by rocky cliffs. It is backed by gently sloping heathland with some machair formation present closer to the beach, on which significant archaeological remains from the 17th to the 19th century are found. On the beach itself, the remains of a Viking longhouse are located on the southern end of the beach (Bigelow, 1985; … 1989). This longhouse is clearly subject to windblown erosion, having been partially buried in blown sand (Figure 3.5).

Figure 3.5 - Remains of Viking longhouse. Note the blown sand partially covering the ruins.

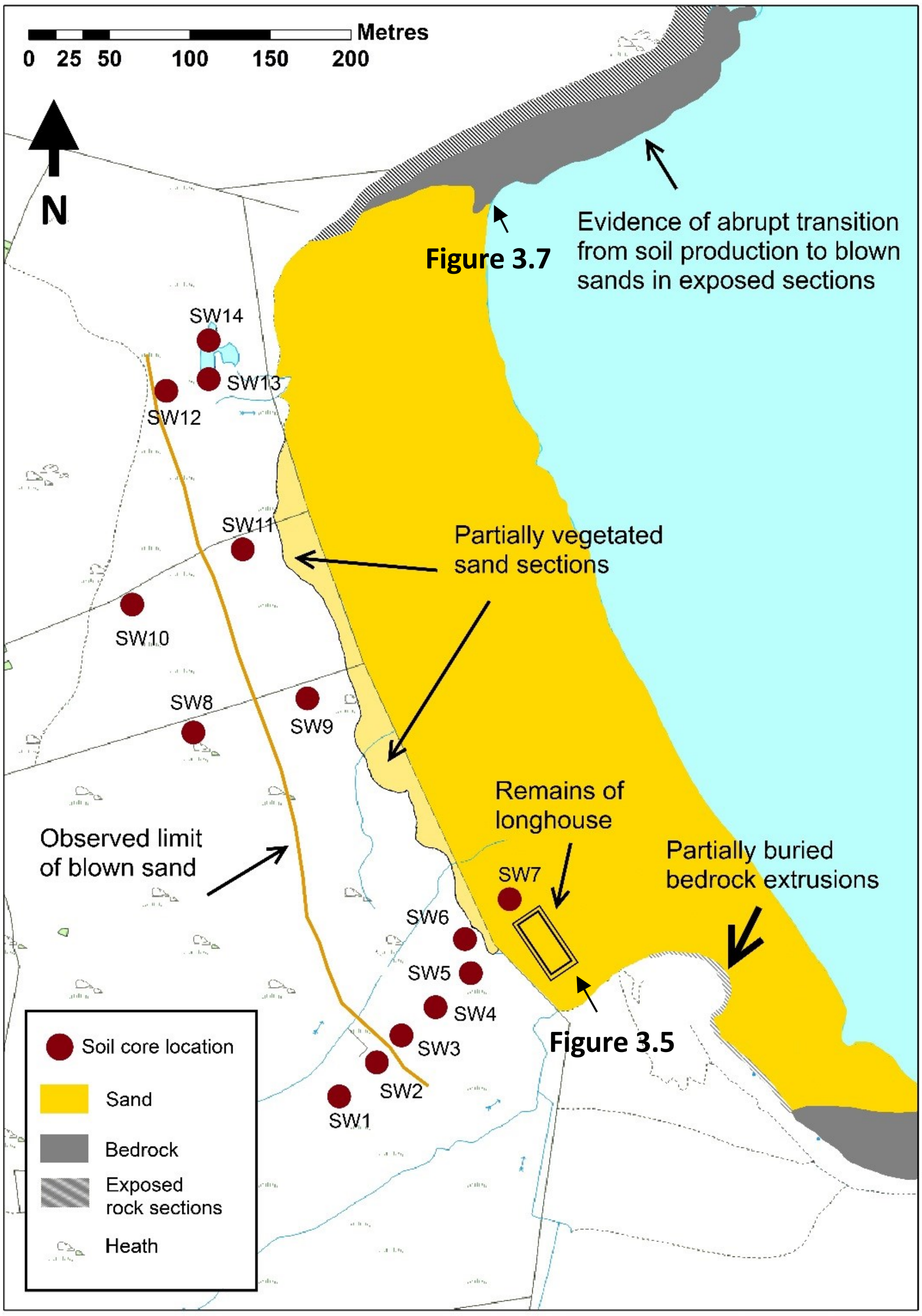


Figure 3.6 – Schematic planform map of Sandwick, indicating major geomorphic features and zones. (Contains OS data. Crown copyright)

3.1.3.2 Geomorphological setting

The slope of the beach is relatively gentle, with an average gradient of 4°. There is some shingle present at the back of the beach, but this is mostly overlain by sand. The beach itself is reportedly underlain by a cobble layer, on top of which lies the sand (Mather & Smith, 1973). No evidence of dune formation is found anywhere near the beach.

Blown sand is a feature of the landscape at Sandwick, with evidence of sand deposits detected approximately 200 m behind the current edge of the beach. Further inspection of the cliffs on the northern edge of the bay revealed evidence of an abrupt change between soils and blown sand in the exposed sections (Figure 3.7).

Figure 3.7 - Exposed section on northern edge of Sandwick.

It can be clearly seen that there is a sharp delineation between the soil layer and the sand layer. This could indicate an abrupt change in climatic conditions that led to blown sand being deposited across the previously sand-free landscape.

A survey of the blown sand deposits behind the beach revealed an approximate extent of blown sand 200 m behind the current backshore, marked on Figure 3.6 (see Appendix C3 for soil core photographs). Similar to the Loch of Vinstrick at Lunda Wick, the Loch of Sandwick is shown on maps to be an open body of water just behind the northern end of the beach. This is now simply marshy land, with significant blown sand deposits under the soil surface.

Sandwick, in summary, shows evidence of an abrupt change in climate, which caused the landscape to be subject to increasingly blown sand intrusion beyond the beach.

3.1.4 Burra Firth

3.1.4.1 Site description

The beach at Burra Firth is an arcuate, sandy bay at the head of a deep voe, 4.3 km in length. The beach itself is approximately 350 m in width, constrained on both sides by high bedrock cliffs. The voe faces almost due north, and as such is open to prevailing winds from the Arctic. As with Sandwick, there is little evidence of dune formation.

There is no evidence that this beach was used as a landing place for either Norse or later settlers. The remains of an Iron Age broch are located on a small headland adjacent to the western end of the beach, otherwise little archaeological evidence is present.

3.1.4.2 Geomorphological setting

The beach itself is a wide, dissipative beach with an average slope angle of 7°, composed mainly of fine-grained sands transitioning into grass at the back of the beach (Figure 3.8). As the beach at Burra Firth is deep within a north-facing, cliff-lined voe (Figure 3.9), with prevailing winds blowing from the north, it is likely that any sediment on the beach will never be able to be removed seaward. This poses an interesting question in terms of beach stability and evolution.

Figure 3.8 - View of Burra Firth, looking south east. Fjord and ocean on the left of photograph.

Figure 3.9 - Looking north east along the voe.

If sand cannot be removed from the beach by wave action, it must either remain on the beach, or be blown and deposited behind the beach. As a test to this theory, several soil cores were taken at intervals between the beach at Burra Firth to the Loch of Cliff (Figure 3.10)

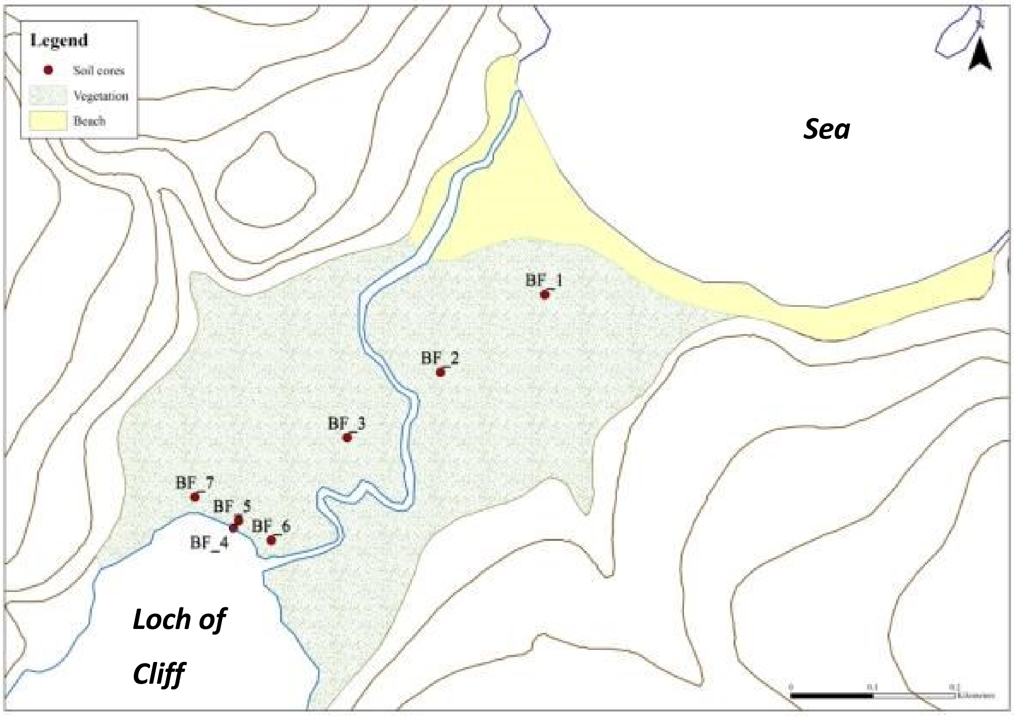


Figure 3.10 - Soil core locations at Burra Firth. Decreasing depth of sands was found in a line from the sea to the loch.

Photos of each soil core can be found in Appendix C1.

Core sample ID	Sample depth (cm)	Description (from top of soil section)
BF_1	32	2cm sandy soil, 30cm sand (sharp transition)
BF_2	42	6cm sandy soil, 36cm sand (sharp transition)
BF_3	44	10cm soil, 34cm sand (gradual transition)
BF_4	45	34cm soil with low sand content, 10cm reddish sand (sharp transition)
BF_5	71	37cm soil with low sand content, 3cm sand, 31cm dark soil with low sand content
BF_6	62	18cm sand with low soil content, gradual transition into 25cm of sandy soil, sharp transition to 19cm sandy soil(final 6cm of section missing)
BF_7	69	64cm soil with low sand content, 5cm sandy soil (sharp transition)

Table 3.1 - Description of soil cores taken at Burra Firth (see Figure 2.8 for soil core locations)

Table 3.1 shows the depth of the blown sand across the vegetated section of Burra Firth. Sand content of the soil decreases with distance from the beach (BF_4 and BF_5, for example). However, there is some evidence of episodic sand deposits in cores BF_4 to BF_7. This could suggest a period of storminess, or even a single storm, that possessed enough energy to transport sand inland, before soil formation was able to continue.

Burra Firth, in common with other sites on Unst, shows evidence of blown sand deposits. Unlike other sites, however, the constrained nature of the location of the beach creates an almost ‘closed system’ for sediment transport. Soil core investigations carried out at the site demonstrates how these can potential changes in climatic conditions.

3.1.5 Wick of Skaw

3.1.5.1 Site Description

Wick of Skaw is a small, east-facing, bay located in the extreme north-east of Unst. The beach itself is in the north-west corner of a roughly square bay, constrained by bedrock cliffs on either side. The southern edge of the beach has a small stream flowing from the west into the sea. The beach is backed by steep grassy slopes.

No Norse settlement has been recorded at Skaw, however the remains of a reportedly Iron Age structure (recorded in RCAHMS) is located on the cliff directly behind the beach (Figure 3.11).

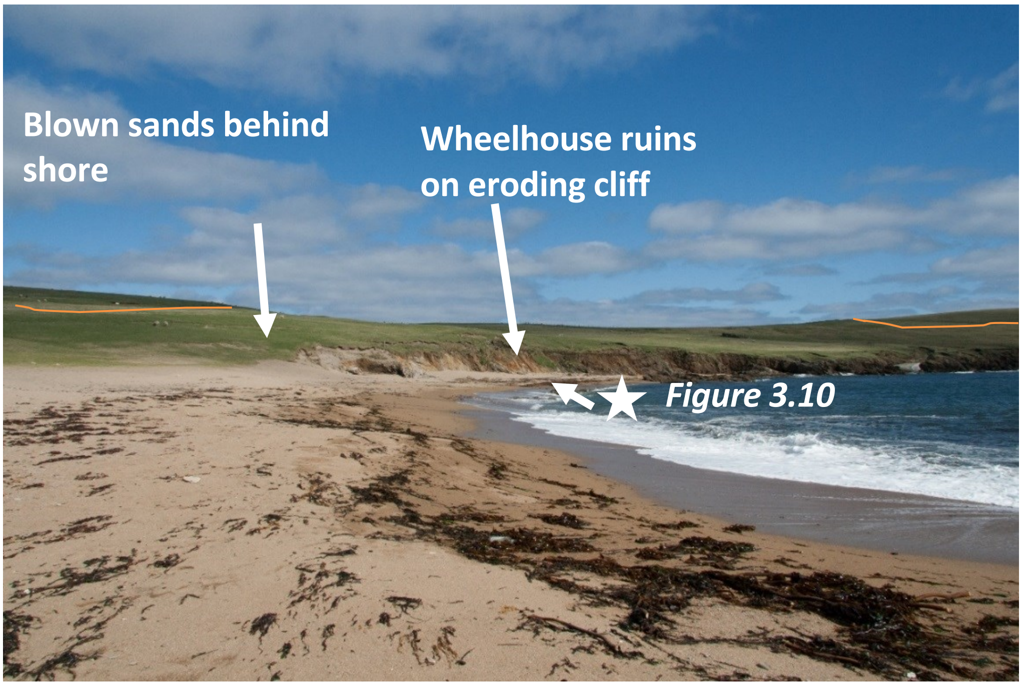


Figure 3.11 - Wick of Skaw, looking north. Evidence of blown sands behind the shoreline is labelled and covers all of the visible hillside to the west (right hand side of photograph) of the orange line (Figure 3.12) Star shows position of photograph in Figure 3.13.

3.1.5.2 Geomorphological setting

The beach at Wick of Skaw is relatively small when compared to the other field sites on Unst, approximately 180 m in width. The southern half of the beach is backed by grass slopes, grading into sand, with a small watercourse bordering the southern limit of the beach. The northern half of the beach is banded by cliffs, which grow in elevation to approximately 7 m above the beach at its northern limit.

At the top of the cliffs near the northern edge of the beach are the remains of a structure. The structure on the cliff is semi-circular in shape, however its location immediately on the edge of the cliff suggests that it was once larger. Indeed, stones of a similar size and shape to the ones used in the structure lie directly below the structure at the toe of the cliff (Figure 3.13).

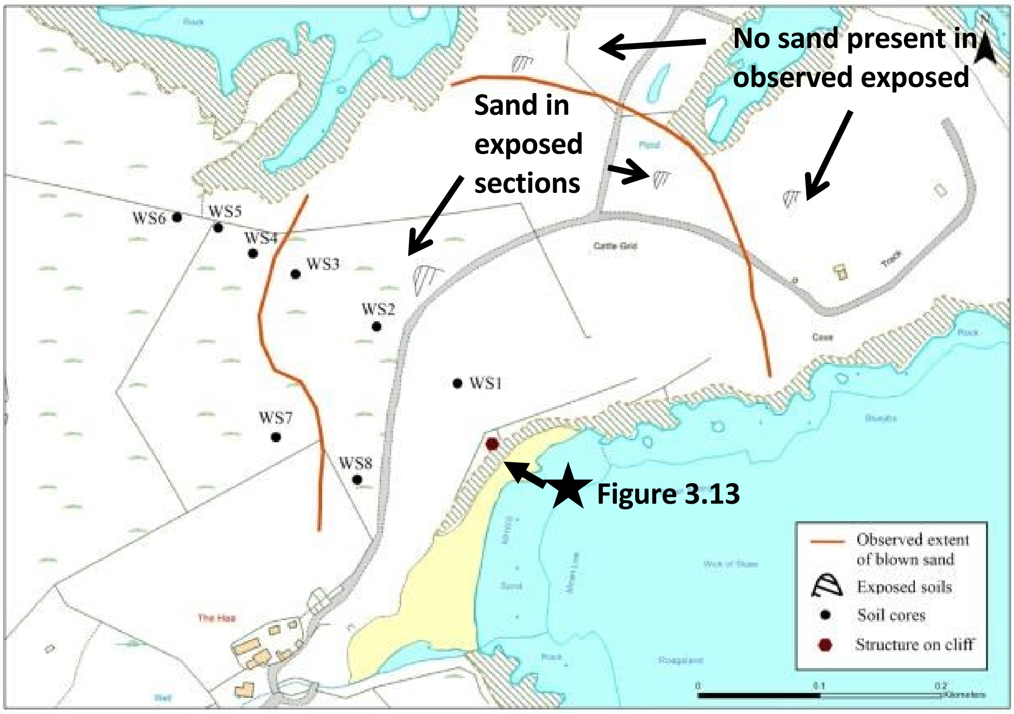


Figure 3.12 - Soil core locations and indicative blown sand area (contains OS data: crown copyright). Labels on soil core locations refer to photographs found in Appendix C2.

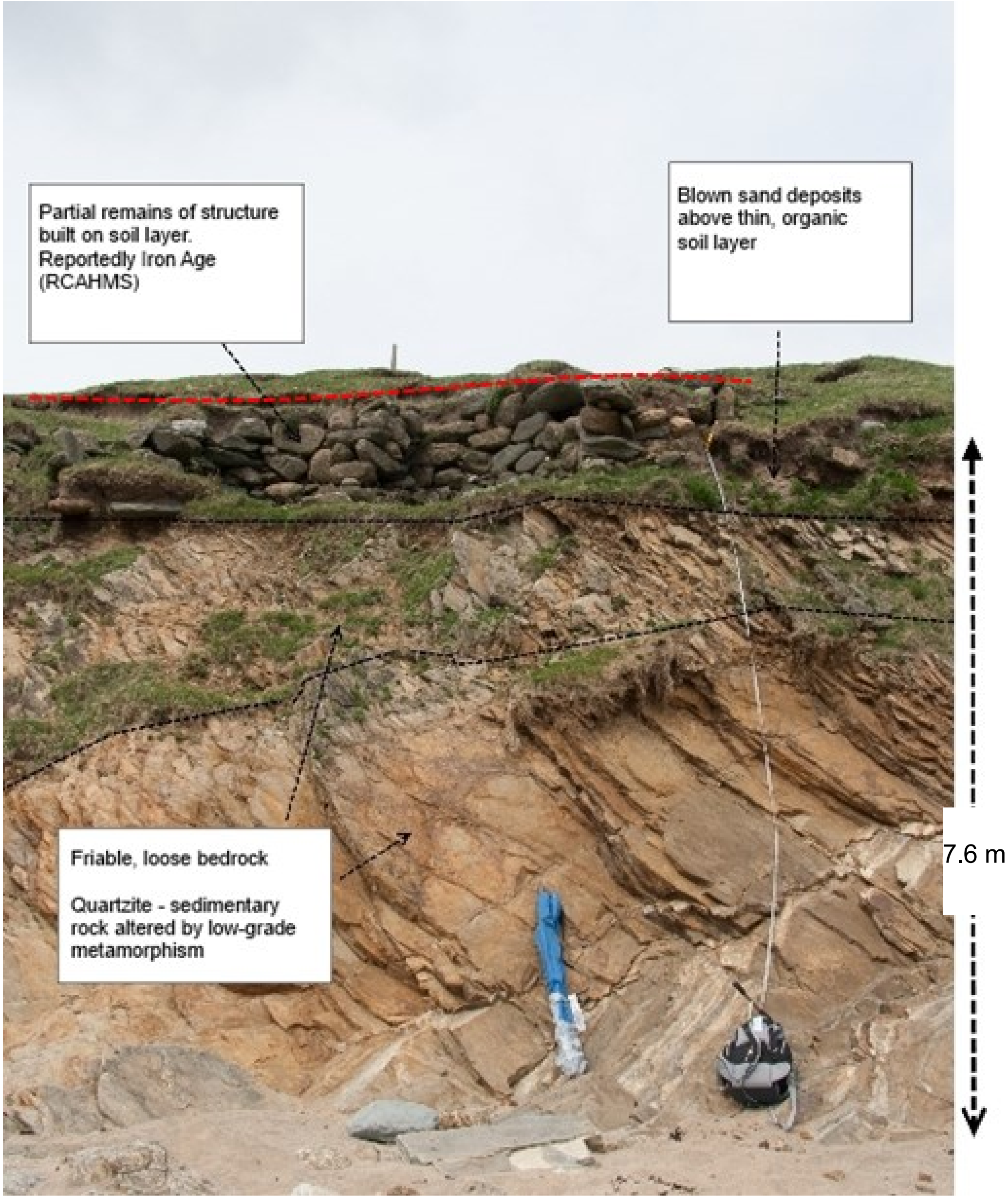


Figure 3.13 - **Description of cliff at Wick of Skaw. Red dotted line indicates approximate level that sand layer reaches above floor layer of ruin.**

The cliff itself is composed of friable rotted quartzite (Mather & Smith, 1973). Approximately 7 m in front of the cliff (from position of photo in Figure 3.13) is a rock outcrop of a similar composition and angle to the cliff itself, suggesting that this may be the remains of the cliff, subsequently eroded.

The maximum rate of cliff erosion could be calculated based on the following assumptions:

- The age of the structure is taken for the end of the Iron Age, ~ 500;

- The bedrock extrusion on the beach is taken to be the maximum extent of the cliff at the time of construction of the structure. This is reasonable, as a structure is unlikely to have been constructed at the extreme edge of a cliff.

This would give an average cliff retreat rate of approximately 2 cm/yr. Compared to other studies on retreat of gneiss cliffs (e.g. Lim et al., 2009), this is a slow retreat rate.

As with Sandwick, evidence of significant quantities of blown sand is present in the hinterland behind Wick of Skaw. Soil cores were taken at intervals behind the beach to determine the extent and volume of this sand. The blown sand deposits extend approximately 300 m behind the beach at their furthest extent. A sharp transition occurs between samples WS3, which shows clear evidence of blown sand under the surface, and WS4, which has no sand content at all. An outline map of blown sand extent was created from observation of exposed soil sections, and extracted soil cores. This established the presence of an extensive sand deposit inland from the beach that contained a large volume of beach sand but has stabilised and is now uniformly vegetated. Figure 3.12 below shows the location of soil cores taken. Photos of each soil core can be found in Appendix C2.

Also in common with Sandwick, the blown sand layer at Wick of Skaw appears to have occurred, or began to occur, suddenly. The walls of the structure on the cliff are constructed upon the thin soil layer over the till. The soils is covered by a uniform blown sand layer. The sand layer is approximately 1.9 m in depth between the floor layer of the structure and the present land surface (Figure 3.13)

Wick of Skaw, therefore, shows evidence of significant threshold-crossing geomorphological change in the relatively recent past. A sharp change is evident due to the clear delineation between blown sand deposits and soils, indicating rapid onset, and the blown sand is covered by uniform vegetation, indicating current stability. In addition, there is evidence of rapid cliff erosion given the truncated nature of the Pictish wheelhouse structure on the cliff top.

3.1.6 Other sites on Unst

The above sites are the ones that show evidence of abrupt changes in coastal geomorphology, as well as being among the few soft sediment coasts on Unst. Other embayments on Unst, however, are interesting to note due to their lack of available soft sediments.

Baltasound is the modern day primary harbour on Unst. Located midway up the east coast of the island, it served as one of the busiest fishing ports in the UK in previous years, and has been continuously settled since at least Norse times. In stark contrast to the sites described above, the shoreline is devoid of any soft sediment and is instead composed of bedrock and large cobbles (Figure 3.14).

Figure 3.14 - View of shoreline at Baltasound (looking north).

Baltasound harbour is protected from wind and wave action by a barrier island (Shetland Island) directly to the east of Balta Sound. This prevents any soft sediment from being transported into the sound and accumulating on shore. Similarly, the harbours at Uyeasound and Belmont (south and south west, respectively) have little evidence of soft sediments on their shoreline. They are both protected from prevailing winds and waves by their south facing aspect. Uyeasound is partially protected by the island of Uyea. Protection by natural barriers does not necessarily mean that shorelines lacking these will be soft sediment coastlines. For example, the Wick of Collaster, an embayment approximately 4 km north of Lunda Wick, shares similar characteristics with Lunda Wick in terms of aspect and exposure to prevailing winds. However, there is very little soft sediment present on the coastline.

Unst, in summary, shows evidence of threshold changes in climate that led to increasing blown sand deposits across the island. However, a complex picture is painted by embayments that share similar characteristics, yet have very different coastlines in terms of soft sediment budget.

3.2 Iceland

Fieldwork in Iceland was carried out between June 29th and July 13th 2014. A return visit was undertaken between June 4th and June 14th 2015 for the purpose of geomorphological mapping, as outlined in Chapter 2.1.2.

3.2.1 Eyjafjorður

Eyjafjorður is the longest fjord in Iceland, approximately 60 km from Akureyri (at its southern end) to the outlet at its northern end (Figure 3.15). The southern half is relatively narrow, approximately 5-6 km in width, widening to approximately 10 km in its northern half, with the island Hrisey located in the middle of its northern half. Observations carried out along both shores of the fjord found that the majority of beaches were composed of cobble/coarse gravel and tended to have steep storm ridges. Evidence of 'cliff' erosion behind these beaches point to the source of the sediment being local (e.g. Figure 3.16).

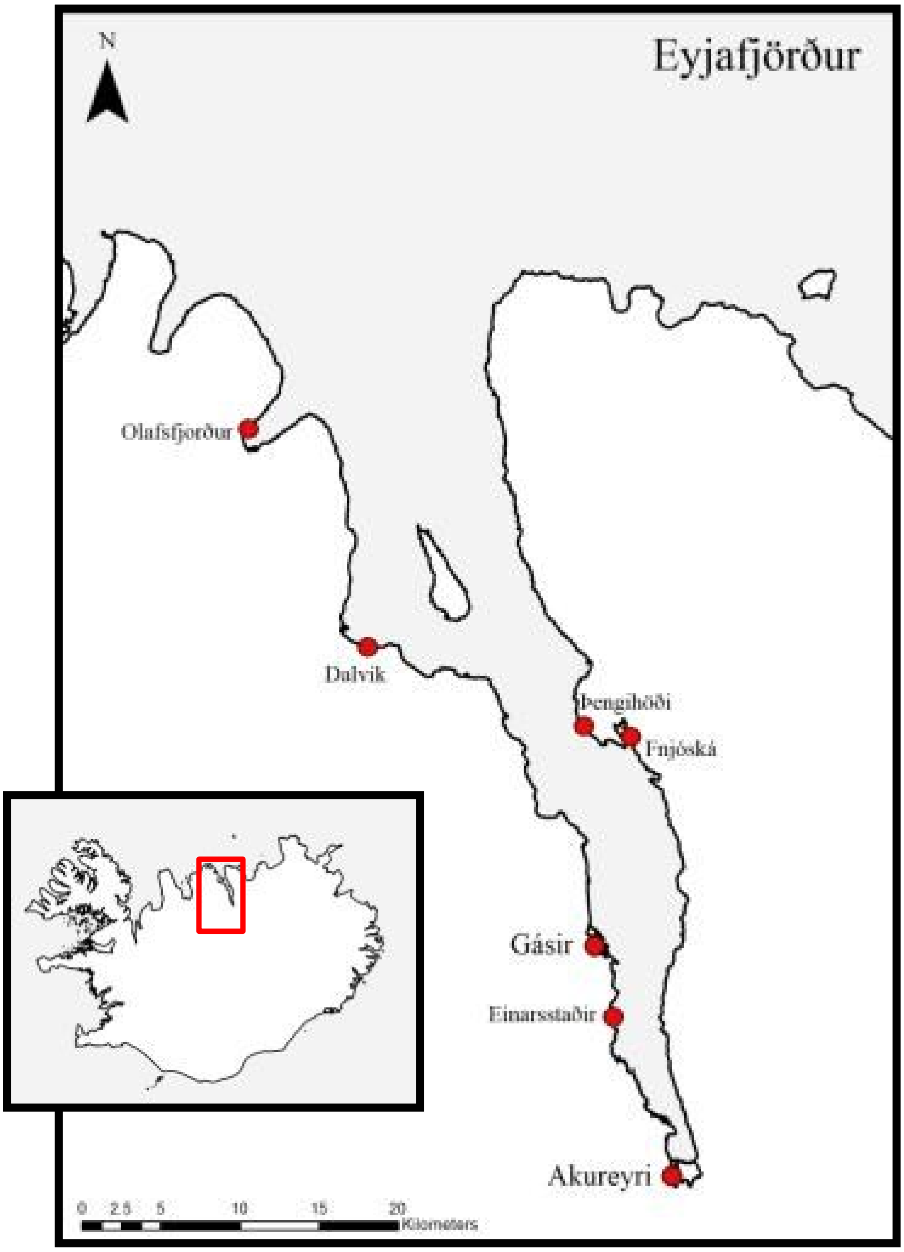


Figure 3.15 - Observed soft-sediment coastline locations in Eyjafjorður.

Figure 3.16 - Olafsfjorður, looking north. Cobbles apparently derived from erosion of moraines and glacial diamicton behind beach. Cobbles primarily rounded or sub rounded, suggesting limited alteration by wave action from the sub-angular/sub-rounded clasts of the till. Linear feature on hillside above shoreline possibly a raised beach.

The few beaches that were composed of fine sediments (primarily black volcanic sands) tended to be located adjacent to an estuary delivering sediment from inland (e.g. Dalvik, Gásir, Fnjóská estuary, Einarrstaðir). The only sand beach found that did not have an obvious source of sediment was a unnamed small beach (85 m width) at the foot of Þengihöði, a small peak south of Grenivík.

Figure 3.17 - Einarrstaðir, looking north. Sands derived from cliff erosion behind beach.

This observed localisation of sediment, and lack of evidence for sandy beaches away from the sources of sediment suggests that longshore drift may not be a significant mechanism operating within the fjord. One hypothesis is that sediment is generated locally and transported via rivers to estuaries, but does not tend to be transported away from this area. This would also suggest that beaches that do form will be relatively stable as long as sediment supply is not interrupted.

These observations feed into the understanding of a specific study site, Gásir, described below.

3.2.2 Gásir

Gásir is a delta on the western shore of Eyjafjorður, approximately 10 km north of Akureyri. The major morphological features of the delta are two outer bars and two inner bars, both composed of fine sediment (Figure 3.18). The water is noticeably turbid within the boundaries of the delta and offshore, showing ongoing sediment deposition. The weather had been rainy before our visit (early July 2014) and a late thaw that year may have been responsible for such obvious observed sediment.

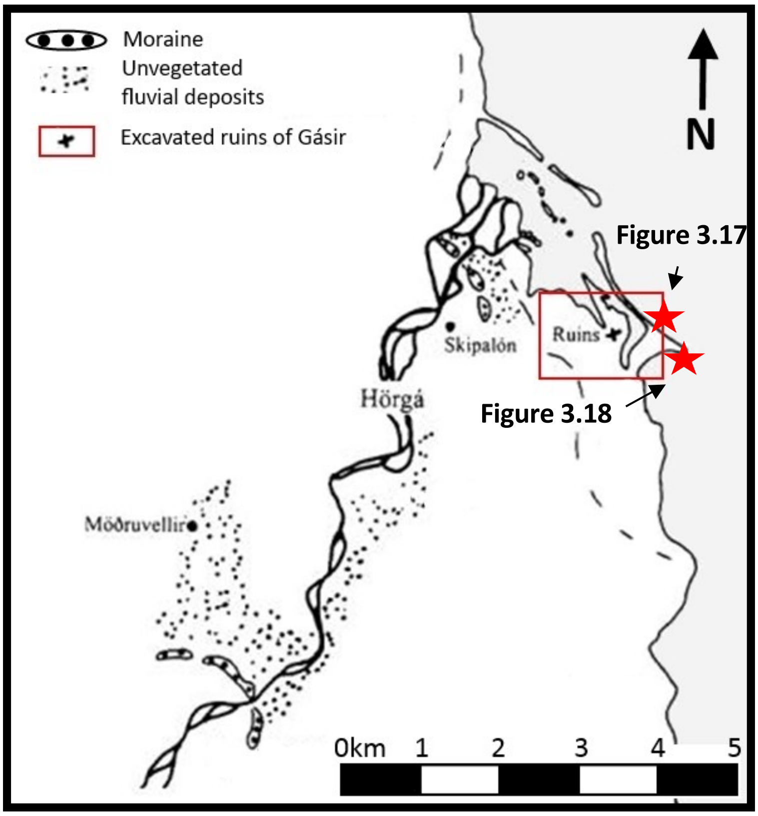


Figure 3.18 - Outline geomorphological map of Gásir (modified from Pétursson, 1999). Red stars indicate position of photographs in Figures 3.17 and 3.18.

Significant quantities of fresh soils were observed washed up on the southern outer bar (Figure 3.19 and Figure 3.20). This is evidence that sediments exit the river and accumulate along the outer ridge. Old soils and wood were buried were also observed partially buried on the outer ridge.

Figure 3.19 - Fresh soils (containing still living vegetation) accumulated on the southern outer ridge of Gásir (looking north).

Figure 3.20 – Typical view of outer bar, looking east towards centre of fjord.

Gásir is the outlet of the river Horgá, flowing through Hörgárdalur (literally "Valley of the Horg river"). It is a braided river, with varying stable and unstable bars (based on observed vegetation cover), and has a floodplain with an approximate width of 1 km while constrained by hillsides, widening approximately 5 km before the delta.

3.2.2.1 Landslides

Hörgárdalur is a relatively steep sided glacial valley, with slopes approximately 1 in 3 gradient in some places. It is orientated NE-SW, with the river Horgá flowing NE and emptying into Eyjafjorður at Gásir.

There is evidence of many landslides on both sides of the valley from observed landslide scars (Figure 3.21). Test pits dug on the valley slopes and tephra profiles (Figure 3.22) identified show that the hill slopes have been unstable potentially even before settlement began in Iceland.

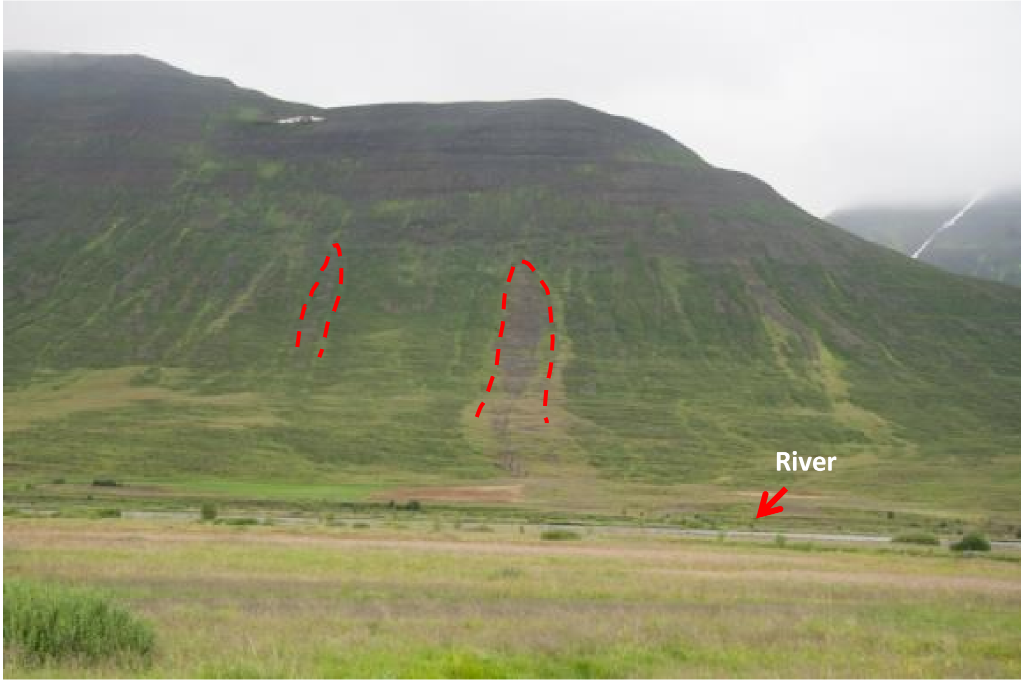


Figure 3.21 - Landslide scars on northern side of Hörgárdalur **(river just visible in middle distance).**

Figure 3.22 – Soil section indicating slope processes. A white silicic tephra layer has been overfolded since initial deposition.

Contemporary sources describe a catastrophic landslide occurring on 17th November 1390 in Hörgárdalur, burying several farms and killing many people (Pétursson, 1999). It is possible that the event of 1390 may have led to such significant change at Gásir that it was a catalyst of abandonment of the harbour, as no mention of Gásir being used after 1400 is seen in historical sources (Roberts, 2002; Harrison, 2008).

3.3 Greenland

Four sites were visited in southern Greenland: Hvalsey, Igaliku, Igaliku Kujalleq and Qassiarsuk (Figure 3.23). These sites were chosen due to the Norse ruins there being adjacent to the sea.

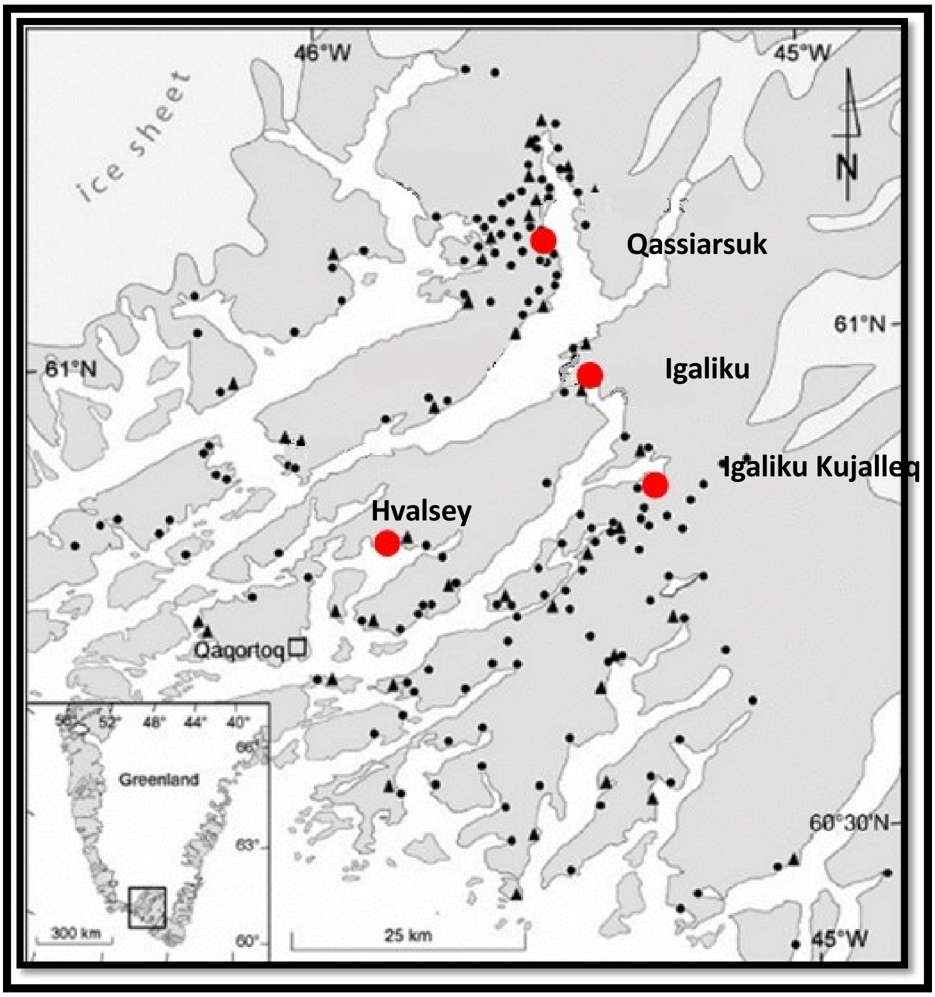


Figure 3.23 – Location of field sites in Greenland. Black points mark surveyed Norse farm sites. Black triangles denote location of modern farm sites. Harbour sites visited marked in red (modified from Bichet et al., 2013).

3.3.1 Hvalsey

The site at Hvalsey is located at 60.49N, 45.45W in a small sheltered fjord. It is perhaps the most well-known of Norse Greenland sites due to what is widely regarded as the best preserved ruin group in Greenland. The church at Hvalsey and the surrounding large farmstead indicates the site must have been of importance in the Norse settlement (Figure 3.24). The actual site of the harbour serving the site, however, is unknown (Madsen, 2014).

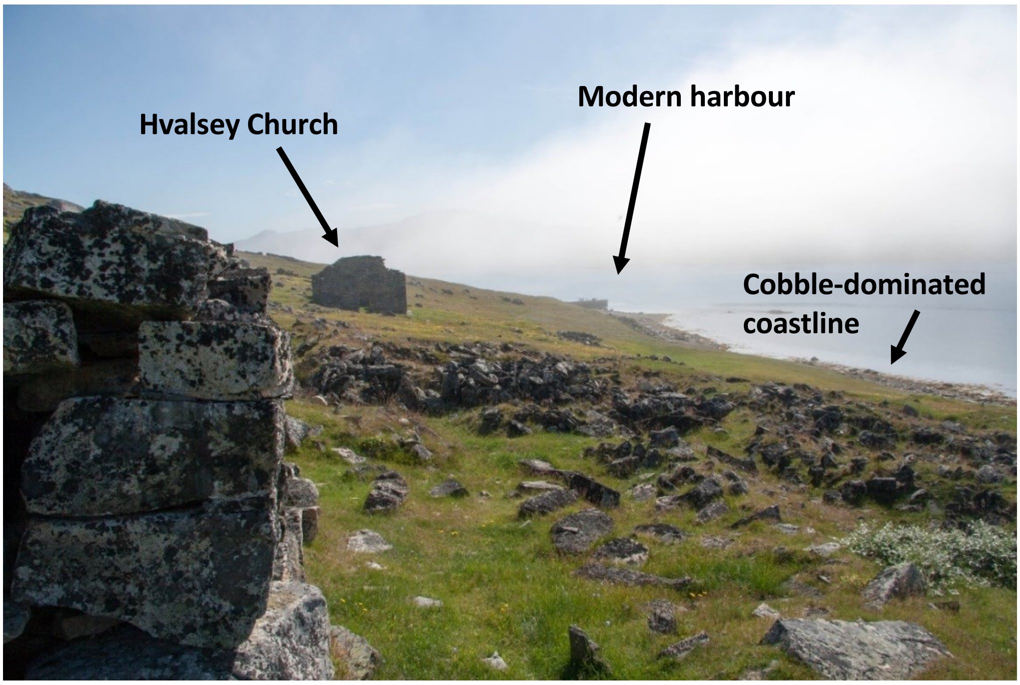


Figure 3.24 – View of Hvalsey, looking north. Church ruins, modern jetty and coastline visible.

The shoreline at Hvalsey, and the wider fjord, is characterised by irregularly spaced coarse-clastic beaches (typically 2 – 50 cm sized cobbles), situated between bedrock slopes. Apart from one area of coarse sand, there is virtually no evidence of soft sediments in the area.

Figure 3.25 – Typical coastline at Hvalsey, looking north. Coastline mostly composed of large gravels, cobbles and boulders. No sand-sized sediment observed anywhere on coast in the fjord.

See Appendix B3 for site and geomorphological map of Hvalsey.

An initial bathymetric survey was carried out on the nearshore area close to the modern jetty at Hvalsey. This was achieved by a diver reaching a pre-determined depth and following the contour of said depth with a dive computer. A Zodiac then followed the diver on the surface, with GPS points frequently recorded along the contour. This built up a picture of the bathymetry below the sea surface at the site (See Appendix B3 for bathymetric map).

This survey demonstrated the ability for a diver to gain basic bathymetry of a harbour, which was employed further at Igaliku (see Chapter 3.3.4).

No skerries or other obstacles were found in this area, suggesting that the beach at the modern harbour site may well have been suitable as a landing site in Norse times. The uniform nature of the sea bed nearshore suggests also that, with sea level rise of 2 m (Kjuipers et al., 2008) the shoreline is likely to have been of a similar morphology as seen today.

3.3.2 Igaliku Kujalleq

3.3.2.1 Setting

The site at Igaliku Kujalleq lies at the head of a side fjord from Igalikufjord. It is a large arcuate bay dominated by the outlet of a glacially-fed river, deriving from the Jespersens Dal glacier, the snout of which is approximately 12 km north east of the river mouth. This river is the source of significant quantities of sediments that are deposited within the fjord. The main group of Norse ruins lie approximately 150 m south of the present day shoreline. One structure, classified as a warehouse, is located approximately 500 m north of the main ruin group, close to the modern day harbour. See Appendix B4 for site and geomorphological map of Igaliku Kujalleq.

3.3.2.2 Geomorphological setting

At the junction between the side fjord and Igalikufjord, there is a very clear delineation between turbid and non-turbid water, due to the sediments entering the fjord from the glacially-fed river. At high tide at Igaliku Kujalleq, the water is a noticeably “milky” colour. At low tide, the entire head of the fjord becomes an exposed mud flat, making it impossible for boats to approach the beach shoreline (Figure 3.26).

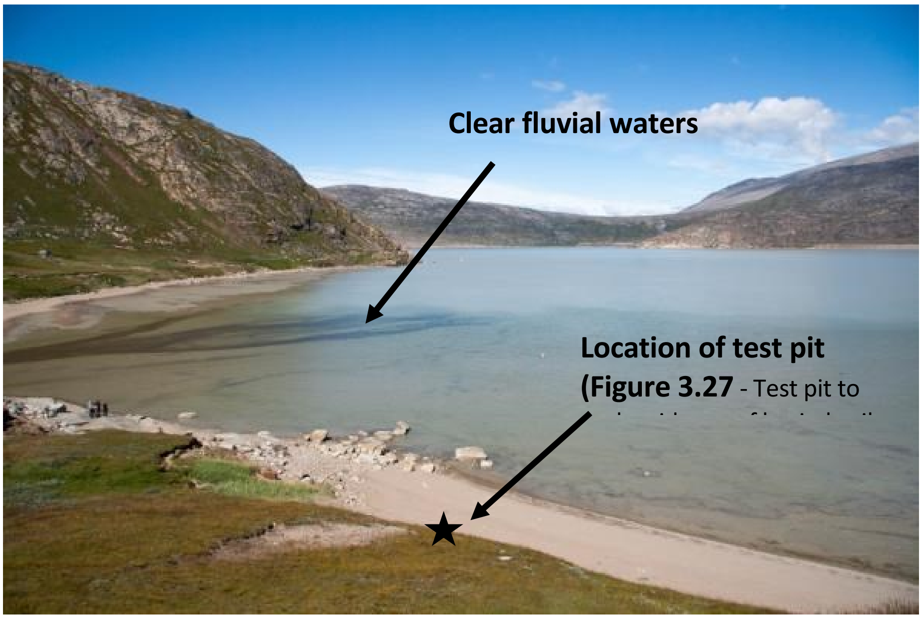


Figure 3.26 - View of Igaliku Kujalleq, looking north west. Note turbid fjord waters, and comparatively clear waters of river flow on the centre left of the picture.

The beach is composed of fine-grained sands, grading into coarser glacial sediment at the beach margins. There is a relatively clear delineation between vegetation and the backshore, however evidence of significant quantities of blown sand exists throughout the landscape behind the beach, in some cases persisting for several kilometres.

Kjuipers et al. (2008) proposed that rising sea levels caused the loss of significant quantities of grazing land, which was situated where the mud flats now lie. A core taken by them at the edge of the beach revealed old soils at a depth of 80 cm below sand. A repeat of this experiment (Figure 3.27) on fieldwork found no evidence of soils to a depth of 88 cm (before water ingress). The core location chosen by Kjuipers et al. (2008) may have yielded old soils that were eroded from the vegetated slopes behind the beach, and does not represent a uniform soil surface. Alternatively, the location chosen in this experiment was incorrect and the soils were missed.

Figure 3.27 - Test pit to seek evidence of buried soils on beach. 88 cm was reached before water ingress.

In summary, Igaliku Kujalleq is by far the most affected by soft sediments of all the sites surveyed in Greenland. However, dating the ingress of glacial sediments and blown sand into the fjord and surrounding landscape could prove problematic due to the scale of these deposits.

3.3.3 Qassiarsuk

3.3.3.1 Setting

Qassiarsuk (61°09’ N, 45°30’ W), along with Hvalsey, is probably the most famous Norse site in Greenland. It was the location of Brattahlíð, the farmstead of the first settler in Greenland, Erik the Red, as recorded in *The Saga of Erik the Red*. As such, the ruins of the settlement are extensively excavated and recorded. The old farmstead buildings and church are located typically between 50 m and 100 m from the shoreline.

3.3.3.2 Geomorphological setting

A site plan and geomorphological map for Qassiarsuk can be found in Appendix B5.

The shoreline at Qassiarsuk is characterised by a series of relatively steep coarse-clastic pocket beaches (typically 2 cm to 30 cm in clast diameter), constrained by thin headlands.

The rock the headlands are composed of is a reddish, sedimentary rock that appears to have undergone partial metamorphosis. It is friable, easily broken by handling. A small sea arch is forming on one headland (Figure 3.28). This would suggest that this section of the coast is actively eroding. However, the location of the ruins of Brattahlíð suggests that the coastline has not moved back significantly in the past 1000 years.

Figure 3.28 - Typical view of Qassiarsuk coastline, looking south.

A side scan sonar survey of the nearshore bathymetry carried out by Hoffman et al. (1999) revealed relatively shallow depths (<3 m typically) up to 100 m offshore, with the remains of a drowned beach 100 m offshore, which could represent lost grazing land due to relative sea level rise. A small skerry was observed approximately 100 m offshore, visible at low tide, which may represent the remains of an eroded headland for this drowned beach (consistent with the shoreline reconstructed by Hoffman, 1999).

3.3.4 Igaliku

3.3.4.1 Setting

Igaliku is a small settlement located on the west shore at the head of Igalikufjord, South Greenland (approximate Lat/Lon 60° 99’ N 45° 42 W). It was the site of the important Norse settlement of Garðar, the seat of the bishop of Greenland from the 12th century.

3.3.4.2 Geomorphological setting

The shoreline is characterised by a mixture of gravel/cobble beaches and bedrock cliffs, composed primarily of Igaliku sandstone with basalt intrusions.

The modern harbour makes use of a shallow gradient gravel bay with an artificial jetty.

Three small islands lie just offshore (islands 1, 2 and 3, Figure 3.29, Figure 3.30). Islands 2 and 3 connect at low tide, with island 2 containing three large ruins. Island 1 lies approximately 100 m off the mainland (from shore to ruin on the island at high tide), and contains one ruin. This island is composed of bedrock, lacking any vegetation. It is almost entirely covered at high tide.

The channel between island 1 and the shore is shallow, even at high tide. The seabed of the channel consists of mostly bedrock, with some sandy deposits overlaying coarser gravels on the southern edge of the channel. An initial diving survey revealed the shallowest depth to be approximately 1.1 m at low tide.

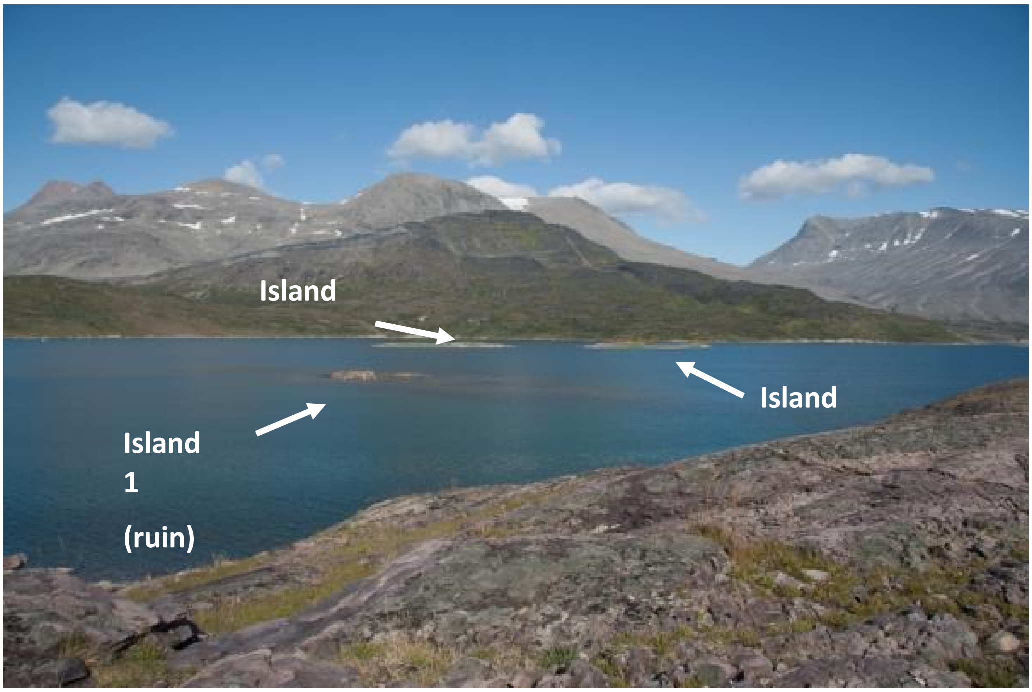


Figure 3.29 - View of Igalikufjord from shore, at high tide. Islands 1, 2 and 3 visible. Note that only the ruin present on island 1 is the only part of the island above water, approximately 100 m from the shore to the ruin on the island (at high tide).

Figure 3.30 - **Aerial view of Igaliku harbour (Google Earth). Transects 1, 2 and Profile 1 are indicated.**

This diving survey was followed up by three GPS transects, carried out at low tide (11:30am, 9th August 2014). One was undertaken along the channel from shore to island, and two across the width of the channel (Figure 3.30). Depth points were taken at several points along the transect to build up a bottom profile of the channel.

The following graphs show the depths recorded in the transects.

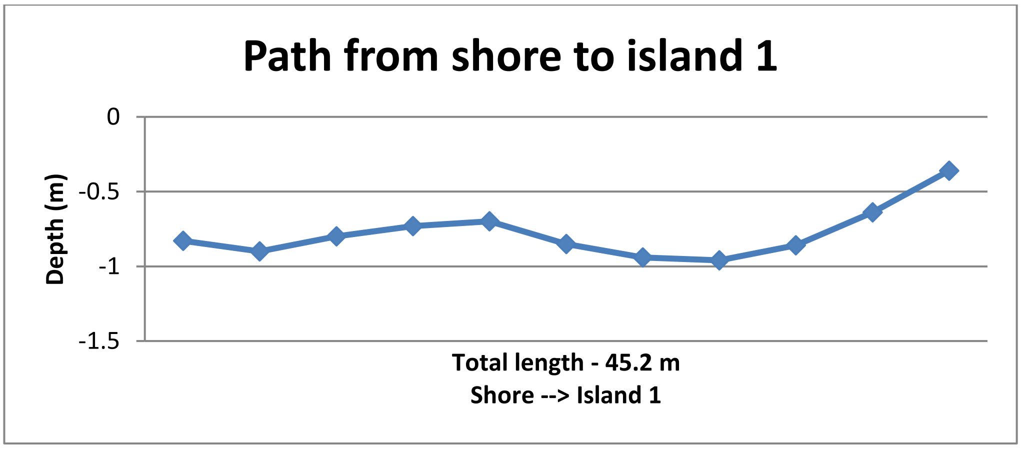


Figure 3.31 - **Transect between shore and island 1.**

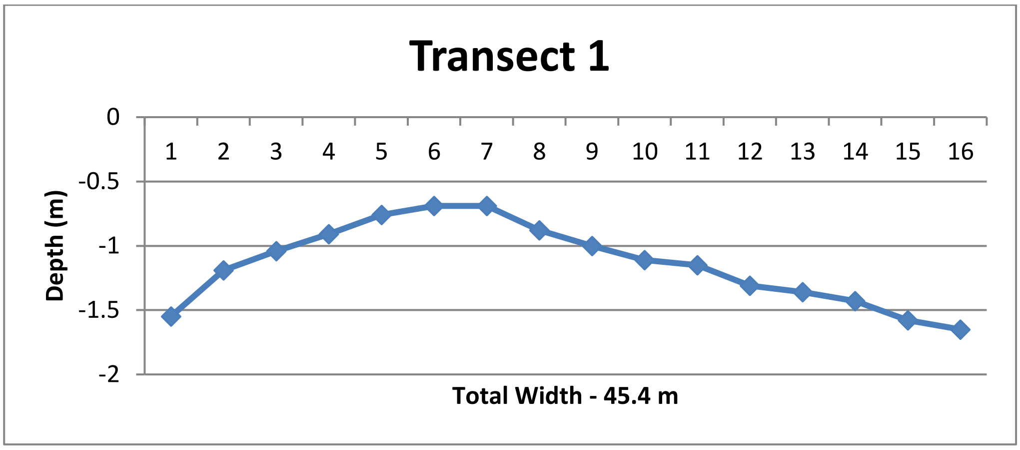


Figure 3.32 - Transect 1 (marked T1 on Figure 3.28).

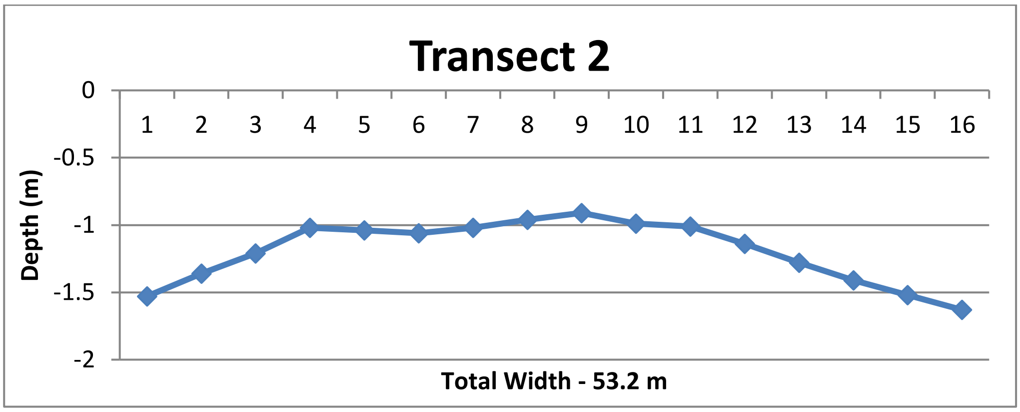


Figure 3.33 - Transect 2 (marked T2 on Figure 3.28).

Sea level change estimates as described in Kjuipers et al. (2008) give an estimated sea level rise of 200 cm/1000 years in Igalikufjord. Table 2.2 calculates the average sea level change in Norse settlement times. Depth change is calculated from the maximum recorded depth of 1.63 m.

Year	RSL change in depth (m)	Average depth (m)	ontext
1000	-0.37	-1	Approximate date of first settlement
1250	0.13	-0.5	‘Height’ of Norse settlement
1500	0.63	0	Approximate date of collapse of Greenland settlement
1750	1.13	0.5	Approximate date of ‘rediscovery’ of settlement
2000	1.63	1	Present day

Table 3.2 - Change in relative sea level at Igaliku harbour.

Table 3.2 shows that even the deepest depth recorded in the bathymetric survey would have been above water at low tide until the year 1200. The average depth of water would have remained above water at low tide until 1500, shortly after abandonment of the Eastern Settlement (e.g. Dugmore et al., 2012). Assuming that the difference between high and low tide has remained the same, the peninsula may have been above water at least at low tide during the height of the settlement, allowing its use as a causeway between the shore and the structure.

3.4 Data collection summary

The fieldwork campaign captured data from a key range of geomorphological settings according to the research questions being addressed in the thesis.

As stated in section 1.4, the thesis questions rely on understanding the drivers of coastline change, in terms of both the forces acting upon the coastline, and the potential for the coastline itself to change shape (i.e. soft sediments, sea level change). With this in mind, the study sites were considered in terms of their relative exposure to wind and wave action, as well as their relative availability of soft sediments. We can now draw qualitative comparisons between the sites, populating the matrix presented in Chapter 2.2 with data from the field sites described (Figure 3.34).

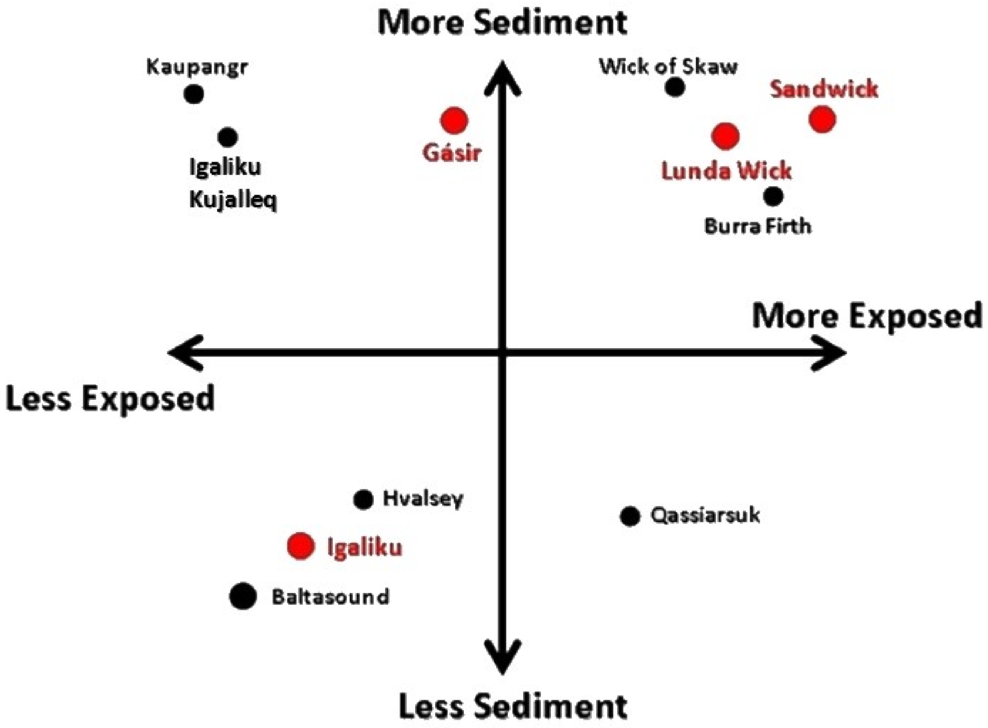


Figure 3.34 - Sediment/exposure matrix populated with field sites. Sites marked in red were chosen for in-depth study for this thesis.

It can be seen how the sites lie in relation to the conceptual overview. It is interesting to note how sites that are separated geographically show similar characteristics in terms of sediment and exposure. The sites on Unst are composed of the softest sediments, and are relatively exposed compared to other sites. At the opposite site of the graph, Igaliku and Hvalsey are relatively sheltered and lacking in soft sediments, therefore the basic morphology of their coastlines are unlikely to change directly due to wave action. Gásir has a contrasting geomorphic setting, sheltered but with inputs of soft sediment, and trajectories of change at the harbour site could be controlled by geomorphic change in the valleys behind.

To address the research questions presented in Chapter 1.7, three locations were chosen for more in-depth study because they typify different geomorphic settings and allow for an exploration of both the stability and instability of coastlines, and their relation to continued use as harbour and landing places. These are marked in red on Figure 3.34.

1) Unst

The island setting of Unst is ideal to investigate the effects of wave and wind action from the open ocean on soft sediment shorelines. Specifically, the sites of Lunda Wick and Sandwick will be investigated using computational modelling and optical-stimulated luminescence (OSL) dating to determine the stability of these landing places for Norse and Medieval seafarers. The evidence of blown sand and potential sudden shifts in climatic state also allows the answering of questions about thresholds of change that cause a stable coastline to become unstable, fulfilling research questions 1 and 2.

2) Igaliku

This site lies at the head of a relatively sheltered fjord, but has very little evidence of soft sediments. Instead, the primary process controlling the morphology of the shoreline appears to be relative sea level change. Not only that, it was the most important harbour of the Eastern Settlement. Quantifying the change in shoreline morphology at a harbour site due to sea level change will offer a perspective on how a harbour site not directly controlled by either exposure or sediment flux responds to geomorphological change. This will fulfil research question 3.

3) Hörgárdalur **and Gásir**

Gásir was a major Norse harbour that shows clear evidence of siltation, evidence for which seems to derive not from offshore sources of sediment, but from inland sources. Investigating the morphological evolution of Gásir, and the effect that changes in available fluvial sediment budget had on its morphology will offer new insights into both the response of the harbour site to these significant changes, and landscape stability in northern Iceland.

Each site analysis will of course fulfil research question 4, which shall place these investigations into context in the discussion chapter.

4 Sediment accumulation in embayments in response to changes in slope and wind-wave climate: implications for beach formation and persistence

The following chapter was published in *Earth Surface Processes and Landforms* on 3rd May 2018: https://onlinelibrary.wiley.com/doi/abs/10.1002/esp.4405

It has been lightly edited for inclusion into this thesis.

4.1 Introduction

Numerous factors control the form and persistence of sandy beaches, including sediment supply, incident wave direction, alongshore and cross-shore sediment transport mechanisms, and tidal range (Masselink & Short, 1993; Masselink & Pattiaratchi, 2001; Cooper et. al, 2004; van Rijn et. al, 2003; Aagaard et. al, 2004; Austin et al., 2009). A number of authors have explored the morphological response of existing embayed sandy beaches to wave and storm attack (e.g., Masselink & Short, 1993; Short, 1996; Forbes et al., 2004; Jackson et al., 2005), and embayment morphology is known to be sensitive to wave driven alongshore (Ratliff & Murray, 2014; Hurst et al., 2015) and cross-shore (Harley et al. 2011) sediment fluxes. The patchy recovery of embayed beaches in the face of storm action has been also noted recently in several studies (e.g., Loureiro et al., 2009; Roelvink et al., 2009; Loureiro et al., 2016). The long-term presence or absence of beaches has received far less attention, however. Recently landscape-scale models of beach and headland erosion have focused on sediment supply from headland erosion to maintain beaches (Limber & Murray, 2011), but less attention has been paid to the sediment transport dynamics that may promote or inhibit beach formation and stability.

Beaches have important economic and cultural value to coastal communities. Not only is the desirability of living by the coast a major economic factor, with associated tourism and recreational activities, but also beaches and coastlines hold many cultural and archaeological sites. Understanding what drives their formation, stability and distribution is crucial for effective management strategies and adaptation in the face of future climate change (e.g., Zhang et al, 2004; Dawson, 2013). Beach sediment is eroded during storm events and often lost offshore, but beaches can recover these sediments gradually over seasonal to decadal timescales (e.g. Harley et al., 2015; Scott et al., 2016).

Beach formation is dependent on the availability of sediment, as well as its movement and residence time at the nearshore. Sediment can be derived from three basic sources: on-shore (e.g., shoreline- derived sediment from coastal erosion or delivered by rivers), off-shore (e.g., glacial or fluvio-glacial sediments, other sub-marine sediment and biogenic materials, re-worked by rising sea levels) and alongshore (i.e. supplied by alongshore drift). At specific locations, sediments from these different sources are reworked by the interplay of currents, waves and wind with topography (Castelle & Coco, 2012; Maspataud et. al, 2009).

Offshore sediment supply to replenish beaches is transported nearshore and is often deposited as sediment berms and sand bars, which the formation and stability of which can be impacted by storm events (e.g. Ruessink et. al, 2016). High-energy coastlines without headlands lack barriers to the lateral movement of sediment, thus beaches can be formed or replenished wherever alongshore drift is active and there is sufficient sediment supply. In contrast, the irregularities of high-energy, headland-dominated coastlines inhibit alongshore sediment flux (e.g., Short, 1996, Limber & Murray, 2011; da Silva et al., 2016), allowing beach material to accumulate between headlands to form embayed beaches (e.g., Limber & Murray, 2011). Aeolian erosion and deposition, particularly in these storm-prone high-energy environments, can be a driver of beach destruction and formation without oceanic interaction. For example, some beaches in sheltered embayments may be due to interactions with dune systems, with cycling of sediment replenishing beaches from dune material, and vice versa (e.g., O'Connor et al. 2007), but in many cases dunes are absent and a beach-hinterland cycling model cannot explain phases of beach formation and destruction.

Despite similarities in sediment supply, exposure to wave and tides and other forces as described above, we observed that not all embayments along a coastline will contain beaches (Figure 4.1).

Figure 4.1 - Headland-dominated coastline on Unst, Shetland, and Cape Trehel and Hut Point, Falkland Islands. Lunda Wick (a) contains a sandy beach, yet Westing (b) and Collaster (c) do not (gravel or cobble dominated), despite being geographically close and sharing similar geomorphological characteristics and similar offshore sediment supply. In the Falkland Islands example embayments (d) and (f) contain sandy beaches, yet embayment (e) does not despite similarity in geomorphological characteristics and exposure to external forcing. Armantine Beach, to the east of embayment (f), is not constrain by headlands thus alongshore drift mechanisms can operate (Map data: Google, Digital Globe. Unst imagery taken 05/08/2008, Falkland imagery taken 01/09/2012).

Our aim is to better understand what controls the input of offshore sediment to beaches on high energy, headland dominated coasts and what controls the formation, stability and replenishment of these beaches. In this paper we combine morphological analysis and coupled morphodynamic and hydrodynamic exploratory modelling to investigate how offshore slope and wind regime, two driving factors behind coastal sediment transport, can affect migration and accumulation of sediment in the nearshore environment.

4.2 Approaches and methods

We adopted a research strategy that combines empirical observation and numerical modelling. Firstly, we analysed bathymetric data from examples of headland-dominated, high-energy coastlines to highlight an empirical relationship between local offshore slope and the presence or absence of sandy beaches in headland-bounded embayments. We sought to understand this relationship through numerical modelling of embayments with different offshore slopes and wind conditions.

4.2.1 Observations of offshore gradient and the presence of beaches

We used bathymetric charts compiled by the United Kingdom Hydrographic Office (UKHO) to quantify offshore slope in a range of locations (Figure 4.2). Formerly glaciated coastlines with high energy, headland dominated coastlines were chosen for analysis, because extensive glaciation leaves a legacy of unconsolidated offshore sediment that could form a ready supply of material for beach formation (e.g. Clark et. al, 2012). Bed elevations were determined at 1 km from shore roughly perpendicular to the orientation of the shoreline in the centre of the embayment. These were used to calculate the average offshore slope. We fully acknowledge the seemingly arbitrary nature of the 1 km distance, however this distance was chosen to avoid a bias towards small-scale nearshore features, such as shore platforms, that are poorly resolved on most Admiralty chart data.

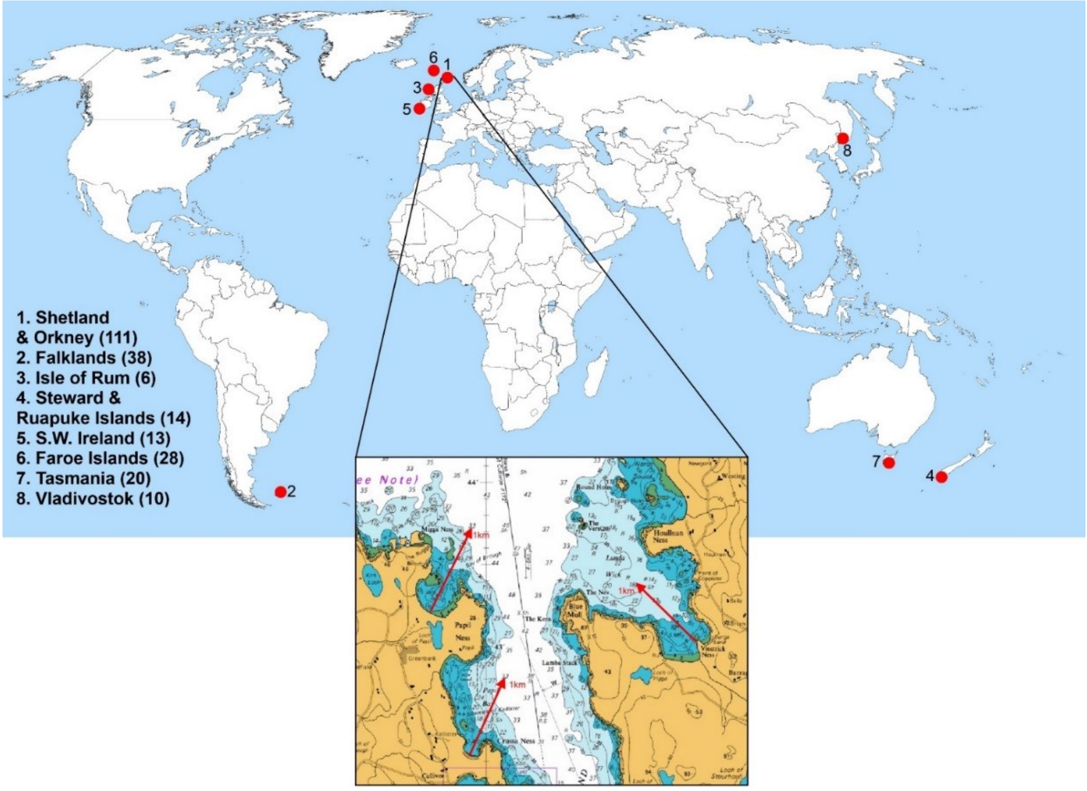


Figure 4.2 - Global distribution of analysed embayments. Numbers in parentheses are number of embayments analysed in that location. Embayments were partly constrained by the availability of Admiralty charts of a high enough resolution. Inset: example Admiralty chart from Shetland. Local geomorphological variations along this gradient, such as shore platform or other features were ignored (source: UKHO).

At each site, we selected stretches of headland-dominated coastline and measured average offshore slope in every embayment within that stretch. Coastlines were initially identified by availability of high resolution Admiralty charts (greater than 1:75,000). Sites were not filtered by onshore factors. We removed embayments that had skerries or barrier islands within 1 km of the shore. Embayments with major inputs of sediment from terrestrial sources (such as those containing river deltas) were also omitted, to ensure that sediment supplies moving across the offshore slope was the principle factor under consideration.

Google Earth imagery was used to determine the presence or absence of a sandy beach. A qualitative analysis of the colour and texture of beaches on aerial imagery supported by any other available photographic evidence (for example, Panoramio photographs in Google Earth, and Google Image searches for specific embayments) was used to determine if beaches were sandy or not. A total of 239 embayments were analysed, of which 119 contained sandy beaches. These data were grouped based on 0.05 m/m increments in offshore slope derived from admiralty charts. We calculate the probability of finding a beach as the number of beaches in the slope bin divided by the number of sites analysed in that bin. We find that whereas the majority of sites with slopes less than 0.025 m/m had beaches, far fewer beaches were found at sites with slopes greater than 0.025 m/m. For slopes greater than 0.025 m/m, the probability of finding a sandy beach decreased with increasing bathymetric slope (Figure 4.3). During sampling, few suitable embayments were identified with gradients above 0.034 m/m and below 0.009 m/m, thus these end members bins should be treated with caution.

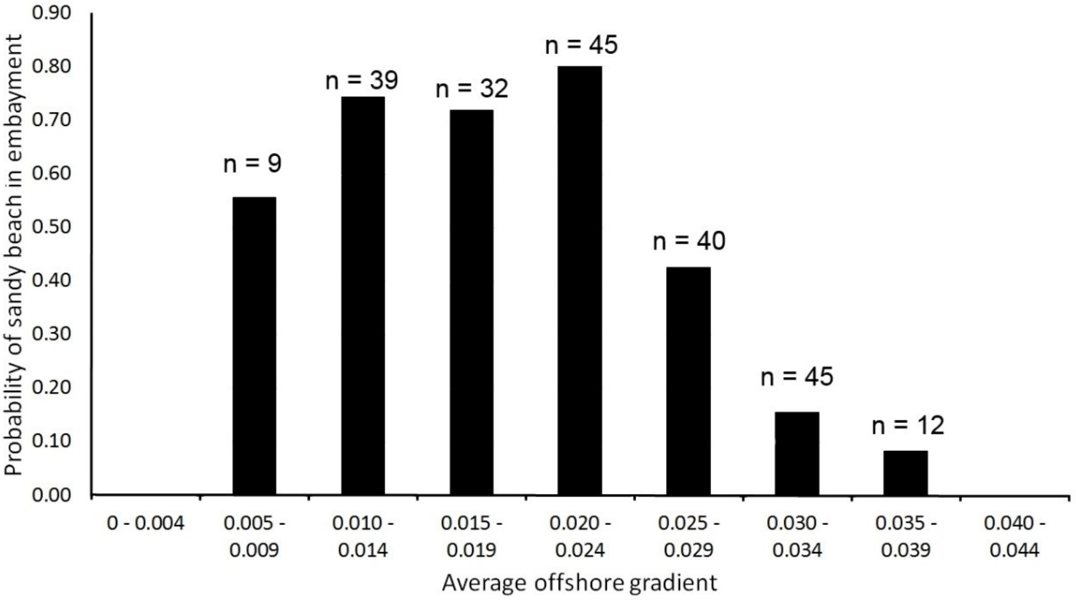


Figure 4.3 - Probability distribution of beach location as a function of offshore slope, with bin size indicated. N numbers are number of embayments analysed in bin. No suitable embayments with slopes less than 0.004 m/m or greater than 0.040 m/m were identified.

We acknowledge that compounding factors exist that may impact the relationship presented in Figure 4.3. Specific morphological factors such as sediment composition and headland amplitude, as well as hydrodynamic factors such as local wave and tide conditions can all impact the accumulation of sediment in embayments suitable for beach formation. However, this association was of sufficient clarity for us to undertaken exploratory morphodynamics modelling to better understand the controls on this relationship.

4.2.1.1 **Model domain**

We designed an idealised embayment formed by a rectilinear grid, 2 km in length and 1 km in width, created using the MIKE21 domain generator. We chose these dimensions to be as representative of embayments found along high-energy coastlines from our Admiralty chart analysis (Figure 4.4).

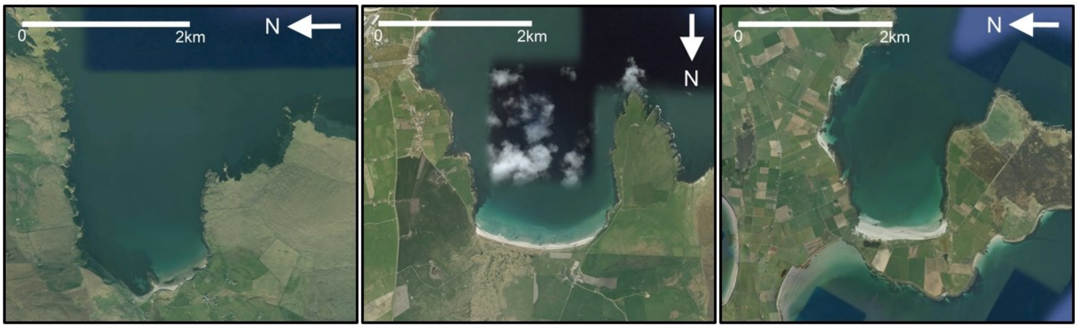


Figure 4.4 - Examples of bays of similar dimensions to idealised model. a) Norwick, Unst, Shetland; b) Quendale, Mainland, Shetland; c) Rothiesholme, Orkney (source: Google Earth).

We set a non-erodible land boundary for the shoreline, and two land boundaries representing non-erodible headlands for the lateral edges of the domain (see Figure 4.5). The open boundary was set so that the spatial change in sediment flux across the boundary was zero. This allowed sediment to both enter and leave the domain as demanded by the changing hydrodynamic conditions, without suddenly depositing or eroding material at the boundary, avoiding a glass wall effect (Keen et al., 2003; Manson, 2012). We chose this boundary condition to avoid artificial accumulation of sediment against the boundary. **Error! Reference source not found.** lists the model initial conditions. Note that these boundary conditions are specific to embayments that do not have a significant terrestrial sediment input.

Parameter	Initial condition

Sediment	1 m thick sediment layer
Tidal range	2.56 m, Uniform direction throughout model run (0°, parallel to shoreline)
Winds	Calm conditions (1 – 15 m/s) Stormy conditions (1 – 60 m/s), angle 345° to 45° (NW to NE)
Slope	0.020 m/m to 0.030 m/m, 0.001 m/m increments
Model simulation time	10 years

Table 4.1 - Summary of range of initial conditions used in model simulations

Non-erodible bathymetry (the hard bedrock substrate) was created as a uniformly sloping plane where the seaward side (1 km from shore) was set to depths ranging from 20 m to 30 m, to generate shoreface slopes ranging from 0.02-0.03 m/m. We added low-amplitude noise to the nearshore bathymetry with an average amplitude change of 0.15 m (Figure 4.5). This is intended to reflect minor morphological heterogeneity to the underlying bedrock surface by simulating small irregular undulations in nearshore contours. These perturbations are 'smoothed out' after initial model timesteps and final model results are not sensitive to the amplitude of the noise imposed.

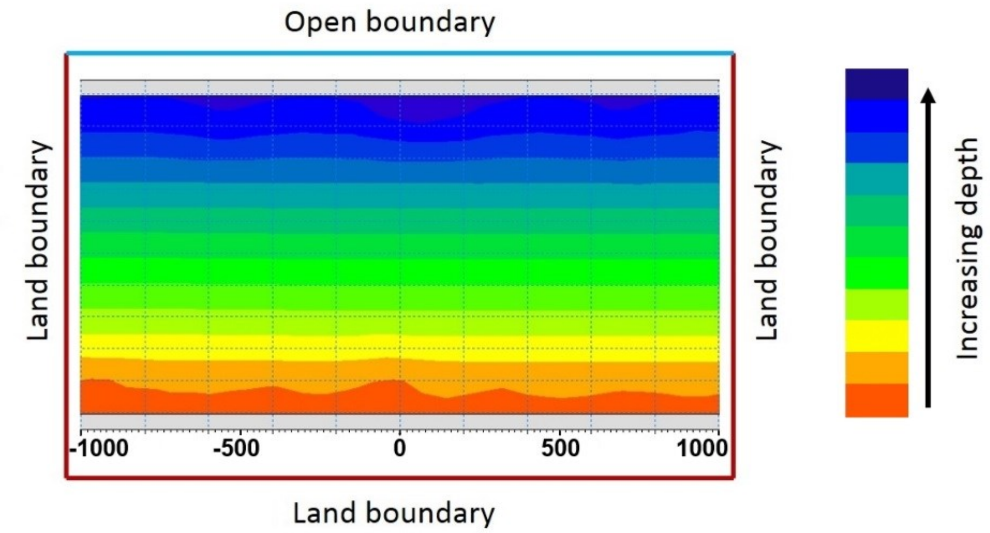


Figure 4.5 - Model schematic of typical idealised embayment, with lateral land boundaries representing headland walls, horizontal land boundary representing the shore, and the open boundary representing the open ocean. The grid itself represents bedrock bathymetry, with depth increasing offshore. The depth at the open boundary varies according to the offshore slope.

4.3 Initial conditions

We added a uniform 1 m thick sand layer across the entire domain, representing an initial sediment volume in the domain of 2×10^6 m^3. The properties of this sediment layer were generated in MIKE21 using the Q3D sediment generation table. This utility produced a file containing sediment properties that were used by the ST module and applied for each time step. **Error! Reference source not found.** lists the sediment properties chosen for the modelling exercise. There is no simulation of the actual presence of a beach above the water line as MIKE21 cannot resolve mesh elements that become ‘dry’ (i.e. at low tide where a beach may form), but sand bars form just below minimum water level, which acts as a ready sediment supply for beach building. Our aim here was to explore climate and slope effects on the shoreward migration of coastal sediment.

Q3D table properties	Parameter value	Justification
Sediment density	2650 kg/m³	Standard density of quartz/carbonate particles , representing 'shell' sands as derived from offshore.
Grain size d_{50}	250 µm	Grain size of fine/medium sand
Wave theory:	Isobe and Horikawa (1982)	Appropriate for deep and shallow water, breaking and non-breaking waves. Chosen in part due to the inclusion of bed slope effects on time-varying orbital velocity. Sensitivity analyses for two more wave theories, Stokes and Cnoidal, showed negligible change in the results.
Sediment transport theory:	Engelund & Fredsoe (1976)	Calculates total sediment load (bed load + suspended load)
Average current speed	0.05 m/s	Left as default as included in the model.
Offshore Significant wave height	1.5 m	Based on Shetland buoy data, average significant wave height under 'calm' winds.
Wave period	5 seconds	Based on Shetland buoy data, average wave period observed over 1 year period in 2011 (Station 63112 – Cormorant AWS)
Offshore Wavelength	28.86 m	

Table 4.2 - Sediment properties and wave conditions driving model simulations.

We chose a meso-tidal range of 2.56 m for the modelling, derived from the tidal range as recorded in Lerwick, Shetland, UK. This is a typical high energy headland-dominated coastline with a long tidal gauge record. Model sensitivity analysis shows the model to be insensitive to tidal range (see supplementary information).

To remove bias of specific storm surges or other tidal swells, we based the tidal record on the Lerwick data. Rather than using gauge records, this was generated using tide-prediction software JTides (JTides, 2017) (To capture the impacts of wave action on sediment transport, a time step of 30 minutes was used for the tide. A tidal record of 1 year was generated (the maximum the program allows), and extended to create a 10 year record. We chose a simulation time of 10 years to provide a sufficiently ‘long term’ evolution of an embayment, capturing the influence of multiple years of storm impacts on the coastline. This allows an understanding of beach formation, persistence and recovery framed by a timescale on which economic uses of the coastline rely upon, whether modern or historical.

The specified *significant wave height* (SWH) and the *peak wave period* (T) are modified by wind-generated waves in the HD and SW module, and act as initial conditions for the wave field. Wind fields specified in the HD module modify surface waves as they transform across the bathymetry, modifying SWH and period each time step. SWH and T values were derived from average values over a year (2011) from the closest sea buoy to Shetland (NOAA, 2016) (see Table 4.2). While storm surges are important for subsequent sediment transport, we do not include any specific surges beyond that which is calculated as part of the SW results as the purpose of the experiment is to understand nearshore sediment transport on a long-term basis, rather than any specific storm.

Radiation stresses produced by wave action are governed by the output of the SW module and applied to the HD module for the simulation of sediment transport. Radiation stresses are calculated based on SWH, which is subsequently modified each timestep due to wind-sea and swell conditions. Thus there is no specific swell-wave significant wave height chosen. Peak spectral wave period (the wave period corresponding to the maximum wave energy level in the wave spectra) is an output of the spectral wave module based on an initial peak wave period. Wave direction at the offshore boundary is set as perpendicular to the model shoreline (0°) to represent fetch-unlimited waves impacting the shoreline without interference from refraction around the headlands (or islands). Wind-sea and swell conditions are calculated in the spectral wave module, with the JONSWAP formula added. While this is fetch-limited by definition, the maximum fetch length specified in the model is 1000 km, thus the formula calculates an essentially 'unlimited' fetch for our purposes. Wind-sea and swell conditions are derived from the SW module and applied to the HD module.

We split wind forcing into two categories, calm and stormy. Median wind speeds on Shetland (as stated, a typical high-energy coastline prone to storminess) are ~7.36 m/s (average monthly mean 1930 - 2010), and so tlm conditions were chosen to reflect this. Thus calm conditions were specified to range from 1 to 15 m/s, and stormy conditions to range from 1 – 60 m/s. The maximum value of 60 m/s (active for only 6 hours out of 10 years of model simulation) was chosen to represent persistently stormy conditions on the coastline as it is the median of the highest wind gusts recorded in Shetland in each of the past 30 years, which range from 45 m/s to 77 m/s (Shetland Islands Council, 2011).

We set wind direction to be randomly selected between north west (325°) and north east (45°) every 6 hours. Figure 4.6a illustrates the running mean wind speed distribution (over a model 3 day period) applied in the model over a typical model 'year' in 6-hourly increments, for calm and stormy scenarios. While this method does not take into account seasonal storminess, we chose this to subject a headland embayment to constant storminess and thus determine the physical effect these persistent conditions have on sediment transport onshore, regardless of storm season. Onshore winds (i.e. those blowing from onshore to offshore) were ignored, as were across-shore winds (i.e. winds parallel to shore). This is a limitation, but we deliberately built this into the experiment so as to isolate the effect that purely offshore wind-generated waves and subsequent wave energy has on nearshore sediment transport (Van Donk et al, 2005). Wind speed randomly varied at the same temporal frequency based on a Weibull distribution of the bounds listed above (Figure 4.6b), common of wind speed distributions at many coasts (e.g. Tuller & Brett, 1984; Van Donk et. al, 2005; Kidmo et. al, 2015).

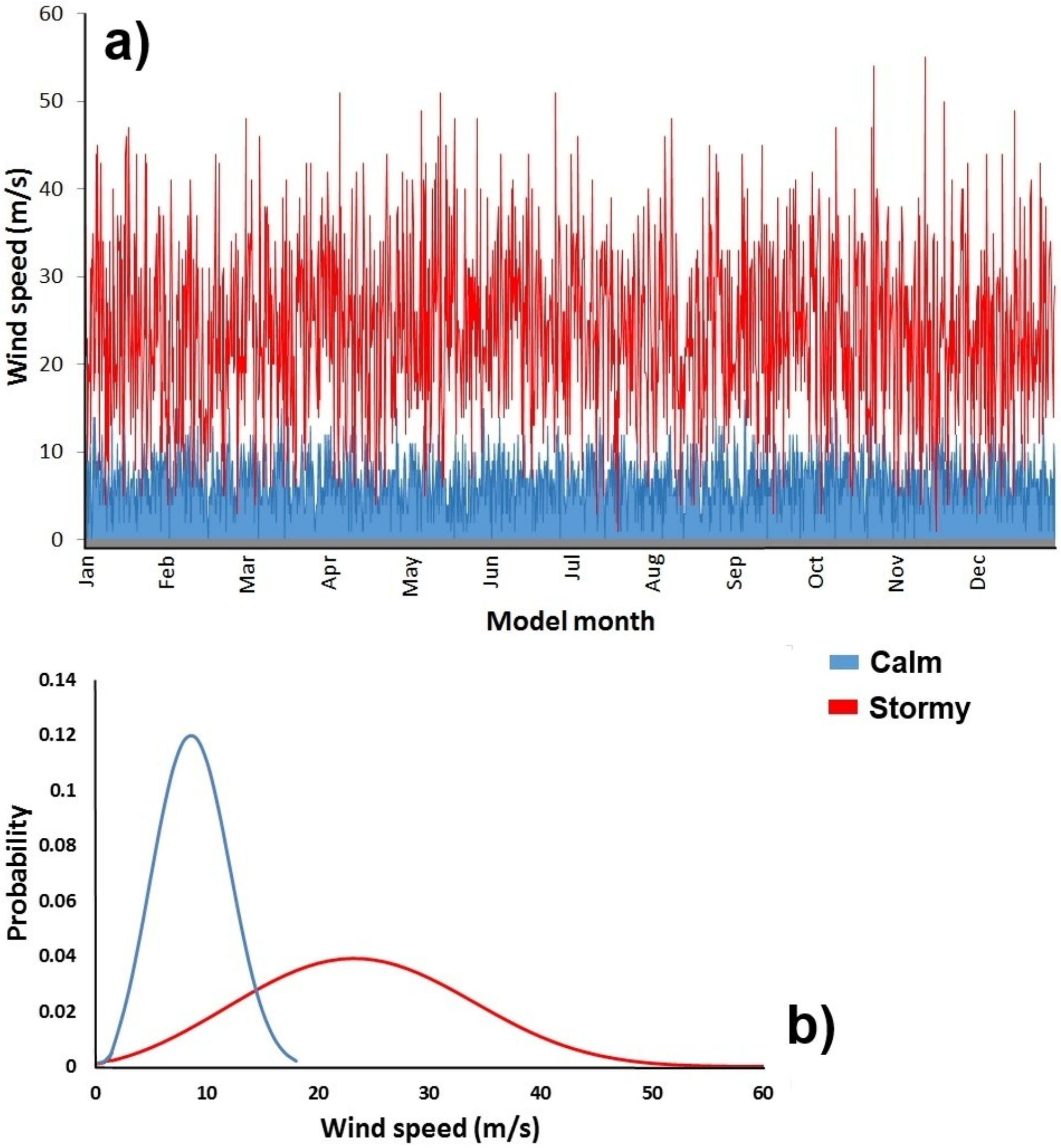


Figure 4.6 – a) typical wind speed distributions experienced in the model over a model year, for calm and stormy scenarios. Each unique value is selected by the model every 6 hours to represent wind speed in that time step. b) Weibull distribution of wind speeds in the sediment transport model. Probability of a wind speed value is calculated for the model period of 10 years and selected at random by the model every 6 model hours.

4.4 Sensitivity analyses

We carried out the sensitivity analyses on the model to lend confidence that our results are not unduly influenced by choice of model parameters (**Error! Reference source not found.**). Sensitivity analyses can be found in supplementary information.

While both bedload and suspended load are operating in the model and reported as total load, both Bagnold (1966) and Bowen (1980) demonstrated bedload transport was the dominant process nearshore for sand particles of 250 μm in diameter when horizontal orbital velocity are less than 0.35 m/s. Mean horizontal orbital velocity in calm scenarios for all slopes is less than 0.1 m/s, and less than 0.3 m/s in stormy scenarios for all slopes.

MIKE21 calculates model results based on mesh elements in the domain, essentially model ‘cells’, which can then be interrogated once the simulation is complete. Both numerical and graphical representations of mesh elements are output. These were interpolated from the model results mesh and exported to a 10 m resolution grid in order to perform differencing in bed elevation and to visualise results.

4.5 Modelling results

We explored the morphological evolution of idealised embayments with contrasting bathymetry and differing wave forcing conditions.

4.5.1 Planform sediment patterns

Figure 4.7 shows planform views of the final time step (10 year model simulation time) for model simulations under calm and stormy conditions for gentle and steep bathymetric slope.

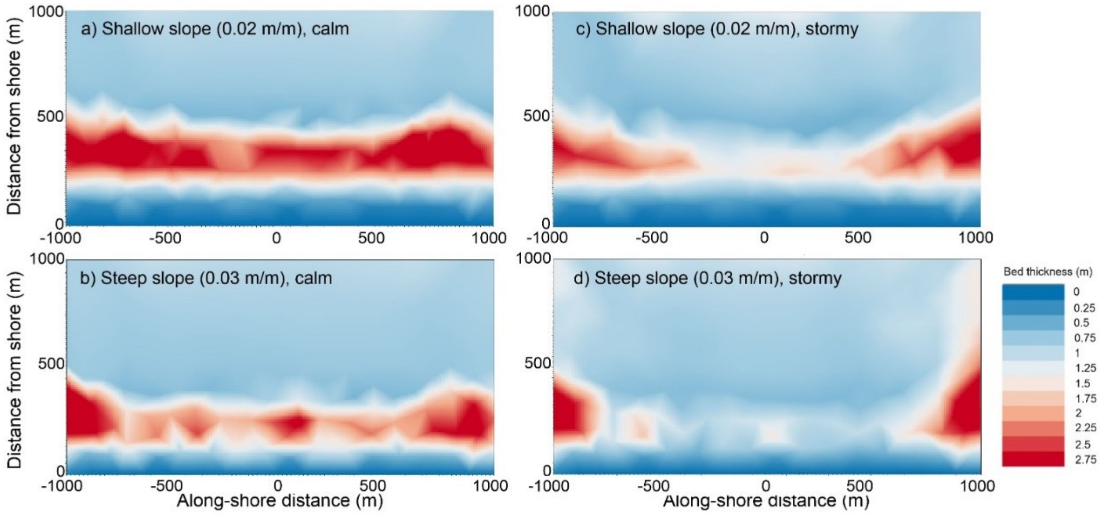


Figure 4.7 - Simulation of planform sediment thickness, a) under calm conditions for the 0.020 slope, b) under calm conditions for the 0.030 slope, c) under stormy conditions for the 0.020 slope, d) under stormy conditions for the 0.030 slope (10 year model simulation time).

Sand bars form just below mean low water for both shallow and steep slopes under calm conditions, although on the steeper slope sediment deposition is patchy, with thinner sediment deposits towards the centre of the model domain. MIKE21 does not resolve sediment accumulation within the swash zone where model cells become 'dry' as the tide ebbs (approximately 150-200 m from the shore, depending on offshore slope), but sediment for beach formation is available offshore if the bar is present. Under both calm and stormy conditions, the sand bar formed after one month of model simulation time and stayed relatively uniform throughout the 10-year simulation time.

A marked difference in shallow and steep slopes was observed in terms of sediment distribution forced by stormy conditions. On shallow slopes, sandbars form in both calm and stormy conditions but sediment is thinner in sandbars formed in stormy conditions. On steep slopes, sandbars also form in calm conditions however, no sandbar formed under stormy conditions, with sediment instead rotated towards the headland walls and offshore into deeper water.

4.5.2 Volume flux

Figure 4.8 shows swath profiles of sediment thickness at the end of the model runs. In both calm and stormy scenarios, sediment has aggraded toward shore, whereas sediment has been lost (i.e. is less than the initial 1 m thickness) in the seaward side of the model domain. The steep drop-off of sediment thickness close to shore is representative of the tidal range in the model, and thus sediment transport cannot be resolved in this part of the domain as the cells go 'dry' as the tide ebbs. We find maximum sediment thickness at offshore distances just below mean low water (MLW).

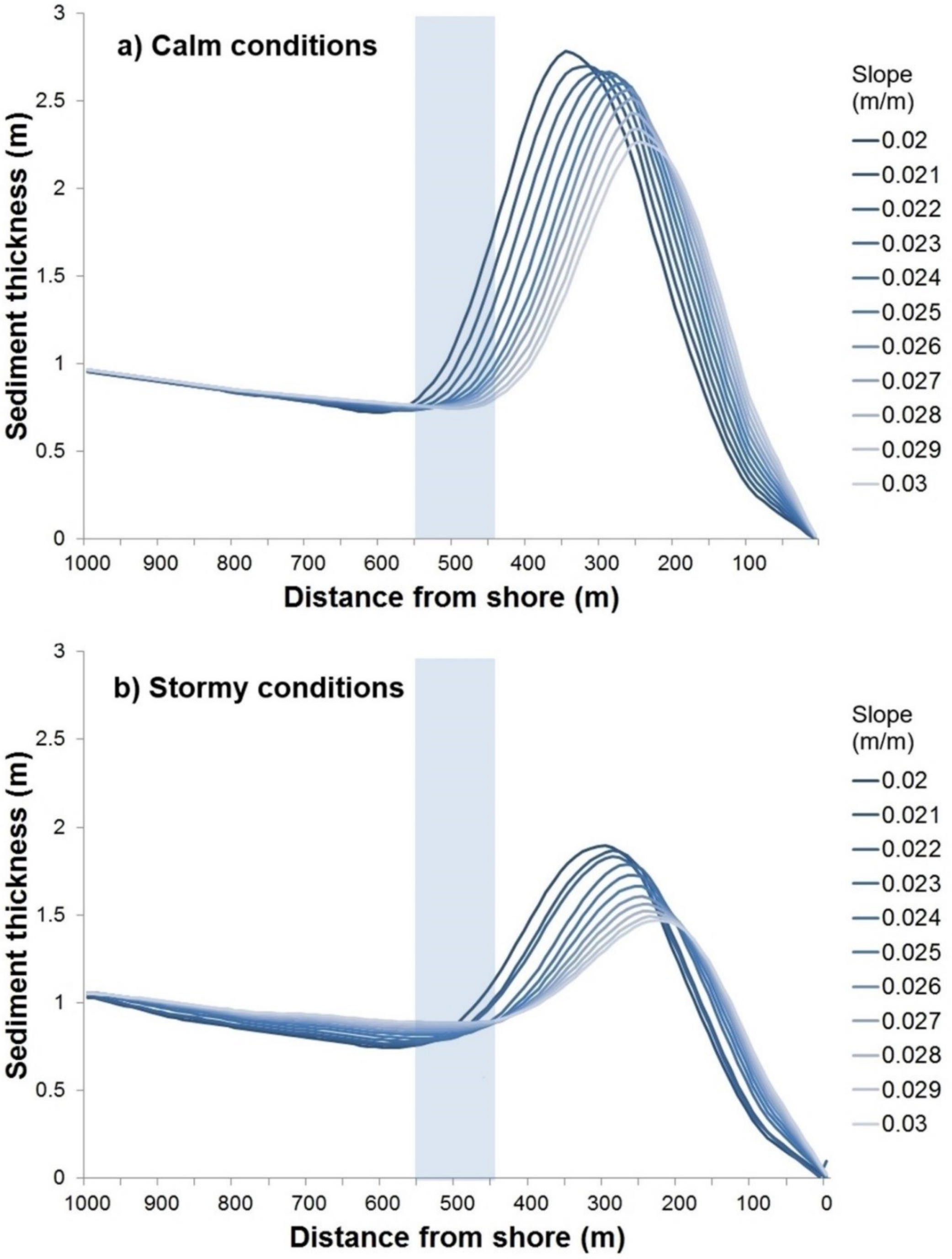


Figure 4.8 - Swath profile of sediment thickness under (a) calm and (b) stormy conditions. Inferred wave base distance from shore represented by blue box. The thickness of the nearshore sand bars reduce as gradient increases across scenarios, and the sandbar builds nearer the landward boundary for steeper bathymetric slopes. The steep reduction in sediment thickness close to shore represents the swash zone in the model.

In both calm and stormy scenarios, there is a distance from shore where sediment thickness increases from the initial 1 m. varying between 450-550 meters offshore dependent on slope. These locations are roughly coincident with wave base, ~14.4m in our model set up, defined as half the wavelength (e.g. Peters & Loss, 2012), varying slightly between stormy and calm conditions. We therefore restrict our analysis of volumetric sediment flux to the shoreface landward of this depth where there is significant change in bed elevation and sediment thickness. Figure 4.9 shows volume change over time for each slope scenario, for calm and stormy conditions in the shoreward half of the domain. The sharp drop in volume seen between initial conditions and the first model time step in both calm and stormy scenarios is caused by initial sediment mobilisation in the model domain.

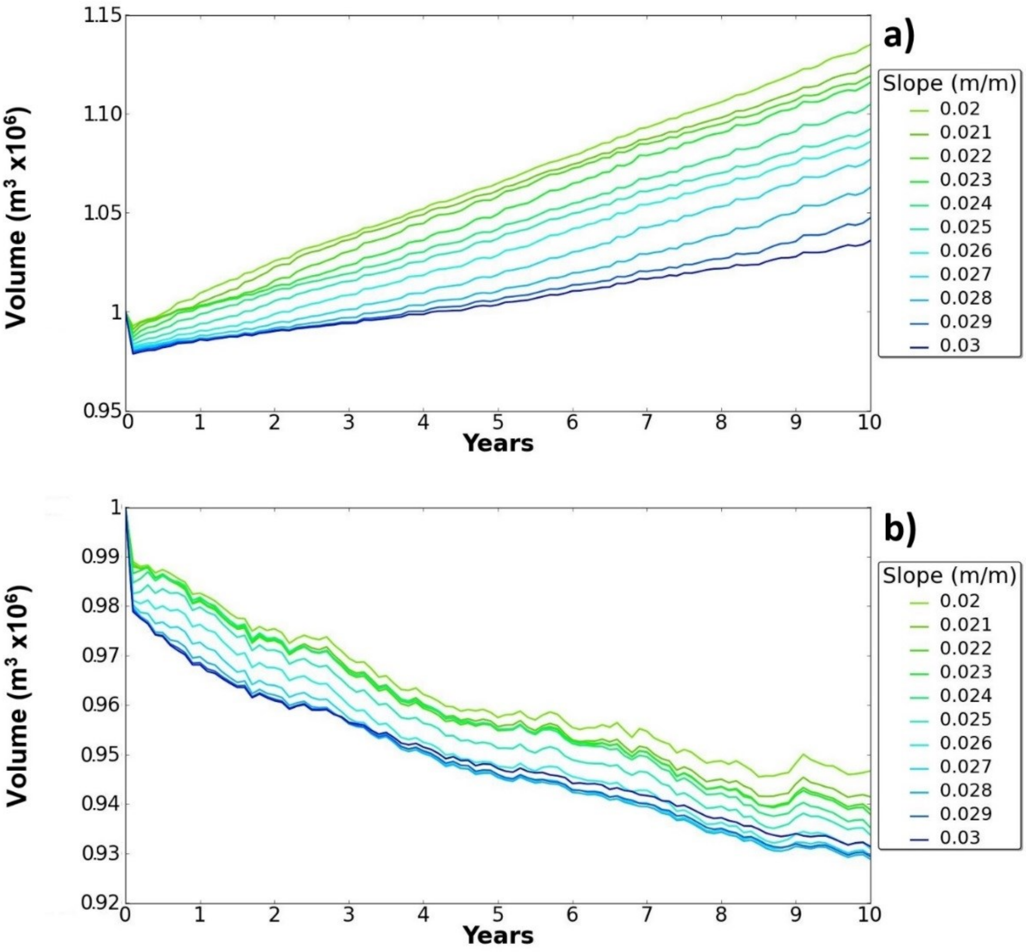


Figure 4.9 - Shoreward volume change under a) calm conditions, b) stormy conditions, for all depth scenarios, shoreward half of model domain.

Under calm conditions, sediment volume generally increases over time in the shoreward half of the domain (Figure 4.9a), consistent with the planform sediment accumulation seen in Figure 4.8. The increase in sediment accumulation is fed by the zero sediment flux boundary in the model. Figure 4.10 shows the mean sediment flux within the model domain, averaged per time step, as a function of bathymetric slope. Under calm conditions the rate at which sediment accumulates in the model domain decreases with steeper bathymetric slope, particularly when the slope exceeds 0.023 m/m.

Conversely, under stormy conditions, sediment volume in the model domain decreased through time (Figure 4.9b) and the rate of sediment loss was insensitive to the bathymetric slope (Figure 4.10). During stormy conditions, sediment within the model domain was lost across the open boundary to deeper water. Sediment depletion rates are relatively insensitive as slope increases under stormy scenarios. An interesting impact can be seen in Figure 4.9b just before year 9 of the stormy simulation, in which volume flux becomes positive for slopes of less than 0.026 m/m due to wind speeds falling to 15 m/s for an extended period of time, but then return to negative flux when stormy conditions resume. For slopes of 0.026 m/m and steeper, no positive flux is seen. This negative sediment flux is exhibited for all modelled scenarios but a weaker relationship exists between mean sediment loss per time step and increasing slope. Rates of sediment loss per time step are relatively stable as slope increases between 0.022 m/m and 0.028 m/m (Figure 4.10).

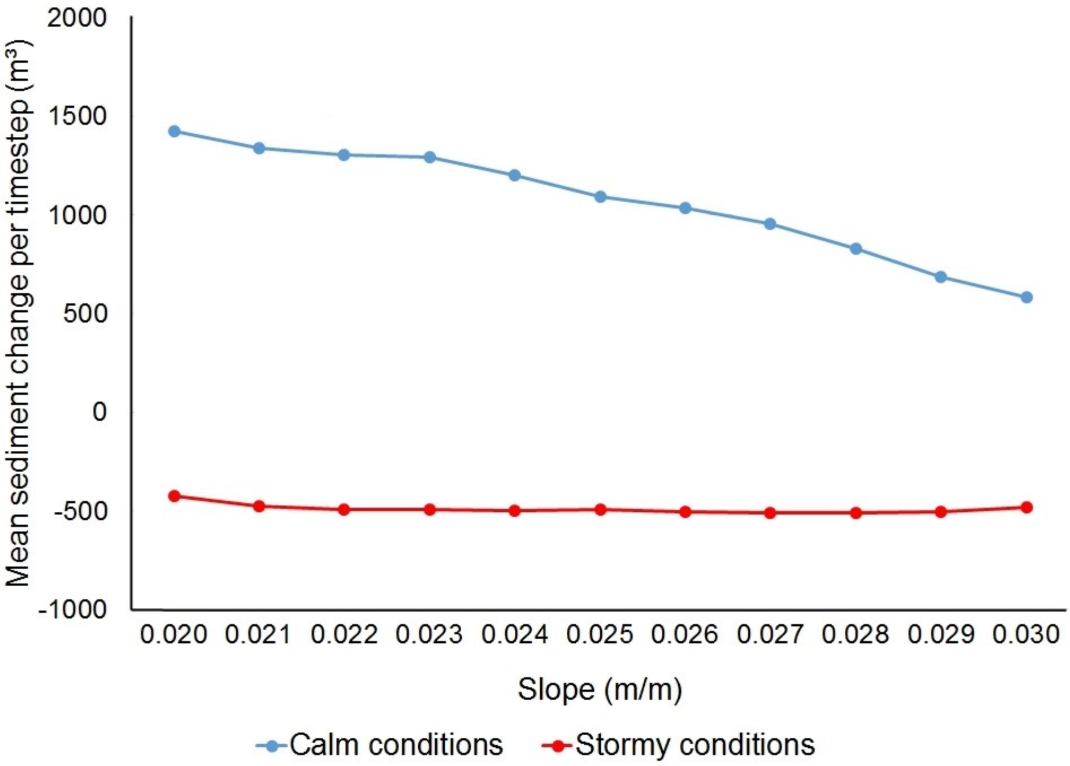


Figure 4.10 - Mean sediment volume change nearshore per model time step under calm and stormy conditions as a function of slope. Under calm conditions, sediment is gained nearshore but decreases as slope increases. Sediment loss per timestep under stormy conditions is relatively uniform as slope increases.

If we further explore the change in sediment flux observed in Figure 4.9b when climatic conditions briefly switch from stormy to calm, Figure 4.11 shows the impact on shoreward volume of switching climatic conditions halfway (i.e., 5 years) into the simulation:

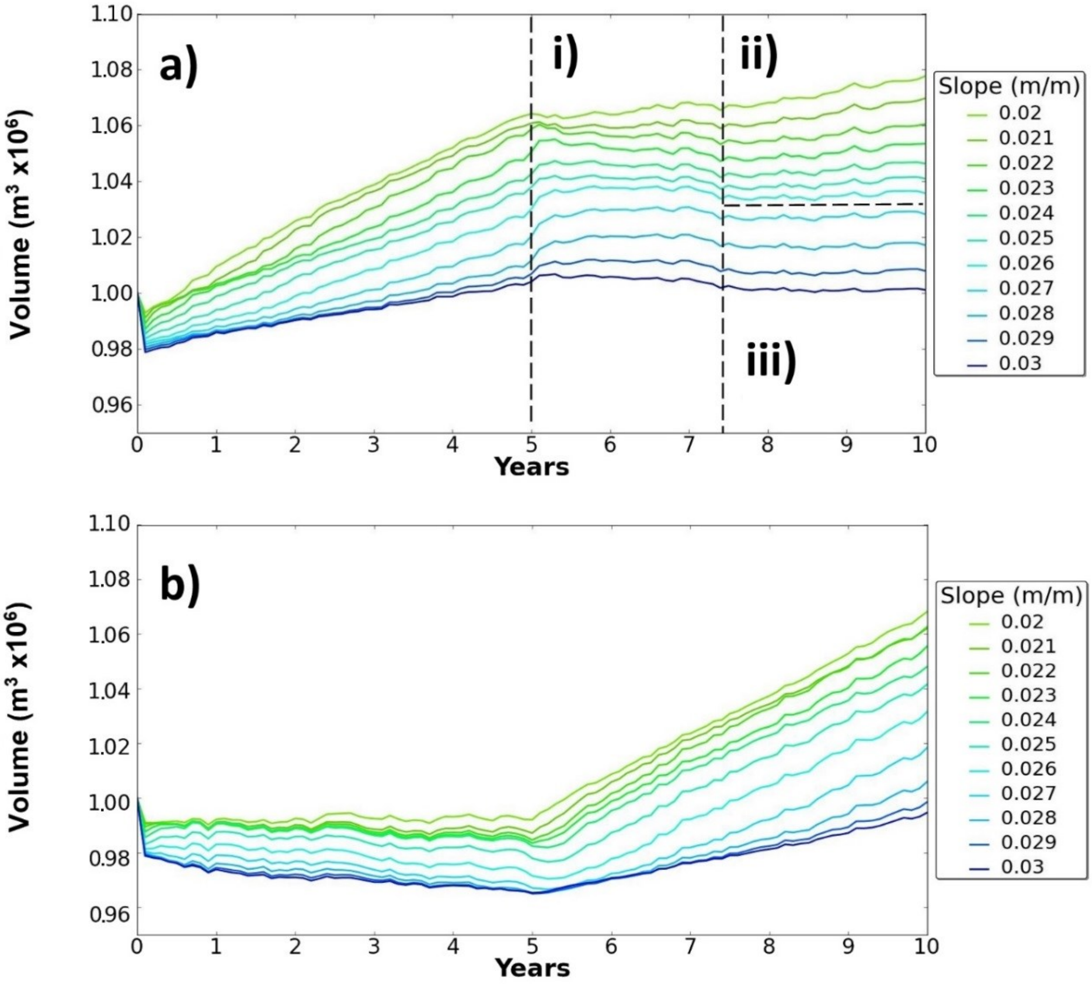


Figure 4.11 - a) Shoreward volume change from calm to stormy conditions 5 years into simulation. In i) sediment flux switches from positive to flatlining/slightly negative. Sediment flux on shallow slopes begins to turn positive after 2.5 years (ii), but remains flatlining on steeper slopes (iii). b) Shoreward volume total, from stormy to calm conditions 5 years into simulation. Lag time in return to positive volume flux can be seen in slopes of 0.025 m/mand steeper, between 3 and 6 months as slope increases.

Change in volume flux as slope increases is sensitive in a nonlinear fashion to a stepwise change from calm to stormy conditions (Figure 4.11a). For shallower slopes (0.020 m/m to 0.024 m/m), volume flux response time is almost immediate once stormy conditions take effect, with volume flux switching from positive to slightly negative (section i), Figure 4.11). A threshold gradient appears to be 0.025 m/m, consistent with the Admiralty chart analysis, from which steeper slopes all share a similar volume flux response time of approximately 3 months from the onset of stormy conditions to the change between positive and negative volume flux (Figure 4.11a; section i). As the scenarios progress, slopes shallower than 0.025 m/m begin to exhibit some volume recovery approximately 2.5 years (Figure 4.11a; section ii) from the onset of stormy conditions but at a reduced rate when compared to calm conditions. Slopes steeper than 0.025 m/m do not exhibit this recovery during the model simulation time and continue to flatline (Figure 4.11a; section iii), suggesting no loss or recovery of sediment nearshore on this timescale. When stormy conditions give way to calm conditions (Figure 4.11b), volume flux on shallower slopes begins to increase almost immediately for slopes shallower than 0.025 m/m.

4.6 Bed elevation change

We present comparison plots of sediment accumulation as a function of the bed elevation in Figure 4.12 for all model time steps, with initial bed profile plotted for comparison. The standard deviation indicates the areas where there are gradients in sediment flux through time, and thus represent the areas of sediment motion in the model.

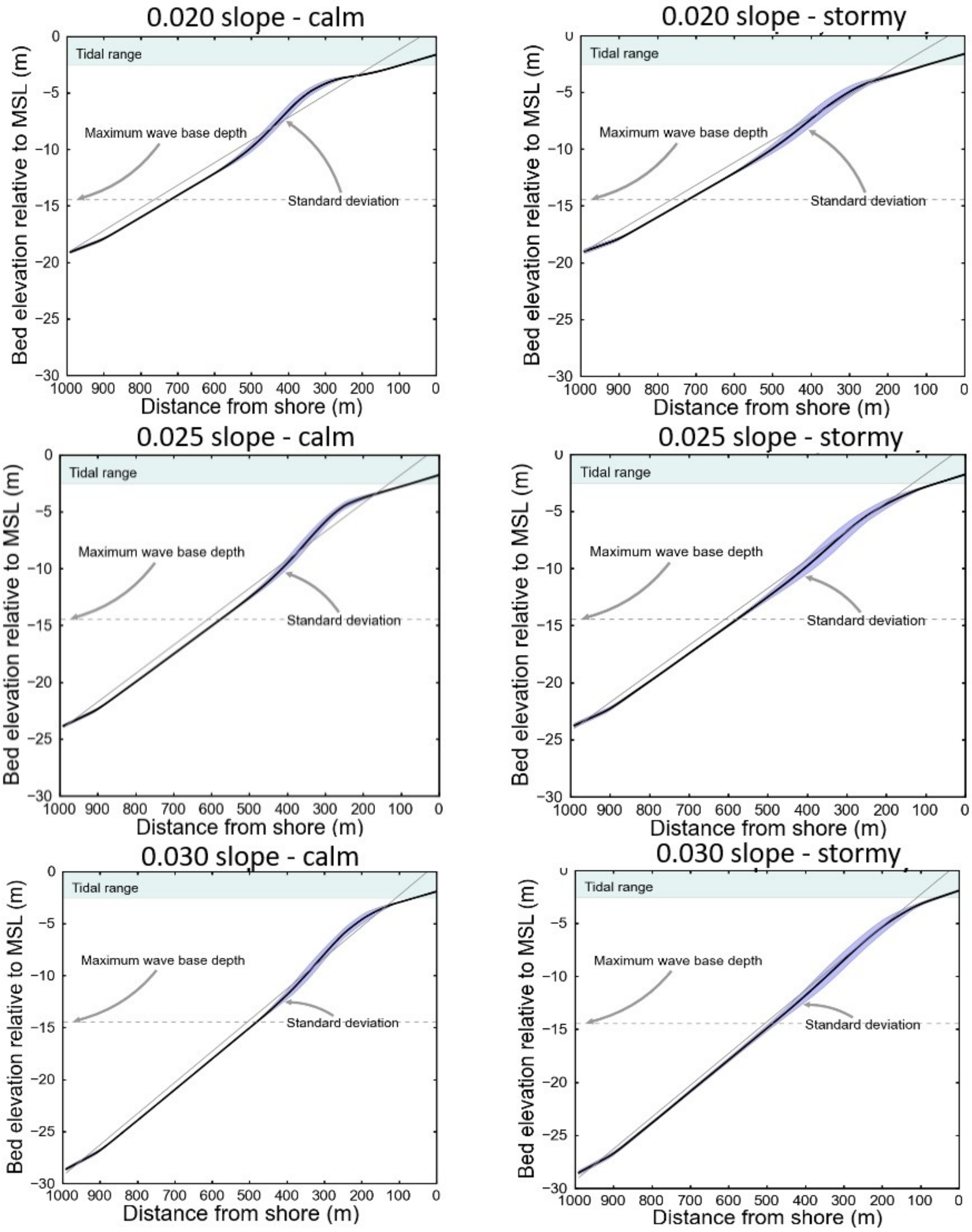


Figure 4.12 - Cross-shore swath profiles (distance offshore vs elevation) of bed elevation for final model results. Grey line indicates initial conditions. Solid blue line and shaded region represents the mean and standard deviation bed elevation in the swath profile. The standard deviation represents areas of sediment motion in model for all model timesteps. Most sediment transport occurs above wave base. Some minor sediment transport is observed below wave base (primarily current driven).

Sediment gets mobilised across the entire model domain in all cases, however the majority of sediment motion occurs above wave base in most scenarios. Under calm conditions, significant sediment motion occurs above the wave base in all scenarios, however during stormy conditions, some sediment motion can be seen occurring below the calculated wave base along the steeper slope, beginning to occur at the 0.025 m/m slope. This may indicate the storm wave base being deeper than under calm conditions.

4.7 Shear stress

Shear stress is not a direct output of the model, but can be calculated using equations (1) and (2) from the horizontal orbital velocity model output. Figure 4.13 and Figure 4.14 show both absolute mean and maximum dimensional shear stress in both shoreward and seaward directions and a probability density function (PDF) for Shields values for the 0.020 m/m and 0.030 m/m slopes, for calm and stormy scenarios. The mean and max shear stresses are calculated, as for the volume flux, of the shoreward half of the domain. This is the area of significant sediment motion, above wave base, and thus is most critical to the understanding of how storminess and bed slope impacts sediment accumulation nearshore. Values reported are taken at approximately 3-day model intervals:

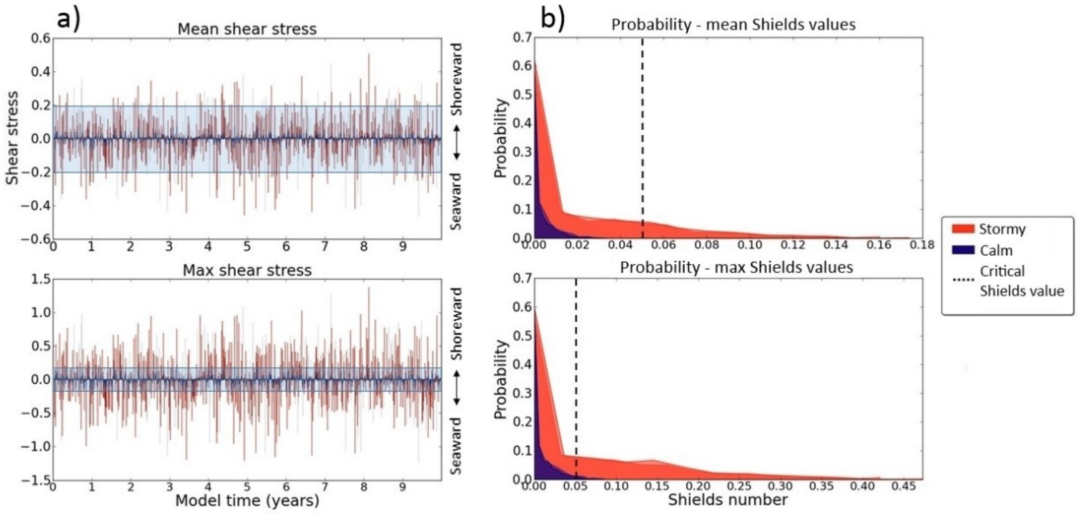


Figure 4.13 – a) mean and maximum shear stress throughout model simulation for calm and stormy scenarios in both seaward and shoreward direction, 0.020 slope. Values of shear stress outside translucent envelope are able to entrain sediment. b) Probability density function of mean and maximum Shields values, 0.020 slope. Dashed line represents critical Shields number for incipient sediment motion. Shields values under calm conditions is an order of magnitude lower than under stormy onditions, but roughly equal in the shoreward and seaward direction.

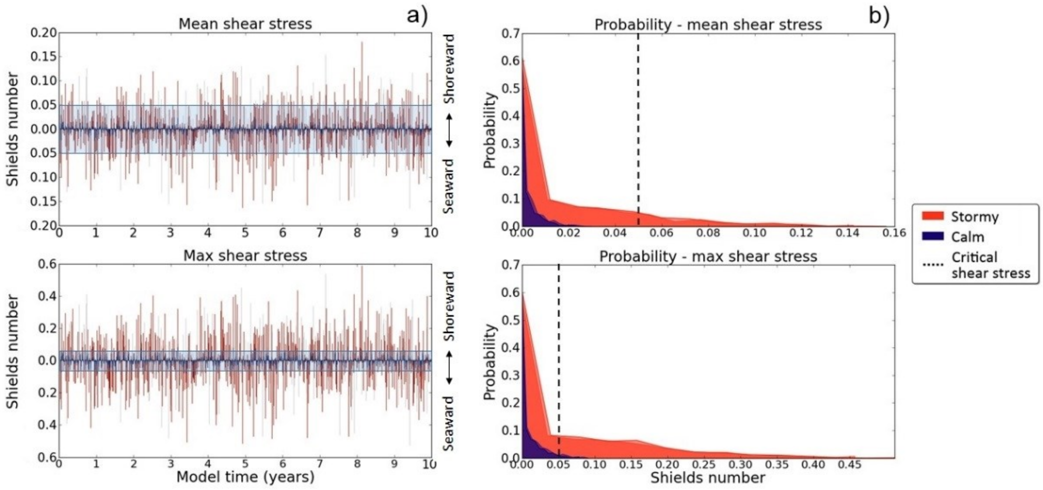


Figure 4.14 – a) mean and maximum shear stress throughout model simulation for calm and stormy scenarios in both seaward and shoreward direction, 0.030 slope. Values of shear stress outside translucent envelope are able to entrain sediment. b) Probability density function of mean and maximum Shields values, 0.030 slope. Dashed line represents critical Shields number for incipient sediment motion. Shields values under calm conditions is an order of magnitude lower than under stormy conditions, but roughly equal in the shoreward and seaward direction.

Figure 4.13 and Figure 4.14 when viewed together suggest slope does not play a significant role in the bed shear stresses experienced in the model domains, with minimal difference throughout the model simulations between the shallow and steep slopes. Both time step plots and PDFs show the Shields values, and therefore shear stress, increasing by an order of magnitude between calm and stormy scenarios, well above the 0.05 threshold for incipient motion in the model. The PDFs overlay the Shields number in both the shoreward and seaward direction, which are seen to be roughly equal. Under calm scenarios, sediment is under entrainment <10% of model time, and >50% of model time under stormy scenarios.

4.8 Discussion

Our model results show that when an offshore sediment supply is present within 1 km of shore, the shoreward accumulation of sand-sized sediment in embayments under calm climatic conditions is relatively uniform but diminishes with increasing bathymetric slope (Figure 4.9a). With a supply of sand-sized sediment for beach material from offshore, and all other conditions equal, pocket beaches could form and persist in embayments with offshore slopes of all gradients. In contrast, under stormy conditions (Figure 4.9b) the sediment distribution becomes more variable and volume flux is negative, with net sediment loss nearshore, which over time would render a pocket beach unviable due to the starvation of nearshore sediment. . If environmental conditions switch from relatively calm to relatively stormy, sediment volume change on offshore slopes with a gradient of less than 0.025 m/m begins to turn positive after approximately 2 years of stormy weather, while volume flux on steeper slopes remain slightly negative. Switching from stormy to calm climatic conditions, volume change on shallow slopes turns positive almost immediately and volume begins to accumulate nearshore, whereas steeper slopes exhibit a lag time of several months before volume change turns positive. Bathymetric slope is a major control on the nearshore sediment budget under calm climatic conditions, and thus critical to the recovery and persistence of a sandy beach after storm-induced erosion. However, stormy conditions have a stronger impact on sediment loss nearshore than slope. When climatic conditions are variable, slope controls how quickly nearshore sediment budgets recover. The accumulation of nearshore sediment berms that the model simulates are broadly consistent with recent empirical studies of beach evolution undertaken on specific embayments (e.g.Loureira et al., 2009; Harley et al., 2015; Loureiro et al., 2016), as well as agreeing with flume experiments undertaken by Ruessink et al. (2016) in terms of sand bar accumulation nearshore. Our model results are also consistent with recent examples of storms that have removed beaches that have received attention in the news, including Porhtleven beach in Cornwall UK in 2015 and Collaroy beach in Sydney, Australia in 2016. These beaches exist on very shallow offshore slopes, and thus our model results suggest they are liable to recover quickly once calm conditions return. Our modelling results suggest that a beach in an embayment with a steeper nearshore gradient, depleted by successive storm action, is less likely to recover its beach volume during inter-storm calm periods than a lower gradient embayment. Figure 4.15 is a conceptual summary of model behaviour, consistent with observed patterns of beach location from the Admiralty chart analysis.

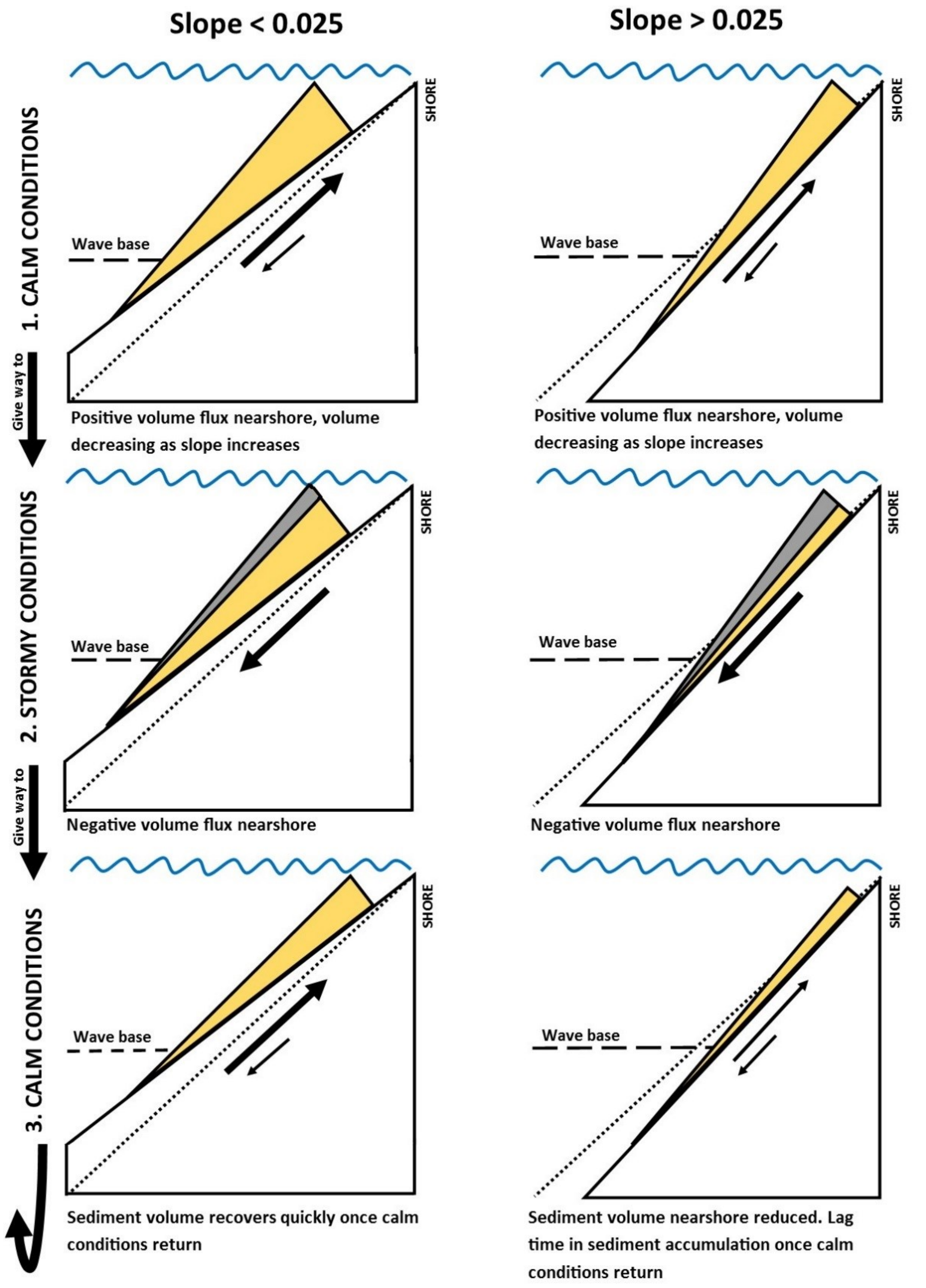


Figure 4.15 - Conceptual summary of model behaviour depicting volumetric flux on bed slope under differing climatic conditions. Sediment wedge on shallower slopes, in comparison to baseline conditions, recovers volume more quickly than on steeper slopes, thus is more resilient to volume loss during periods of storminess, and pocket beaches in these embayments may persistent. Sediment becomes increasingly depleted on steeper slopes during periods of storminess, and over time beaches in embayments would become starved of sediment and not reform.

4.8.1 Processes of beach formation/removal

Model results suggest that a relatively well understood concept of coastal morphodynamics, the wave base (the maximum depths at which wave orbital motion is considered significant), can be used to explain the mechanisms observed in the model results and the Admiralty chart analysis, in that the formation and persistence of sand bars, and thus beach material, is primarily dependent on wave energy.

Figure 4.8 shows that at most a few tens of centimetres of bed change occurs further than 450 m – 550 m offshore compared with changes approaching a metre further onshore, depending on slope. These distances are coincident with the calculated deep water wave base (Figure 4.13) of 14.43 m, and change as a function of bed slope. While these figures shows minimal bed change at depths deeper than the wave base (although significant changes during initial model timesteps) , this does not necessarily mean minimal sediment flux. Sediment transport at depths greater than wave base are likely to be current driven, while transport above the wave base is likely to be wave dominated, consistent with the modelling results. Wave heights may be amplified due to wind forcing during stormy conditions, and thus the largest waves may agitate the bed at greater depths.

4.8.2 Bed shear stress

The shear stress exerted on sediment in a system, controlled by wind and wave action, governs sediment transport. Sediment is at rest until enough shear stress is imparted upon sediment to initiate motion, which is described in terms of dimensionless shear stress by equation (3) (Shields, 1936; Paphitis, 2001; Simões, 2014). Under calm conditions, mean bed shear stress is mostly under this value, although it rises above it at multiple points throughout the model simulation (Figure 4.13 and Figure 4.14). Under stormy conditions, mean bed shear stress is roughly an order of magnitude higher than the critical shear stress parameter for incipient bed motion, and thus is under almost constant entrainment throughout the model simulation. Patterns of planform sediment accumulation (Figure 4.7), show that sediment is depleted at the centre of the embayment under stormy conditions and generally rotated towards the headland as waves diffract around the headlands walls.

Sediment motion nearshore is governed in part by horizontal wave orbital velocity (Dean & Dalrymple, 1991; Chou et. al., 2015, Aagaard & Hughes, 2017), in which sediment bedload will move both shoreward and seaward. Increased horizontal orbital velocity,and thus shear stress as describe above under stormy conditions carries sediment further upslope as each wave passes, but also further downslope when the orbital velocity reverses. A small volume of sediment under each wave is lost below the wave base. This volume is not replaced with subsequent waves under stormy conditions, and over time, there is a net sediment volume loss shoreward. Constant sediment entrainment under stormy scenarios explains the insensitivity of the model to an increase in tidal range. An increase in the swash zone and thus an increase in surface area along the shoreface for sediment to accumulate does not promote an increase in sediment accumulation in stormy scenarios as the sediment is removed and rotated towards deeper waters. This explanation is also consistent with the coincident maximum sediment accumulation at wave base depth (Figure 4.12) found in both calm and stormy conditions.

4.8.3 Implications

The study presented here shows an empirical relationship exists between beach formation and persistence, and average offshore slope. Our modelling results suggest that while embayments with a range of offshore slope gradients have the ability to form nearshore sand bars and thus beach material, embayments with steeper offshore slope, and those subjected to stormier conditions, are less likely to maintain a beach. These relationships have real world implications, as in periods of changing magnitude and frequency of storm events, such as from the Medieval Climate Anomaly to the Little Ice Age, or indeed from the present to future climate scenarios of the latest IPCC report (IPCC, 2013), our results highlight that there is the potential for seemingly persistent beaches to disappear and never reform. To counter coastal erosion and improve the economic and social function of coastlines, beach nourishment is often used to rebuild eroding beaches (e.g., Gopalakrishnan et al., 2011). Yet our modelling suggests that for embayed beaches where offshore gradients are steeper, long-term success is unlikely, or may require increasing volumes of beach sediment or frequency of nourishment due to significant losses of sediment offshore during storms. Where beaches are currently under threat due to increased storminess, maintenance through beach nourishment schemes may be unviable in the face of predicted climate change.

4.9 Conclusions

Our review of bathymetric maps and satellite imagery indicated that the presence or absence of beaches on high energy, headland-dominated coastlines might be controlled primarily by the average gradient of the shoreface. Embayments with gradients steeper than 0.025 m/m were notably less likely to have a sandy beach than those with a shallower bathymetry. We have used numerical modelling to explore the physical processes that could explain the observed relationship. Our experiments have shown that embayments can form under calm conditions on coastlines with steep offshore slopes, yet persistent stormy conditions inhibit formation of beaches in steeper sloped embayments. The threshold gradient also appears to control the recovery time of these beaches; the return to positive sediment flux on nearshore slopes (> 0.025 m/m) can take months once stormy conditions give way to calm conditions. Successive or persistent stormy conditions can completely deplete the sediment supply, particularly on steeper slopes, such that an embayed beach lost during a storm may not recover due to the loss of supply with beach material from offshore.

Under stormy conditions, shear stresses nearshore tend to be greater than the critical shear stress and sediment thus cannot accumulate nearshore to provide material for beach replenishment. This research has implications for future coastline management in terms of a new understanding of the stability of pocket beaches along headland dominated coastlines, and the potential for this to be used as a predictive tool. The mapping of coastlines in terms of their stability can be undertaken, providing a useful resource for planners and coastal engineering efforts along socially and economically important coastlines, e.g., Fitton et. al. (2016).

5 Dynamic beach response to changing storminess of Unst, Shetland: impacts on landing places exploited by Norse and Early Medieval communities

Building on the theory I have presented in Chapter 4 for the formation and persistence of pocket beaches, this chapter explores beach stability on Unst, Shetland and the implications for landing sites used in Norse times here.

This paper has been accepted for publication in *The Journal of Island and Coastal Archaeology.* This chapter contributes to answering research questions 1, 2 and 3 as presented in Chapter 1.7 of the thesis.

5.1 Introduction

A soft-sediment coastline is one of the most dynamic geomorphic settings on the planet. These coastlines are susceptible to storm events which can lead to beach erosion due to both wave attack and aeolian transport. Indeed, it is these processes and the subsequent movement of sand inland that are the genesis of dune and machair formation in the backshore environment (Aagaard et al., 2007; Partelli et al., 2009). While rocky coastlines can exist in a comparatively stable state over multi-century and millennial timescales (e.g. Limber & Murray, 2011), soft-sediment coastlines are dynamic and can be very changeable on seasonal to decadal scales (Falqués & Calvete, 2005; Ashton & Murray; 2006; Slott et al., 2006, Thomas et al., 2016). These mobile coastlines have been extensively utilised by people as beaches, particularly those found in sheltered headland bays, can form safe harbours, and provide storage, launching, and landing places for small boats (Graham, 1969; Stylegar & Grimm, 2005; Marriner et al., 2005; Marriner et al., 2010; Mehler et al., 2015). But the utilisation of beaches can be uneven; waxing and waning through time. This may be a reflection of actual changes in use, or a fragmentary archaeological record, both of which could be driven by geomorphological instability (Mehler et al., 2015).

Changes to soft-sediment coastlines can severely disrupt coastal communities (Bigelow et al., 2005; Sommerville et al., 2007; Kinnaird et al., 2013). There are, for example, numerous historical and archaeological examples of the impact of drifting beach sands on coastal communities throughout British Isles, which has a very varied coastline located in the path of major storm tracks in the North Atlantic (Griffiths 2015). Of particular interest is the period of transition between the Medieval Climatic Anomaly (MCA) and the Little Ice Age (LIA). Beginning around 1250 CE, this was a time of increasing storminess and crossed climatic thresholds (O'Brien et al., 1995; Mann, 2002; Meeker & Mayewski; 2002; Mann & Jones; 2003; Dawson et al., 2004; Dugmore et al 2007; Mann et al., 2009; Harris et al., 2017; Stewart et al., 2017) affecting the Norse community of Shetland. It is important to point out that in this study we use the term 'Norse' in the sense of Bigelow (1985, 104) who has defined it as the period between c. 800 and 1500 CE, with a chronological framework for the Late Norse Period between c. 1100 to 1500 CE. The Late Norse Period has produced significant evidence for the destabilisation of beaches utilised by coastal communities for trade, food and transport. In particular, for social groups who utilised both terrestrial and marine resources, the loss of reliable landing places and the compromised access to marine environments could produce significant stress.

In coastal settings lacking large rivers delivering sediment from inland, offshore sediment supply is a major controlling factor on beach formation and stability. In these settings, such as those common on small islands, sandy beaches tend to form as limited pockets in embayments bound by headlands as opposed to unbroken macro-scale barrier beaches. However, a coastline with a uniform offshore sediment supply (e.g. in the form of a large offshore glacial deposits) can have a non-uniform distribution of beaches along a coastline even in seemingly favourable embayments (Everest et al., 2013; Preston et al., *in press*). As currents and waves reach the shoreline from different directions, their impact varies. Along micro- to meso-scale coastlines (<10 km in length), significant changes in beach morphology may be observed due to some areas being more sheltered from prevailing wind and waves than others, as well as geometric factors such as mean offshore slope (Preston et al., *in press*). Wind-blown sands in coastal regions in the Northern British islands are primarily derived from sandy beaches along their coastlines (e.g. Orford et al., 2000; Dawson et al., 2004; Dawson et al., 2011, Ashmore & Griffiths; 2011; Sandweiss & Kelley, 2012; Bampton et al., 2017). These are distinct from ‘cover sand’ deposits, which are glacial in origin (Sherman et al., 1998, Udo et al., 2008), but the mechanisms responsible for delivering sand to a coastal embayment to form a beach, or indeed what deprives an embayment of sandy material, have rarely been considered.

The impact of beach instability on coastal settlements is poorly understood, but can be inferred. Blown sands can affect coastal communities by inundating fields and burial of structures, and beaches can be removed, either gradually or rapidly as a result of a single large storm. Sandy beaches maybe preferred landing sites, but rocky coasts can also be used by small boats as long as weather and sea conditions are favourable. Storms that remove beach materials may also create significant offshore hazards for boats in the form of submarine obstacles. Abrupt, large-scale movements of beach sand may result in the destruction of coastal settlements. Many examples of beach destabilisation have been recorded, from recent examples of beaches in Porthleven, Cornwall, UK and Dooagh Bay, Mayo, Ireland, to historical examples such as the Great Candlemas Storm recorded on the island of Streymoy in the Faroe Islands in 1602, which was reported to have removed seven beaches overnight (Guttesen, 1992). If a beach returns swiftly (such as the example of Porthleven) then continuity of use as a landing place may be possible. Should the beach take years to return, or never return (such as Dooagh Bay, or at Streymoy), then this could have a significant impact on settlement that relied upon these beaches for access to the sea. Some impacts of beach instability can be positive for coastal communities as a small scale inland flux of sand from a beach may have beneficial impacts on some acidic soils and peats and create ‘machair’, sand-rich fertile low lying grassland near the coast (Angus, 1994; Gilbertson et al., 1999; Dawson et al., 2004; Barber, 2011).

By understanding the interplay between geomorphological processes on high-energy, headland dominated coastlines that drive beach instability, we can better understand some key environmental pressures on coastal settlements and thus be in a position to better understand the role of geomorphological change in both settlement history and the formation of an archaeological record.

The overall aim of this paper is to understand the trajectories of geomorphic change experienced by Norse (users of sandy beaches on the coastline of Unst, Shetland and the likely impact of these changes on the archaeological record. We focus on the known landing places of Sandwick and Lunda Wick and use a combination of geomorphological mapping, luminescence dating, near shore slope analysis, fetch analysis and numerical modelling to investigate beaches stability across the MCA-LIA transition.

5.2 Approaches and methods

The research in this paper is guided by the following research questions:

- Is it possible to quantify and qualify past beach destabilisation?
- How might the stability of beaches within embayments change in the face of shifting climatic conditions?
- What are the implications for settlement continuity and the archaeological record?

The work has been undertaken at two scales - that of an island as a whole and that of two specific sandy embayments: one on the east coast and one on the west coast of the island. We use geomorphological mapping to assess the cumulative past impact of Earth surface processes; we mapped beaches to identify their key structures and composition, and tracked the extent of blown sand using aerial photographs, natural exposures and auger survey. The geomorphology has been integrated with existing archaeological surveys, land use mapping compiled to the beach hinterland and the offshore bathymetry collated to created detailed morphological data for modelling specific embayments and conducting a more general slope survey around the coasts of the island. We have also used innovative applications of optical-stimulated luminescence (OSL) analysis - to both understand rates of accumulation through profiles as well as determining specific dates.

Numerical sediment transport modelling was undertaken using MIKE21 (well-developed modelling software used in a variety of coastal scientific and engineering studies, e.g. Siegle et al., 2004; Manson, 2012; Houser, 2013; Vincinanza et al., 2013) to quantify the ability for both embayments to accumulate stable nearshore sediment supplies and thus form beaches. The differing geomorphic complexity of both embayments presents an interesting challenge. While the model may not be able to simulate the full geometric complexity of varied topography, the numerical modelling can produce worthwhile results for this study that fit into the broader themes and patterns observed. The sediment transport modelling was also coupled with wind fetch (i.e. the distance the wind travels in a certain direction over open water) modelling to determine the most sheltered areas in both embayments.

5.2.1 Study sites

We chose the island of Unst (Figure 5.1), the most northerly of the British Isles as a case study due to its complex coastline of embayments, deep inlets and headlands, as well as a non-uniform distribution of sandy beaches. The island has a long history of human habitation, stretching from at least the Neolithic to the present day (e.g. Small, 1968; Hansen, 2000; Smith, 2007; Bond, 2007; Swindles, 2013). A rich archaeological record straddles the key climate shifts between the MCA and LIA and our focus is on this period and the related Norse settlements, as part of the wider HaNOA project (Mehler et al., 2015). Many Norse longhouses are scattered around the island, with a more densely settled area in the southwestern part of Unst at Underhoull and Lunda Wick (Turner & Owen 2013, fig. 11.7), some are concurrent with contemporary coastal settlements, and some exist on coastlines where no current settlement exists.

Unst is the most northerly of the British Isles (60°45’N, 0°53’W). It is roughly rectangular in shape, extending c. 20 km north to south and c. 9 km east to west. The coastline is a mixture of deep inlets (‘voes’), and arcuate bays. The northern and western coats of the island include sections of high cliffs while the south, particularly the south east, has comparatively low relief (Figure 5.1).

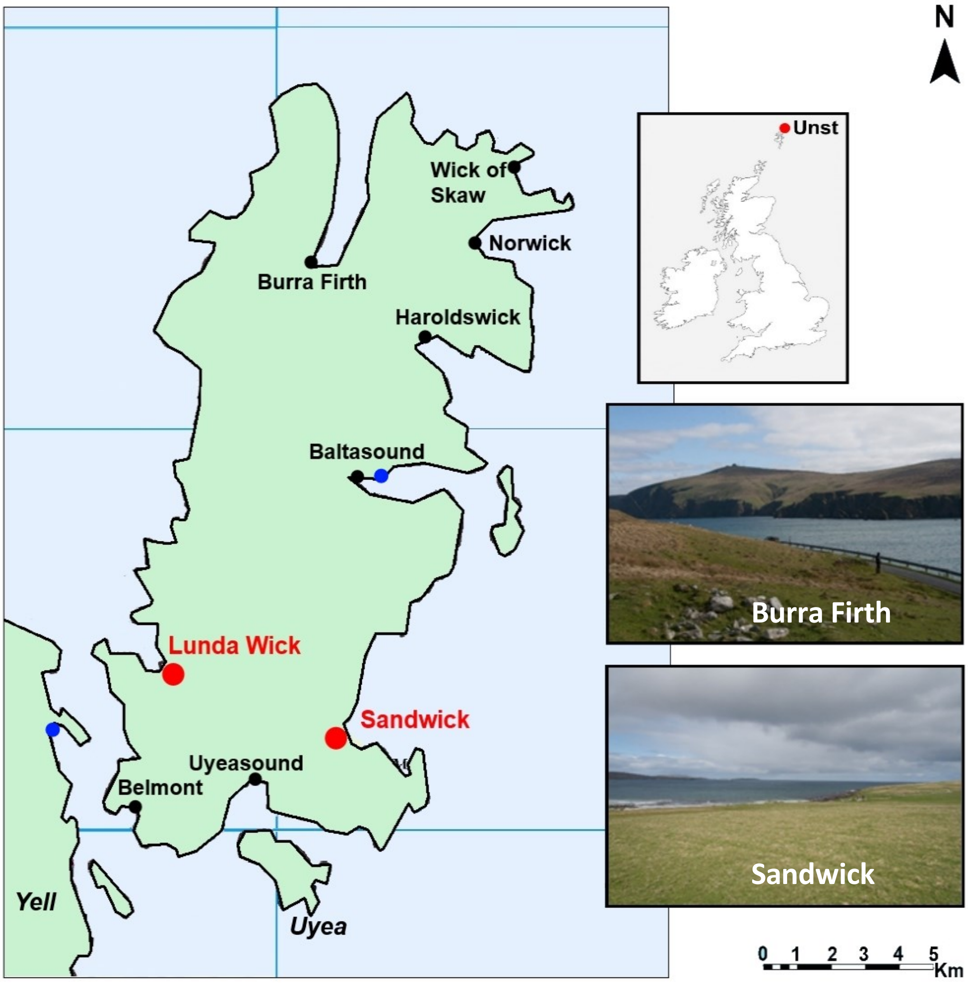


Figure 5.1 – Location map of Unst, with names of large embayments marked. Location of tide tables used in numerical modelling marked with blue dots.

Unst has a varied bedrock geology and a coastline of rocky headlands, geos, cliffs, capes and bays. Unst was ice covered during the Last Glacial Maximum, which resulted in the formation of multiple offshore moraines, that arc around Unst's east, north and west coastlines in a 'horseshoe', and could act as a source of offshore material for beach formation (Clark et al., 2012).

The earliest known remains of the Norse settlement on Unst date to the 10th and 11th centuries (Turner and Larsen 2013), although excavations at Norwick have yielded evidence for a Viking age settlement dated between the 7th and the early 10th century AD (Ballin Smith, 2007). Unst was not uninhabited, however. Evidence that the Vikings subjugated or destroyed the Pictish inhabitants of Unst is scant, with a more likely co-habitation of the island in which the Norse culture eventually dominated

(Turner & Owen, 2013). The Viking Unst project recorded some 30 known longhouses and 20 possible longhouses on Unst alone, the highest concentration of longhouses known outside of Norway, pointing to Unst's importance as a settlement in the Norse world (Turner, 2012; Turner & Owen, 2013; fig. 11.7; Dyer et al., 2013).

The Norse subsistence economy was based on the exploitation of both marine and terrestrial resources. Several place names on Unst survive to suggest widespread farming practices, such as Collaster and Colvadale (derived from Old Norse *kalfr*, for calf) and Clipprigarth (derived from *klippari*, Old Norse for sheep shearer), amongst others (Marttila, 2016). Fishing, as with the rest of Shetland was extensively engaged in on Unst as well. Artefactual evidence from excavations undertaken at longhouse sites at Lunda Wick and Hamar discovered line sinkers and hook-sharpening artefacts (Bond, 2007), pointing to this industry present in these locations. Midden excavations at Sandwick reveal a mix of fish bones and shellfish also, with the shellfish possibly used as bait for fishing (e.g. Bigelow, 1985; Bigelow, 1989; Barrett & Oltmann, 1998; Harris et al., 2017).

A combination of a declining rural population and a modern focus on animal husbandry has resulted in a well preserved archaeological record with upstanding monumental ruins from all time periods (Fojut, 2006). Coastal archaeological sites are particularly susceptible to environment change, with many examples of coastline retreat and sea level rise destroying important sites throughout the British Isles (e.g. Long et al., 1998; Lowe & Boardman, 1998; Bromhead & Ibsen, 2006; Westley et al., 2011; Dawson, 2013; Graham et al. 2017). In the case of Unst, work at Sandwick by Kinnaird et al. (2015) for example, identifies periods of sand blows dating to around the mid-13th century, concurrent with the late Norse period. Thus a lack of evidence for former landing sites may be due to an 'absence of evidence' rather than 'evidence for absence'. After a desk-based assessment and an initial survey, two specific sites were chosen to study in detail: Lunda Wick (Figure 5.2) and Sandwick (Figure 5.3).

5.2.2 Lunda Wick

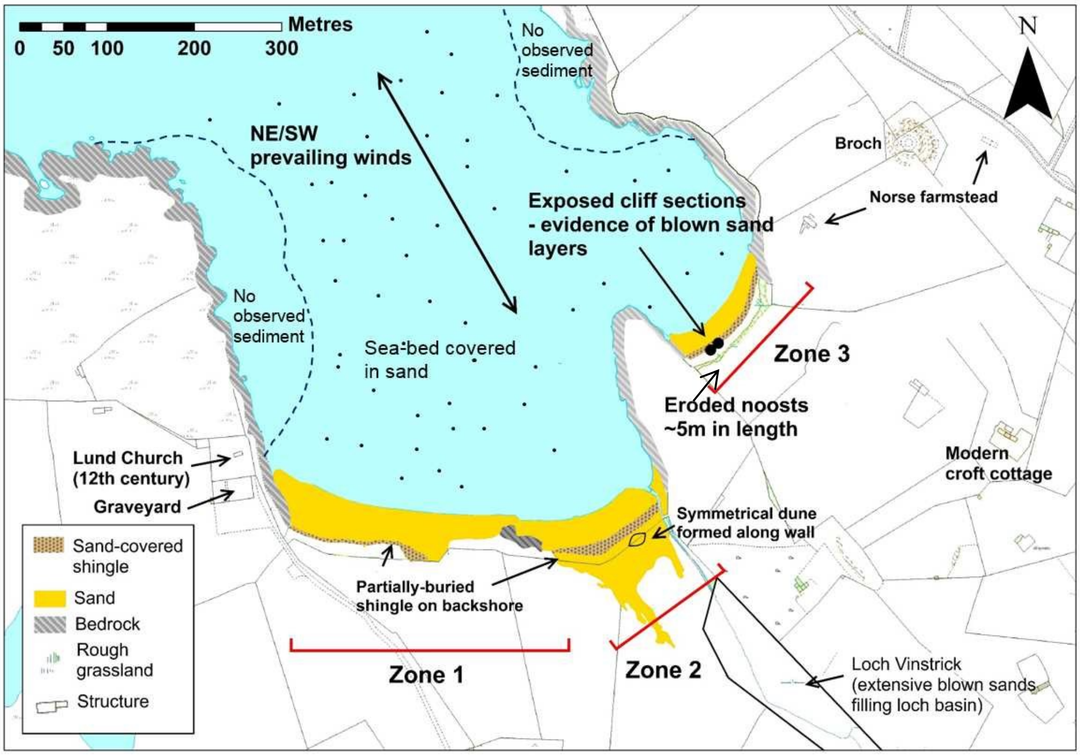


Figure 5.2 - Schematic planform map of Lunda Wick, a twin embayment on the south west coast of Unst, indicating major geomorphic features and zones. Lunda Wick is partially sheltered from the open ocean by the coast and several small skerries. Two sandy beaches are separated by the Vinstrick Ness headland. Three zones can be identified with very different patterns of sand blow. (Contains OS data. Crown copyright)

Lunda Wick is a twin embayment on the south west coast of Unst. It faces north, and is partially sheltered from the open ocean by an headland 1 km to the north, and several small skerries approximately 2 km to the north. It has two sandy beaches separated by a small headland known as Vinstrick Ness. The smaller, eastern beach is known as Burga Wick, named after the prominent broch mound overlooking the bay at Underhoull.

Two Norse farmsteads have been excavated in Underhoull, to the east of Lunda Wick (Canmore ID 28, 53) (Small 1967; Bond & Dockrill 2013). The farms lie on opposite sides of the broch (Canmore ID 31). On the opposite side of the bay lies St. Olaf´s kirk, also known as the church of Lunda Wick, which is believed to date back to the 12th century, and which was abandoned in the late 18^{th} (Canmore ID 64). Modern farms such as Lund House (Canmore ID 216963) are near, most of which were abandoned in the course of the 19th century.

The beaches of Lunda Wick are composed of fine-grained sands along the waterline backed with cobble storm ridges. Evidence of blown sands stretch behind the beach, and indicates a changeable pattern of local coastal and potential landing places with less evidence of blown sands in Zones 1 and 3 which are partially sheltered by headlands, and more in Zone 2 open to the ocean.

Zone 1, adjacent to the church, is relatively sheltered from offshore winds. The beach has a sharp transition between fine-grained sand at the water's edge and a shingle storm at the inland margin. No evidence of recent blown sand is present behind the beach, although small exposures on the vegetated slopes behind the beach show evidence of past blown sands, which now lie below well-grazed turf (c.f. the machair of Mathers & Smith, 1973).

In contrast to Zone 1, Zone 2 has well-developed inshore blown sand deposits. The shingle storm ridge in this zone is almost completely buried by sand, with dune formation stretching behind the beach zone in a south-easterly direction. A locally-prominent feature is an almost symmetrical dune that has formed on both sides of a dry stone wall at the eastern end of the beach. The SE-NW orientation of this dune, as well as the orientation of scars behind the beach records the cumulative effects of recent sand movement and indicates the contemporary prevailing wind directions for Lunda Wick.

Burga Wick forms Zone 3, which is composed of coarser sands than Zones 1 and 2. A limited amount of blown sand exists behind the beach, suggesting that here the beach is more stable and sheltered from geomorphologically-active winds. The headland approximately 1 km north of Zone 3 is likely to reduce the impact of the NW winds that act upon Zone 2.

The excavations at Underhoull in the 1960s also uncovered the remains of a boat shelter at Burga Wick (Canmore ID 88166), not far from the (lower) Norse farmstead (Figure 5.5) (Small 1967, 242). The Shetland term for this type of structure is *noost*, Old Norse/Norwegian *naust.* As opposed to the large Iron Age boat houses in Norway, noosts in Shetland were mostly modest, unroofed structures consisting of a boat-shaped depression bordered with stone beyond the reach of the sea that were used to store rowing boats in winter. Boat shelters like this were used in Shetland until the early 20th century (Tait 2012, 469-72). Based on a digital surface model created for the HaNoA-project in 2014, the noost at Burga Wick is at least 4 m long and 2-2.5 m wide, although Small stated that it may originally have hosted a boat up to 5.5 m in length. Although there was no direct dating evidence, Small suggested that the noost may well be Norse, based on its location and a fragment of a soapstone vessel that was found in a section outside the noost. The excavation also revealed that the structure had been narrowed at a later stage through the addition of a retaining wall along the western wall, most likely to convert it into a sawpit for processing driftwood (Small 1967, 242). “A layer of rotting sawdust on sand inches above the roughly cobbled floor” confirmed this interpretation and also suggests that this secondary use was fairly recent. According to Tait (2012, 112), saw pits only became a part of the Shetland vernacular in the 19th century and often made use of existing structures.

It is interesting to note that the noost is located on top of a backshore step with a 2-3m high drop to the beach that would make their use impractical nowadays. The steep, freshly-exposed faces of the step indicate that erosion is currently taking place. A second depression of similar width – possibly the section that was dug outside the noost in the 1960s – can be seen to the east of the noost. This is bordered to the east by what seems to be another artificial stone setting, suggesting that there may in fact be at least two parallel noosts. Further archaeological field work would be needed to clarify this.

5.2.3 Sandwick

Sandwick is a ~700 m wide embayment bound by headlands and situated on the south east coast of Unst, on the opposite side of the island to Lunda Wick. Sandwick faces north east, bordered to the north and south by low rocky cliffs. It is backed by gently sloping heathland with limited machair formation close to the beach (Figure 5.3).

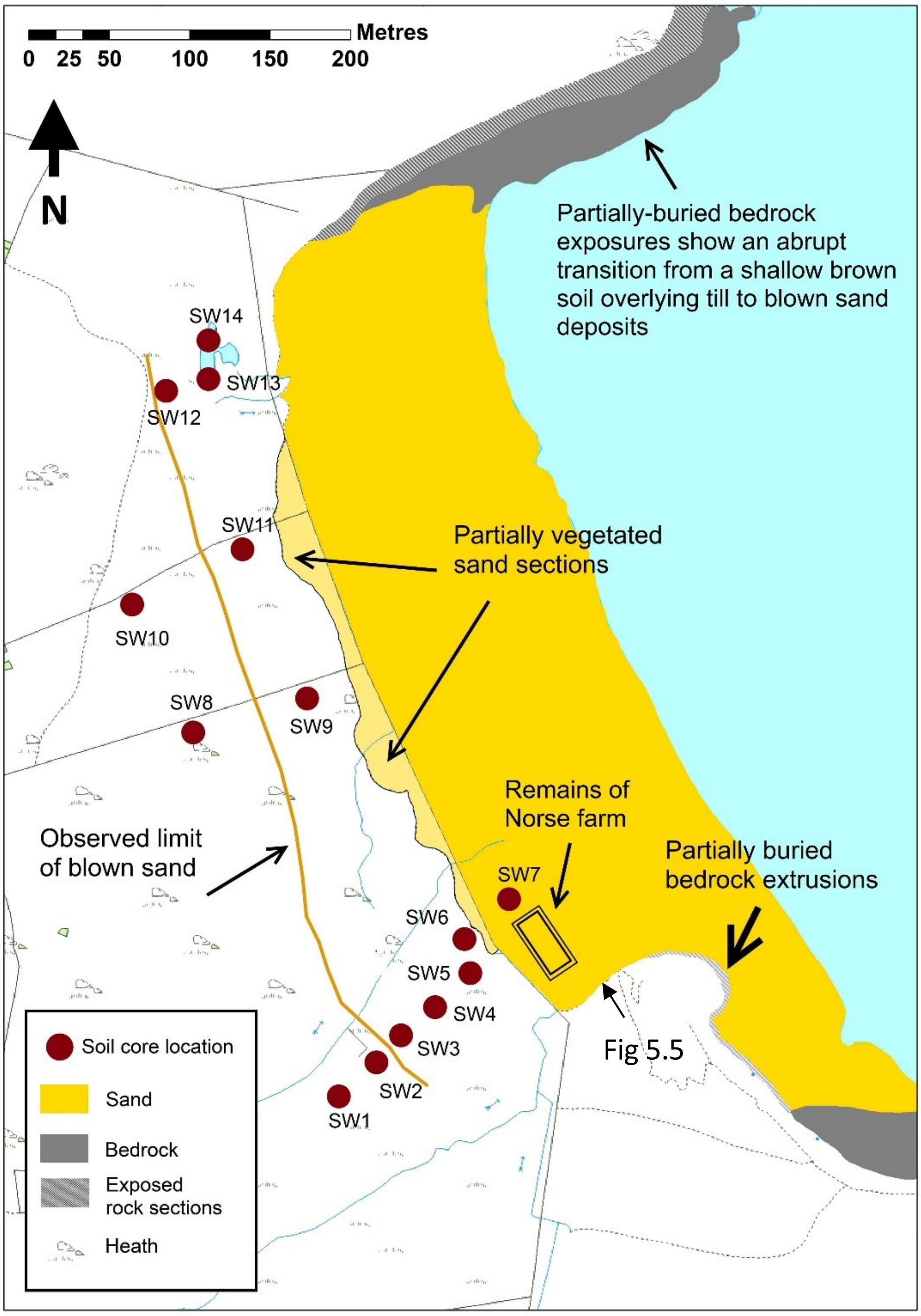


Figure 5.3 - Schematic planform map of Sandwick, indicating major geomorphic features. (Contains OS data. Crown copyright). Labels on soil core locations refer to photographs in supplementary information.

Sandwick hosts a rich archaeological landscape with evidence for settlement reaching from at least the first millennium BC (Lelong 2007) to the late 19th century. The remains of a Norse farm partially buried by sand are located on the southern end of the beach. Excavations revealed a stone built structure which was in use from the 12th to the 14th centuries (Bigelow 1985). Another, heavily eroded Norse farmstead dated to the 11th to the 13th century was excavated in 1980 and 1995 at the northern end of the beach (Canmore ID 126) (Hansen 1995). Remains of a possibly Norse chapel are located at Framgord, just north of Sandwick bay (Canmore ID 131) (Morris et al. 2007, 269).

The slope of the beach face is relatively gentle (~4°), with shingle immediately below the sand that forms the inland margin of the beach (Mather & Smith, 1973).

There are no dunes near the beach or in the hinterland behind the embayment, but blown sand has spread inland. An auger survey conducted as part of this study identified blown beach sand up to 200 m inland of the current visible edge of the beach, but no further than this (core locations marked in Figure 5.3, photographs in supplementary information). The bluffs on the northern edge of the bay show an abrupt stratigraphic change about 0.8 m below the present vegetated surface between the soils overlying basal glacial deposits and superficial blown sand.

5.2.4 Chronology

OSL was used to date the accumulations of blown sand at Lunda Wick. Two areas were selected for study, one in Zone 1 (‘Church section’) and one in Zone 3 (‘Noost section’), approximately 600 m apart (see Figure 5.4). This geographic spread was chosen to provide an embayment-wide chronology. Sections were cleaned back and recorded, and samples were taken under dark conditions and sealed to prevent exposure to light. Five profiles were identified, 4 from the noost section (Figure 5.6), 1 from the church section (Figure 5.7). During fieldwork, all sediment samples collected were immediately appraised for their luminescence behaviour using a SUERC (Scottish Universities Environmental Research Centre) portable OSL reader. 44 sediment samples were examined in this phase of the investigations. From this, plots of infrared-stimulated luminescence (IRSL) and OSL signal intensities versus depth were generated, also, stratigraphic variations in IRSL and OSL depletion indices, and the IRSL/OSL ratio were considered. This allowed for informed decisions to be made on where to position samples for OSL dating. All samples were sealed and immediately made light-safe for transport to the laboratory for additional luminescence investigations. 10 sediment samples were collected for OSL Single Aliquot Regenerative dose (SAR) dating. In-situ field gamma spectrometry measurements were taken at each of these positions.

Table **5.1** documents the OSL samples taken and their context within the sections.

Full details of the analytical protocols used in the luminescence investigations are provided in Kinnaird et al. (2017).

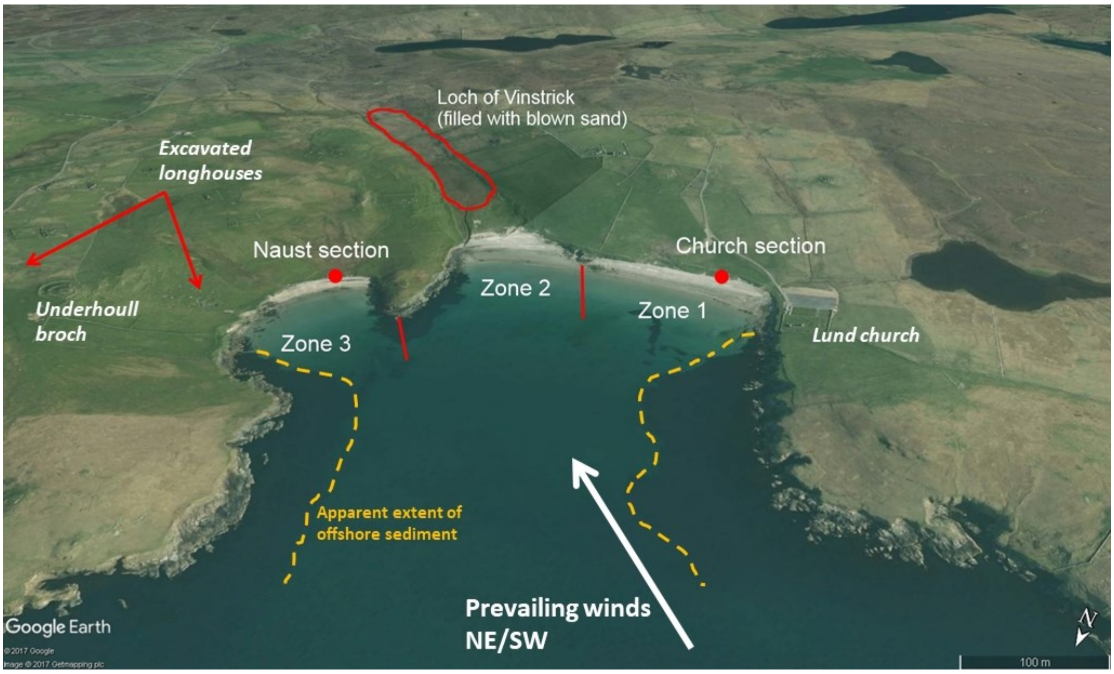


Figure 5.4 - Isometric view of Lunda Wick, facing south. OSL sample sections and geomorphic zones indicated. (Source: Google Earth)

Figure 5.5 - Oblique view of the partly eroded *noost* at Burga Wick, based on a digital surface model created for the HaNoA project by Ronny Weßling (Crazy Eye Perspectives) in 2014.

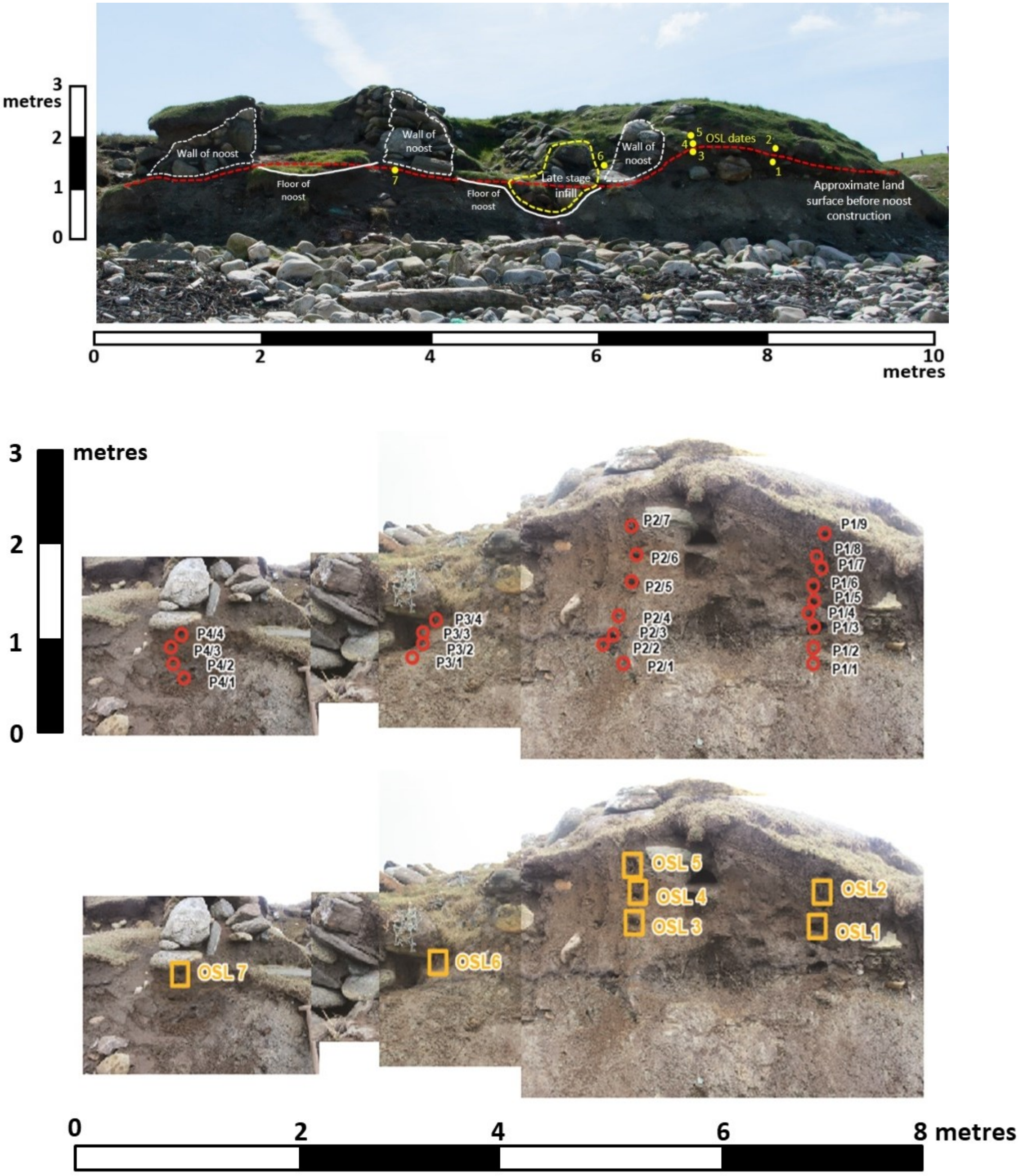


Figure 5.6 – a) setting of the noost section, with major section features marked. Numbered yellow dots represent SAR sample locations, marked in more detail in. b) IRSL/OSL (red) and SAR (yellow) dating sample positions.

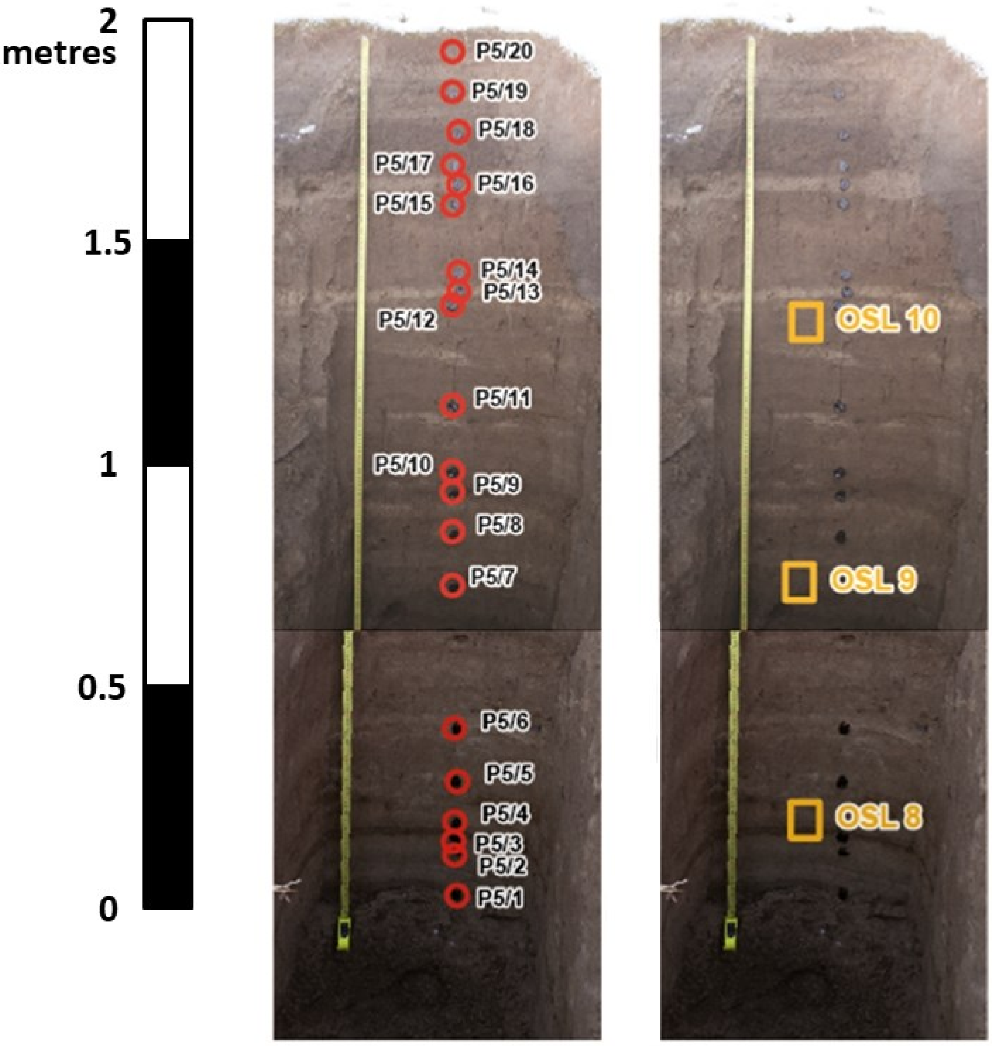


Figure 5.7 - IRSL/OSL dating samples and SAR dating samples, church section. Section 2.15 m from turf.

Profile	Sample number	Depth from surface(cm)	Context within section	Archaeological significance
P1	OSL1	100	Red sand (base)	Onset of sand blow
	OSL2	40	Clean sand	Later sand blow
P2	OSL3	150	Red sand (base)	Onset of sand blow
	OSL4	100	Red sand (middle)	Progression of sand blow?
	OSL5	40	Red sand (top)	Cessation of sand activity
P3	OSL6	50	Sand (top)	Modification of noost
P4	OSL7	40	Sand (top)	Construction of noost
P5	OSL8	175	Sands, above brown sandy soil (lowest sampled in profile)	TAQ for soil formation
	OSL9	65	Sands, top of charcoal-bearing horizon	Constraint on age of charcoal-bearing horizon
	OSL10	31	Sands	

Table 5.1 - Description of OSL SAR dating samples taken across profiles. Initial interpretation of archaeological significance is stated. See Appendix X for further context.

Samples taken in the field dark-packed to ensure no disturbance of the OSL signal and transported by land and sea to the laboratory to avoid x-ray exposure at airport security. IRSL/OSL lab screening was undertaken with the purposes to verify the presence and sensitivity of suitable minerals for dating, to review sensitivities in the profiles and to gain insight through the magnitude of the calibrated doses and their paired reproducibility as to the "apparent age" of the units. This data was then employed in single-aliquot regenerative (SAR) dating.

We measured the radionuclides and modelled the dose rates (effective dose rate). The SAR measurements result in dose determinations (equivalent dose distributions). The final stage was to derive age estimations (OSL age is the quotient of equivalent dose/ effective dose rate). Full details of the dating process can be found in Kinnaird et al. (2017).

Numerical modelling

The model experiment using MIKE21 (DHI, 2014) was set up to explore the ability of these coastlines to form a stable sandy beach in the face of varying climatic conditions- we did not aim to recreate the precise morphology of the coast around Lunda Wick and Sandwick. The model experiment simulates the nearshore movement and final distribution of sand-sized sediments which contribute beach material, but the model does not simulate the presence of an actual beach itself. In essence, the model simulates the availability of sediment to reform a stable beach after a storm has removed an existing beach. Figure 5.8 below shows an idealised schematic of the function of MIKE21.

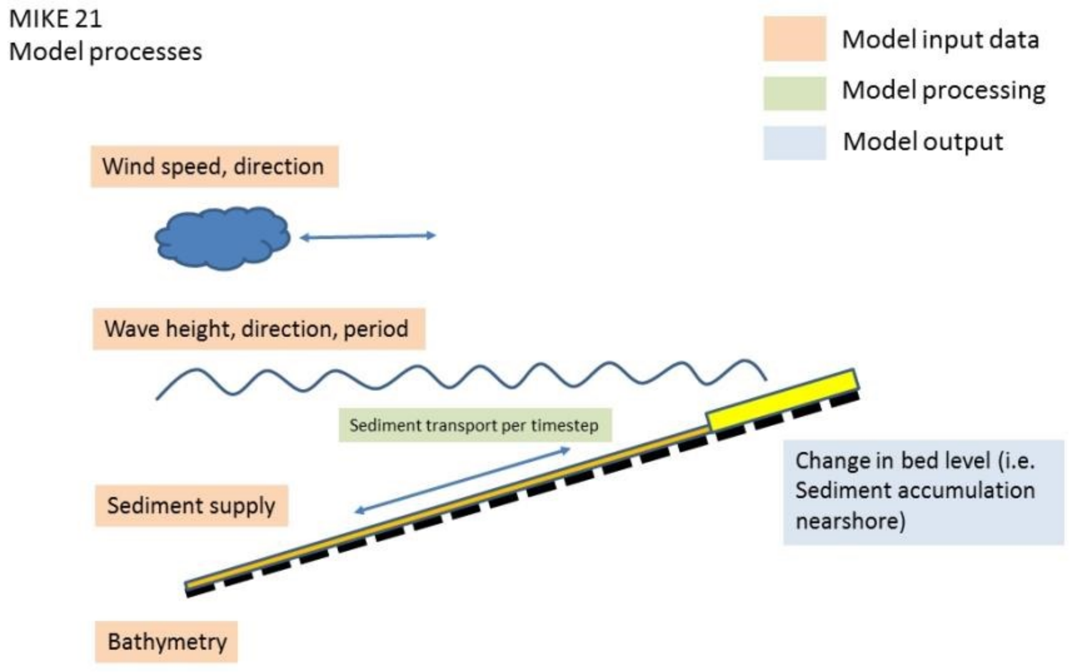
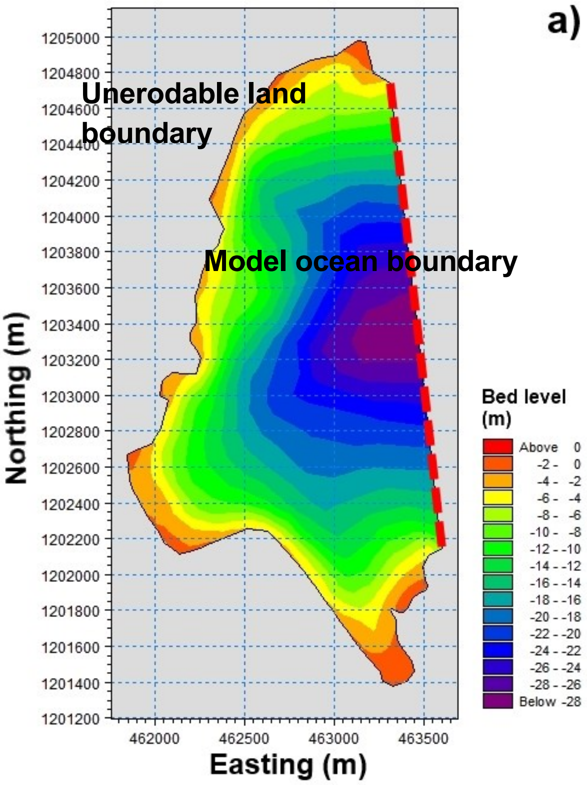


Figure 5.8 - Schematic of MIKE21 sediment transport model processes.

5.2.5 Model domain

Bathymetry data for Sandwick was derived from the MEDIN (Marine Environmental Data and Information Network) database. High resolution 2 m bathymetry was used for the offshore area in Sandwick Bay, with interpolation closer to the coast calculated automatically by MIKE21 Mesh Generator where detail was missing. Digital bathymetry for Lunda Wick bay is lacking, thus bathymetry was generated by digitising known depth points using the smallest scale nautical charts available (1:30,000 scale). This provided an acceptable resolution to build the model meshes (Figure 5.9).



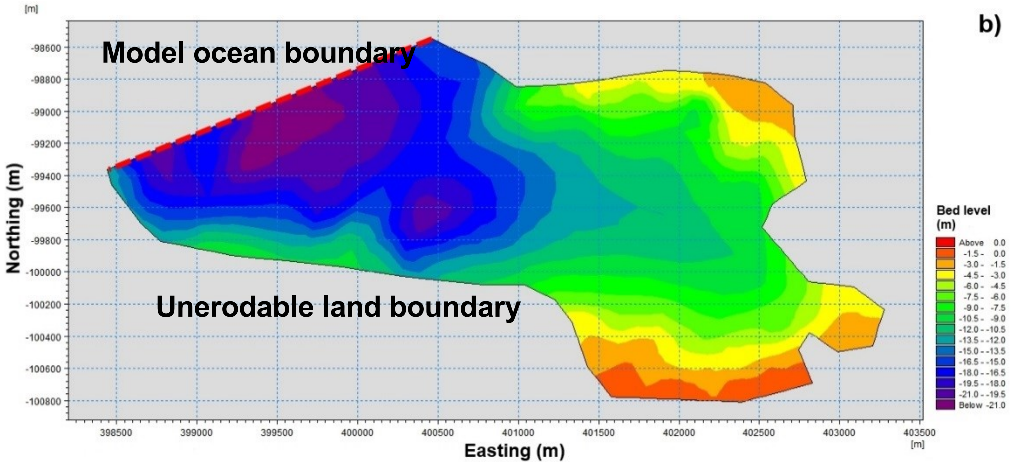


Figure 5.9 - Model bathymetry grid a) Sandwick, b) Lunda Wick.

Detailed model theory and set up is provided in supplementary information to this paper. Moderate and stormy climate scenarios were run to explore the impacts of climatic variability on beach formation on the embayments at Sandwick and Lunda Wick. Table 5.2 lists the initial conditions for these model runs.

Parameter	Initial condition
Tidal range	2.56 m (Bluemull tide gauge data)
Winds	Moderate conditions (1 – 15 m/s) Stormy conditions (1 – 60 m/s), angle 270° to 360° (W to N, directions Lunda Wick open to ocean)
Grain size d_{50}	250µm (grain size of fine/medium sand), 1 m thick sediment layer (~thickness of layer at Sandwick as recorded by Mathers & Smith (1972))
Sediment density	2650 kg/m^3 (standard density of quartz/carbonate sand)
Model simulation time	10 years (15 m model timestep, ~1 months results outputs)
Sediment transport theory:	Engelund & Fredsoe (1976)
Wave theory:	Isobe and Horikawa (1982)

Table 5.2 – Parameters used for the sediment transport modelling.

The tide cycle at Bluemull Sound and Baltasound were used for Lunda Wick and Sandwick, respectively, to generate the tidal range for the model as these are the closest tide tables available to the study locations.

Wind forcing was split into two categories, moderate and stormy. Median wind speeds on Shetland (as stated, a typical high-energy coastline prone to storminess) are 7.5 m/s (30 year median 1981–2010 as recorded by the UK Met Office), and so the bounds of the moderate conditions were chosen to reflect this. Thus moderate conditions were specified to range from 1–15 m/s, and stormy conditions to range from 1–60 m/s. The value of 60 m/s was chosen to represent persistently stormy conditions on the coastline, as it is the median of the highest wind speeds recorded in Shetland in each of the past 30 years, which range from 45 m/s to 77 m/s (Shetland Islands Council, 2011).

5.2.6 Fetch analysis

Wind fetch, i.e. the distance the wind travels in a certain direction over open water, is one of the main factors that determine wave height. On open sea, wave height is a function of the fetch, wind speed and wind duration (Groen & Dorrestein, 1976). Although wave dynamics in shallow coastal waters can be more complex, as they are affected by several other factors such as shoaling, wave refraction, bottom friction and currents (e.g. Holthuijsen, 1998), fetch is still an essential determinant. By measuring the fetch in various directions and relating these measurements to local, long-term wind statistics, we can quantify the exposure of the coastline to high waves and identify sheltered or exposed areas. Coastlines that are exposed to high waves are also prone to erosion, while sheltered areas may see a higher degree of sedimentation. Measuring the fetch also allows to understand the location of harbours and settlements. The fetch method, in which wave height is calculated on the basis of the fetch, has been developed to evaluate the quality of landing-places, and to explain why archaeological sites along the coast are rare in some areas, but numerous in others (Elvestad et al., 2009; Nitter and Coolen, *in press*).

The fetch along the coast of Unst was calculated using the Wave Tools toolbox for ArcGIS (Rohweder et al. 2012). A digital surface model of Unst and the adjacent islands with 10 m horizontal resolution, provided by NextMap, was used as input data. For the fetch models used in this study, the fetch was calculated in all secondary-intercardinal directions (N, NNE, NE, ENE etc.), using the toolbox's 'SPM' calculation method. Rather than calculating the fetch along a single radial (which does not observe minor deviations in wind direction and may also produce misleading results due to the accuracy of input data), this method calculates the mean fetch across a 24°-wind sector by spreading nine radials around the central direction at 3° increments and calculating the arithmetic mean. To get a better impression of the overall fetch distribution, the mean, maximum and cumulative (sum) fetch were calculated from the 16 individual fetch rasters using the cell statistics tool in ArcGIS's spatial analyst tools.

5.2.7 Offshore slope

Previous work undertaken by some of the authors has revealed a fundamental relationship between average offshore slope and the formation and stability of sandy beaches (Preston et al., 2018). Direct line-of-sight average offshore slope measured from the shoreline to 1 km from shore, and the depth point taken here, gives an average m/m gradient (Figure 5.10). This semi-quantitative method deliberately ignores small-scale morphological features, such as shore platforms, as the resolution of nautical charts is often insufficient to take these into account. A shoreline with an average offshore < 0.025 m/m is more likely to form a stable sandy beach under both moderate and stormy conditions than those > 0.025 m/m. Taking a measurement point 1 km from the shoreline, Sandwick has an average offshore slope of 0.017 m/m while Lunda Wick has an average offshore slope of between 0.018 m/m to 0.027 m/m.

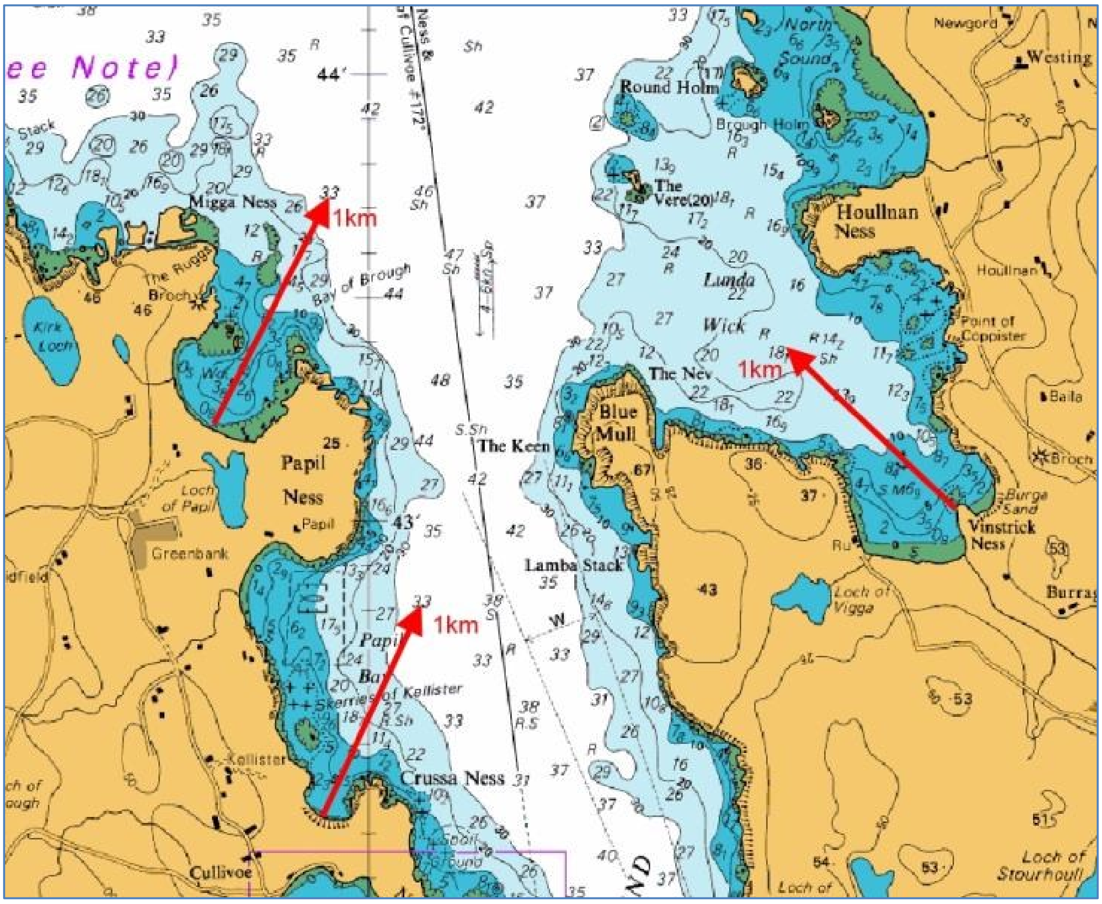


Figure 5.10 – Offshore slope measurement example methodology at Bluemull Sound, Unst. Local geomorphological variations along these gradients, such as shore platform or other features were ignored (source: UKHO).

Admiralty charts 3282 (1:75,000) and 3292 (1:30,000) were used to measure the average offshore slope of the coastline at intervals of approximately 500 m (dependent on availability of depth point) around the coast of Unst, and then mapped to create a coastline stability model of Unst.

5.3 Results

5.3.1 Luminescence chronology

	Sample number	**Archaeological significance (relative to other sample points)**	**Years / ka**	**Calendar years (CE – Common era)**
Profile	**Zone 3 (Noost) section**			
P1	*OSL1*	Red sands, base, in position of profile 1 (=OSL3)	3.22 ± 0.29	1210 ± 330 (290) BCE
	OSL2	Clean sands, top, in position of profile 1 (< OSL4)	0.12 ± 0.06	CE 1900 ± 60 (50)
P2	*OSL3*	Red sands, base, in position of profile 2 (= OSL1)	1.99 ± 0.15	CE 30 ± 210 (150)
	OSL4	Red sands, middle, in position of profile 2 (>OSL3, <OSL5)	0.63 ± 0.06	CE 1380 ± 70 (60)
	OSL5	Red sands, top, in position of profile 2 (>OSL4, >OSL3)	1.10 ± 0.10 *0.64 ± 0.10*	CE 920 ± 130 (100) *CE 1370 ± 100 (80)*
P3	*OSL6*	Red sands, top; modification of E noost	0.48 ± 0.06	CE 1540 ± 320 (60)
P4	*OSL7*	Red sands, top; construction of W noost	0.81 ± 0.07	CE 1210 ± 190 (70)
	Zone 1 (Church) section			
P5	*OSL8*	Sands, above brown sandy soil (lowest sampled in profile) (OSL8<OSL9<OSL10)	0.70 ± 0.05	CE 1320 ± 50 (50)
	OSL9	Sands, top of charcoal-bearing horizon (OSL8<OSL9<OSL10)	0.52 ± 0.04	CE 1500 ± 40 (40)
	OSL10	Sands (OSL8<OSL9<OSL10)	0.31 ± 0.02	CE 1710 ± 20 (20)

Table 5.3 - Quartz OSL sediment ages. Errors stated ± weighted standard error to 1 STD. OSL numbers in parentheses indicate sample location equivalence, whether located above (>), below (<) or same depth (=) as a sample point in adjacent sections.

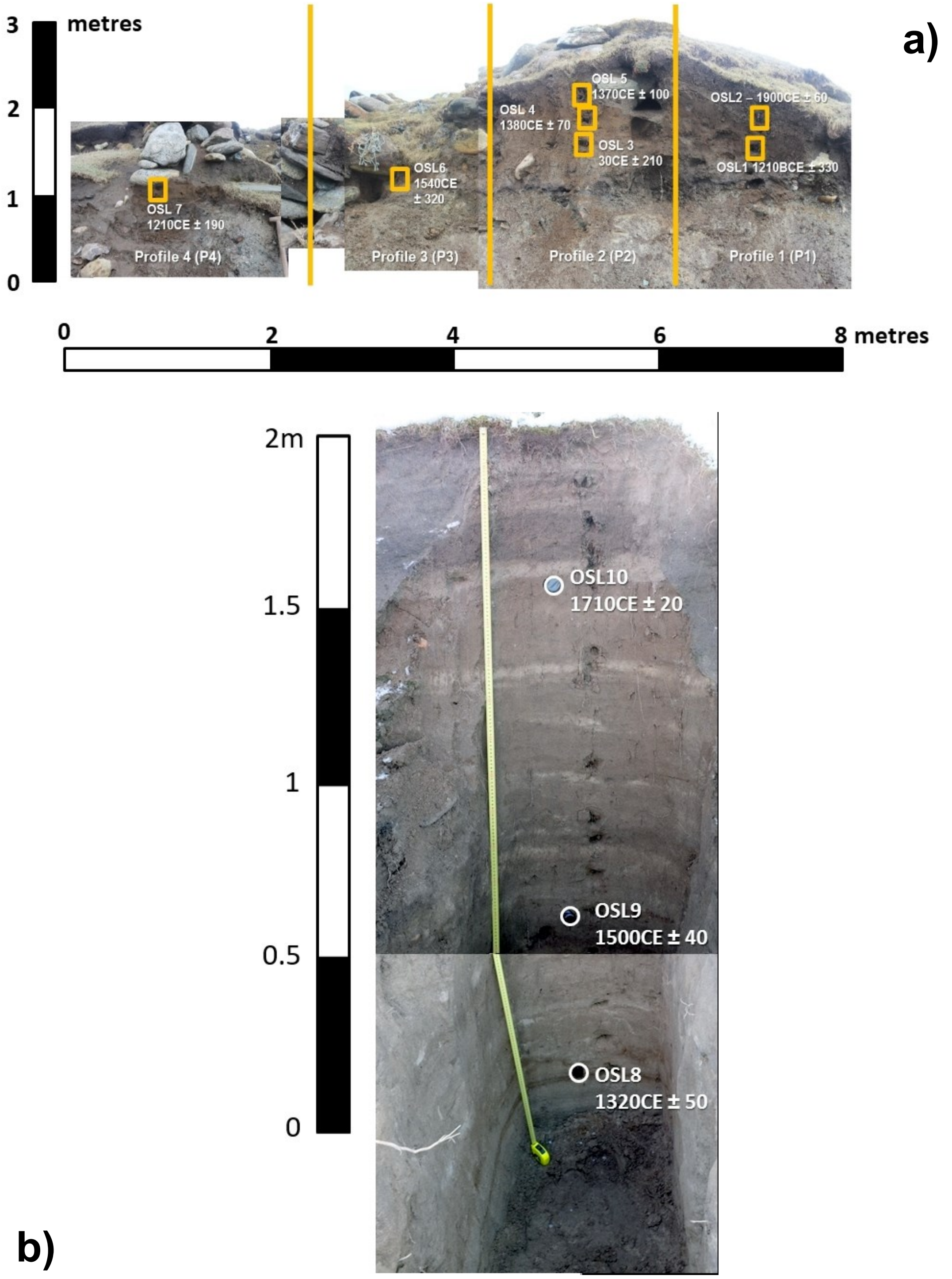


Figure 5.11 – a) Noost section OSL samples with calendar years, b) Zone 1 section OSL samples with calendar years.

The analysed OSL sand samples present in Table 5.3 reveal a complex picture of environmental change at Lunda Wick. Four profiles were samples in Zone 3, the Noost section. P1 (OSL 1 – 2) covers a period of approximately 3,500 years, however there is a high uncertainty in the date of OSL1. This is most likely due to an unconformity in the sediment accumulation, with subsequent layers lost to erosion. P2 (OSL 3 – 5) covers a range of at least 1,030 years, consistent with the upper age range of P1. OSL4 and OSL5 are very similar in age and error, suggesting this section accumulated at the same time as the others. In P3, OSL6 gives a date of 1540 ± 320 at the contact between the sediment and the secondary revetment wall inside the noost. Hence, this sample provides a *terminus post quem* (TPQ) for the re-use of the noost as a tentative sawpit. A large age range (± 320) suggests the secondary wall could have been positioned at any time from late Norse period to the early 19th century, the end of this range being in line with the later date suggested above.

OSL7 (P4) was taken directly below the eastern wall of the noost and thus provides a TPQ for the building of the original structure. The sample provided a date of 1210CE ± 190 and thus confirms that the noost was built during the late Norse period. This noost was found to have been modified from its original construction (Small, 1968), which could explain the larger dose distribution found for this noost. These dates represent the first known OSL dating of noosts anywhere, and further archaeological cut-back and resampling may provide further tightening of the date range here.

At the Zone 1 church section, a maximum date span of 430 years (*terminus post quem* 1270 CE) and a minimum of 320 years is recorded (*terminus ante quem* 1730 CE), with approximately 200 years in between each sample. Multiple phases of blown sand can be seen throughout the profile, interspersed with soil horizons that indicate phases of relative stability. OSL8 was taken from the sand bed overlying an organic-rich layer, which, if this represents the local onset of storm driven beach instability after more stable conditions, constrains this to CE 1320 ± 50. The age for OSL9 (1500 ± 40) puts this sample point within the LIA proper, with significant sand deposits having taken place both before and after this horizon was formed, with a similar age to OS5, noost 2, albeit with a tighter dose distribution. Flecks of charcoal are found both before and after c. 1500 CE, evidence of anthropogenic impacts and a possible management strategy for coastal grazing in the face of sand influx. Similar soils are know from elsewhere in Shetland, where they have been interpreted in terms of land management strategies (e.g. Davidson et al., 1998). OSL10 is dated to around the turn of the 18th century, and represents the time when the sand influx reduces and brown soil formation begins in earnest once again.

5.3.2 Modelling results

5.3.2.1 Sandwick

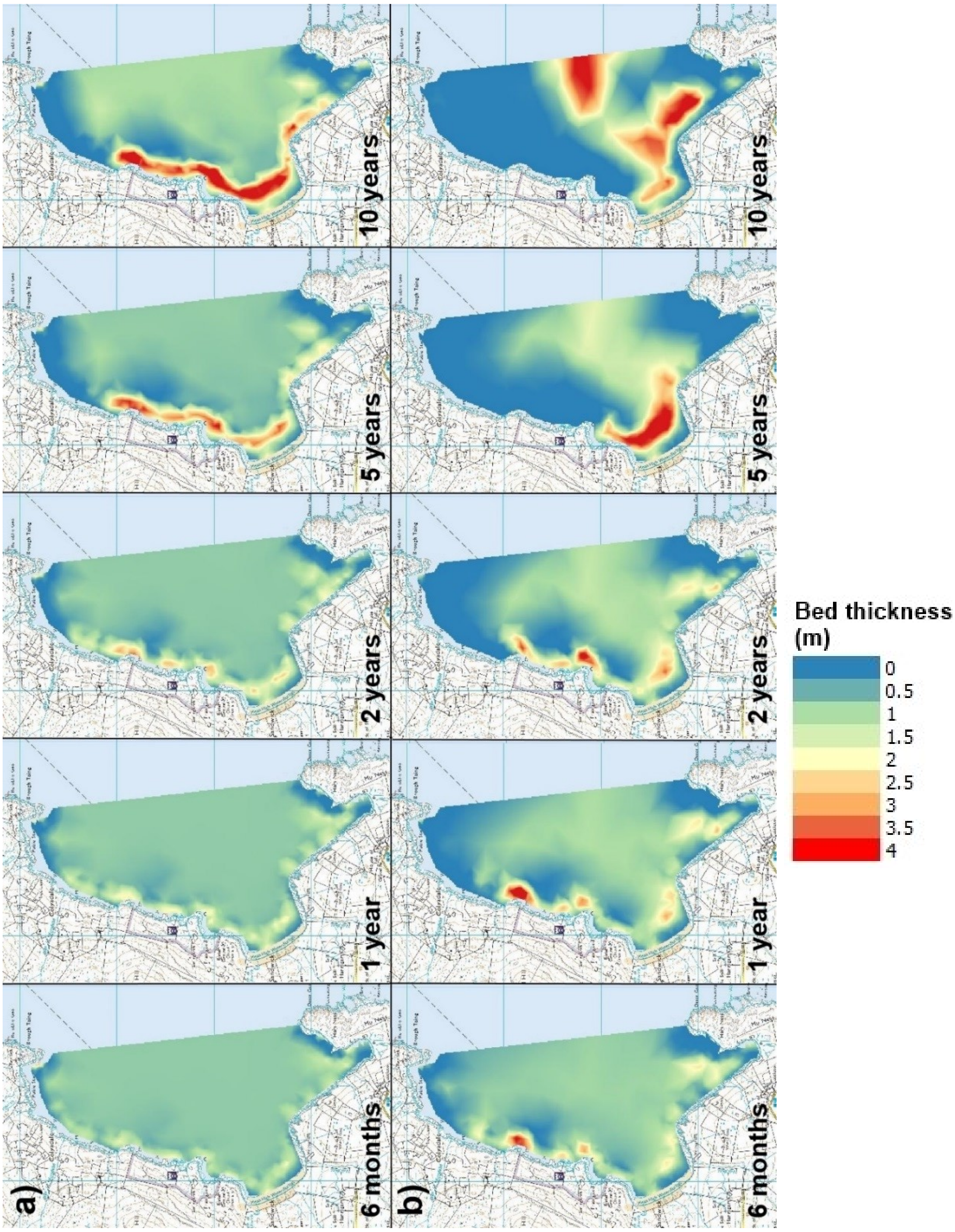


Figure 5.12 - Bed thickness after 10 years of model simulation at Sandwick, a) moderate wind conditions, b) stormy wind condition (contains OS data. Crown copyright)

Modelling results for Sandwick indicate that sandy sediment should accumulate in the nearshore environment of Sandwick Bay regardless of whether winds are moderate or stormy (Figure 5.12). With moderate prevailing conditions, fine sediment very rapidly accumulates nearshore in a relatively unbroken sandbar extending to both the north and south of Sandwick Bay, with significant quantities accumulating by 6 months into the model simulation and a prominent sand bar formed within a year. Key limits are established with no sediment accumulation is seen near Colvadale at the northern tip of the modelled embayment.

Under prevailing stormy conditions, sand banks generally accumulate further offshore, with very little sediment approaching shallow waters. The exception to this is the largest embayment in the south west of Sandwick Bay, which does form a sandbar just offshore, albeit in a reduced form compared to those of moderate wind conditions. The formation of sandbars takes longer under stormy than under moderate conditions, with significant quantities of sand only beginning to accumulate nearshore after 2 years. These results agree are consistent with observed bed conditions, with Admiralty charts marking sand banks approximately 800 m north of Ham Ness, roughly the area where the model also produces sandbanks in stormy conditions. Small nearshore sandbanks form in the small embayments along the coastline to the north of the largest embayment, and persist before being removed 5 years into the model simulation.

Aerial imagery that reveal bed conditions through shallow water also record limited patches of sandy bed conditions in small embayments north of the large south western embayment, also consistent with model results under moderate conditions. It is therefore likely that the current nearshore sediment distribution is a function of a combination of moderate and stormy conditions within the modelled area. Crucially, the modelling and empirical data show that under both moderate and stormy conditions, a nearshore sand supply for beach formation endures close to the largest embayment in Sandwick Bay. Beaches could therefore reform within a year or two of a hypothetic beach removal. The model results for Sandwick also agree well with the fetch analysis of the bay (Figure 5.13).

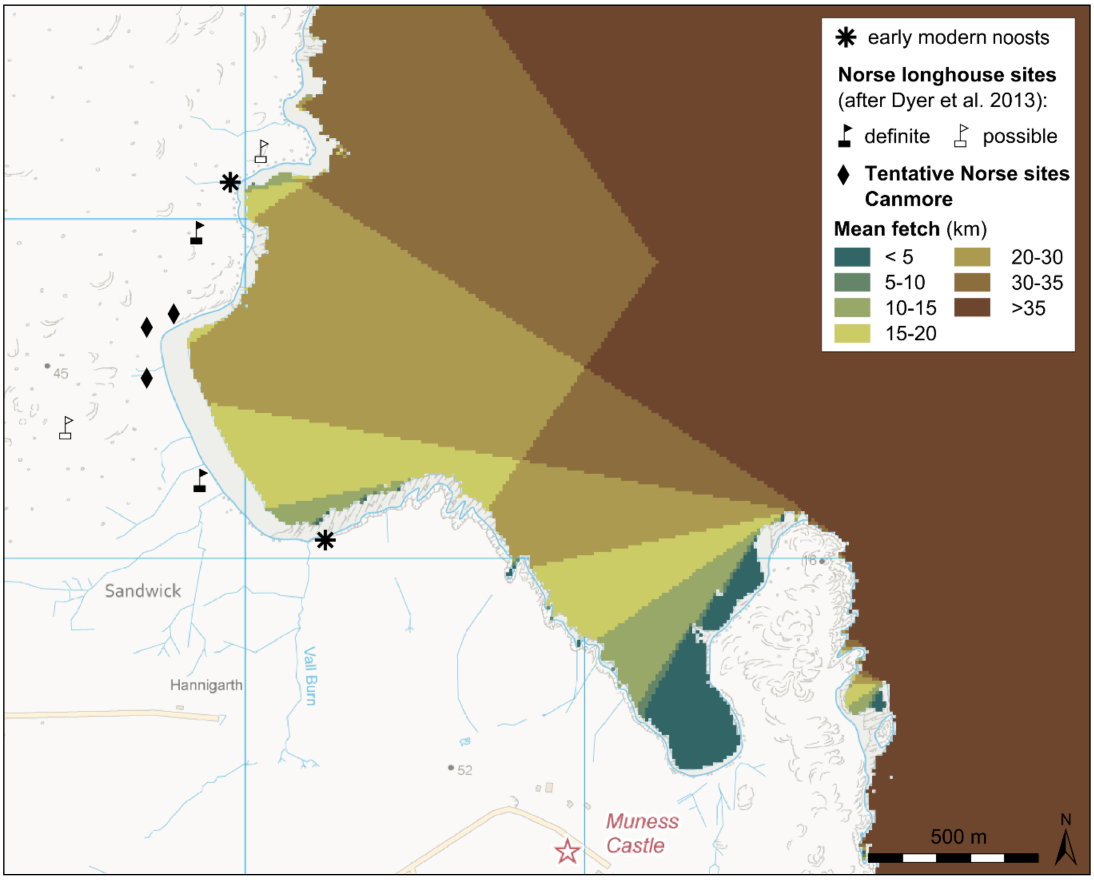


Figure 5.13 - Distribution of mean fetch in Sandwick with the location of *noosts* and tentative Norse settlements. Graphics: Joris Coolen. Contains OS data © Crown copyright and database right (2018)

Under moderate and stormy conditions, sediment accumulates in the zone of lower fetch in south west embayment in Sandwick Bay. Only in moderate conditions does sediment accumulate nearshore in zones of higher fetch (north of the embayment). Fetch analysis also identifies the bay of Mu Ness, south of Sandwick, as being a sheltered embayment, but, there is no sandy beach there today, and neither does one appear on 19th century maps (1st edition Ordnance Survey maps dating from 1888 onwards). This is consistent with the modelling that does not lead to a minimal offshore supply of sediment reaching this embayment. It is possible that geomorphic factors not captured in the input data are in play to prevent a sandy beach accumulating in this embayment, but our modelling is consistent with observed data in identifying sheltered embayments where sandy beaches do not form even though there may have initially been a suitable sediment supply in the local region.

Lunda Wick

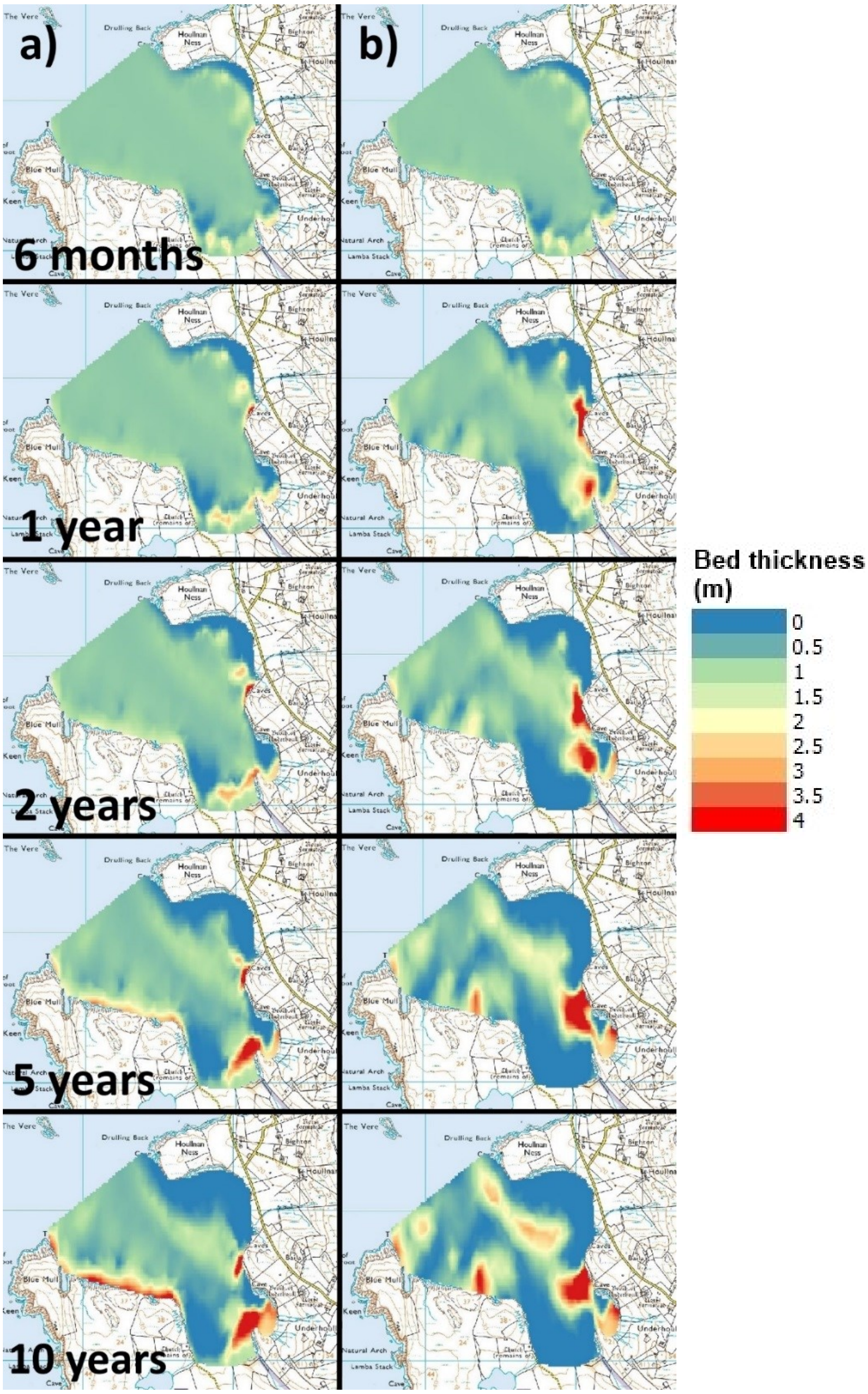


Figure 5.14 - Bed thickness after 10 years of model simulation at Lunda Wick, a) moderate wind conditions, b) stormy wind condition (contains OS data. Crown copyright)

Modelling results for Lunda Wick (Figure 5.14) reveal a more complex picture of nearshore sediment accumulation than Sandwick Bay. Under moderate conditions, sediment accumulates nearshore within 6 months of model time and stays close to shore throughout the model simulation, albeit with some slowly accumulating material close to Vinstrick Ness by the tenth year of the model simulation. Accumulation is also seen close to the headlands to the west, but this coast is formed from cliffs plunging into deep water and no beach could form there.

Under stormy conditions, modelling results are similar to Sandwick; sand bars generally form in deeper waters without moving closer to shore. Some sand is seen accumulating nearshore within 6 months of the stormy model simulation, but this begins to rotate away from shore and ends up in deeper water by the end of the model simulation. There are crucial local variations; sand does accumulate in Burga Wick (Zone 3) as under moderate conditions, but under stormy conditions no long term sand accumulation is seen in Lunda Wick (Zones 1 and 2).

As Lunda Wick has a more complex geometry than Sandwick and has a more complex offshore environment in terms of nearshore platforms and skerries (details not captured in the model), thus small scale, very localised currents and eddies operating nearshore, are likely to explain some of the discrepancies between modelled and observed sand distribution. Despite this, there is however, a broad agreement between observations and modelled results for Lunda Wick that a beach is more likely to form and remain stable under moderate conditions than stormy, although Burga Wick appears to contain a persistent beach under any conditions. This also broadly agrees with the fetch analysis of Lunda Wick (Figure 5.15):

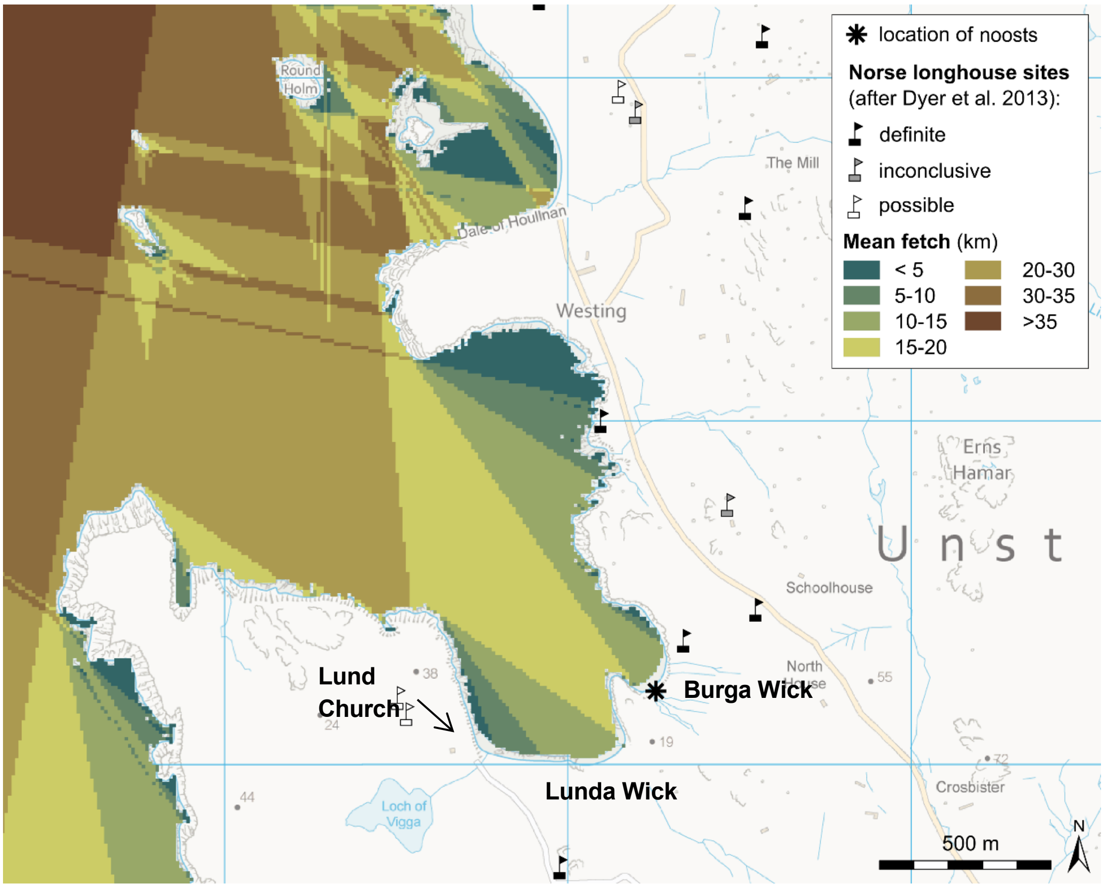


Figure 5.15 - Distribution of mean fetch in Lunda Wick with the location of *noosts* and tentative Norse settlements. Graphics: Joris Coolen. Contains OS data © Crown copyright and database right (2018)

Burga Wick is very sheltered from prevailing winds, thus once sediment accumulates in this embayment it is unlikely to be removed by wind-generated wave action. Even though Zone 1 of Lunda Wick is as equally sheltered as Burga Wick in terms of fetch, the corridor of moderate fetch and increased wave energy centred on Zone 2 could well prevent sediment accumulation in Lunda Wick. Thus fetch analysis compliments that of the numerical modelling and enables some of the complexities of the Lunda Wick geomorphic environment to be assessed.

5.3.3 Offshore slope

Measured 1 km from the shoreline, Sandwick has an average offshore slope of 0.017 m/m which is less than the critical threshold of <0.025 m/m identified as a key limit of sustained beach formation (Preston et al, 2018). The line-of-sight offshore slope for Burga Wick (Zone 3) is 0.018 m/m and for Lunda Wick (Zone 1 and 2) is 0.022 m/m.

However, the gradient steepens to 0.027 m/m at the Point of Coppister, which presently has very small accumulations of sand in the embayments.

Figure 5.16 shows a schematic of Unst as a function of offshore slope, with coastline that can form a stable beach marked in red. These are cross-referenced with the existence (or lack) of sandy beaches along these coastlines.

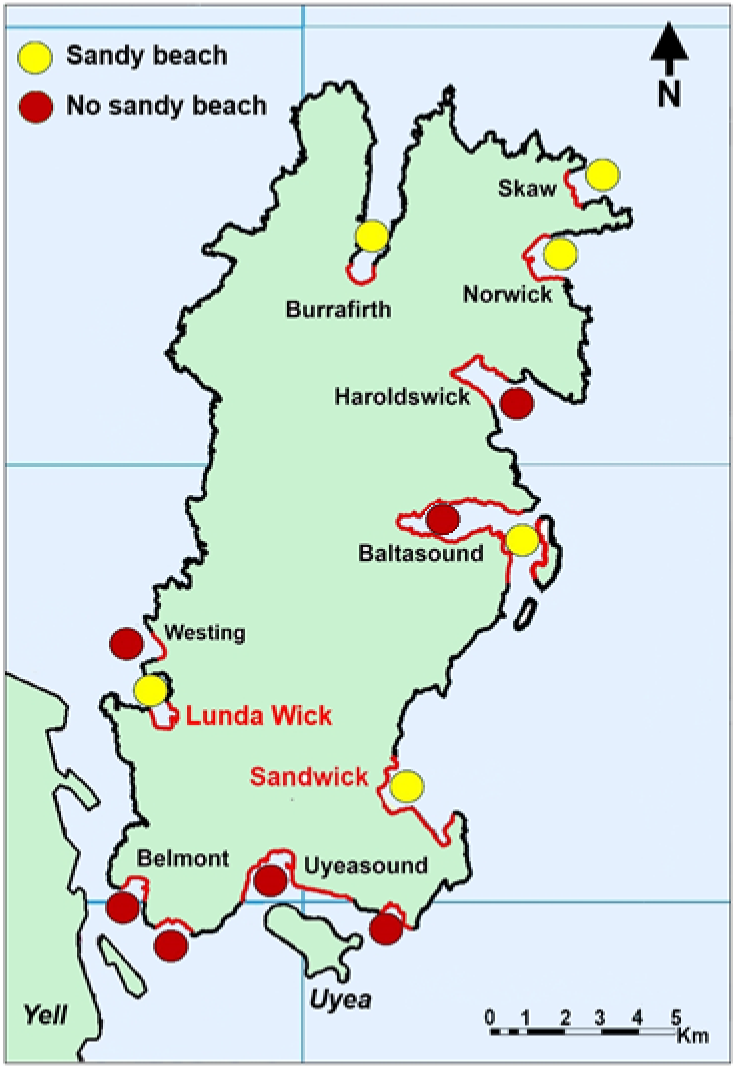


Figure 5.16 - Map of Unst coastline as a function of average offshore slope with embayment names marked. Red coastline indicates coastline with <0.025 m/m average offshore slope. Red and yellow circles indicate the existence of an extant sandy beach.

The slope analysis highlights the bays of Norwick, Wick of Skaw and Burra Firth as having potential for sandy beaches, and these do exist there today. Offshore slopes would suggest that several embayments could support sandy beaches where none are present today, yet these can be explained by other disruptive geomorphic reasons: Baltasound is of sufficiently shallow offshore slope to allow a beach to form, however this is sheltered from offshore sand supply by a barrier island. This is also the case in the vicinity of Uyeasound on the south coast, where the island of Uyea could prevent offshore sediment from moving into the critical nearshore zone. Belmont bay is similarly sheltered by the island of Yell. The embayment at Westing is sheltered by multiple skerries nearshore which could feasibly disrupt sediment accumulation nearshore. No sandy beach is currently present at Haroldswick, despite the embayment aspect being towards the open ocean, although the offshore slope could allow one to form.

5.4 Discussion

The model convincingly simulates nearshore sediment supply at both Lunda Wick and Sandwick, results of which are consistent with both our observations and fetch analysis. Under moderate wind conditions the modelling suggests that there should be a continuous sand supply for the beach, consistent with the present situation at both sites.

Model simulations show that under stormy conditions a stable nearshore sand bar can form rapidly at Sandwick Bay, but not at any other point along the coastline. Deeper water sandbanks form as well and these are consistent with known sea bed data. The embayment at Sandwick, therefore, should be able to maintain a persistent beach regardless of climatic condition, and thus local people are likely to have always been able to rely on the beach as a landing place.

In contrast, under stormy conditions, numerical modelling suggests that sediment is ‘churned’ in the nearshore environment around Lunda Wick and does not form a stable offshore sand supply for beach formation. In this situation, the modelling has some notable limitations because it does not capture the detailed topographic and bathymetric variability of the embayment, but in terms of broad scale contrasts it does successfully identify a more complex and nuanced local pattern of geomorphological change where long term beach persistence is far more problematic than at Sandwick. This is consistent with the observed archaeological record; at

Sandwick a Norse longhouse has survived on the beach and the ground levels of Norse time are demonstrably similar to those of today, some ten centuries later. In contrast, the noosts of Lunda Wick have been truncated and bluffs have formed at the upper edge of the present beach where the modern surface has been incised by 2-3 m. The best conditions for persistent beach formation are in Zone 3, where there is prehistoric settlement in the form of the Broch, the noosts were built, and inshore of this section of the bay is the site of the Norse settlement. For a culture based on the exploitation of both terrestrial and marine resources, regular access to the sea in small boats is vital. This is especially so when wild resources are the key to resilience and making good short falls from farming, a situation that may have recurred frequently as the comparatively benign climates of the MCA transitioned into the more variable and stormy LIA.

These sand movements can be successfully dated using OSL and our results help to build a picture of changing environmental conditions experienced at Lunda Wick in the latter stages of the Medieval Climatic Anomaly (MCA) and the transition into the Little Ice Age (LIA), around 1250 CE. The timing of sand blows is consistent with Kinnaird et al. (2015)'s findings at Sandwick and other work carried out in Shetland (e.g. Burbidge et al., 2001, Sommerville, 2003; Bampton et al., 2017). The implications of these bodies of work is that large-scale sand movements occurred from the 13th century onwards. Storms would have driven this change and our modelling shows that under these circumstances beach persistence at Lunda Wick becomes problematic. Our dating suggests that noost 2 is late Norse in origin (TPQ 1210 ±190), while noost 1 could represent a later construction, or a later stage of modification. These dates, coupled with the nearby Norse longhouse, strongly imply that this embayment was a landing place during the Shetland Norse period. Significant blown sands are present in the Zone 3 section, with some evidence of both unconformities (OSL 1 and 2 area separated by ~3000 years in a relatively small section), and thick deposits formed at similar times. OSL4 and 5, taken with in a deep stratigraphic unit, are approximately the same age and are dated to 1270 -1480 CE, somewhat later than the mid-13th century dates of blown sands found at Sandwick (Kinnaird et al., 2015), but broadly consistent with the crossing of key environmental thresholds associated with the climate changes around the MCA-LIA transition, beginning in the mid-13th century. This also is broadly consistent with the phase of discrete sands units separated by thin soils found in the Zone 1 section. This evidence indicated a period of oscillating change of sand blows and stabilisation within a general shift towards increased storminess as experienced in other areas of the North Atlantic as the LIA progressed.

These units of blown sand contain shell, showing they have a marine origin and were derived from offshore (Mathers & Smith, 1972). If the discrete episodes of sand blow occurred across the whole embayment, the beach at Lunda Wick could have been progressively depleted of sand. Thus Lunda Wick, while currently containing a sandy beach, has been prone to periodic instability from Norse settlement times and throughout the LIA, and our modelling data suggests that offshore conditions would not be conducive to a swift reformation of the beach, and thus its continuity as a landing site.

Sandwick has also experienced sand movements inland, particularly in the mid-13th and mid-18th centuries (Kinnaird et al., 2015). These events would have shifted significant volumes of sand inland, but model results suggest that Sandwick would have had a consistent nearshore sand supply for beach replenishment. Thus the beach could have persisted even under sustained periods of heavy storms, making it a reliable landing place for small boats when sea conditions permitted offshore operations. Yet abandonment of the Norse farm site at Sandwick appears to have occurred in the mid-14th century, because a fragment of tephra found in the immediate post-occupation sand deposits in the excavated longhouse on the beach (believed to be related to the 1362 eruption of Öræfajökull; Harris et al., 2017). This date is broadly coincident with the sand blows identified by Kinnaird et al. (2015) and may suggest the abandonment is due to these sand inundation events.

A key difference between Lunda Wick and Sandwick that is likely to drive contrasting geomorphological responses is the average offshore slope. The more uniform shallow gradient of Sandwick is conducive to maintaining sediment in the nearshore environment, while the steeper offshore gradient in parts of Lunda Wick's nearshore environment are more likely to result of a diffusion of sediment into deeper waters and their removal from any possible contribution to beach formation. Analysis of off shore slope seems to be a robust and effective way to identify likely trajectories of coastal change. Analysing offshore slope island-wide, we have identified only limited areas where beach formation is likely if offshore slope is a controlling factor. Figure 5.16 illustrates those stretches of coastline on Unst that fall below an average offshore gradient of 0.025 m/m and thus may be conducive to beach formation. Overall, the coastline of Unst, therefore, possesses only a few embayments that allow a stable beach to form and persist under stormy conditions, which include Lunda Wick and Sandwick. However, the results of both the modelling and luminescence dating show Lunda Wick to be marginal in this respect, and this marginality is reflected in the patterns of settlement preserved in the archaeology.

5.5 Conclusions

These investigations reveal a nuanced picture of Late Holocene (MCA -LIA) environmental changes in the embayments of Sandwick and Lunda Wick on Unst that seem to follow a set of overarching principles and thus illustrate major potential themes in coastal and island archaeology.

Numerical sediment transport modelling reveals clear differences in the persistent beaches in both embayments and shows the potential of modelling to usefully complement both geomorphological mapping and archaeological survey and identify likely trajectories of change in beach stability.

Sandwick has a relatively consistent beach-forming environment under both moderate (MCA) and stormy (LIA) conditions. Near shore sediment supplies can persist under a very wide range of weather conditions promoting beach stability. Lunda Wick, however, has a more complex environment, where nearshore sediment supplies for beach nourishment are inconsistent. Under persistent stormy conditions, sediment is diffused away into deep water and blown inland. OSL dating of blown sand deposits indicates that as the LIA progressed beaches were swept away and the coastline became increasingly unreliable for landing boats. This is supported by the OSL dating of blown sand deposits and the first successful use of OSL to date the construction of noosts.

Under stormy conditions, the major geomorphic control on nearshore sand accumulations in the embayments is the average offshore slope. Sandwick has a shallow and generally more uniform offshore slope than Lunda Wick. A slope analysis of the entire island shows that few embayments on Unst are able to form stable beaches under persistently stormy conditions where offshore slopes are steeper than 0.025 m/m.

Offshore gradient analysis is a simple task that can effectively inform studies of coastal environments: gradients < 0.025 m/m have the potential to sustain persistent beaches under a range of climate conditions. Areas with these slopes where beaches do not form are likely to have a restricted inshore supply of sediment, a situation that can occur with barrier islands or skerries offshore.

Where offshore slopes are marginally steeper than 0.025 m/m (as in the main embayment of Lunda Wick), beach formation under stormy conditions can be episodic with significant implications for both the preservation of an archaeological record and the persistence of settlement where the local economy is reliant on the exploitation of marine resources using small boats.

6 Morphological change of the Norse harbour at Garðar, Eastern Settlement, Greenland due to relative sea level rise

6.1 Introduction

So far in this thesis I have shown how geomorphological change on a short-term spatial and temporal scale (I.e., soft sediment movement) impacted landing places in Unst. The short-term loss of a beach due to storm erosion can lead to the equally short-term recovery of the beach in certain circumstances should geomorphological and climate conditions allow, offering the chance of continuity of use on these coastlines. However, in other circumstances this beach loss can prove more permanent and thus the temporal scale of this geomorphological change extends, potentially beyond a timescale feasible for continuity of use.

Harbours located on coastlines with less sediment, and less exposure to climatic and oceanic forcing are not as prone to sudden, short-term geomorphological change as those with soft sediments and more exposure. Yet within the North Atlantic realm these will not necessarily remain static because of local sea level changes which will affect coastlines over centennial/millennial time scales. If we consider the sediment/exposure matrix once again (Figure 6.1), we can add an additional axis to help visualise this.

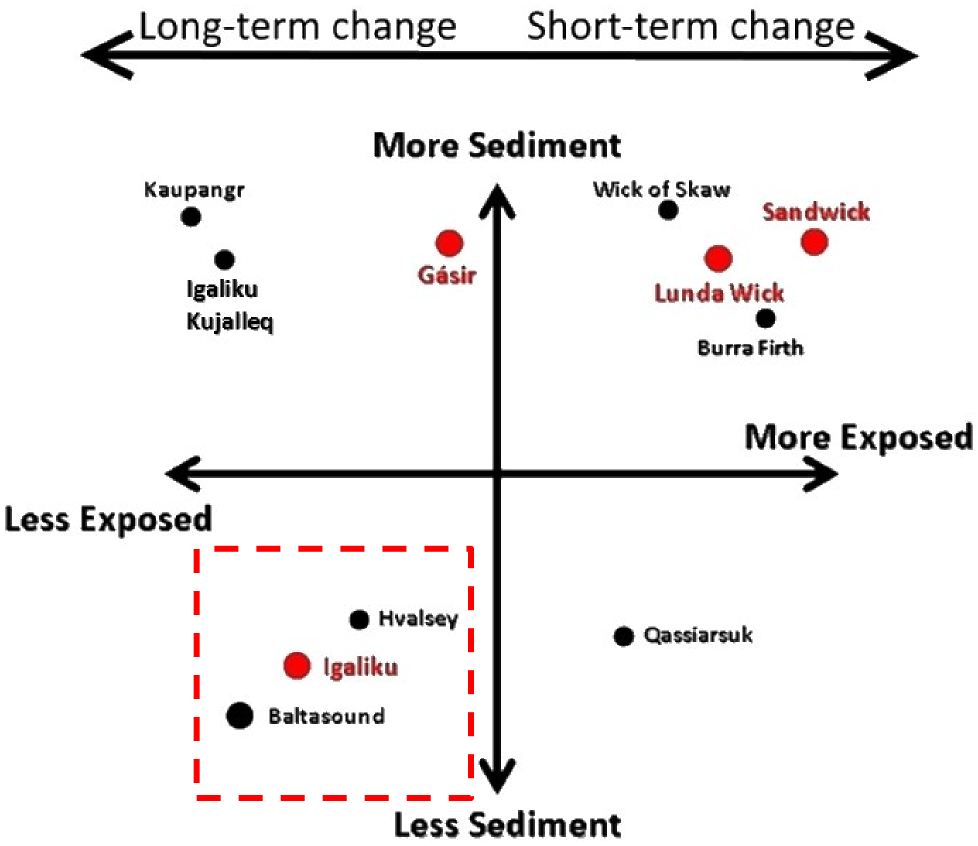


Figure 6.1 - Sediment/exposure matrix, with the addition of a temporal axis. Red box highlights sites discussed in detail below.

The addition of a temporal axis to this conceptual model illustrates how sites that possess the most soft-sediments as well as being the most exposed tend to be the ones that are liable to undergo geomorphological changes on shorter-term timescales. Sites that have large volumes of sediment yet are relatively sheltered, are a more complex case, which shall be discussed in Chapter 7. However, relatively sheltered sites with a lack of soft sediments are those that must be considered on a longer-term timescale for any evidence of geomorphological change.

Long-term erosion on rocky coastlines can cause significant geomorphological change on a centennial/millennial timescale as cliffs and shore platforms retreat [e.g. Trenhaile, 2002; Trenhaile, 2011; Limber & Murray, 2011, Rosser et al., 2013; Barkwith et al., 2014; Hurst et al., 2016 ;). But for those coastlines that are well sheltered from oceanic forcing, the most prominent mechanism of geomorphological change is that of relative sea level (RSL) change, independent of both exposure and local movements of sediment. This form of change would not impact coastline use on a sub-generational timescale for Norse settlers, however over a multi-decadal to centennial timescale profound changes may occur to force the relocation of activities or settlement, particularly if productive land, such as used for grazing livestock, was lost. Grazing land loss at the farm sites of Brattalið and Sondre Igaliku due to sea level rise may have been significant, but in other areas comparatively limited (Kjuipers et al., 1999; Kjuipers et al., 2008)

On the matrix, three examined field sites may fulfil this criteria of well-sheltered and sediment-poor coastlines. Baltasound, in Shetland, has a persisting settlement to the present day and thus does not experience abandonment. Hvalsey, in southern Greenland, is a well-known settlement site composed of a large farm and a church site, but evidence for the continuing use of a harbour at this site is poor. A key illustration of sites within this quadrant of the matrix is Igaliku/Garðar, in southern Greenland, because of its importance as a harbour site in the Eastern Settlement, its complex geomorphic shape and its ultimate abandonment along with the rest of the Norse colony in Greenland.

6.2 Historical context

One of the most compelling mysteries of North Atlantic archaeology, and an iconic example of settlement change, is that of the disappearance of the Norse settlements in Greenland (Diamond 2005, Barlow et al., 1997; Dugmore et al., 2012). A large and ongoing body of work continues to shed light on the nature and operation of Norse Greenlandic society in the first half of the second millennium here, and particularly the circumstances which led to its demise at some point during the 15th century. The Western Settlement is thought to have disappeared around 1400, and the Eastern Settlement came to an end in the mid-15th century (e.g. Gad, 1970; McGovern, 1980; Barlow et al., 1997; Dugmore et al., 2012), although the precise dates for final abandonment is currently uncertain. Several attempts were made in intervening centuries to rediscover Greenland with some success throughout the 17th century, but Greenland was only recolonised by the Danish in the first half of the 18th century, by which time only enigmatic ruins remained of the original Norse inhabitants. (Etting, 2009).

The current understanding of the mysteries surrounding the Norse disappearance does not favour one particular cause, but probably a series of changes (environmental and cultural) occurring over time. Although each event may not have been significant in isolation, their combined impacts resulted in the eventual demise of the Norse settlement of Greenland (Dugmore et al., 2012). The changing trade patterns and proto-modern economic structure that was developing in the rest of Europe from the 14th century began to place a heavier emphasis on the bulk production of goods as opposed to luxury items. The Norse economy in Greenland had traditionally relied on the production of these luxury items, such as walrus tusks, fur and animal hides and even ‘exotic’ arctic fauna such as falcons, walrus tusks, narwhal tusks and live polar bears While these were valued in earlier centuries, they became less important as European economies and fashions changed. The rise of the Hansa League favoured bulk commodities such as stockfish (mostly cod) and wool, products that Greenland did not supply. Regular trade missions to Greenland from the rest of Europe began to wane, and eventually stopped altogether in the early 15th century (McGovern, 1985; Mikkelsen et al., 2001; Dugmore et al., 2007; Dugmore et al., 2009a, Frei et al., 2015).

Occurring alongside these economic and political changes was a shift in climate and the transition between the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA), with the LIA characterised by increased storminess and more variable cooler conditions (e.g. O’Brien et al., 1995; Lassen et al., 2004; Dawson et al., 2007; Mann et al., 2009). Increasingly unpredictable sea conditions made the crossing from Europe to Greenland more treacherous and costly, compounding the shift in trade that marginalised Greenland. Little Ice Age conditions also made themselves known to the Norse living in Greenland, with major impacts being felt with increasingly marginal farming yields and land loss (Kjuipers et al., 1999; Arneborg, 2012). Evidence from the GISP2 ice core suggests storminess increased significantly as the Little Ice Age progressed. (O'Brien et al, 1995, Meeker & Mayewski, 2002; Dugmore et al., 2007; Vinther et al., 2010). One key environmental change occurring on a centennial timescale found in the Eastern Settlement is RSL rise (Sparrenbom et al., 2006; Kjuipers et al., 2008; Dugmore et al., 2012; Madsen, 2014). As mentioned above, this is thought to have caused the loss of many hectares of valuable grazing land for animals, as well as disproportionately impacting infrastructures and field systems adjacent to coastal areas, which increased pressure on Norse terrestrial food sources. Archaeofaunal evidence from middens and isotopic data from human remains show that in the mid-13th century there was a major shift in Norse diets from mostly terrestrial to mostly marine as marine foods (principally marine mammals) came to be of primary importance (Arneborg et al., 2012, Dugmore et al., 2012).

The Norse settlement at Garðar, located at modern day Igaliku, was a key settlement in the Eastern Settlement (Figure 6.3). It was the centre of Ecclesiastical power, and the seat of the Bishop of Greenland. According to the *Saga of the Greenlanders*, the farm in the area that became Garðar (which, roughly translated, means *Gardens,* suggesting a cultivated area at the very least) was settled by Erik the Red's daughter Freydis, and her husband Torvald at some round around the year 1000. These elite settlers would have certainly chosen very good land to occupy, and archaeological evidence shows that the farms at Garðar prospered (McGovern 1980). The Bishopric of Greenland established in 1124 with the first Bishop of Greenland, Arnald, taking his seat in 1126. The Greenlandic settlements were formally incorporated into the Norwegian Crown in 1261 at the time major changes were happening in Norse diet and the switch to increased marine provisioning began to occur. The Bishopric endured until the end of the Eastern Settlement ,although no Bishop sat at Garðar after 1378 (Bruun, 1918; Arneborg, 2003; …, 2006; Guðmundsson, 2009; Etting, 2009; Buckland et al., 2009). Extensive ruins of both the cathedral and the wider settlement are readily visible today (despite being used as a source of building materials for modern settlement). As with other Norse settlements in Greenland, the date and process of abandonment is unclear, but it likely to have occurred at some point after 1450 (Dugmore et al 2012). As the centre of Ecclesiastical power, Garðar was also an important harbour for the Eastern Settlement and would have been a key centre for international trade to and from Europe. The ruins of several storehouses and warehouses near the present day shoreline provide evidence for an extensive use as a harbour, and it is important to establish what localised changes this drove.

Igaliku, as with all of southern Greenland, has been subject to a complex picture of RSL change for much of the Holocene. Land around the ice margins of the Greenland ice sheet has been subject to significant isostatic adjustment throughout the Holocene, leading to equally significant change in relative sea level in the areas close to the ice margin. This has been well studied in west Greenland and other areas (e.g. Rasch et al., 1997; Long et al. 1999; Rasch, 2000; Fleming & Lambeck, 2004; Bennike & Weidick, 2001). Isostatic response to the loss of ice since the Last Glacial Maximum (LGM) around Greenland is spatially variable, as observed by variable marine limits around the island (Funder & Hansen, 1996; Fleming & Lambeck, 2004).

Marine limits in southern Greenland were estimated by Funder & Hansen (1996) to be between 20 m and 40 m above modern sea level. Studies in southern Greenland of RSL change have been fewer than those in other areas of the island (e.g. Bennike & Weidick, 2002; Weidick et al., 2004; Sparrenbom et al., 2006a; *ibid*, 2006b; Kjuipers et al., 2008; Nielsen et al., 2017), yet the emerging picture is one of RSL fall in the first half of the Holocene, replaced by slow, but steady, RSL rise throughout the last 3,000 years to the present day, controlled by rapid isostatic rebound after deglaciation of the land margins around the present day Greenland Ice Sheet (Figure 6.2).

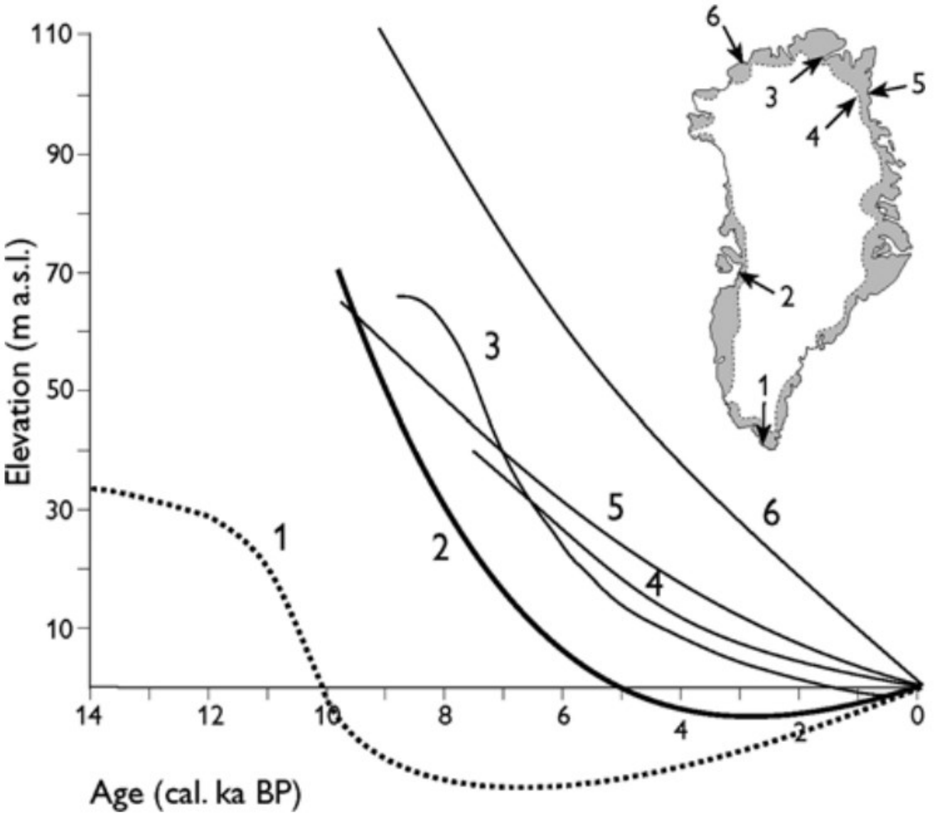


Figure 6.2 – Relative sea level changes in Greenland, from Kjuipers et al. (2008), itself modified from Bennike et al. (2002). 1, South Greenland. 2, Disko Bugt, west Greenland. 3, Jorgen Bronlund Fjord, north Greenland. 4 and 5, Nioghalvfjerds Fjord, north east Greenland. 6, Washington Land, north west Greenland. The south Greenland curve extends further back in time compared to the north and central west Greenland curves due to the earlier deglaciation of South Greenland. The south Greenland sea level curve drops below present day sea level in the early Holocene. This only occurs during middle of late Holocene at other localities.

Sea level fell rapidly after the LGM by an estimated 6-8 m in Qaqortoq area and up to 10 m in the Nanortalik area by 6-7000 years before present. Isostatic rebound reduced mid-Holocene, and an estimated RSL rise in the Qaqortoq area began approximately 3,750 years B.P that continues to the present day (inferred by the interplay between eustatic and isostatic change in the area), at an estimated 3 mm/year (Sparrenbom et al., 2006a), in keeping with other observations of steady sea level rise in the latter Holocene. Nanortalik, while in southern Greenland, is approximately 100 km from the study site and thus is not suitable for use as an RSL analogue. Qaqortoq is closer, being 30 km to the south of the study site and thus can be a useful analogue for understanding the RSL change in the area. In particular, the Qaqortoq sea level curve broadly agrees with the sea level curve derived by Kjuipers et al. (2008) in Igalikufjord from Sondre Igaliku.

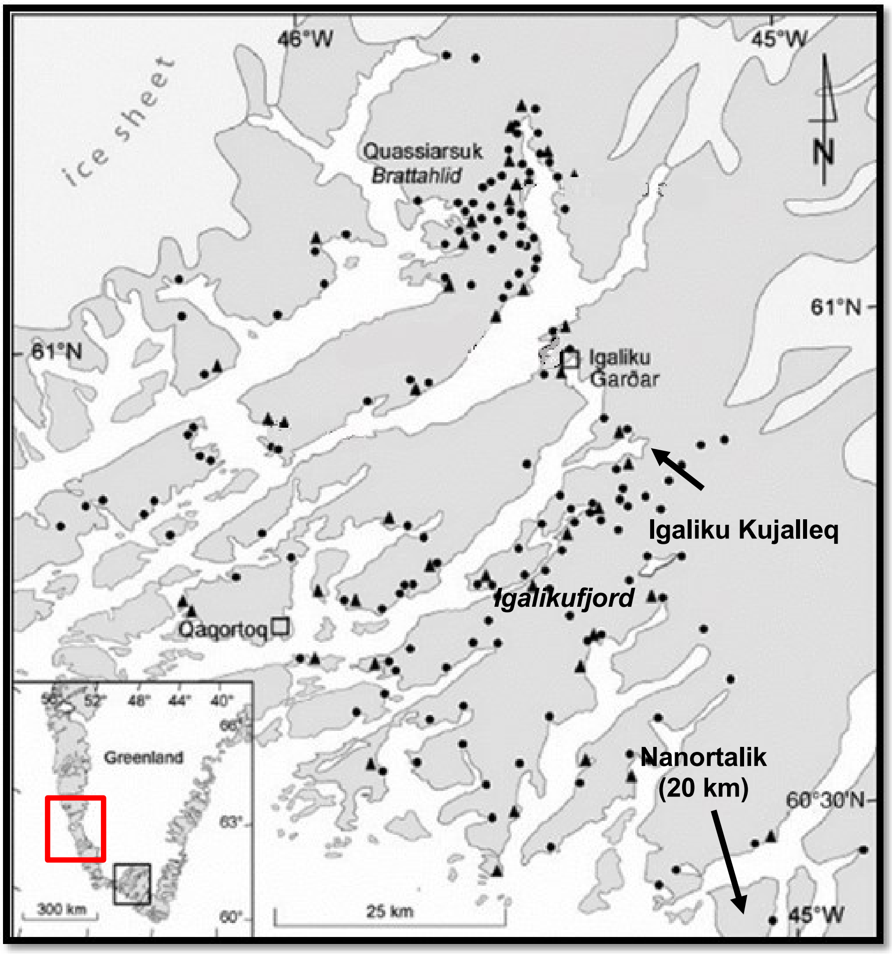


Figure 6.3 - Map of ruins of Eastern Settlement. Red box on inset map shows location of Western Settlement. The central location of the Garðar can be seen when compared to known Norse ruin groups (dots) and modern day farm sites (triangles) (modified from Bichet et al., 2013). See Figure 6.3 for detailed outline of Igaliku coastline.

Kjuipers et al. (2008) suggested a sea level rise rate of 2 m in the past 1000 years (2 mm/yr.) in Igalikufjord, and possibly as much as 300 cm/1000 years in adjacent fjords (Kjuipers et al., 1999), in agreement with mentioned observations from other studies.

In all harbours, the bathymetry and topography of the coastline are critical controls on viability of use. In the case of Garðar, rising RSL over time would have dramatically changed the topography of the harbour. This chapter will address the impact of RSL change on the morphology of the harbour at Garðar for the first time, and thus shed new light on the effects of this for harbour use during times of increasing pressure on the Eastern Settlement of Norse Greenland.

6.3 Site setting

The remains of Garðar are located in the modern day settlement of Igaliku (Figure 6.4, Figure 6.5). It was founded in 1783 by Anders Olsen, a Norwegian trader, after an approximately 250 year hiatus in settlement from the end of the Norse colony in Greenland, and has a current permanent population of approximately 50 people. It is located on the west shore at the head of Igalikufjord, at 60°59’15”N 45°25’13”W. The shoreline in the area is composed of a mixture of sandstone outcrops, composed of red ‘Igaliko’ sandstone (Scharbert, 1963) and small, arcuate gravel/cobble dominated beaches. Fine, sand-sized sediment is observed in deeper waters offshore, however no evidence of sandy deposits are found around the shoreline. It is thought the regular katabatic winds blowing off the Greenland ice cap remove any fine grained sediment from the shore and deposit in the deep waters of the fjord. Figure 6.5 shows the surveyed archaeological remains at Garðar (from Krogh, 1982).

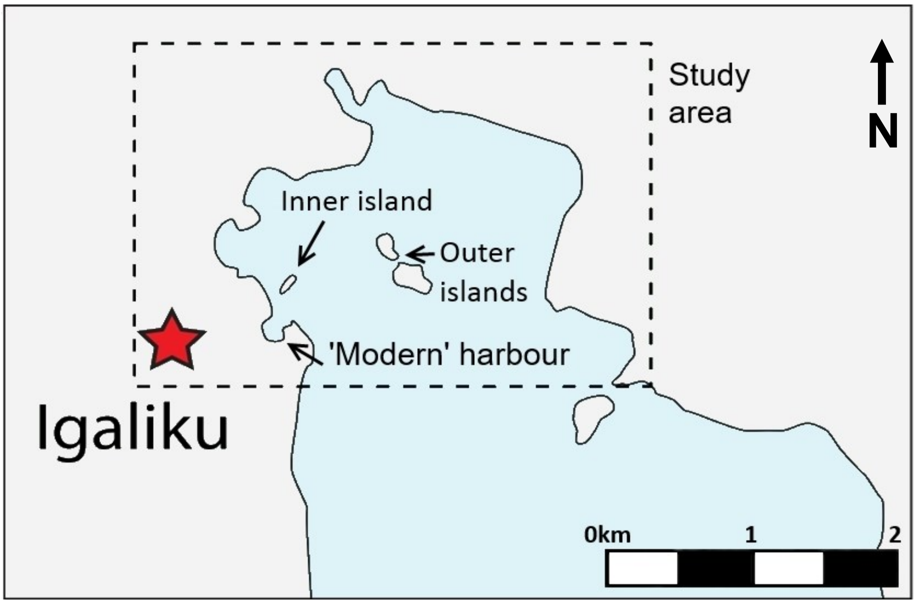


Figure 6.4 - Location map of Igaliku/Garðar. Red star indicates general location of the modern settlement of Igaliku. Dashed box represented the study area for this chapter.

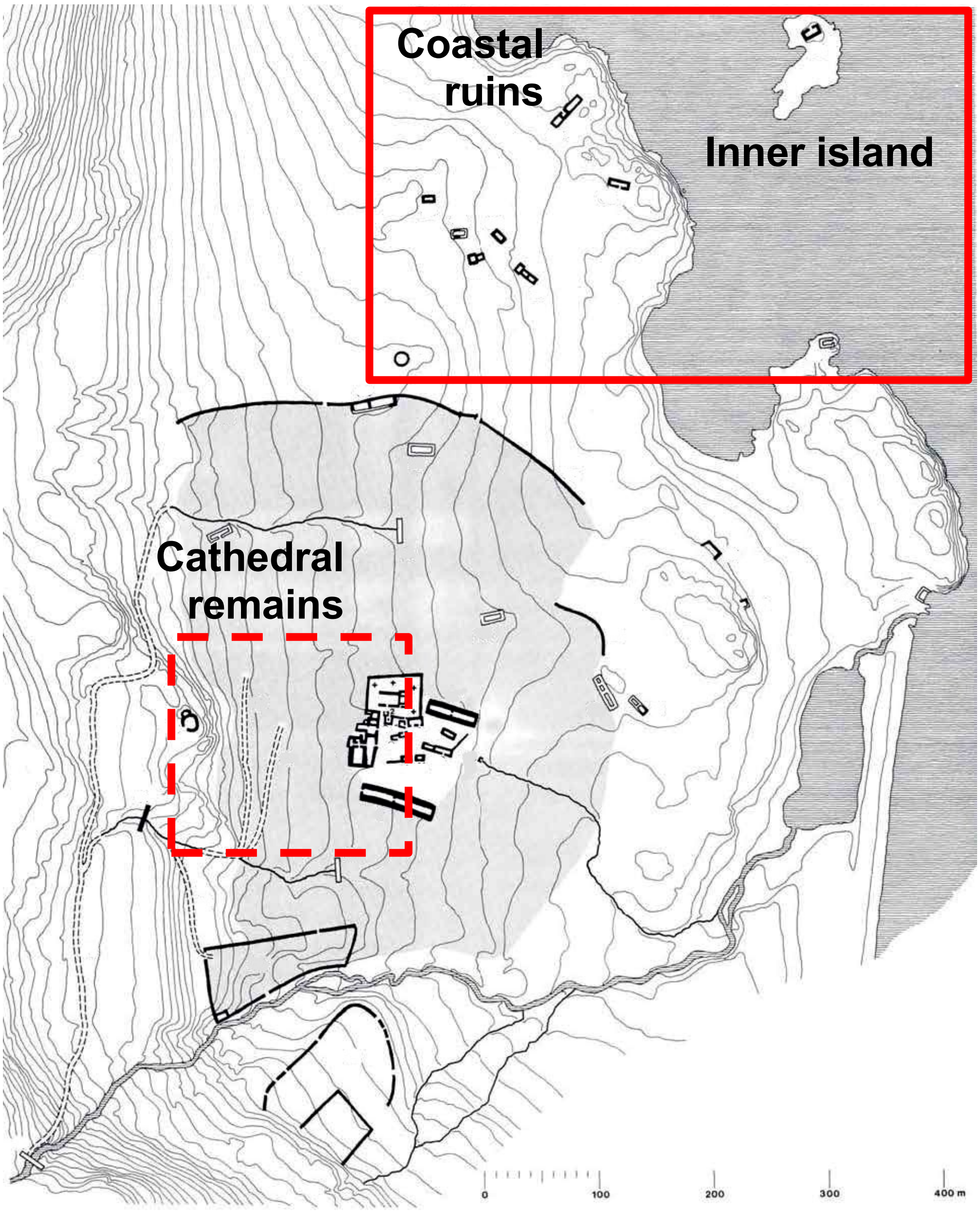


Figure 6.5 - Surveyed location of remains of Norse structures at Garðar, located in present day Igaliku (contours are 1 m interval). The extent of Garðar closely matches the size of the present day settlement. Solid red box indicates coastal remains and the focus area of this study. Dashed red box shows location of cathedral/bishop's seat (modified from Krogh, 1982).

Two larger outer islands, connected at low tide, lie approximately 1.7 km from the shore. The southern island of these two has the remains of two very large (~30 m x 6 m) stone structures of Norse origin. The precise use of these structures is unknown, but thought to be related to harbour activities (Figure 6.6). A small island ('inner island') lies approximately 100 m off the mainland.

This island is composed of sandstone bedrock and lacks terrestrial vegetation. It is almost entirely covered by water at high tide (Figure 6.7, Figure 6.8). This island has one ruin at its northern end thought to be a Norse-era warehouse related to harbour activities, first described in surveys in the late 19th century (Steenstrup & Kornerup, 1876).

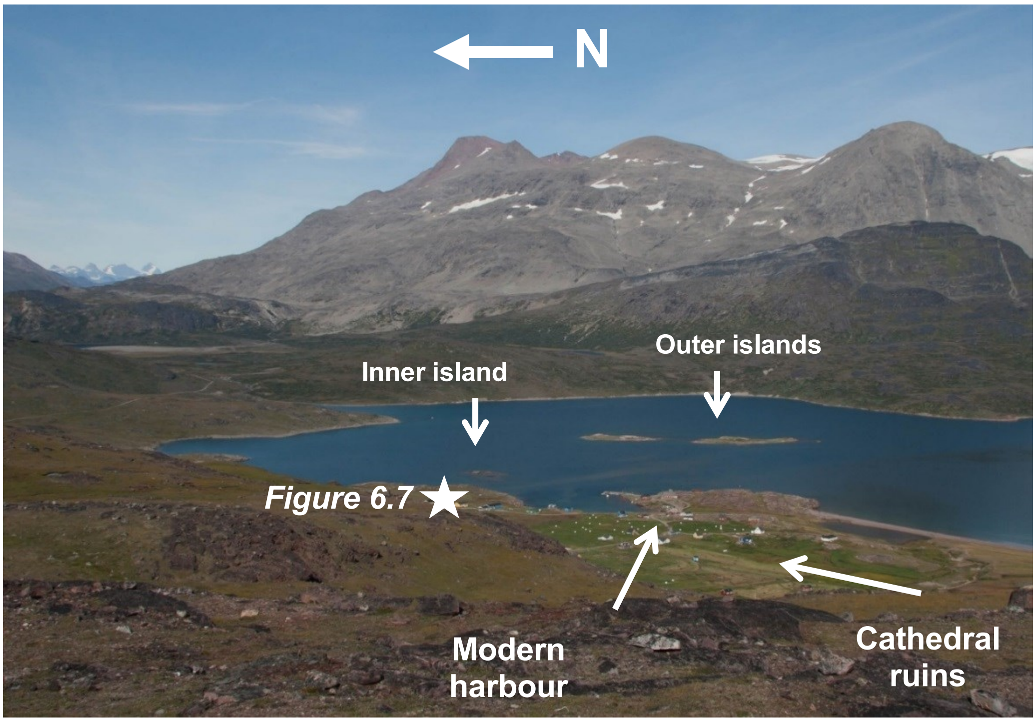


Figure 6.6 - Overview of the fjord head, looking east. Inner island and outer islands visible, along with modern harbour and the modern day settlement of Igaliku (looking north).

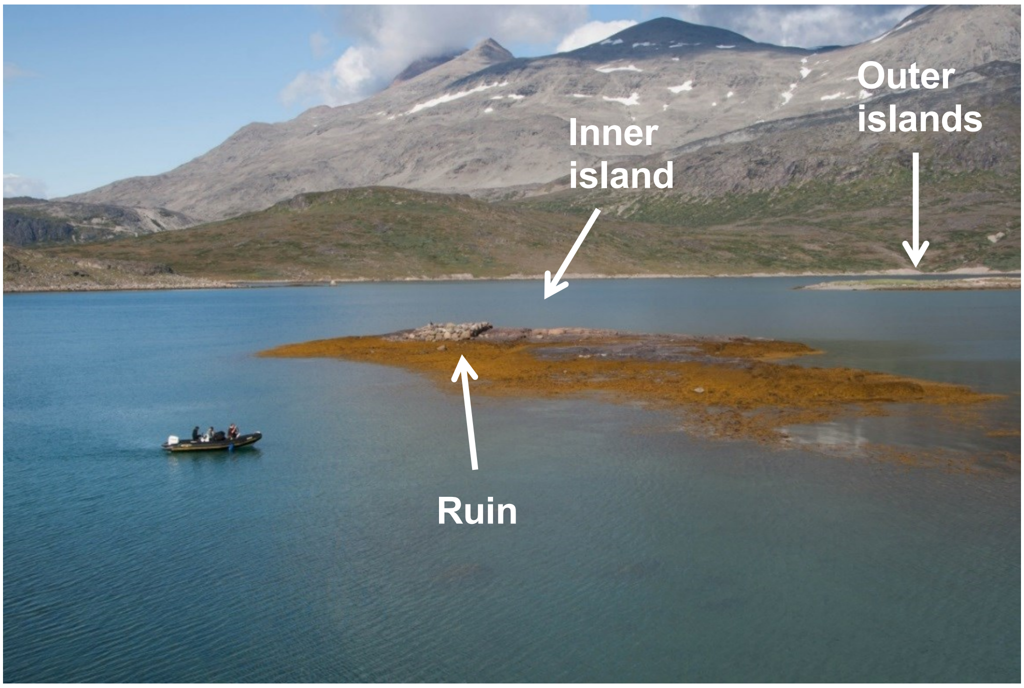


Figure 6.7 - Island 1, with ruin. Boat for scale. Tidal level is approximately halfway between high and low tide at time of photo (looking east).

Figure 6.8 - Inner island at high tide. The ruin is the only part of the island visible above water.

An initial investigation of the site was undertaken in July 2014. It was observed that the inner island at low tide is separated by a very shallow channel of water with depths as shallow as 0.7 m. This was determined by wading between shore and the inner island with a ranging pole and GPS unit. With sea level estimated presented by Kjuipers et al. (2008), this suggests that the inner island would have been a peninsula in Norse settlement times, and the location of the 'modern' harbour 500 m south would be nothing more than exposed mudflats. This would significantly alter the morphology, and use, of the coastline at Garðar compared to as we see it today.

6.4 Results

The methodology as outlined in Chapter 2.1.1 was followed. Figure 6.9 shows the path of the kayak bathymetry survey.

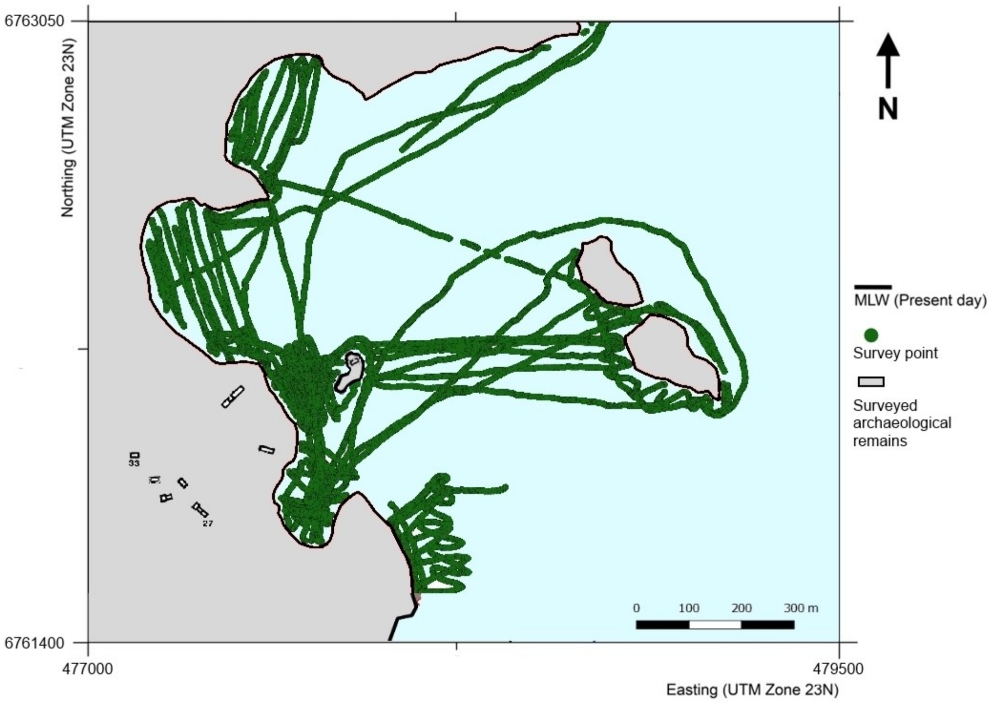


Figure 6.9 - Path of kayak and survey points collected by echo sounder.

Figure 6.10, Figure 6.11 and Figure 6.12 illustrate the reconstructed coastline of Garðar at for three time periods derived linearly from sea level data in Kjuipers et al. (2008): 1000, and the beginnings of Norse settlement; 1250 during the height of the Eastern Settlement, the switch towards an increased dependence of marine resources and the formal annexation of the Greenland colony by the Norwegian Crown in 1261; and 1500, by which time the Eastern Settlement had come to an end. Each figure shows one time period prominently as well as the other time periods for comparison.

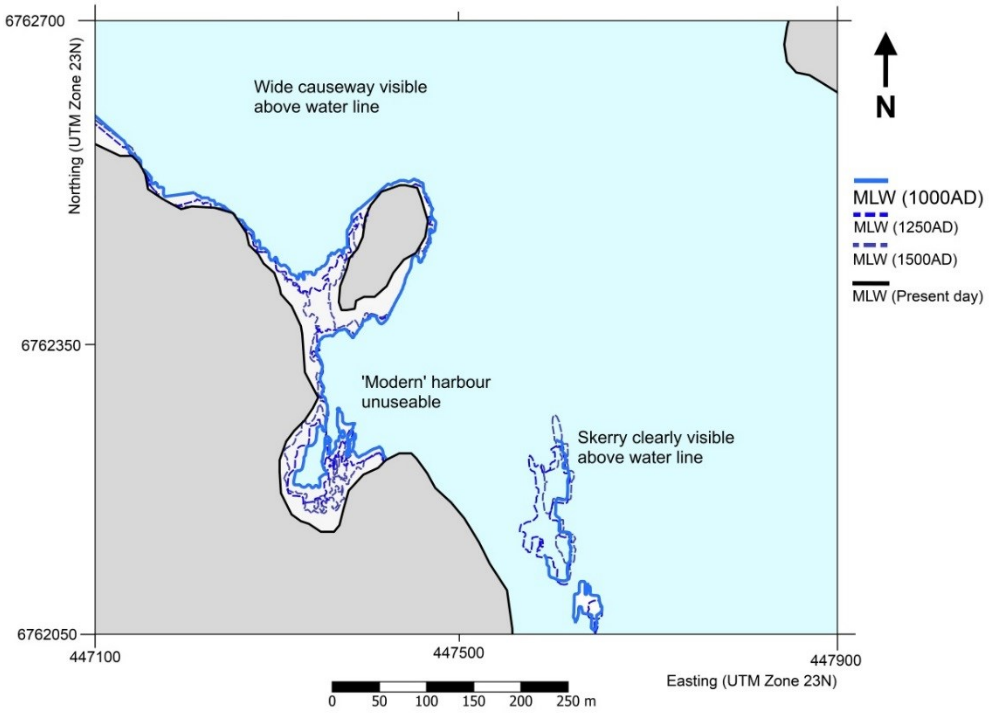


Figure 6.10 - Reconstructed coastline, mean low water, 1000.

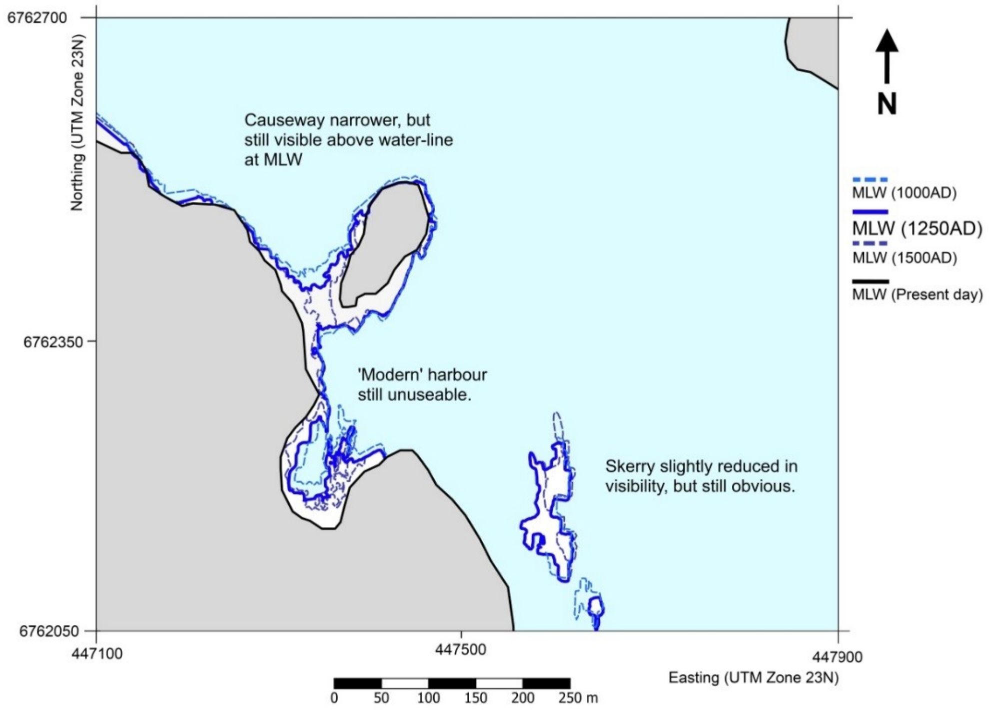


Figure 6.11 - Reconstructed coastline, mean low water, 1250.

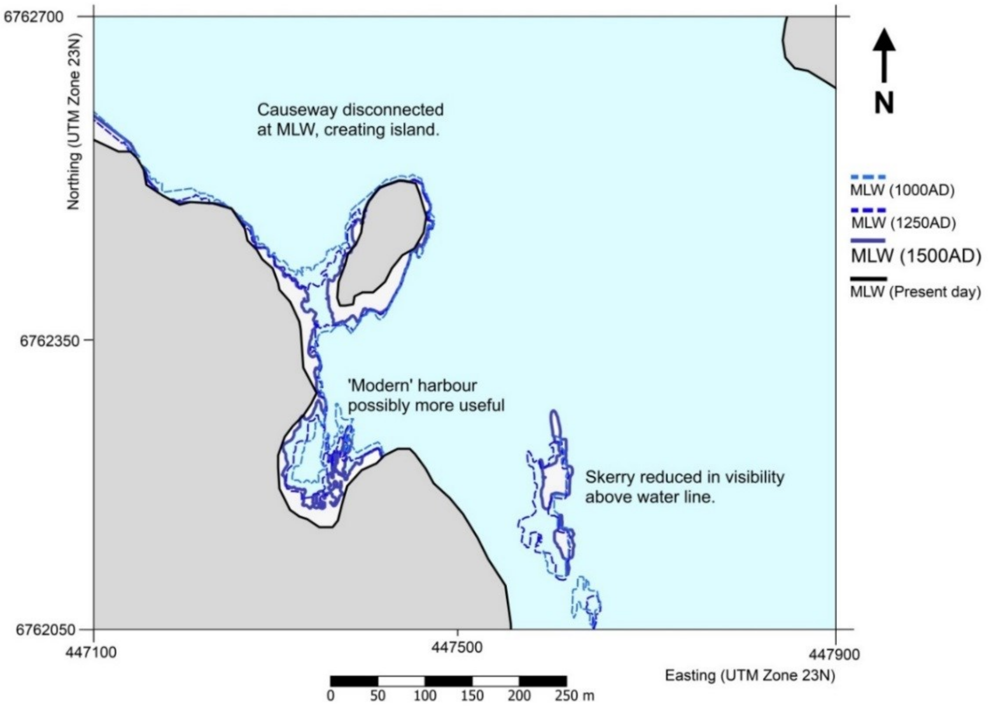


Figure 6.12 - Reconstructed coastline, mean low water, 1500.

It can be seen comparing Figure 6.10 and Figure 6.11 that from 1000 until 1250 that the coastline of Garðar adjacent to the modern day harbour was significantly different than the present day. The inner island was a peninsula, connected by a narrow spit of bedrock to the mainland north of the modern harbour. South of this, and just to the east of the modern day harbour, several skerries were visible above water between 1000 and 1500.

Figure 6.12 shows that between 1250 and 1500, the inner island disconnects from the mainland and begins to resemble the island seen today, even at low tide. South of this, the skerries visible above the water in the earlier Norse period also begin to disappear under water. The site of the ‘modern’ harbour continues to deepen and possibly presents itself as a more useful place to anchor boats than in previous periods.

Figure 6.13 shows the coastline in 1000 with a speculative ‘ship’ of similar dimensions to the class of trading ship that would have visited Garðar (knarrs were 15 m in length, and cogs between 15 – 25 m in length) (Crumlin-Pedersen, 1991). The peninsula could have act as a breakwater sheltering a ship from prevailing winds blowing from the south up the fjord. Sufficient depth would have existed that would have allowed a boat like a cog (draft of ~2 m) to moor very close to the peninsula for ease of goods transfer on and off the ship at this point.

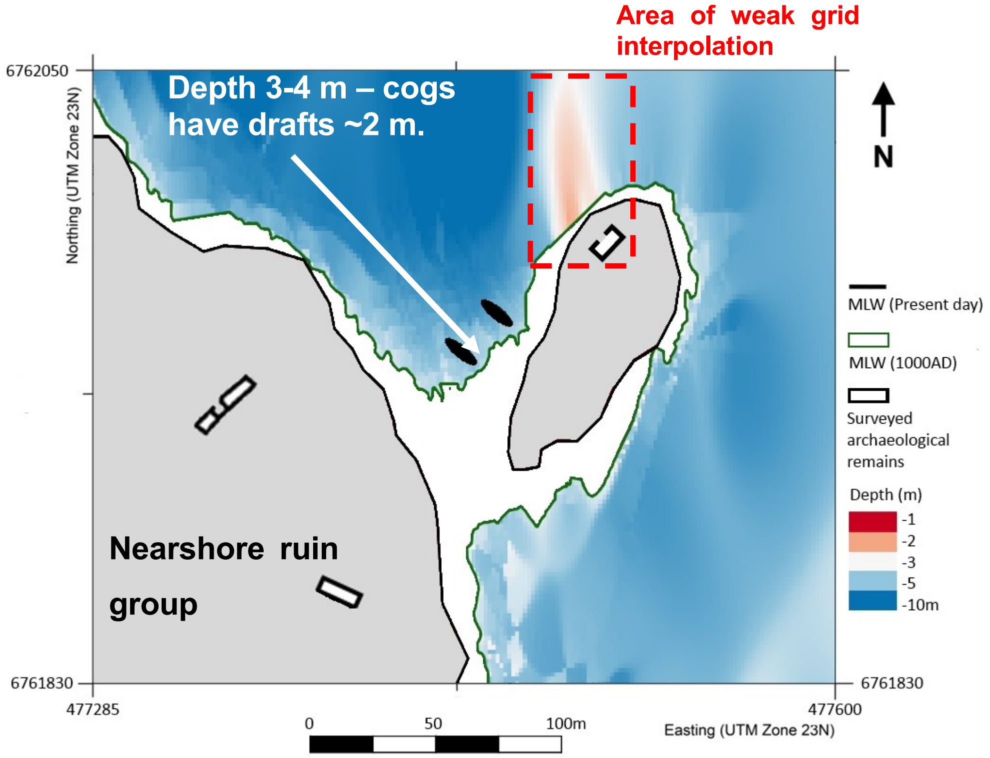


Figure 6.13 - Inner island, 1000 MLW (blue line) and modern day MLW (black line). Ample depth is present on the northern side of the peninsula to act as a sheltered anchorage for a boat with similar dimensions to knarrs and cogs. An area of weak grid interpolation is seen north of the inner island due to poor point resolution in this area.

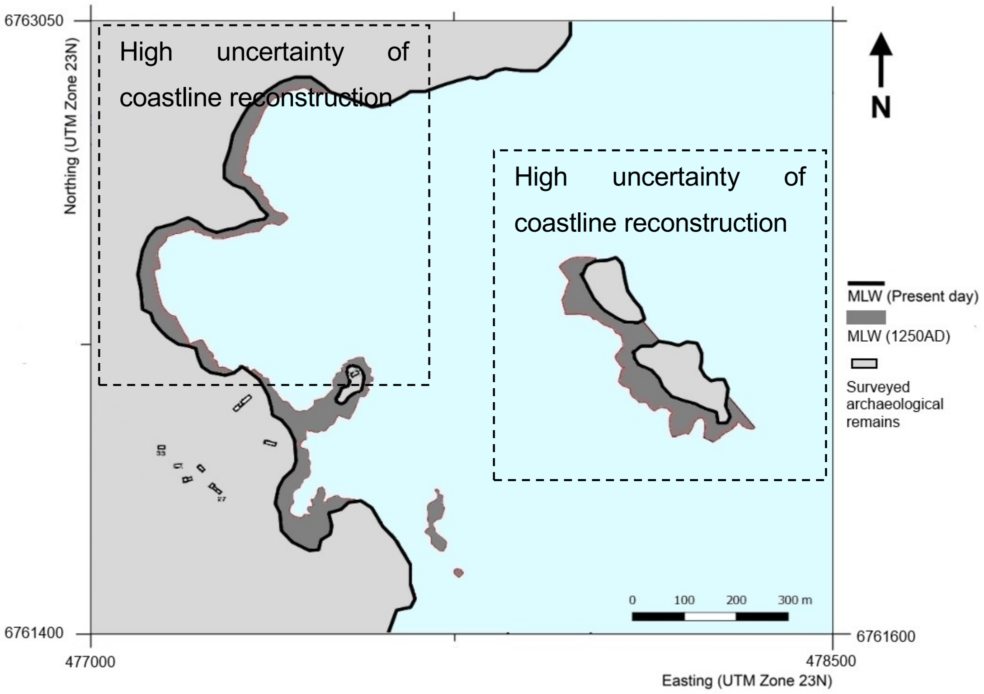


Figure 6.14 - Entire fjord head with 1250 coastline mapped. Data point resolution around the outer islands and the upper embayments make these areas of coastline reconstruction uncertain.

Figure 6.14 shows the wider fjord environment and the reconstructed coastline from 1250. Data resolution is uncertain in the outer islands and the embayments to the north of the inner island due to density and coverage of track points in the survey. However, it can be seen that the outer islands were likely to have been one large island at the height of the Norse settlement at Garðar.

6.5 Discussion

One of the themes running through research into the collapse of Norse Greenlandic society is that of increasing pressure on fodder production to support livestock through the long winter months. Both terrestrial environmental change and rising sea levels contributed to the slow degradation and loss of valuable coastal pastures (Dugmore et. al., 2007). This, plus sea level analyses (e.g., Sparrenbom, 2006) point to an additional sources of pressure on the Norse in the 15th century and a potential contributions to the conjunctures thought to be fatal for the colony (Dugmore et al., 2012). Our bathymetric analysis of Garðar is consistent with this narrative, in which rising sea levels put pressure on both the coastal land exploited by Norse colonists, landing places and critical coastal infrastructure. The area of land lost in the immediate vicinity of Garðar is relatively limited, when compared to adjacent fjords such as Sondre Igaliku where many hectares of farmland were lost. Up to 50 ha of pasture loss is estimated to have been lost at Qassiarsuk (Brattalið) between Norse colonisation and the end of the Eastern Settlement, due to sea level rise. (Kjuipers et. al., 1999; Kjuipers et. al., 2008) This new bathymetric analysis adds a new thread in these discussions of land pressure on Norse colonists: that of pressure on harbour use and nearshore navigation.

The analysis presented here shows that the morphology of the coastline at Garðar was significantly different from that observed today. With sea level 2 m lower than today (~1000, Norse colonisation), the inner island would have been connected to the mainland at low tide, creating an arcuate natural breakwater. The presence of the ruin on the inner island, may indicate that this was used as the original location of the harbour in Norse times, as it is logical to assume storage of tradeable goods adjacent to ship anchorages, which was geomorphologically possible (Figure 6.13). Unlike surrounding areas the causeway between the mainland and the inner island has a smooth surface, lacking large stones, suggesting if may have been cleared for use as a walkway. This causeway may be formed from a basaltic dyke, several of which were observed in the surrounding area. Depths adjacent to the north and east of the inner island are steep, rapidly dropping to ~8 m (at modern high tide). At Norse low tide up to 1250, these depths would have been approximately 3.7 m, safe to navigate for even larger boats typically used in the early Norse settlement era (Unger, 1980; Crumlin-Pedersen, 1991; McGrail, 1998). Projected sea level rise of 0.5 m from 1000 to 1250 (derived from Kjuipers et al., 2008) indicates that the causeway between the present day mainland and the inner island would still have been above MLW and thus practical for use as a natural breakwater or jetty for harbour purposes at the height of the Eastern Settlement. Figure 6.15 shows a reconstruction of the peninsula of the inner island how it may have looked from shore, circa 1250. Figure 6.16 presents a wider view of Garðar as the coastline may have looked in the same time period.

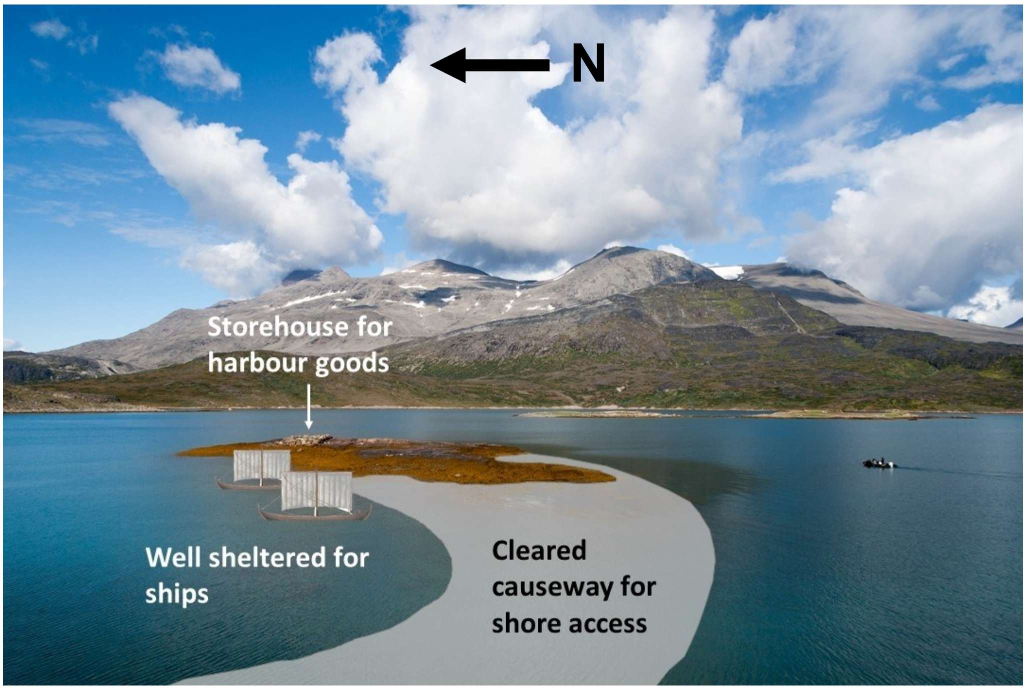


Figure 6.15 – Speculative reconstruction of inner island coastline of its likely morphology, 1250, from shore looking east towards the outer islands.

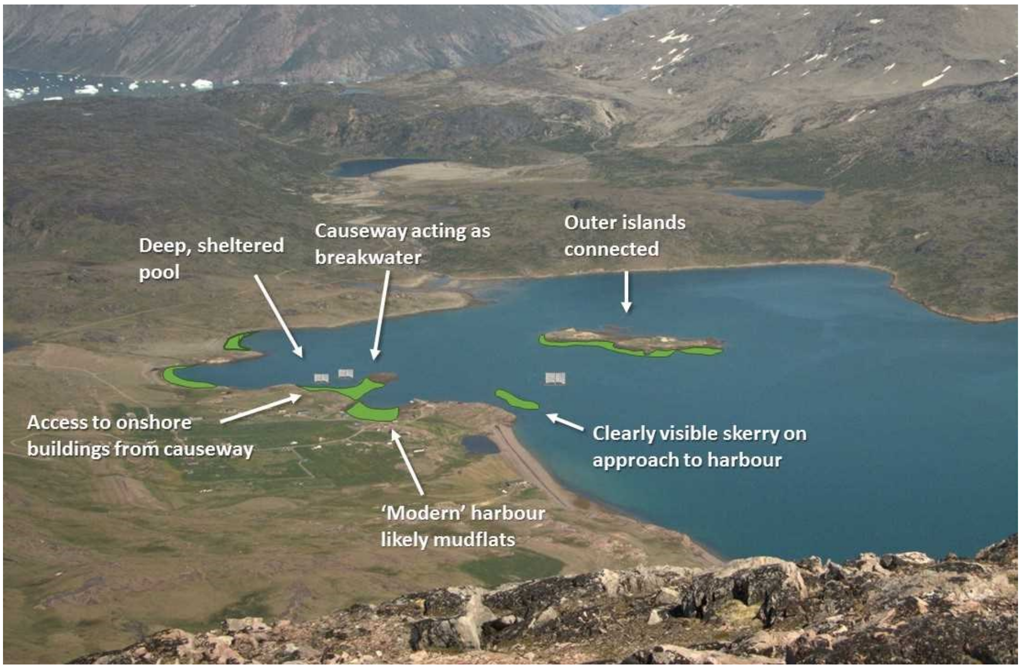


Figure 6.16 - Speculative reconstruction of likely morphology of Garðar, 1250, from summit of Nuuluk (823 m), looking north. Green areas indicate dry land in 1250.

However, by just after the estimated time of the collapse of the Eastern Settlement, ~1500, projected sea level rise has covered the causeway even at low tide, creating the inner island as it is seen today. Also by this date, the skerry previously visible on the southern approach to the breakwater is significantly reduced in area at MLW, and covered at MHW. This would have presented navigational difficulties for incoming seafarers from Europe unfamiliar with the harbour, with added dangers close to shore of skerries and shallower waters nearshore. The location of the modern day harbour would most likely still have been exposed mudflats and would not have offered the same shelter and facility as the breakwater.

Journeys to Greenland became increasingly infrequent towards the later Norse period for a variety of reasons, both environmental and economic/cultural. The Black Death in the mid-14th century had a devastating effect across Europe and in Norway, which reduced contacts with Greenland (Dugmore et. al., 2007.; Etting, 2009; Dugmore et. al., 2012) The collapse of Norwegian royal authority would have compromised the Greenlanders key European contact. The rise of Hansa merchants would not have replaced these links as they traded in bulk commodities which were not produced in Greenland (Mehler, 2009; Mehler & Gardiner, 2013; Mehler, 2014). Seafarers venturing west to Greenland would have relied upon the knowledge of previous sailors who had visited Garðar for advice on the route to take and the finding of the harbour. After the devastating plagues these people could have been increasingly hard to find. Sea conditions on the long voyage would be changing with the more variable and stormy conditions of the LIA (Meeker and Mayewski 2002; Dugmore et al. 2010). As voyages lessened in frequency, first-hand knowledge would have been more limited, just as critical changes of the harbour geomorphology at Garðar would have become increasingly obvious. After 1378 no bishop sat at Garðar after the death of the last bishop, Álfur, which would suggest a decrease in the importance of this settlement (Buckland et. al, 2009). The last evidence of contact with Europe occurs in 1408, with the record of a visit for a wedding in

Hvalsey Church (e.g., Mikkelsen et. al., 2001). No contemporary written evidence of contact with the Eastern Settlement exists after 1408, by which time the harbour at Garðar would have been more dangerous to navigate than at the height of the Norse settlement 150 years earlier, as shown by my analysis in this chapter.

6.6 Conclusions

The Norse settlement at Garðar is located on a coastline that experiences geomorphological change on a centennial timescale due to rising local sea levels. Over multigenerational timescales these changes can alter the local coastline on a scale to affect maritime activities and harbour infrastructure. New bathymetric analysis shows that, in early Norse settlement times, the natural morphology of the coastline at Garðar would have made a useful natural harbour with the presence of a rocky breakwater adjacent to deep water and lack of hidden skerries and other navigational hazards. The natural breakwater persisted above sea level until at least 1250. However, by the later Norse period, as contacts with Europe and Scandinavian settlement Greenland came to an end, the breakwater had been submerged to create the inner island as we see it today. Navigational hazards on this section of the coastline increased as the centuries passed, with the large skerries on the southern approach to the breakwater becoming more obscured by high tides and thus posing a danger to sailors unfamiliar with the harbour. The location of the modern harbour would likely have been an unnavigable mudflat until at least 1500. When a farming settlement was re-established at Garðar during the early modern period, to reuse the field systems first established by the Norse, the harbour site was relocated about 300 m to the south.

The findings of this new bathymetric survey add to the broader narrative of increasing environmental pressure on the Eastern Settlement in the later medieval period, and for the first time quantify the coastal changes and loss of land due to sea level rise at the seat of ecclesiastical and colonial power in

Greenland. Although limited to the immediate area around Garðar, the survey shows that this loss of land may have critically compromised harbour activities adding a significant extra pressure onto the settlement as a whole. Here geomorphological change is likely to have created pressures to abandon a long-used harbour and landing place, and that abandonment could have had cascading consequences extending from the harbour to the colony as a whole.

7 Continuous and discrete changes in coastal geomorphology as a function of changing onshore sediment supply: Gásir, Iceland

7.1 Introduction

As discussed in previous chapters, the Norse expansion and colonisation led to the utilisation of beaches on coastlines with a wide range of geomorphological characteristics. Certain coastlines appeared to be favoured above others, with *stability* of beaches being the most valuable geomorphic attribute, particularly in regions that lacked inlets large enough to sail into such as the Shetland Islands and other small island settlements. The contemporary quantification of stability was not always evident for harbour users, as a beach may appear 'stable' when first settled and for many years afterwards, but may be removed by one storm and not reform for many years. On the beaches utilised by the Norse in the Northern Isles, where sediment input is primarily derived from offshore, I have shown that beach stability is driven by ocean and climatic conditions on a sub-decadal timescale (discounting relative sea level change, which tends to operate on a decadal- to centennial-timescale). However, coastlines and beaches that also derive sediment from onshore sources are subject to a more complex mixture of forces governing relative stability, with terrestrial forcing also playing an important role in the dynamics of these coastlines.

Looking again at the sediment/exposure matrix (Figure 7.1), sites that fulfil the geomorphic criteria of significant sediment presence yet relatively sheltered from wind and wave forcing are Gásir and Kaupangr in Iceland, and Sondre Igaliku in Greenland. Each site is at the mouth of actively prograding deltas with significant terrestrial sediment discharge. The slow but continual progression of sedimentation within the channel network and the changing patterns of deposition makes the analysis of precisely when these sites became non-viable as landing sites difficult even if long term trends are predictable. Igaliku Kujalleq, in particular, is located at the mouth of a river fed by the retreating Jespersens Dal glacier (Chapter 3.3.2). Today, the volume of sediment present in the fjord head turns shallow water into treacherous quicksand at low tide and this situation is likely to have been similar or worse in medieval times despite less sediment because of lower sea levels (Kjuipers et al., 2008).

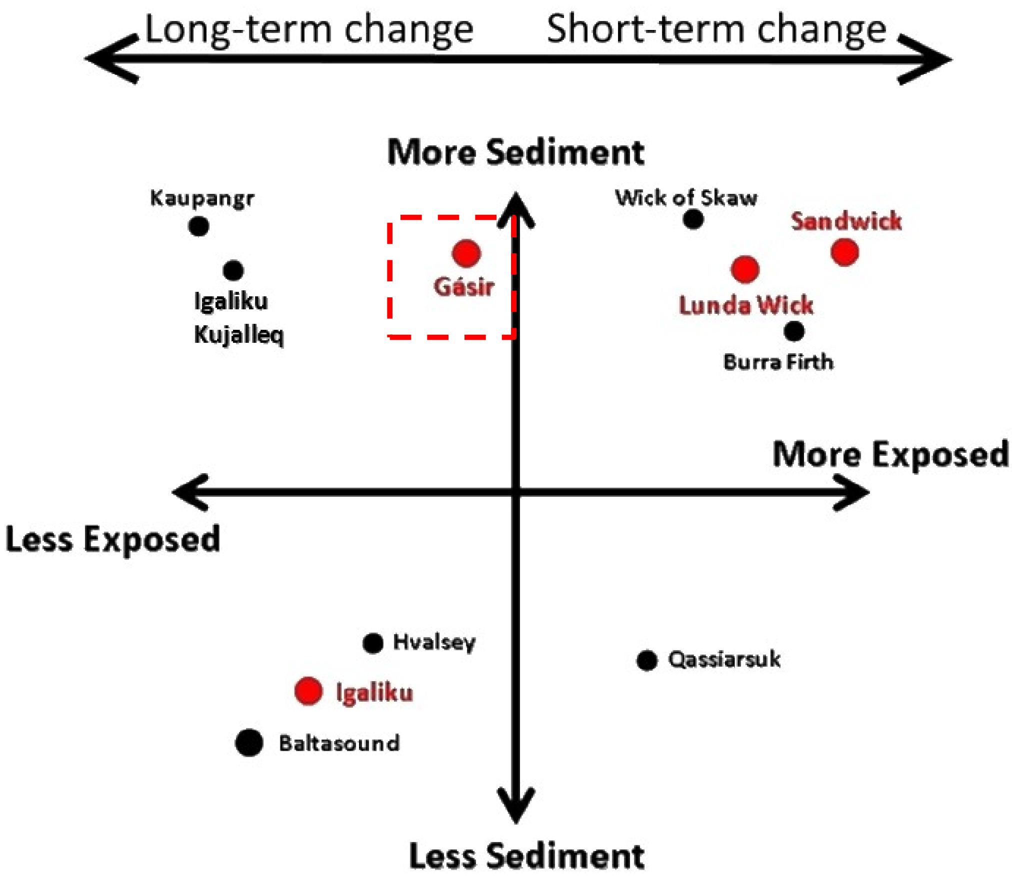


Figure 7.1 - Sediment/Exposure matrix with Gásir highlighted.

The site at Gásir, however, offers a more complete picture of both harbour abandonment and onshore geomorphological change. In particular, a combination of continuous geomorphological change in terms of delta progradation, but also the potential for brief episodes of non-linear stepwise changes in the form of pulsed sediment inputs from landslides in the valley feeding the delta. This places Gásir in a somewhat unusual position on the sediment/exposure matrix. Progradation of the delta on which it is located will tend to be a gradual longer term geomorphological process given normal supplies of fluvial sediment, yet landslides have the ability to deliver episodic pulses of increased sediment input to the fluvial system which could change coastlines on a short- to medium-term timescale. Gásir's position, deep within Eyjafjorður limits the fetch and thus the impact that storms will have on the coastline. Chosen because of Gásir's importance as an important harbour, this chapter will assess the geomorphological setting and dynamics of the Gásir delta and the apparent forces acting upon its morphology and evolution.

7.2 Historical context

Gásir was one of the most important Norse harbours in Iceland. Never a permanent port (it did not operate during winter months), it nonetheless became the focus of considerable trade around the region and to Europe as a whole. It was first mentioned in 1163 in the Saga of Guðmundur as a trading harbour, and operated until at least 1400, when the last mention of its use was made in 1391 (Roberts, 2002). No mention of Gásir is made after this date in any contemporary records, there Gásir's abandonment is roughly contemporaneous with the decline of Norse Greenland. But in this case the end of a harbour was not related to the end of an entire colony, as Iceland continued to prosper. Gásir's hinterland was large with multiple important farm sites accessible nearby (Figure 7.2). This would have allowed the local community enviable access to a major harbour. Archaeological evidence of items such as sulphur and falcons excavated in Gásir points to the trading importance of the site and connections with other areas of Europe and Greenland (Roberts, 2002; Harrison, 2010; Harrison, 2013).

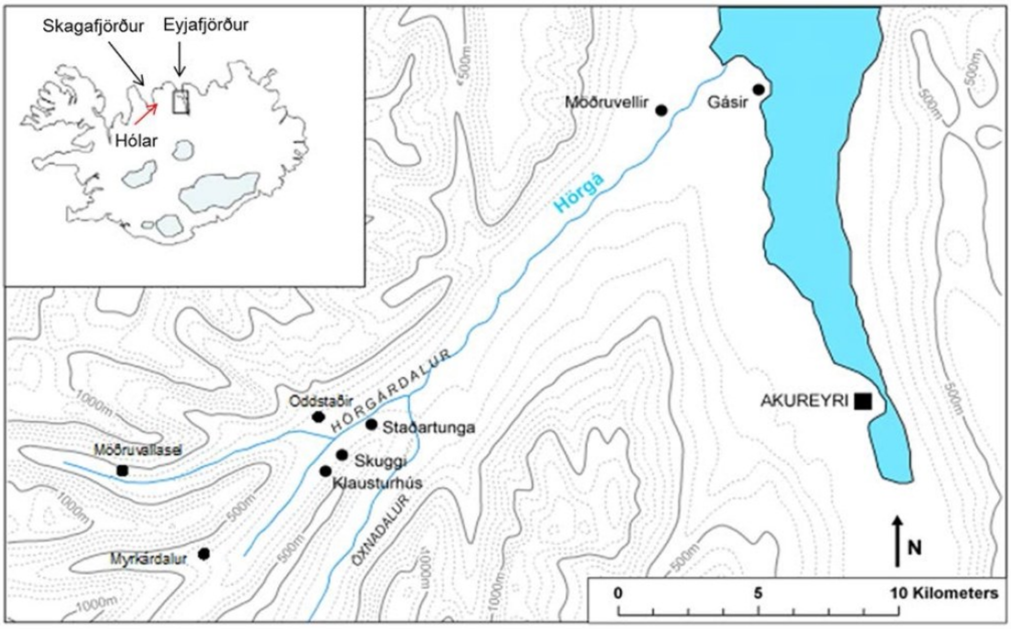


Figure 7.2 – Example of hinterland farms close to Gásir which have been subject to archaeological investigation (source: Harrison, 2013).

Recent archaeological investigations (Harrison et al., 2008; Harrison, 2013.) have revealed an extensive complex of booths and other structures clustered around it, as well as a church, an indicator of the importance of a site to the Norse. Churches close to harbours such as this often served as administrative centres to deal with taxing and levies on cargo brought by ships during the trading season (e.g. Watt, 1998; Harrison, 2013). The larger monastic church farm at Möðruvellir, approximately 5 km west of Gásir, may have been involved in the administration of Gásir also. Roberts (2002) highlights the role Gásir played as a node of communication between North Atlantic settlements, with an example of ecclesiastic documents passing through here in 1262.

As the impacts of the Little Ice Age began to be felt in earnest ~1400, coincident with the last mention of Gásir in historical literature, the presence of sea ice around the coast of Iceland increased. Lamb (1982), following work undertaken by Koch (1945), reconstructed sea ice coverage around the coast of Iceland, and found that in approximately 1400 the whole coast was locked in ice for approximately six weeks of the years. These weeks are more likely to have been in winter, and as Gásir was used as a summer harbour sea ice would have proved an unlikely reason for abandonment, thus we must consider other environmental factors.

Historical literature mentions that Gásir began to silt up, decreasing its usefulness as a harbour, and this may have been the reason for its eventual abandonment. While progradation of a delta can be a gradual process, explicit mention of harbour siltation in contemporary literature may suggest that a shift in geomorphic conditions occurred rapidly enough to be notable to record keepers at the time.

Gásir is located on the shore of Eyjafjorður, a typical steep-sided fjord environment. A strong long-shore drift current running from north to south operates in Eyjafjorður, evidenced by the asymmetrical shapes of the outer sand bars (Figure 7.3).

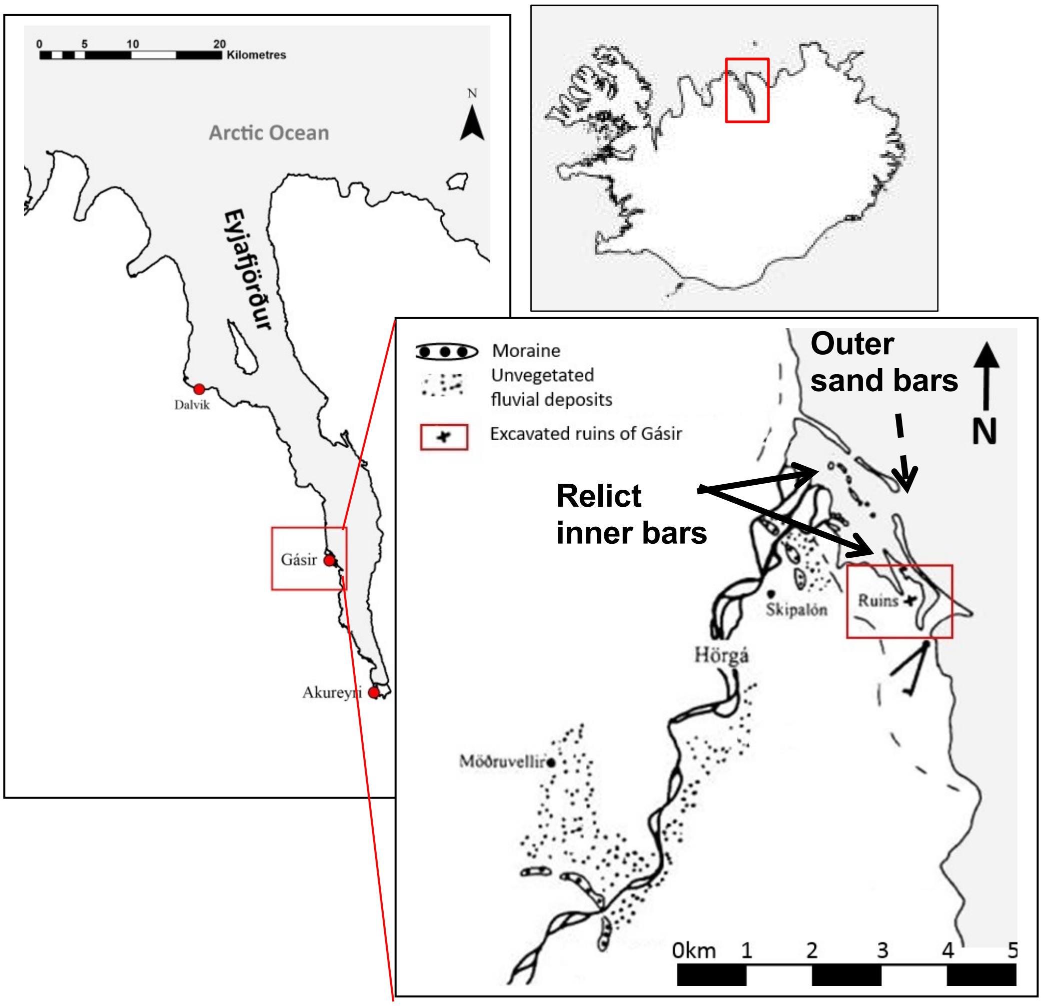


Figure 7.3 - Plan map of Gásir (modified from Pétursson, 1999). Planform map of Gásir shows the complex geomorphology in the delta formed from significant siltation. The Hörgá river is composed of multiple channels and readily depositing sediment on unvegetated bars. The red box shows the location of the ruins of the harbour site, now located just behind the southern 'outer bar', on the edge of the southern inner bar.

Today, these sand bars are changeable, indicating a very dynamic environment where landforms regularly erode, reform and sediment is reworked. Landsat imagery recorded between 1984 and 2016 illustrate the decay and rapid growth of the northern sand bar as it fluctuates in length by over 750 m, combined with some minor geometry changes of the southern sand bar (Figure 7.4).

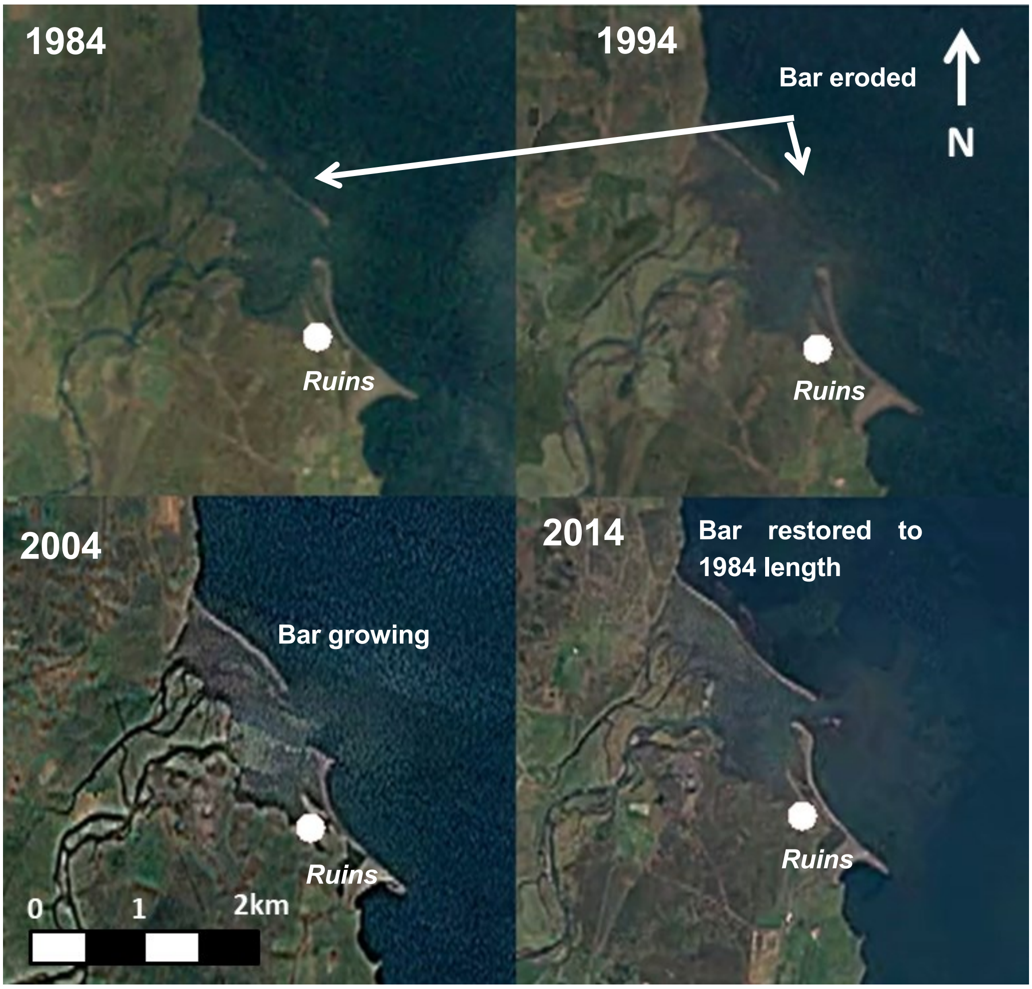


Figure 7.4 - Evidence of rapid erosion and deposition at Gásir (source: Landsat imagery, Google Earth Engine). From 1984 to 1994 the northern outer bar loses approximately 500 m from its length, which is restored between 1994 to 2004. The bar grows seawards at a slower pace between 2004 and 2014.

No source of sediment was observed on the coastline of Eyjafjorður north of Gásir that would be transported south by longshore drift, thus the material to build these sand bars must be derived from the valley of Hörgárdalur and transported fluvially to the delta. This was supported by field investigations of the southern outer bar, where recently deposited soil with attached vegetation was found, which had been carried by the river to the outer bars and then reworked by the longshore drift (Figure 7.5). The erosion of the northern outer bar and subsequent growth again, with little evident morphological change elsewhere in the delta, suggests also that sediment accumulation in the delta is in relative equilibrium with sediment deposition. This apparent equal mass balance is an important observation for understanding how Gásir may have evolved from Norse settlement times, through abandonment to the present day.

Figure 7.5 - Southern outer bar, looking north. Delta mouth indicated. Fresh soils and vegetation can be seen on the shore from recent discharge.

A set of relict inner sand bars is an indication that in the past mass balance may have been unequal in the delta (Figure 7.5). The morphology of the inner bar remnants suggests that these were also open to a longshore drift current shaping them. The presence of these inner bars landwards of the outer sand bars could suggest a stepwise increase in sedimentation that led to the sudden formation of the outer sand bars. As the sediment is derived from Hörgárdalur, a change in geomorphological conditions in the valley, whether gradual or sudden, would impact on the geomorphological structure and evolution of the delta. A geomorphological survey was undertaken in Hörgárdalur to determine the possible mechanisms for stepwise geomorphological changes of the coastline at Gásir.

7.3 Geomorphological setting of Hörgárdalur

The study area is made up of four major valleys: Lower Hörgárdalur, Upper Hörgárdalur, Oxnádalur and Barkádalur (Figure 7.6).

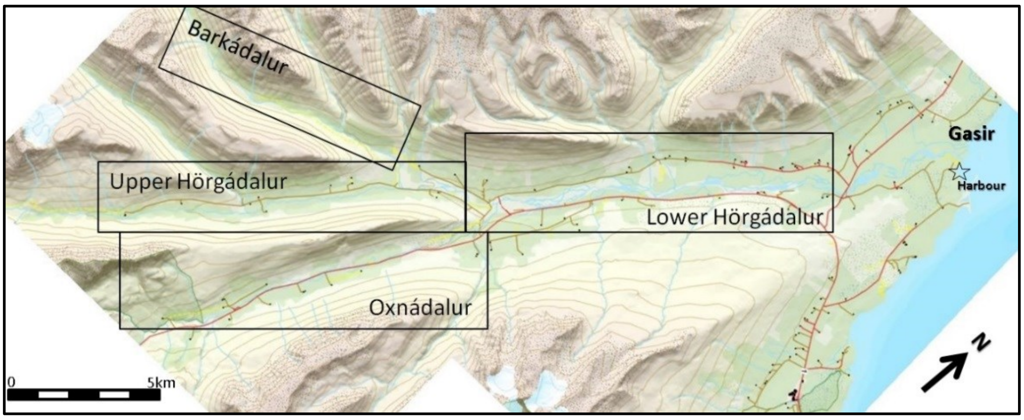


Figure 7.6 - Major valleys of the Hörgárdalur **study area.**

The centre of the Hörgárdalur valley system study area is at roughly 65°40’43N 18°24’56W. It is a typical u-shaped glacial valley, orientated roughly SW-NE, with the direction of flow to the NE. The river Hörgá is a braided channel approximately 30 km in length through the study area, emptying into Eyjafjorður at the delta of Gásir. Channel characteristics are those of a classic braided river, with significant sediment supply from the upper catchment area and tributary catchments. Evidence of regular channel avulsion is present on the valley floor in the form of abandoned channels with varying degrees of vegetation (Figure 7.7).

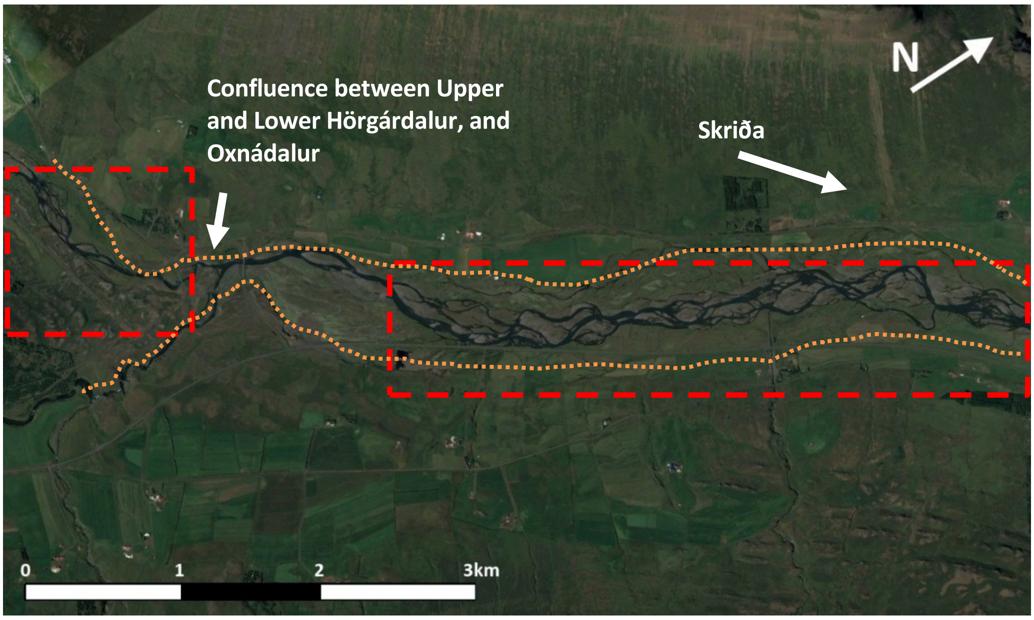


Figure 7.7 - Planform view of part of Lower Hörgárdalur**. Red dashed boxes show areas of significant braiding, with evidence of high sinuosity and channel avulsion to each side of the valley floor. Dotted orange line shows transition between slopes and valley floor.**

7.4 Data collection and analysis methodology

The methodology set out in Chapter 2.1.2 was followed for the geomorphological mapping and ST:REAM analysis of the Hörgárdalur valley system. A walkover survey of the watercourse and its tributaries was undertaken and the reaches classified visually into the regimes as set out in Table 2.1. Figure 7.8 is a map of the results of the ST:REAM analysis.

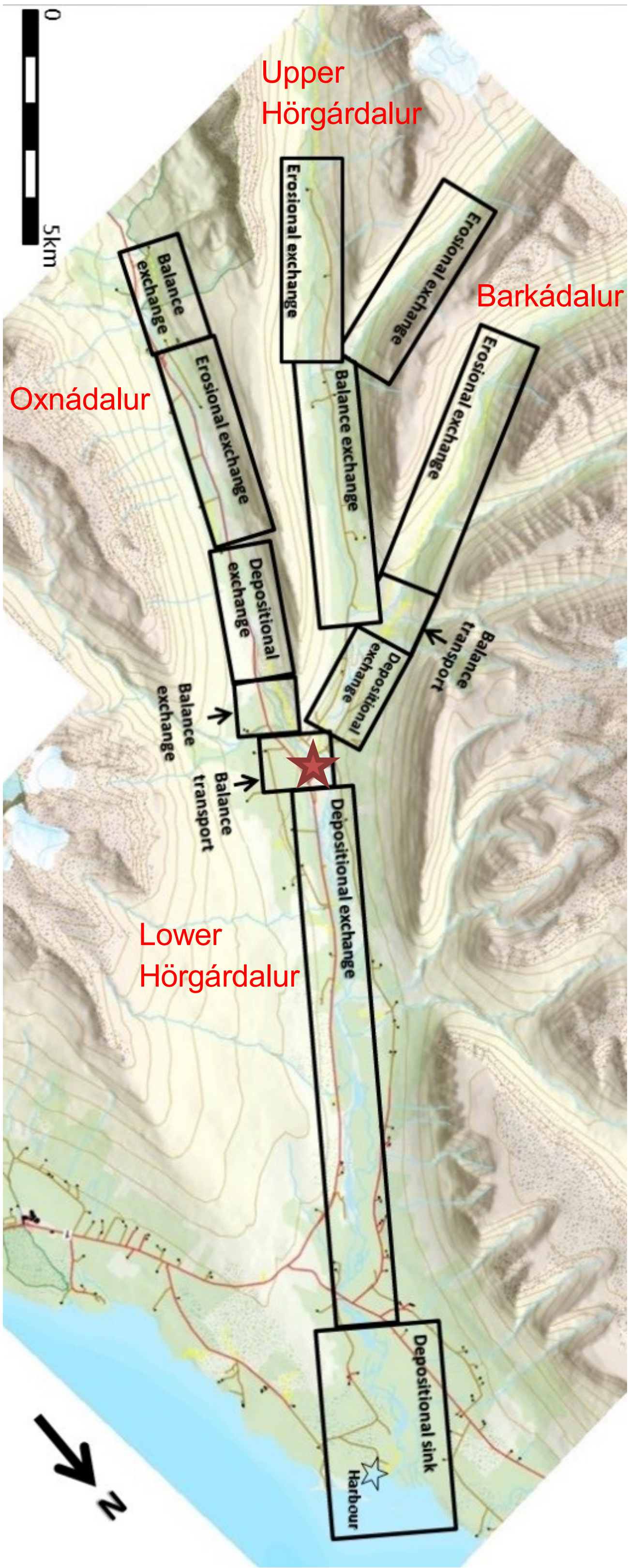


Figure 7.8 - Hörgárdalur and adjacent valleys classified by ST:REAM. Hörgárdalur itself is mostly a depositional environment, while the upper valleys are a complex mixture of erosional and depositional environments. Red star indicates pinch point in fluvial system.

The ST:REAM analysis shows that Lower Hörgárdalur is a primarily depositional environment, evidenced by the well-developed braided river channel, yet still has requisite stream power to transport sediment to Gásir, the depositional sink. Moving upstream, a complex pinch-point reach exists at the confluences between Upper Hörgárdalur, Barkádalur and Oxnádalur, where a Balance Transport reach exists in the steep, constricted bedrock found there. There is less sediment restriction between Barkádalur, Upper Hörgárdalur and Lower Hörgárdalur, suggesting this is likely to be the primary source of sediment flowing downstream.

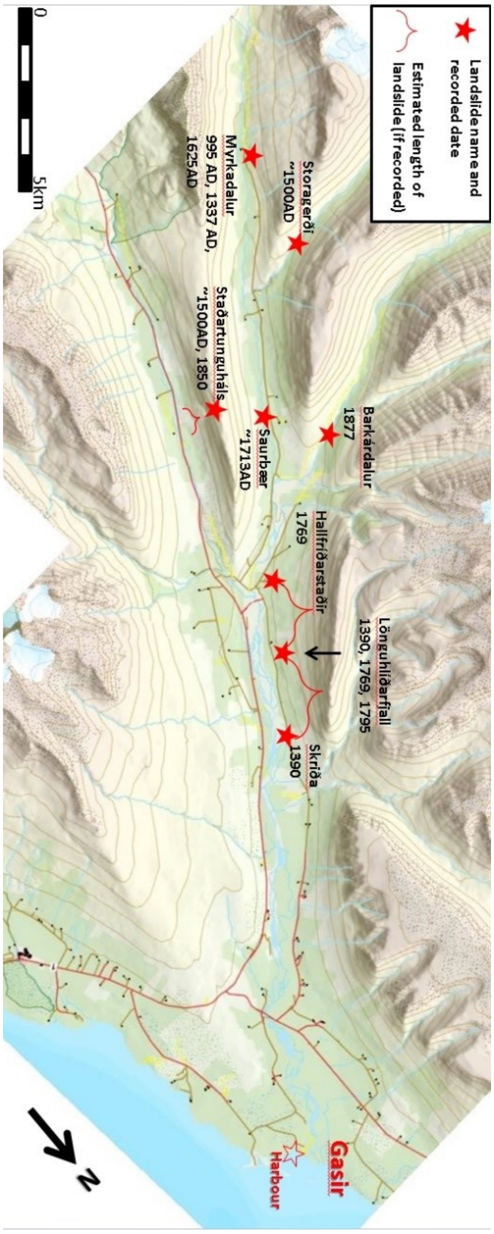
7.5 Sediment characteristics

A noticeable change in sediment properties occurs at the junction between Oxnádalur and Upper Hörgárdalur. Sediment observed in the river throughout Oxnádalur was mostly reddish in colour (Figure 7.9). As the survey progressed downstream into Lower Hörgárdalur, prevalence of this sediment type disappeared and was replaced increasingly by grey sediments. These were observed to emanate mostly from Upper Hörgárdalur and Barkádalur. Observation of sediment type at Gásir does show that the delta is mostly composed of greyish sediments with very little red sediments mixed in. Coring with a soil auger revealed only uniform grey sediment to a depth of 1.2 m. While this depth is not definitive, this suggests that sediment carried from Upper Hörgárdalur and Barkádalur is responsible for the progradation of Gásir, with little input from Oxnádalur. Both reddish and greyish sediments appeared to be of a similar sand-sized fraction. This is consistent with the ST:REAM analysis, where the pinch points at the confluence between Oxnádalur and Lower Hörgárdalur appear to restrict sediment procession downstream more so than sediment procession from Upper Hörgárdalur and Barkádalur. The superficial geology of the surrounding region has never been mapped in detail, thus the source of the red and grey sediments is unknown. Bedrock geology in Upper Hörgárdalur and Barkádalur is mapped as basic basaltic extrusive rocks of late Miocene age (>11 Mya). Oxnádalur is largely similar, but has some silicic intrusions in its upper reaches, composed partially of rhyolite and granite (ISOR, 2017). It is possible that these extrusions are the source of the reddish sediment.

Figure 7.9 - Red loamy sediment at edge of river in Oxnádalur (handheld field tablet case for scale, 30cm length). This sediment type was not observed downstream of the confluence of Oxnádalur and Barkádalur.

7.6 Landslide evidence

The evidence from both contemporary literature and archaeological investigations points to Hörgárdalur and adjoining valleys being prone to frequent landslides since Landnám, continuing to the present day. This is in keeping with the rest of central north Iceland being recognised as a particularly landslide-prone region (Jónsson & Ágústsson, 2005). The first recorded landslide was mentioned around 990 in Myrkádalur at the top of the Upper Hörgárdalur valley, with another being mentioned in 1330 in the same valley (Pétursson, 1999). The reason for the length of time between mentions of landslides is unknown. These are only the first *recorded* mention of landslides, and not the first landslides ever that would have occurred in the valley. Yet these landslides are recorded at a point of profound environmental change, with extensive land clearances occurring throughout Iceland, discussed in more detail in section 7.7 (Streeter et al., 2015). Figure 7.10 maps the major landslides mentioned in contemporary sources between 995 and 1877.



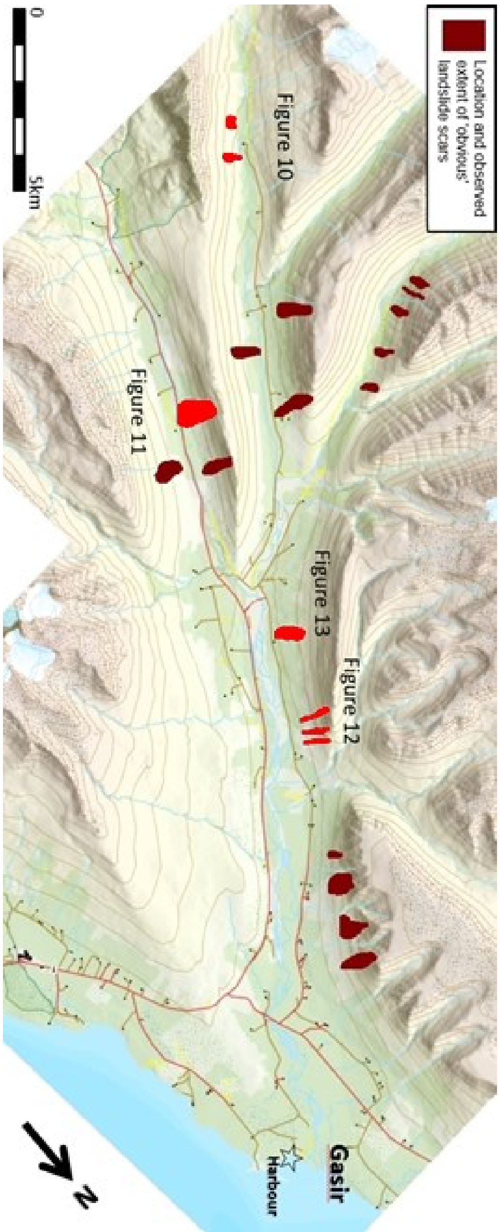


Figure 7.10 (left) - Historic landslide locations and dates recorded in Hörgárdalur and adjacent valleys. Figure 7.11 (right) - Geomorphological mapping of landslides clearly visible in Hörgárdalur**. Landslides marked in red are those that occur at roughly the same location as a recorded historical landslide.**

Multiple landslides have occurred in the same locations over the past millennium. This could point to particular geomorphic instabilities of these locations, or that these locations were populated and thus worthy of mentioning in records, or both. It can be seen that the northern slopes of Lower Hörgárdalur is a particularly landslide prone area, with contemporary sources recording a major landslide estimated to be 1 km+ in width on the 17th November 1390 between Lönguhlíðarfjall and Skriða, reportedly killing over 20 people and burying several farms. Indeed, the name 'Skriða' means 'Landslide' in Icelandic. Another major landslide of a similar magnitude occurred just upstream between Hallfríðarstaðir and Lönguhlíðarfjall on the 23rd September 1769. Multiple landslides continued to occur and be recorded in the study area throughout the 19th century and 20th century. It is reasonable to assume that many other unrecorded landslides have occurred in the valley systems, particularly in earlier settlement times when record keeping was poor, or records lost (Pétursson, 1999).

Landslides continue to be recorded in the study area today, with the most recent being recorded in 2013 (Pétursson, 2015, pers. comm.). These appear to have reduced in magnitude however, rarely being observed to be more than few tens of metres wide, far smaller than the ones recorded in 1390 and 1769. This suggests that there has been a reduction in the amount of available slope material over time, and /or a reduction in landslide triggers such as weather conditions and earthquakes, which means that landslides on the scale of 1390 and 1769 cannot form. Figure 7.11 shows the clearly observed landslide scars seen during the geomorphological survey. Some of these occur in locations of recorded historic landslides, however these are not necessarily the remains of those historic landslides, which may have been buried by subsequent shallow slides rather than larger bedrock movements.

Clear landslide scars are visible in multiple locations throughout the study site, of which several reach the valley floor and thus sediment from these is potentially available for transport downstream by the river should the channel make inroads into to these locations or large enough flood wash against the landslide deposit (Figure 7.12 to Figure 7.15). It is important to note that, the mapped landslides are the ones that are visible today and thus represent *minimum* landslide coverage; others are almost certainly obscured by subsequent slope processes and vegetation growth. The age of the mapped landslide deposits are not understood in detail, but in many cases coincide with landslides recorded in contemporary sources. Excavations carried out at the Skuggi site (Figure 7.2) by Harrison & Roberts (2014) revealed landslide deposits just above a tephra layer thought to be from an eruption of Hekla in either 1104 or 1158. This landslide has no surface expression, supporting this observation that landslides mapped are the *minimum* that have occurred in the valley. The geomorphological survey also revealed a striking lack of sediment and soils on the upper slopes of mountains forming the sides of Hörgárdalur, with scant vegetation cover present at these altitudes (e.g. Figure 7.12).

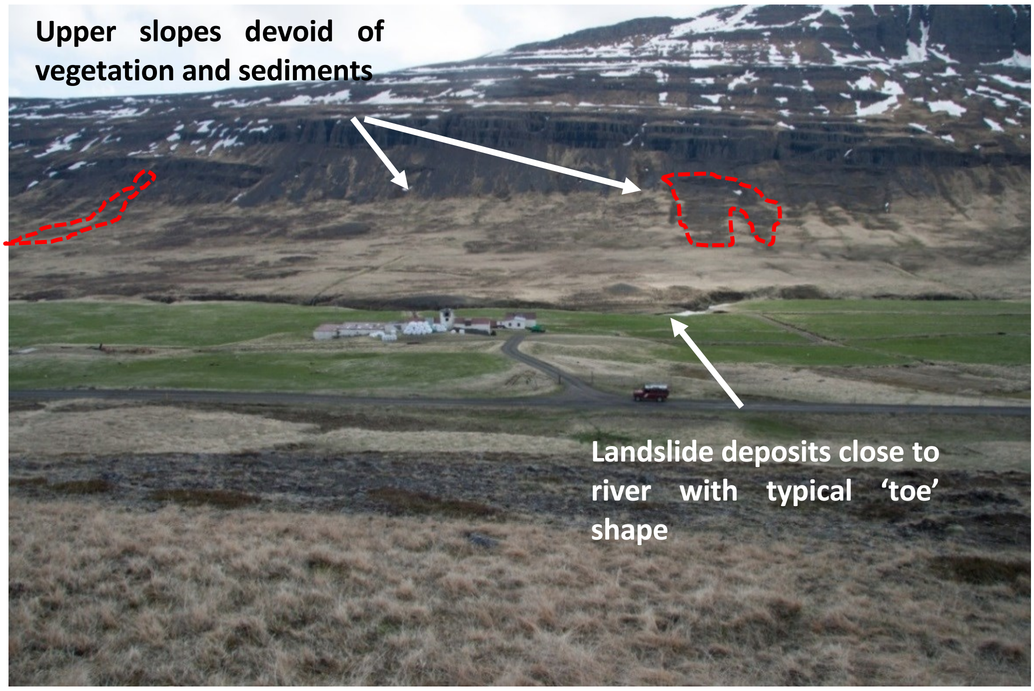


Figure 7.12 - Myrkádalur, site of reported landslides in 995, 1337 and 1500.

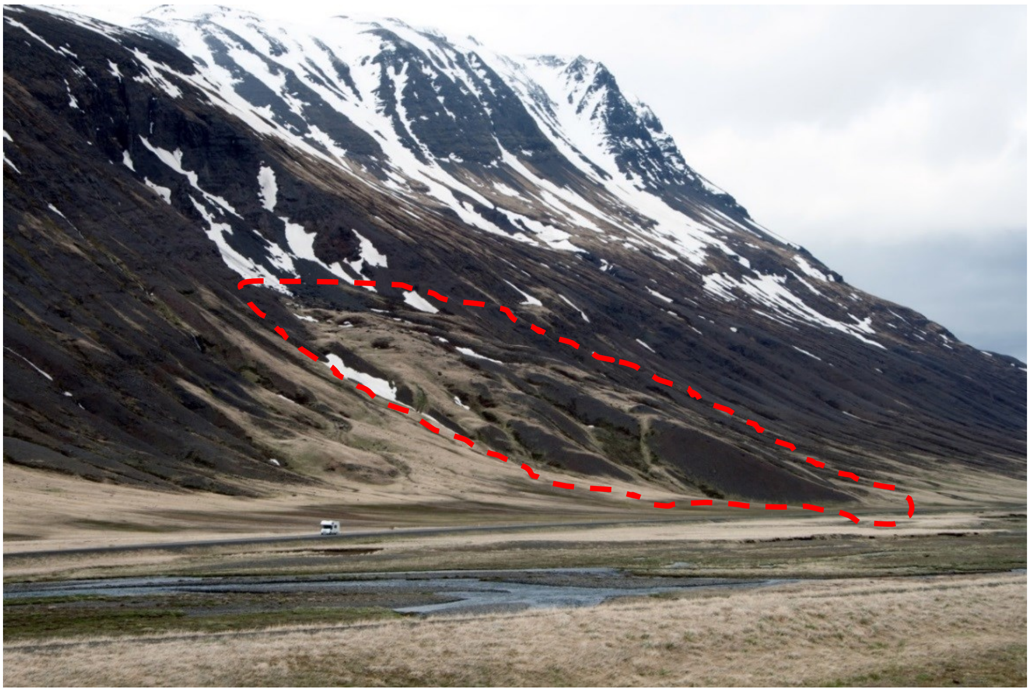


Figure 7.13 - Major rotational landslide in lower Oxnádalur, reaching valley floor. Age indeterminate, but location is coincident with recorded landslide around 1500. The mobilised sediments have been highlighted. While there is no obvious erosion of the toe as a result of undercutting by the river, landslide deposit is heavily gullied which shows that significant volumes of sediment have been moved from the landslide deposit onto the flood plain of the river.

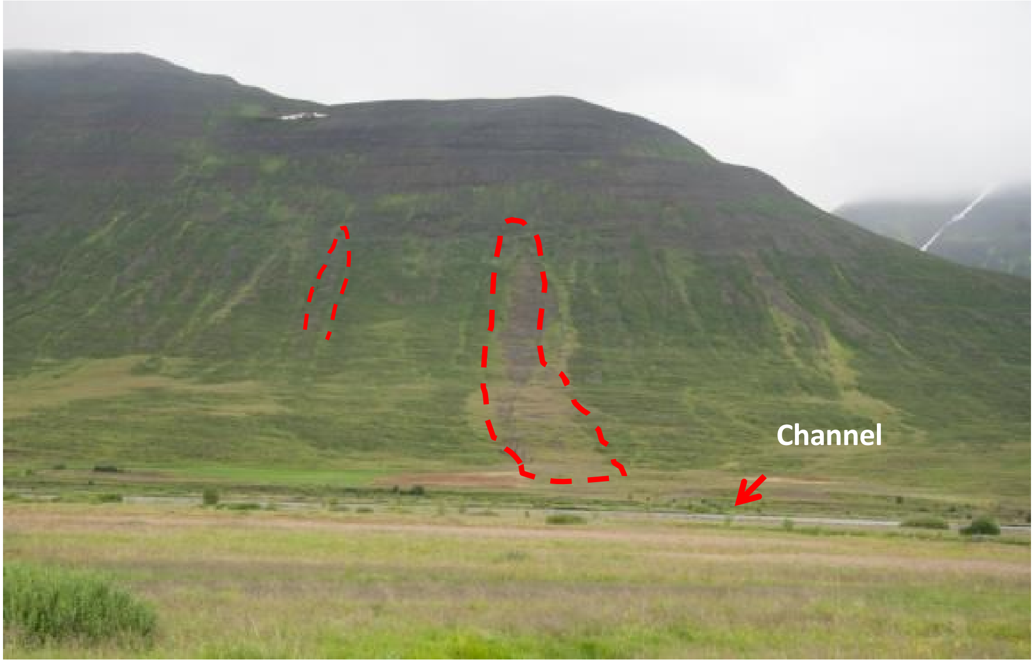


Figure 7.14 - Landslide scars on northern side of Hörgárdalur reaching valley floor (river just visible in middle distance).

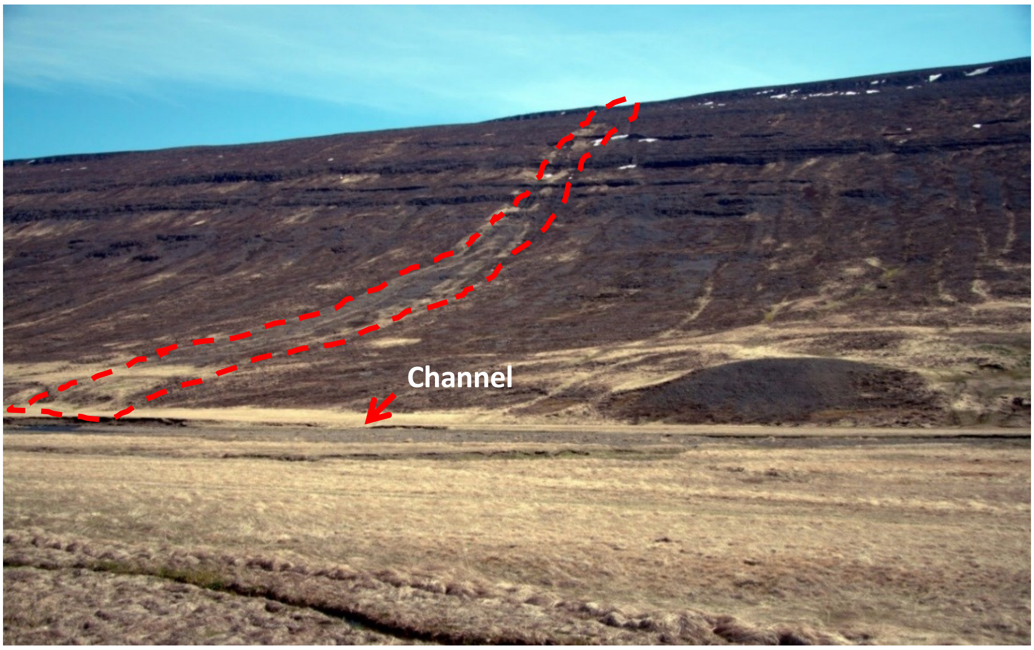


Figure 7.15 - Landslide scar in Lower Hörgárdalur reaching valley floor.

Geomorphological observations, supported by historical sources, point to landslides being the major source of geomorphic change in the study area. These large, discrete events could have introduced large pulses of sediment into the river. Coupled with exposed and loosened soils from landslide impacts would also lead to an increase in slope erosion, increasing the sediment budget in the river.

7.7 Landslide triggers and impact on fluvial sediment budget

Landslides are a feature of mountainous landscapes all across the planet, in many different climatic regimes. Iceland in particular is susceptible to landslides, with many examples of catastrophic slope failure throughout the Holocene. Mapping of Holocene landslide locations in northern Iceland suggests that landscapes that have undergone deglaciation and para-glaciation, such as the Hörgárdalur valley systems, are particularly susceptible due to such factors as stress-fracturing of slopes through exposure to freeze-thaw cycles, isostatic rebound from de-glaciation destabilising slopes and increased slope steepness (Norðdahl & Pétursson, 2005; Mercier et al., 2013; Feuillet et al., 2014; Coquin et al., 2015; Decaulne et al., 2016). A slope can undergo a sudden, catastrophic landslide that is over in a matter of minutes as well as undergoing extremely slow slope failures that can increase sediment yield to a river for many years (Swanson & Swanston, 1976, Iverson, 2000). Even one landslide can add a significant volume of sediment to the river system. If we take one of the larger landslides observed in the geomorphological survey (Figure 7.13,

Figure 7.16), we can calculate the landslide volume following Cruden & Varnes' (1996) volume equation:

$$V = \frac{1}{6}\pi D_r W_r L_r \tag{7}$$

Where V is landslide volume, D_r is surface of rupture depth, W_r is surface of rupture width, L_r is surface of rupture length.

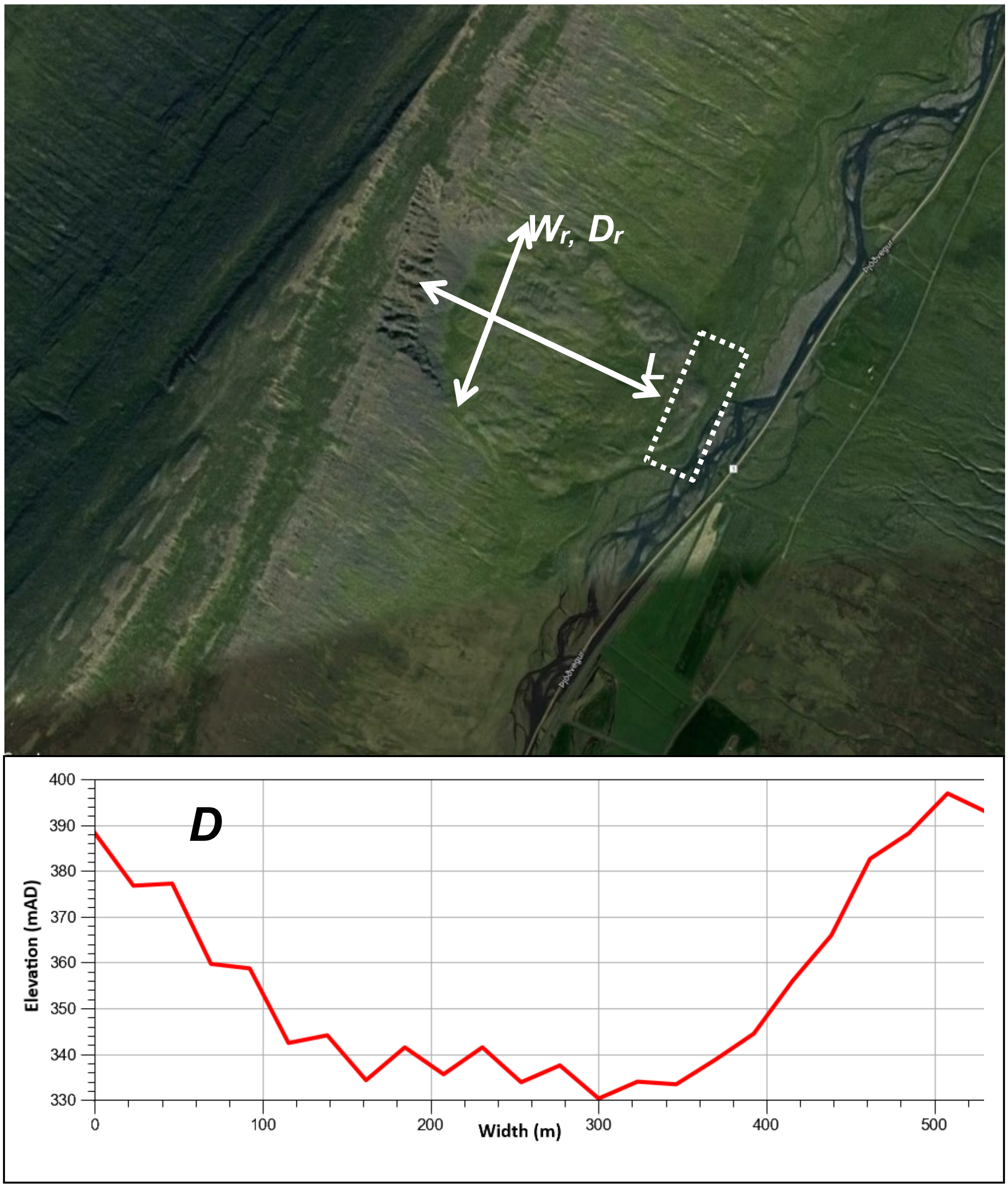


Figure 7.16 - Dimensions of Oxnádalur landslide. Box represents portion of landslide reaching valley floor (approximately 10% of landslide area). Inset: Cross-profile of landslide showing depth of landslide scar.

In this case, *Lr* = 715 m, *Wr* = 505 m, *Dr* = 60 m. The maximum volume of this landslide alone is 11, 343, 505 m^3. While only about 10% of sediment from this particular landslide reaches the valley floor (a minimum volume of 1,143,350 m^3) and is thus open to fluvial entrainment from channel avulsion or flood events, this calculation demonstrates the significant input of sediment that even one landslide can contribute to the fluvial system which is ultimately deposited at the delta.

Landslides are also a function of topography. A study of landslide susceptibility in the Faroe Islands (Dahl et al., 2010), similar in climate and topography to northern Iceland, found that slopes with gradients between 25° and 40° were most susceptible to landslides. No landslides were found to occur on slopes shallower than 20° (which were considered too flat to promote landslide development) and none were found on slopes steeper than 40° (due to the angle of repose). Figure 7.17 below classifies slope angle in the Hörgárdalur valley system in accordance with these parameters.

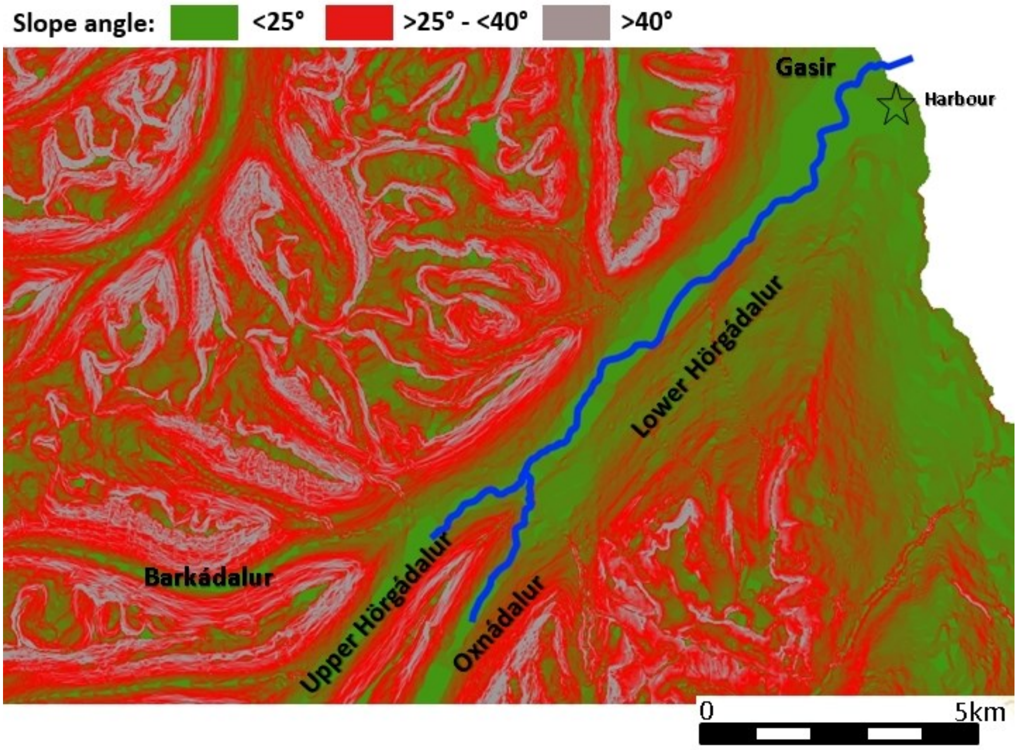


Figure 7.17 – Slope analysis of study site. Barkádalur, Upper Hörgárdalur and Oxnádalur all show high susceptibility to landslides. The northern slopes of Lower Hörgárdalur show a marked increase in landslide susceptibility compared to southern slopes.

A significant proportion of the valley systems are *topographically* susceptible to landslides based on Dahl (2010). The majority of slopes in Oxnádalur, Barkádalur and Upper Hörgárdalur are of a sufficient gradient to promote landslide development. In particular, the northern slopes of Lower Hörgárdalur are far more susceptible than the southern slopes. This is consistent with the historic landslides recorded on these slopes as well as the observed and mapped landslides, which all occur within the red areas. This increase in sedimentation over time from slope failures may have been responsible for a transition between a stable, single-channel Hörgá river to a more unstable, braided channel. This in turn could promote channel avulsion and allow the river to more readily entrain sediment reaching the valley floors from slopes.

Coupled with the topography, soil characteristics can be a major control on the prevalence of landslides, and can explain why Hörgárdalur and surrounding valleys are so susceptible. The soil characteristics of Hörgárdalur, as mapped in Arnalds & Oskarsson (2009), show the majority of soils in the valleys are histosols or brown and gleyic andosols. Histosols and histic andosols have a high water-retention capacity due to their capillary porosity as opposed to macro-porosity (i.e. water retention is more diffuse and soils remain cohesive). Icelandic andosols in particular lack phyllosilicates common to andosols in other parts of the planet, which decreases the cohesiveness of these soils. However, the presence of gleyic andosols in the valleys suggests a high clay content mixed into the soil layers, which has higher capacity for water retention and thus will saturate quicker than the histosols (Arnalds, 2015). The porosity of the histosols and histic andosols, and the shrink-swell properties of the clay-rich gleyic andosols, suggests that the soils present on the slopes of Hörgárdalur could hold a significant amount of water until they become saturated and fail more readily, creating large landslides.

Other factors such as vegetation cover are also controls on the prevalence of landslides in a valley. Tree clearance, as occurred in most parts of Iceland from Landnám (Simpson et al.; 2004; Kirkbride & Dugmore, 2005) would likely have made the slopes of Hörgárdalur more susceptible to landslide events. No specific evidence of when trees in Hörgárdalur were felled, however if it followed a similar pattern to other settled areas of Iceland (e.g. Church et al., 2007), it would have progressed to near completion by the mid-13th century. While landslides are likely to have still occurred with 'full' vegetation coverage across susceptible slopes in Hörgárdalur (such as the landslide recorded in

Myrkádalur in 995), the general shift in landscape state recorded island wide along with intensification of sheep grazing in the area related to wool production is roughly coincident with landslides beginning to be recorded in known contemporary literature, (e.g. Dugmore, 2005; Streeter et al.,2015).

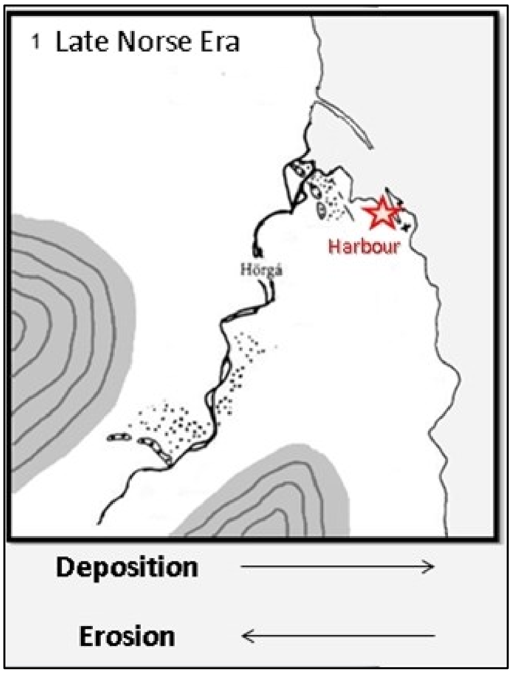
Removal of vegetation destabilises slopes by removing root binding sediments, but also increasing the surface area of the slope that rainfall hits and percolates into allowing more water retention in the soils on the slopes and thus greater slope loading. Landslide events are often triggered by rainfall, with mass movements occurring once soils becoming waterlogged by rainfall (Zaruba & Mencl, 2014). Indeed, the most recent landslides in Hörgárdalur and adjacent valleys are known to have occurred after periods of intense rainfall in Spring, as the winter thaw sets in and waterlogs soils. Lack of vegetation makes sediment less cohesive and thus more susceptible to mass movement once waterlogged. Precipitation related to the onset of 'Little Ice Age' climate conditions (e.g. O'Brien et al., 1995; Ogilvie & Jónsson, 2001; Mann et al., 2009) would have led to an increase in landslide events. This would have led to an increase in the sediment budget of the Hörgá River, creating a positive mass balance in the delta and overwhelming the delta's ability to discharge sediment into Eyjafjorður. The result of this would have been an increase in progradation of the delta due to the increase in sediment.

7.8 Gásir – geomorphological evolution model

With the available evidence considered, the following is the most plausible conceptual model of geomorphic change that may have led to the abandonment of Gásir as a harbour:

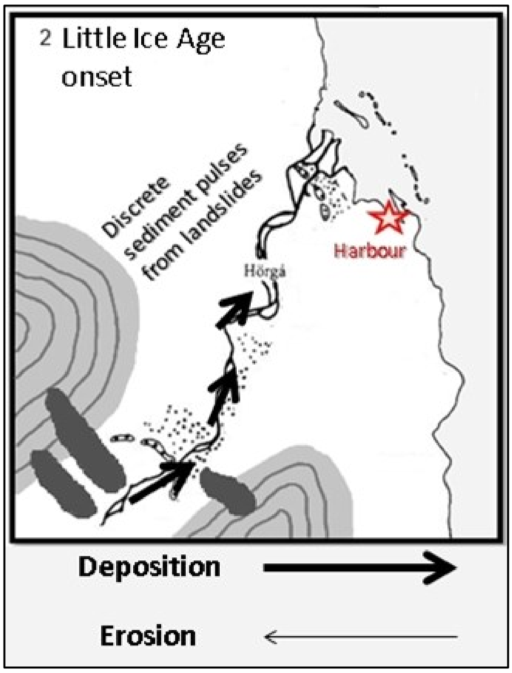
1.

The balance between sediment accumulation and discharge at Gásir is relatively equal. Sediment deposited in the delta environment is discharged offshore, creating relatively deep water in the delta. With the addition of sand bars partially blocking the delta entrance and deep pool behind, this created an ideal anchorage.



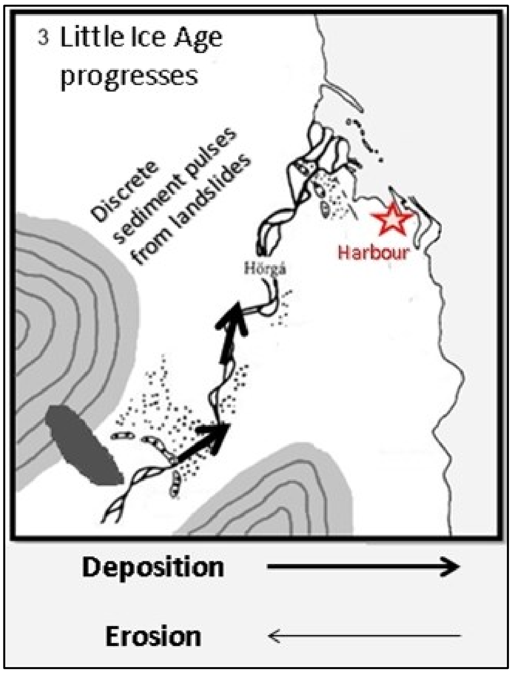
2.

Increase in landslide activity in Hörgárdalur leads to irregular pulses of sediment into the river channel, as well as a general increase in sediment availability from increased rainfall and a more variable river discharge. This increase in sedimentation disrupts the mass balance of Gásir, leading to progradation. Sediment accumulates, starting to form outer bars as the increase in sediment is not flushed into the deeper waters of Eyjafjorður.



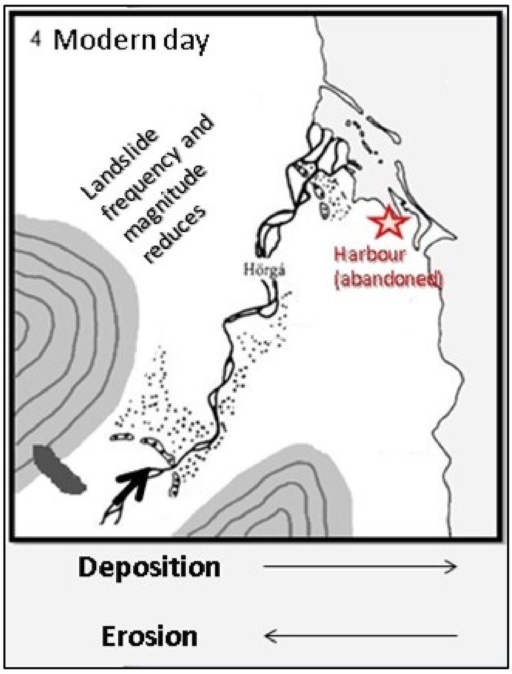
3.

As positive mass balance continues from Hörgárdalur, the outer bars continue to form with the inner bars becoming increasingly eroded by increased discharge from inland. The reworked sediment, coupled with increased sedimentation from the river, leads to shallower waters in the delta and becoming an increasingly difficult place to navigate craft into for anchorage purposes.



4.

Landslide activity decreases due to depletion of available slope material. Mass balance in the delta equalises with outer sand bars fully formed and inner sand bars eroded. Inner delta very shallow (<1 m depth at high tide), rendering it useless as an anchorage, thus Gásir abandoned.



7.9 Socio-economic consequences

Gásir transitioning over time from an ideal anchorage to a more marginal one, eventually falling out of use around 1400, occurred concurrently with changing maritime technologies. The *knarr*, a 16 m x 5 m ship that was the 'backbone' of Norse Atlantic trade, was in use from the 10th century onwards (Crumlin-Pedersen, 1991). This class of ship would have regularly visited the harbour in summer months, easily navigating the relatively deep waters of Gásir due to its shallow 1 m draft. As the centuries passed and the anchorage at Gásir becoming shallower, ship technology moved towards deeper draft boats such as the *cog* that were larger and could carry more cargo that vessels such as the *knarr* (Unger, 1980). A *cog* had a draft over twice as deep as the *knarr*, and with increasing shallow waters present in the harbour, changing technology such as this may well have exacerbated the decline of Gásir as an important harbour, and stimulated the growth of Akureyri as a town and port, 10 km to the south.

7.10 Conclusion

Gásir as an important trading harbour in medieval Iceland, like other harbour sites in the North Atlantic, was initially a geomorphologically favourable location. However, as with other sites, environmental changes eventually disrupted the geomorphic equilibrium of the area leading to changes to which defeated in-situ adaptation by Norse seafarers. Rather than catastrophic, short-term geomorphic changes such as those seen in Shetland, or continuous but long-term change as seen in Greenland, Gásir suffered a combination of both continuous and discrete geomorphic change that, while not avoidable on a long-term scale due to changes in storminess wrought by the Little Ice Age, was exacerbated by land management practices in that tree clearance made slopes in Hörgárdalur more susceptible to landslides. Changing ship technologies as the centuries passed may have exacerbated Gásir's decline as an important harbour along with the marginality of the site geomorphologically. In contrast to Greenland where pressures on harbours could have simply added to pressures on the colony as a whole, in Iceland in the late medieval period the economy was changing and the growth of both the stockfish trade and wool production would have created new opportunities. Gásir declined and was abandoned, but the Icelandic settlements endure to eventually thrive.

8 Discussion – The geomorphology of Viking and Medieval Harbours in the North Atlantic

8.1 Introduction

This chapter brings today the answers to research questions 1, 2 and 3 and considers them together to answer research question 4 as presented in Chapter 1.6 of this thesis, "What is the relationship between harbour sites and coastline stability?"

The story of civilisation is often linked with the story of civilisation's ability to adapt to outside challenges. And often the most compelling stories are those where a civilisation loses the battle between these outside challenges and goes into decline (Tait, 1988; Dugmore et al., 2012).

Some outside challenges can include war, such as the Carthaginians (e.g. Polybius, 2012), or diseases such as with some Mesoamerican cultures in North America (e.g. Acunu-Soto et al., 2005) or some other pressure. But also the physical environment can play an important role in the success of a culture, and the ability for inhabitants to adapt to potentially detrimental changes in the environment (e.g. Diamond, 2005, or Sahlins, 1963). Adaptation would be necessary in the face of rising sea levels slowly drowning cultivated land, or successive catastrophic storms destroying land and infrastructure relied upon and previously thought safe. Yet environmental thresholds exist beyond which no adaptation is possible, triggering abandonment and/or migration. The Norse were no different to any other culture in falling prey to these forces.

Due to the diasporic nature of early Norse population, the environments in which the Norse settled and built their culture were diverse, with equally diverse coastlines exploited for use. The wild and tempestuous currents faced around Cape Farewell in southern Greenland were far removed from the more gentle sheltered bays of the Norwegian fjords. The freezing shores of northern Iceland were quite different from the more clement conditions found along the coasts of Northumbria or the Western Isles of Scotland, storms notwithstanding. But for safe anchorages, not all coastlines were equal, and certain criteria had to be met in terms of shelter, exposure, fetch, geomorphic stability (at least *apparent* stability at the time of settlement), and other criteria to establish a safe harbour. This diversity in coastlines also exposed the Norse to a great diversity in terms of geomorphic change, of which the *trajectories* of change were just as diverse.

So far in the thesis, I have assessed geomorphic changes occurring on diverse spatial and temporal scales; from the catastrophic loss of beaches during one storm, to the slow but consistent change in sea level of an entire region. Adaptation to these changes not only depended on the competence of harbour users and the technology available to them, but whether these changes were adaptable to at all if they crossed certain thresholds.

8.2 Short-term geomorphic change

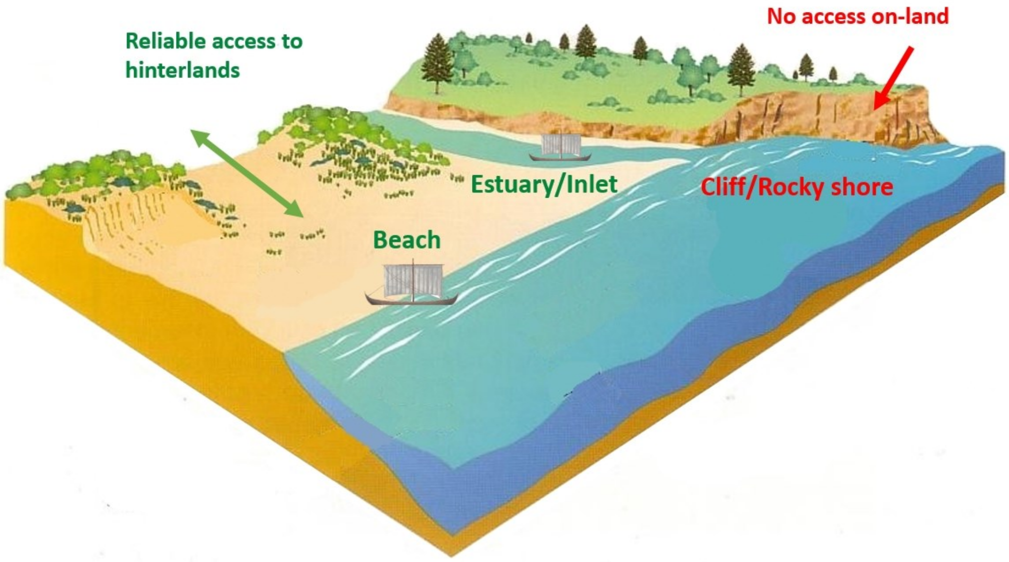


Figure 8.1 – Idealised coastline, illustrating favourable landing places (soft sediment beaches, inlets and estuaries) versus unfavourable (cliffs and exposed rocky shorelines). Reliable access to hinterlands is an important consideration in the placement of a harbour also (modified from Salvioli, 2006).

Figure 8.1 shows the types of coastlines often used for landing places and harbours. Changes occurring on a micro-scale spatially and temporally (such as small landing beaches being swept away in a matter of hours by a single storm event) could be intuitively thought of as perhaps the most disruptive and difficult to adapt to for harbour users in these areas. Sandy beaches in headland-dominated bays were favoured landing places due to the relative shelter afforded by the headlands, and sand being a safe material to land boats without threat of damaging their hulls (Morrison, 1978). As settlements utilising these landing places became established the landesque capital of the area increased. Landesque capital as defined in archaeological terms by Brookfield (1984) are fixed agricultural areas, field systems, major land improvement measures (such as machair production) and other large scale projects to improve a landscape. These efforts require significant expenditure of resources and energy by settlers, and as the landesque capital of an area increased, the likelihood of its abandonment would decrease (Brookfield, 1984; Leach, 1999; Håkansson and Widgren, 2014). Remains of infrastructure (such as noosts) adjacent to sandy embayments and soil improvements (charcoal found mixed with sandy soils) on Unst and elsewhere point to the landesque capital invested in these coastlines.

As demonstrated in Chapter 4, geomorphic stability of sandy beaches within headland-dominated embayments in the face of climatic variability is largely dependent on the mean offshore slope of the embayment. A single storm has the ability to completely remove a beach, and this change may either be temporary or permanent. Where offshore sediment supply is available, embayments can receive a constant supply of offshore sand under calm conditions to replenish the embayment and build a stable beach. However, sand supply to embayments is restricted under stormy conditions on slopes with an average offshore gradient greater than 0.025 m/m. A successive cycle of storms interspersed with comparatively short periods of calm weather would deplete an embayment of sand if its offshore slope exceeds this threshold value.

This control on beach stability was of course not information that Norse seafarers had access to. As the Norse diaspora was underway and settlements became established on high-energy island coastlines such as Shetland, Orkney, Faroe and the Western Isles of Scotland, sandy embayments would have been exploited for their *apparent* stability, i.e. that seen when settlement was established. However, over time the traditional ecological knowledge (TEK) of settled areas (e.g. Inglis, 1993; Berkes et al., 2000; Lauer & Aswani, 2009; Dugmore et al., 2012) of both the land and sea would have increased with time. It would become evident which beaches were ephemeral and which stable in the face of storminess; but this would have taken several years/generations to develop. Yet the TEK of beach stability was only valid as long as climatic conditions were predictable, which the onset of the LIA may have disrupted.

The Norse colonisation began in earnest in the 9th century during the Medieval Climate Anomaly (MCA), a period characterised by comparatively stable weather patterns and limited storminess (e.g. Lamb, 1965; Mann et al., 2002; Mann et al., 2009; Trouet et al., 2009; Graham et al., 2011; Goosse et al., 2012; Surge & Barrett, 2012; Edwards et al., 2017). Trouet et al (2009) propose that the MCA was driven by a persistent 'positive' index for the North Atlantic Oscillation. This was a favourable climate for sea voyages, as well as a favourable climate for the stability of sandy beaches, for reasons described in Chapter 4. Storms would of course have occurred during this period, and depleted or destroyed beaches. However, the frequency of storms was smaller than experienced during the Little Ice Age, and thus the likelihood of beach recovery would have been greater, promoting continuity of use of landing sites in these embayments.

Settlements that found themselves positioned in embayments with 'unstable' beaches that became abandoned (i.e. those embayments with an average offshore greater than 0.025 m/m), such as those settlements close to Lunda Wick on Unst, may have had opportunity to resettle the site or continue limited onshore activities and utilise other suitable landing sites. This was contingent on storm conditions reducing enough to allow the reformation of a sandy beach *and* the landesque capital of the area being high enough (i.e. it was ‘worth’ resettling). The OSL dating of the noosts found on the eroded backshore of Lunda Wick (Chapter 5.3.1), showed that one was dated to late Norse times (~1250), and the other to some point in the mid-16th century, although with a wider age range. While this does not mean that the site was abandoned between these two dates, these dates should be considered with the discrete sand blows found in the OSL dating in the adjacent bay at Lunda Wick. These show a successive series of major sand blows occurring after 1250, and during the height of the Little Ice Age (1400 – 1700), continuing into early modern times. This plausibly suggests that the beach at Lunda Wick became depleted of sand (and not regularly replenished) to the point of unsuitability for boat use sometime after 1250, but eventually reformed (or reformed ephemerally) and likely appeared stable enough for resettlement and re-use, leading to the construction of a new noost at the site. Lunda Wick can be defined as having landform continuity, as while it becomes depleted/destroyed, it apparently eventually reforms.

Norse settlers may well have been aware of the seemingly fickle nature of beaches in these environments as their TEK increased. If we consider other present day sandy beaches on Unst, the beach at Burrafirth would present itself, at least at first glance today, as a fine landing place for boats (Chapter 3.1.4). It is relatively sheltered and having a wide dissipative sandy beach. However, its position deep within the fjord of Burra Firth creates a ‘trap’ for a boat, with prevailing northerly winds preventing craft from exiting easily under oar or sail. Indeed, no longhouses or other infrastructure of Norse age have been found in the vicinity of this beach. This suggests the Norse may have been aware of the impracticality of using this beach as a landing place. It is likely that Burrafirth beach has locational continuity, i.e. a beach is always present, however this does not necessarily contribute to its usefulness as a harbour site.

At Wick of Skaw on the north-east tip of the island, a limited sandy beach exists today, however the remains of the wheelhouse, reportedly Iron Age in origin (Small, 1960), located at the edge of a low, cliff on the current HWM is covered in deep deposits of blown sands. The offshore slope at Wick of Skaw is 0.027 m/m, which suggests that the beach will struggle to reform when eroded by storm action. As mentioned in Chapter 3.1.5, the cliff has eroded since the wheelhouse was constructed. However, this reveals that the floor layer is built on a thin brown soil layer on top of bedrock. This suggests that sand blows were not present in the Iron Age when the wheelhouse was constructed. Blown sand deposition appears to have begun soon after wheelhouse construction, with an unbroken sand layer approximately 2 m thick covering the excavated wheelhouse, with modern soil cover on the surface.

Wick of Skaw, therefore, must have initially been an attractive coastal site for Iron Age settlers to invest in building landesque capital, with a comparatively stable landscape lacking sand blows and offering good quality grazing lands. Yet the lack of Norse remains in the vicinity of Wick of Skaw, may suggest that by this time, a geomorphic threshold had been crossed and sand blows had begun to inundate the land to several hundred metres inland (Appendix C2). This would have depleted or destroyed the beach, which due to offshore slope (0.027 m/m) may have struggled to reform on a short-term (<1 year) timescale once eroded. As with other areas, the TEK of Norse settlers on Unst may have come to include Wick of Skaw as an unreliable place for coastal settlement. A geomorphic shift again, more recently, must have occurred to stabilise the landscape and reduce sand blows to allow the modern day farmstead to exploit this area again, following a trajectory of landform continuity but not necessarily locational continuity.

In contrast, the site at Norwick (Figure 3.1) traditionally considered (and supported by artefactual evidence (Smith, 2007)) the first Norse settlement on Unst, seemingly endured as a settlement to the present day. As with Sandwick, Norwick fulfils the criteria of a shallow average offshore slope (0.012 m/m) and contrasts with Wick of Skaw with its steeper offshore slope (0.027 m/m). Thus the beach at Norwick would have likely reformed rapidly in the event of storm depletion or destruction. The eastern aspect of the embayment, as well as its sheltered position adjacent to the large headland of Lamba Ness may have created a much more favourable landing place than Wick of Skaw which lacked shelter from persistent winds from the north.

Thus, at least on Unst, Norse seafarers had access to stable, persisting beaches when others were lost and did not reform. This offered the chance of adaptation and continuation of settlement, which stands in contrast to other harbour sites elsewhere in the North Atlantic open to different trajectories of geomorphic change.

8.3 Long-term geomorphic change

Coastal settlements without soft sediment beaches would have required a well-sheltered, geomorphically stable harbour for craft to land safely along rocky shores in rough conditions. Such anchorages tend are infrequent along the exposed and very rocky shorelines of Unst and other islands settled by the Norse (e.g. Orkneys, Faroes, and the rest of Shetland).

The examples of harbours along these rocky coastlines surveyed in this thesis tend to be geomorphically stable on a sub-decadal and even sub-centennial timescale in terms of the more catastrophic drivers of change such as storm-driven erosion. But on a longer temporal scale, relative sea level (RSL) change is the primary driver of geomorphic change along these coastlines. The continued use of these harbours depended on the physical geometry of the coastline remaining favourable in the face of sea level change. On coastlines that undergo short-term geomorphic change, geomorphic thresholds are more likely to control the requirement to abandon a landing place, as catastrophic coastal damage would override any landesque capital value and ability to adapt. On coastlines undergoing longer-term change, i.e. RSL change, geomorphic thresholds will reduce in importance and be replaced by a continuum of geomorphic change.

In terms of those harbours that endured on rocky coastlines, Baltasound on Unst exists in a well-sheltered fjord, the entrance to which is protected by a barrier island. This would have limited the fetch in the harbour area and provided a well-sheltered area even in large storms. Relative sea level elevations in Shetland during Norse settlement times are unclear, however it is likely to have been similar or slightly lower than sea level today, as no evidence of higher sea levels has ever been found on Shetland (Shennan & Horton, 2002). Estimates have placed sea level in Shetland approximately 2 m lower than the present day 3450 – 3700 years B.P. (Bondevik et al., 2005). While Baltasound is a relatively shallow harbour (<7 m on approach to the modern harbour site, and shallower closer in), the lack of sediment would make this predictable and stable. The morphological change of Baltasound harbour may have made the harbour even more favourable if sea level was rising, allowing deeper draft boats to enter. Continuity of use, at least from a geomorphological perspective, was possible here.

The physical geometry of Hvalsey (3.3.1) in the Eastern Settlement of Greenland may also have promoted continuity of use as a harbour despite sea level rise. The precise location of the landing place for the inhabitants of the farm is unknown (Madsen, 2014). The coastline adjacent to the farm and church is relatively featureless, with a relatively gentle offshore slope and no skerries or other obstacles close by to present navigational difficulties. It is reasonable to assume that boats were drawn alongside the coastline in this location to minimise overland travel to the church and farm. Sea level rise of a similar magnitude to that experienced in Garðar at Hvalsey and surrounding fjords would not have created many difficulties in terms of anchorages at this site. The morphology of Hvalsey's coastline would be similar with 2-3 m lower relative sea level in early Norse settlement times as it is in the present day. However, the lack of a sheltered anchorage for larger ships at Hvalsey would not have promoted its use as an important harbour handling considerable trade. Hvalsey was more likely an important site for community gatherings, as evidenced by the church and farm with feasting hall, and lack of identifiable warehouses for storing goods to wait for trading ships (Arneborg et al., 2006; … 2009).

The farm site at Brattalið (modern day Qassiarsuk, Chapter 3.3.3) also exhibits similar geomorphological features to Hvalsey, in that simple coastline geometry was unchanged in the face of RSL rise, but also lacked of safe anchorage for ocean-going vessels. Thus Garðar, at least in earlier Norse settlement times, was the preferred anchorage for larger vessels due to its favourable geomorphological characteristics, and subsequently became an important trading harbour and seat of Norwegian power through the establishment of the Greenland bishopric here.

Yet the complex coastline geometry that created such favourable conditions for an important harbour to flourish at Garðar caused significant morphological change to the harbour as sea level rose, ultimately reducing its viability for larger ships to exploit as a safe anchorage, as demonstrated in Chapter 6.

8.4 Irregular geomorphic change

So far, discussion has concentrated upon those harbour sites where beaches can change very quickly in the face of stochastic storm events and those coastlines that change far more slowly, on decadal-to-centennial timescales due to relative sea level change. These sites (e.g. Lunda Wick, Sandwick, and Garðar) tend to be subject to singular, dominant forces disrupting the geomorphological equilibrium of the coastlines. Short-term catastrophic change was likely to lead to abandonment in the immediate aftermath, but potentially recoverable if geomorphic properties allowed and landesque capital invested in the area made it worthwhile. Long-term change in the face of sea level change altering a harbour to the point of unviability was a slow process, survivable in the short-term and even on a decadal/generational timescale, but could ultimately proving unsurvivable. However, sites open to a range of geomorphic forcings could face geomorphic changes of an irregular and unprecedented/unpredictable nature. Survivability at these sites may have been possible dependent on the temporal scale of these changes. The most obvious example of this geomorphic condition I have presented in this thesis is Gásir (Chapter 7).

Continuous geomorphic change occurred with the progradation of the delta, a process that was likely gradual over decadal timescales when discharge in the Hörgá river was at base flow levels and lacking large flood events to increase deposition of sediments above a 'baseline' level of deposition (i.e. not caused by flood events). In general, the process of progradation is mitigated by offshore currents and seabed geometry eroding the outer delta. Landsat imagery recorded over 30 years reveals balance of the forces of progradation and coastal erosion (Figure 7.4). However, discrete and sudden geomorphic change at Gásir as a function of periods of increased landslide activity within Hörgárdalur could overwhelm the gradual geomorphic evolution of Gásir and replace it with sudden, catastrophic geomorphic change in the form of rapid coastal progradation and infilling of parts of the delta.

These episodes of rapid coastal progradation could have been increasingly detrimental to seafarers landing at Gásir. As Gásir was only used during summer months, it is conceivable that winter storms and subsequent thawing of slopes in Spring, in which soils on the slopes of Hörgárdalur became waterlogged leading to increased landslides (Arnalds & Oskarsson, 2009; Arnalds, 2015), change may have been episodic. Seafarers who returned to Gásir in the summer may have noticed increasingly poor and treacherous conditions for vessels with deeper draughts to navigate in. Siltation as a result of Spring thaw and floods may have increased due to increasing storminess through the MCA-LIA transition, along with reduction of vegetation cover in Hörgárdalur due to tree clearance and grazing (Dugmore et al., 2005). Over time, the harbour may have only been accessible to seafarers with particular competence in navigating shallow waters, or only particular vessels that could navigate increasingly shallow waters in the harbour.

8.5 Adaptation, competence and abandonment

The cultural dimensions of competence and technology are of crucial importance to understanding the drivers of a changing utilisation of the shoreline in the face of multiple trajectories of geomorphic and climatic change. How harbour users dealt with these challenges would have varied depending on their seafaring abilities, their cultural resilience (in terms of community and familial links), and their motivations for sea voyages. These differed depending on the type of seafaring activities, whether day-to-day fishing expeditions in nearshore waters or transatlantic voyages.

Competence and ability to adapt would also be partly dependent on the available maritime technology, which changed over time. Boats in the Viking period (~800 – ~1000) were primarily small, shallow-drafted boats such as the traditional ‘long ships’ (e.g. Crumlin-Pedersen, 1978; Crumlin-Pedersen, 1997). This class of boat could be anchored offshore, but unloading cargo was often achieved by grounding boats, and they were also run onshore to be stored in nausts (e.g. **Error! Reference source not found.**c) and boathouses. These vessels were most famously used in the Viking period for raiding and warfare.

The *faering* was a small Norse vessel used for day-to-day fishing activities close to shore (Figure 8.2). The name *faering* is derived from the number of pairs of oars found on the vessel, in this case four pairs leading to a maximum crew of nine (with a minimum of five – four rowers and one helmsman). The typical Norse clinker-design of the *faering* and the relatively few boards required in its construction made it very light and thus easily transported into and out of the ocean, with overland portages more convenient also. This construction however made boats quite fragile, with Morrison (1978, page 61) noting about Norse-designed *faerings*: “The extent to which it was felt profitable to push this aspect of Norse design philosophy to its very limits is illustrated by the occasional structural failures that took place in exceptional sea conditions. Undecked fishing boats far out in the open Atlantic often survived only through their sheer speed in making shelter as heavy weather blew up.”

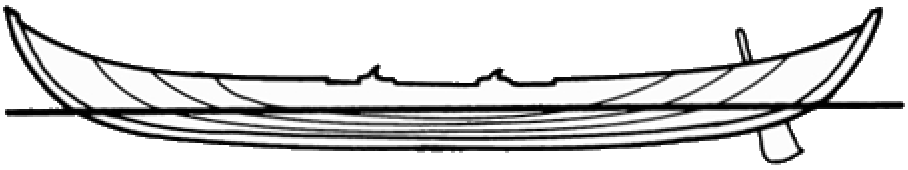


Figure 8.2 - Cross-profile of the 4-oar *faering (source: Morrison, 1978)*

These boats therefore both benefited from and required stable landing places in the form of sandy beaches for their continued use. Indeed, these beaches may also have served a dual function, as good locations to dry the daily catch once back on shore. This practice was recorded as favoured by fishermen on Unst at least as far back as the 18th century (Sandison, 1954; Morrison, 1978). Zooarchaeological analysis carried out on in Shetland (and Orkney) show that marine food sources, particularly cod, significantly increased as the Norse colonisation of Britain began (e.g. Barrett et al., 2001; Harris et al., 2017), pointing to extensive Norse use of local Shetlandic waters for this purpose. It is reasonable to assume that the fishing practice of drying beaches was based on a long tradition, and could well have been favoured as far back as Norse settlement times.

Speedy seamanship (as noted by Morrison), informed by appropriate TEK of the local area, was required in the face of dangerous weather conditions. Therefore, the *competence* of seafarers to navigate treacherous waters to safe landing places was a critical factor. From the study sites on Unst, Lunda

Wick may have proven a more problematic landing place than Sandwick because of the approaches to the landing places. Skerries in the vicinity of the embayment entrance presented a grounding hazard, and additional challenges were posed by the potential for strong currents moving south towards Yell Sound (Figure 3.1). The fetch analysis also shows that zone 2 of Lunda Wick (Figure 5.2) could experience much windier conditions compared to zones 1 and 3, which are partially sheltered by headlands. During high winds, a small boat such as a *faering* would have had difficulty reaching these more sheltered areas without first entering the area of high fetch towards zone 2, a dangerous proposition in the face of an oncoming storm. Inexperienced or incompetent seafarers may have found Lunda Wick too difficult to attempt to land due to the geomorphological setting of the embayment, yet an experienced and competent crew, armed with more robust TEK of the area, may have been able to continue to exploit Lunda Wick successfully.

Where a landing site that became increasingly marginal geomorphically, such as Lunda Wick, increased levels of competence from seafarers was required. In these cases environmental and cultural drivers could reinforce each other. Landing sites may have fallen out of use when the geomorphological conditions created conditions that were too demanding for the seafarers making use of the landing place. A site such as Lunda Wick would have been more marginal in this respect than Sandwick, which had far less complex currents and shore geometry to navigate. Geomorphological ‘survivability’ of landing sites may not have changed suddenly, but initially increased in marginality dependent on the competence of seafarers who were exploiting it at the time. But once a geomorphic threshold was crossed, such as the complete loss of a beach in an embayment, this would make existing TEK of the area obsolete, and no level of competence could keep the landing place in use.

So far, I have discussed the impact of geomorphological change and marginality as it pertained to small craft operating within the vicinity of landing beaches and other *hyperlocal* anchorages. But larger ships, such as the *knarr* (in use by at least the 11th century) or *cog* (in wide use by the 13th century onwards) (Crumlin-Pedersen, 1991; 2002), which were capable of sustained oceanic voyages, would have required different harbour to smaller boats and different competences to operate them. Motivations for their use would also have been different, as would the frequency with which they made landfall. Catastrophic loss of sandy beaches might be insignificant to the operation of these vessels, however, these craft required permanent anchorages to ply their trades. Larger ships used for transatlantic trade required more sophisticated harbour infrastructure, such as wharves, jetties and warehouses, and visited a harbour site only periodically while smaller vessels accessed the sea far more frequently. Trading harbours designed for larger vessels did not necessarily have to be close to settlements and could have operated as semi-independent trading stations, e.g. Gáutavik in east Iceland, and to some extent Gásir (Capelle, 1982; Harrison, 2013). Due to these greater infrastructure demands and less frequent uses of anchorages, larger vessels required a far more geomorphically stable coastline than those exploited by smaller vessels such as *faerings* or longships.

The *knarr* and the *cog* were long-distance cargo vessels that relied on sails for propulsion rather than oars (although the *knarr* could be rowed when necessary), and were the backbone of Atlantic trade in the Norse world. The *knarr* wreck excavated in Roskilde harbour in 1962, ‘Skuldelev 1’, is estimated to have had a draft of 1 m (Crumlin-Pedersen et al., 2002). A *cog* excavated close to Bremen, dated to the late 14th century, is estimated to have had a draught of 2.07 m (Crumlin-Pedersen, 2000). While the *knarr* has a relatively shallow draft, its size, 16 m in length and 5 metres wide, would have been prohibitively difficult to beach and drag on shore (although possible with a large enough tidal range). The *cog* required permanent floatation.

Multiple maritime regulations exist today as to what constitutes the minimum 'safe' depth a ship can enter based on its draught based on location and port authority. But relatively consistently, these regulations suggest that the recommended safe under keel clearance for open water conditions is 50% the static draft, and 10% in harbours (*Ship's Business,* 2010). Although such strict rules did not exist for the Norse, seafarers would have not wanted to risk damaging their ships in water than was too shallow. Therefore, care must have been taken to select landing sites with adequate clearance below the keel. If similar rules of thumb were followed to today, a *knarr* would have required an approximate minimum depth of 1.1 m below its keel in a harbour and ideally an absolute depth of 2.1 m to safely navigate. The *cog* would have required an absolute depth of roughly 4.3 m under these rules. We do not know which exact water depths were acceptable to competent Norse seafarers, but these or slightly shallower conditions must have been around the limits to ensure safe passage and landing.

Competence of seafarers navigated these large vessels through shallow, restricted waters would have been of critical importance, and even the most competent would have been hard pressed to successfully voyage in extremely poor wind and wave conditions. It is reasonable to assume that Norse seafarers would have erred on the side of caution in navigating their vessels through restricted waters and harbours with the absence of reliable technology to know at what depth the seabed was below their vessels. Restrictions on safe under keel clearance as noted in the above paragraph would have been where knowledge of harbour morphology was invaluable. No nautical charts existed, thus navigational knowledge would be passed orally between seafarers (Marcus, 1955; Marcus 1960). It is not unreasonable to assume that seafarers navigating well-trafficked sea lanes and harbours would have had up-to-date knowledge on the environmental conditions as they spoke with their colleagues while ashore in other harbours, therefore any rapid change in the geomorphology at a harbour creating navigational difficulties would likely have been passed on quickly to crews that were set to visit these harbours, thus disseminating TEK of each potential anchorage.

Linked with the idea of competence is the *motivation* of seafarers to embark on sea voyages. Dugmore et al. (2010) introduce this concept as being a variable depending upon the type of seafarer who was making the voyage. For example, ocean going colonists would have had a far higher motivation for a successful journey than an explorer, who may have been content to wait for very favourable conditions to attempt a voyage. A trader's motivation is between an explorer and a colonist, who would have certainly been motivated to seek profit from their trading in different harbours, but not at the expense of possible failure were sea conditions not favourable. Increasingly sophisticated larger and deeper draft ships, however, increased chances of success in a voyage for traders if motivation remains constant.

The larger, more important anchorages and harbours for deeper draft boats handled considerable trade and been important centres of economic activity for the region they were located in (e.g. Roberts, 2002, Arneborg, 2006; Harrison et al., 2008, Harrison, 2013; Mehler & Gardiner, 2015). Geomorphic change disrupting the use of these harbours would have far wider socio-economic impacts than geomorphic change disrupting smaller-scale landing places on beaches. The beach landing places I surveyed for this thesis appeared to have been used on a *hyperlocal* scale, i.e. only one or two farms or small settlements made use of them. The loss of a landing place in one site would create major problems for the local population. The Norse subsistence economy relied on both marine (fishing) and terrestrial food sources, such as crops, hunting, foraging and animal husbandry (McGovern, 1990; Brewington, 2015; Marttila, 2016). If the ability to access fishing grounds was disrupted due to the loss of a landing beach, pressure was added to terrestrial food sources to make up the short fall. Whether a community could adapt to increasing their terrestrial food sources depended partly on the physical resources available for this on land, but also whether the community could rise to this challenge and avoid a ‘rigidity trap’ – an often unintentional state of a system, in this case food production, being maintained beyond its ability to function (Schoon et al., 2011; Brewington, 2015). If climatic conditions such as those experienced at the MCA-LIA transition impacted terrestrial resources also, e.g. loss of pasture land to blown sands or decreasing crop yield, this had the potential to prove fatal to a community (Schoon et al., 2011).

However, on a regional scale, the impact of the loss of one landing beach would have been limited, assuming other beach landing places were suitable for use in the general vicinity. Portages that were easily traversed with the smaller *faerings* and similar vessels could allow access to other landing beaches. Were a landing place lost to a particular community, kin and community networks elsewhere on Unst could have stepped up to offer assistance, but this would have increased natural resource expenditure (e.g. added boats to a fishing area) and social resource expenditure (e.g. lost time and effort helping rather than focused on subsistence) as a result. Sediment transport modelling of Sandwick on Unst suggests this beach would have quickly reformed and persisted in a range of conditions. As this was not far from Lunda Wick, a more ephemeral beach, communities in southern Unst would have been still been able to access the ocean safely from here, as well as being relatively close to other beaches such as Norwick. However, the walking distance (unladen) between Lunda Wick and Sandwick is approximately 2 hours, and 4 hours to the beach at Norwick (along modern tracks). Significant time and energy would have been expended were boats and other equipment ported to and from Lunda Wick from these landing places.

A harbour on the scale of Garðar and Gásir falling out of use, however, would have impacted the entire region and beyond. The population in the hinterland of trading harbours who relied upon them to trade their wares and produce, as well as importing required foodstuffs and other items, would find themselves restricted economically by such a loss (Harrison, 2013). These anchorages would not have been easy to replace as their locations were likely chosen initially for the unique geomorphic qualities that afforded safe anchorage. Garðar was at the head of a sheltered fjord and had the unique qualities of a natural breakwater for deeper draft boats to exploit, as well as being the seat of the Bishop of Greenland and thus becoming the hub of political/ecclesiastical power in the colony. Gásir was sheltered by sand bars that created very calm conditions within the lagoon-like anchorage behind them. No other reaches of coastline in close proximity to these harbours could replace these sites, as settlements had developed in the hinterlands to exploit the harbours for economic use (Arneborg, 2006; Harrison et al., 2008; Harrison, 2013).

8.6 Scales of change

If we return to the sediment/exposure matrix (Figure 8.3), one final axis could be added to take the magnitude of harbour loss into account. The geomorphological changes that smaller sites may experience rendering them unusable on a short-term timescale (i.e. beach destruction and reformation) are *locally* significant, but *regionally* insignificant. Those larger sites that are rendered unusable on a longer-term timescale are more likely to be *regionally* significant, as well as having a major impact on the individuals who used these landing places and anchorages. The impacts of these geomorphic changes may also drive broader changes in society, due to the loss of economic hubs or transport links (e.g. Eastern Settlement's only link to Europe was through Garðar).

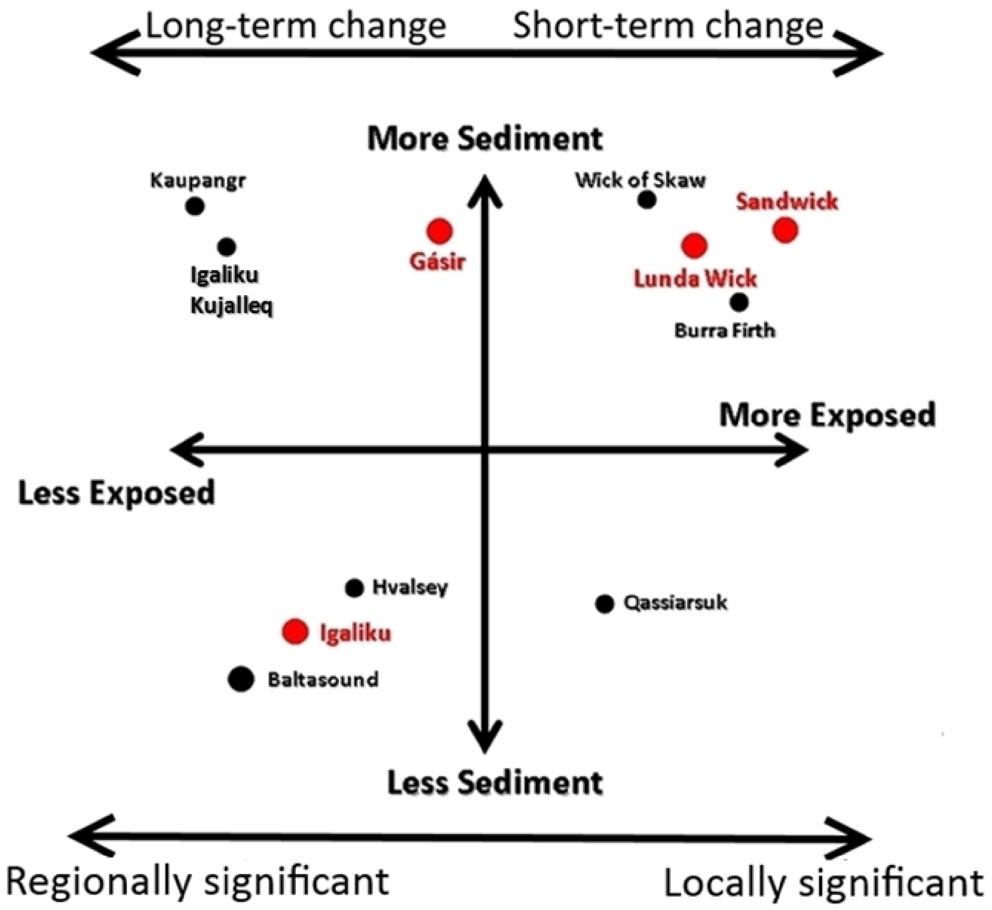


Figure 8.3 - Sediment/exposure matrix. Lower axis places sites on a continuum in terms of their economic impact when abandoned.

Figure 8.3 proposes a qualitative relationship between the impact of harbour abandonment on socio-economic conditions and the geomorphic setting of the harbour site. But if we develop this argument, we can consider sites through their individual use-histories, as well as considering their importance through time to the communities they served. Some sites were located on coastlines where the MCA-LIA transition would see an inevitable geomorphic change and strong environmental drivers for harbour abandonment, whether on a short-term (*active* abandonment) or long-term (*passive* abandonment) scale (Dawson, 2013). These geomorphically 'cursed' sites stand in contrast to geomorphically 'blessed' sites located on morphologically-resilient, comparatively stable coastlines that allowed continuity of use. Figure 8.4

qualitatively places these sites on a continuum illustrating their geomorphic 'destiny' along with their socio-economic important.

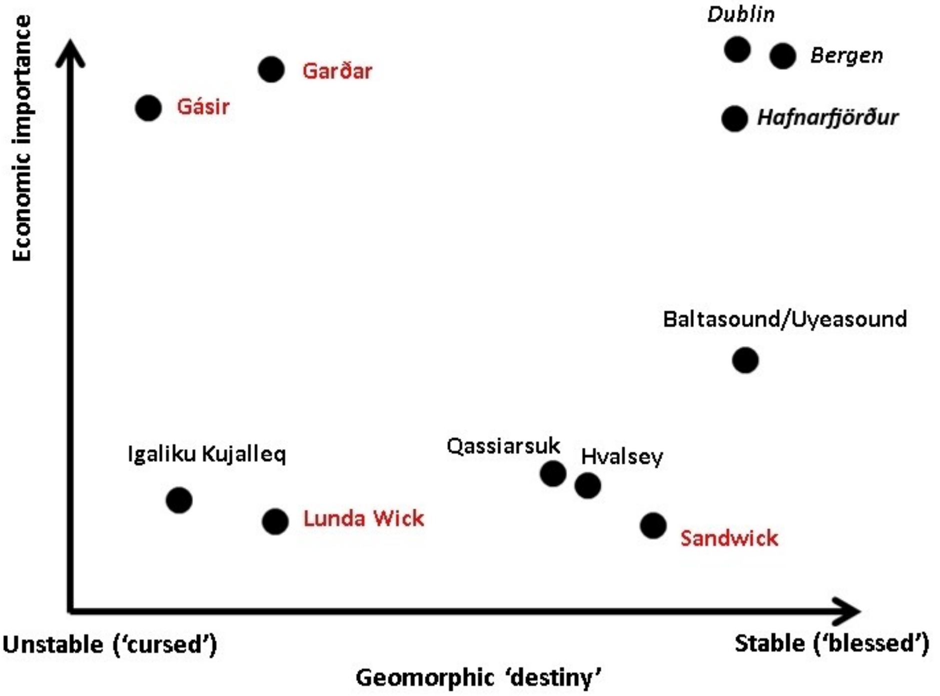


Figure 8.4 – The geomorphic 'destiny' of sites in relation to their economic and cultural importance. Sites in the top right of the graph were not visited as part of the thesis but are known examples of geomorphically stable, important harbours that endured to the present day, included as comparison to the sites considered in this thesis. Sites analysed in previous chapters are in red.

The abandonment of sites found in the top-left hand side of the chart could have triggered the most significant regional changes to Norse and early medieval communities, disrupting important, established trade networks. Their loss, whether gradual or comparatively sudden, would likely have led to a disruptive reconfiguration of settlement in the area, were harbour users forced to other locations that offered the economic opportunities denied to them by the loss of a particular harbour. The loss of Gásir as a harbour may have been partially mitigated against by gradually establishing a harbour at Akureyri, approximately 10 km south. Changing ship technologies along with siltation at Gásir may have made this site more attractive, although this was a non-trivial task (Harrison, 2013).

The abandonment of Gásir was perhaps not as economically disruptive to inhabitants of the area as would have been the loss of Garðar to its inhabitants, because of the comparatively close connection to other nodes on trading networks. The remoteness of Garðar and the Eastern Settlement from the rest of the Norse trading network allowed little opportunity for adaptation to harbour loss. Foreign traders visiting would have had few other suitable harbours to exploit. Also, considerable landesque capital in the form of trading infrastructure (causeway/breakwater, warehouses) located at Garðar, which was lost. The reduction and eventual disuse of these harbours are examples of sites *passively abandoned* (Dawson, 2013).

I have included on Figure 8.4 urban centres that were originally Norse settlements, and both endured and developed to become large and important settlements in modern times (Hafnarfjörður, Dublin and Bergen). These sites are in the top right of the graph, and were the sites that were 'blessed' geomorphically with stable, predictable conditions throughout the centuries and were well placed to become large and permanent settlements, despite changes in technology and climate. These sites can be considered highly resistant to abandonment, at least due to geomorphological reasons.

Sites in the bottom left had less cultural and economic impact when abandoned, but still would have represented a loss to a local community, and are sites that would likely have been *actively abandoned* (Dawson, 2013), with a conscious decision to stop their use being taken in the face of geomorphic change. However, if a large number of sites in close proximity to each other were abandoned, the socio-economic impact of their losses may have become more critical. If the population of these abandoned sites lived in close proximity to sites that fulfil the criteria in the bottom right of Figure 8.4, this may have allowed the culture and economy of a region relying on smaller landing places to endure.

8.7 Implications of harbour abandonment

Due to their society being dependent on maritime resources and trade networks, the diversity of landing places and harbours exploited by the Norse made them vulnerable to climatic and geomorphological change. These changes occurred on a sliding scale of survivability for the harbour dependent on the interplay of both environmental and cultural variables: the nature of climatic and geomorphic change, maritime technology, seafaring competence, motivations and hinterland characteristics. Certain sites underwent geomorphic change so profound and sudden, such as the loss of beaches at Lunda Wick, that environmental drivers would have placed extreme demands on cultural adaptation. But the fate of sites in which geomorphic change was more gradual would have been more amenable to cultural adaptations. As certain sites became geomorphically marginal, seafarers could have the time to adapt, develop new local knowledge and modify practices. Technologies such as larger ships being used towards the later Norse/early medieval eras would have presented new demands on landing sites and so both stable and changing sites could have fallen into disuse regardless of geomorphic change.

The abandonment of smaller isolated landing places would have had less impact on a region. However, the abandonment of the larger harbours could have had a far more profound and wide-reaching impacts economically and culturally. The stresses places on the use of these harbour sites due to geomorphological change could have made a significant contribution to wider changes in settlement patterns in the North Atlantic. This would have influenced the detailed development of trade networks and nodes in the proto-modern European economy.

While this thesis has demonstrated the ability to analyse and quantify geomorphic changes at known harbour sites, this is due to the knowledge that these sites existed, either known through written sources or archaeological excavations. The physical expression and surface exposure of the harbour sites still exist and thus allows such analyses to take place. However, an acknowledged problem is how to identify enigmatic sites where no visible remains exist due to geomorphic processes that may have eroded them away, buried them or obscured them through sea level change. Indeed, the landing site at Lunda Wick is known through the presence of nausts, which are partially eroded and will likely be lost soon by the continued lateral erosion of the shoreface. Additional sea level rise at Igaliku would eventually obscure the ruin on the inner island.

Thus an ‘absence of evidence’ of a harbour does not necessarily denote an ‘evidence of absence’. Computational modelling is both a strength and a weakness in this regard when applied to archaeology. As discussed in Chapter 2.2, the results of *deterministic* computational modelling can be used to understand coastline changes, whether erosional or depositional in nature, as demonstrated in Chapters 4 and 5. This can highlight areas of a coastline most susceptible to change, and potential areas of coastline that may have been harbours that are now *probably* lost. But model results themselves contain a weakness in that there results can never be definitively proved, and thus are only *probabilistic* in application to the location of harbour sites now lost to geomorphic processes.

9 Conclusions

An anonymously composed quatrain found in the margins of an early Irish monastic manuscript, dated to around 850, reads:

Bitter is the wind tonight
It tosses the ocean's white hair
Tonight I fear not the fierce warriors of Norway
Coursing on the Irish Sea

(source: St. Gallen, Stiftsbibliothek, Cod. Sang. 904: Prisciani grammatical, translation by Kuno Meyer.)

This passage sums up very succinctly the requirements of calm, stable weather for the Norse and later seafarers to successfully navigate their vast North Atlantic realm. A network of known harbours and landing places was an absolute requirement for the Norse provisioning system and economy to function. Many harbours established by the Norse across mainland Europe became important ports and cities that exist today, but many others on the Atlantic islands fade from view, despite the key role played by these regions in providing the bulk commodities of dried fish and wool that were engines of growth for the proto-European economy and the development of the European world system that persists to this day.

My thesis has led to a better understanding the key drivers of coastline evolution over a range of spatial and temporal scales and their significance for the development, continuity and/or decline of Norse and Medieval harbours. I have identified the critical role of offshore slope in determining the stability or instability of beaches, and have also demonstrated how many harbours and landing places were made vulnerable to abandonment by geomorphological processes on various temporal and spatial scales.

9.1 Research answers

In Chapter 1.7, I set out four research questions that guided this thesis. Below are the conclusions reached by the work presented for each research question.

1) What are the conditions necessary for a soft sediment coastline (e.g. beaches, deltas, estuaries) to remain stable over decadal to centennial timescales?

Soft sediment coastlines are the quickest to respond to any change in geomorphological conditions. In Chapter 4, I showed how the stability of headland-dominated pocket beaches on high energy coastlines was a function of both average nearshore slope and climatic variability. Storms have the ability to deplete or completely destroy a sandy beach in a matter of hours. For beaches that have an average nearshore slope shallower than 0.025 m/m, recovery of sand for beach reformation is rapid once calm weather conditions return, and can be considered 'stable' thus beaches may persist over multigenerational timescales. This offers a framework to understand the locational and landform stability of these soft-sediment coastlines. This chapter also adds new findings into the literature of coastal geomorphology by addressing the poorly-research topic of beach location and stability.

2) What are the drivers of instability on exposed, soft sediment coastlines?

The answer to this research question makes a key contribution to the role of geomorphological change in the abandonment of Norse and Medieval harbours. Chapter 4 demonstrated that headland-dominated beaches that have an average nearshore slope of greater than 0.025 m/m cannot recover during stormy conditions, and eventually become depleted in a series of successive storm events. Building on this, I demonstrated how this theoretical innovation in Chapter 5 can be applied in an archaeological context. Two known, but abandoned landing places, on Unst, Lunda Wick and Sandwick, differ in their geomorphic stability. I demonstrated multiple instances of beach instability in these locations through OSL dating of sand deposits. Computational modelling effectively illustrates the distinct differences in the recovery of these beaches and provides a physical rationale for their use as landing places for Norse and Medieval settlers.

3) How does geomorphic setting affect the structural equilibrium of coastlines exploited as harbours along relatively sheltered coastlines?

In Chapters 6 and 7 I demonstrated how the structural equilibrium of two distinct geomorphic settings (Garðar, a rocky coastline located at the head of a fjord, and Gásir, located on a prograding delta in a partially-sheltered fjord) are impacted by two distinct geomorphological forces: sea level rise, and episodic catchment landslide activity. Both sites were large, important trading places in the Norse era, distinct from the smaller beach landing sites explored on Unst. But both sites, due to their geomorphic setting, experienced significant morphological changes that compromised their utility over longer-term timescales. In the case of Greenland these harbour changes at a seat of power could have contributed to the ultimate failure of the Norse Greenland settlement as a whole as it was under stress from a conjunction of disparate pressures. In the case of Iceland, the marginalisation a single (but important) habour had a more limited impact at is was part of a resilient and much bigger system.

4) What is the relationship between harbour sites and coastline stability?

In Chapter 8, I have set out the findings of the previous chapters and discuss the implications of changing spatial and temporal geomorphic change and the loss of harbour sites in light of these. I have presented how known changes in maritime technology and the development of larger boats through the early Medieval changed the anchorage requirements, rendering sites unviable as harbours. I have placed sites into context with each other, showing a relationship between the geomorphic properties of the coastlines at these sites (in terms of soft sediment availability, exposure to climate and oceanic forcing, and temporal scale of geomorphic change). I then placed the sites in context of their geomorphic 'destiny', that is, the likelihood of harbour abandonment due to geomorphic change, and the importance of these harbours to the regional economy. This analysis sheds new light on the role of coastline stability on the viability of harbours in the North Atlantic.

9.2 Impact of thesis research

My thesis contributes both to the field of coastal geomorphology and coastal archaeology, and demonstrates how these two disciplines complement each other to answer fundamental questions about the nature of coastal change and the environmental constraints on cultural adaptation.

9.2.1 Geomorphology as a tool for archaeology

My use of computational coastal sediment transport modelling as a tool to answer archaeological questions addresses some of the ‘grand challenges’ facing current archaeological research as laid out by Kintigh et al. (2014) as set out in Chapter 2.2:

- I have provided an answer to ‘How do humans respond to abrupt environmental change?’ by demonstrating the need to adapt or abandon in the face catastrophic beach loss on Unst.

- The question of ‘How do spatial and material reconfigurations of landscapes and experiential fields affect societal development?’ has been addressed by identifying the scales of disruption to societal development if harbour abandonment was required, depending on the importance of a harbour site. Smaller harbours and landing sites lost would have minor disrupt on a regional scale, but the loss of large trading harbours would have a profound impact on the functioning of the regional economy and society.

- ‘How do humans perceive and react to changes in climate and the natural environment over short- and long-terms?’ has been answered by providing the analysis of *competence* and *technology* as a reaction to geomorphic change at harbour sites.

9.2.2 Archaeology as a tool for geomorphology

What began as a geomorphological approach to answer archaeological questions has led to using an archaeological question to discover new geomorphic theories. New findings about the formation and persistence of beaches on headland-dominated coasts, and the ability to predict which of these may become unstable in the face of storminess, has implications for the discipline of coastal engineering also. As the impacts of climate change are felt more and more, with storminess likely to increase, understanding the controls on beach recovery in the face of this is important to the long-term viability of coastal communities in the vicinity of these beaches today.

My research has also shown that the Norse, in their occupation and utilisation of diverse coastlines, also faced a diverse range of geomorphic pressures to their maritime activities. Abandonment of small landing places such as Lunda Wick would have changed the local settlement dynamic, but unlikely to have impacted further on a regional scale. Abandonment of large harbours such as Gásir and Garðar would likely have a fundamental impact on how trade networks were organised or functioned. For Gásir, establishment of new trade routes and harbours (potentially at Akureyri to the south) to mitigate the loss would be required. More dramatically, however, the decline and abandonment of Garðar contributed to the abandonment of the entire Eastern settlement. This adds to the literature in shedding new light on how patterns of settlement may have evolved and the formation of the proto-modern European economy.

9.2.3 HaNOA

As described in Chapter 1.7, this thesis was conceived initially to fulfil the criteria and stated goals of the Harbours in the North Atlantic project, specifically the criteria of SP 5, delivering answers as to the changing geomorphic nature of known Viking and Medieval harbour sites and the associated impact on these harbours. This has been achieved for the conclusions as listed above. It has also demonstrated how geomorphic techniques such as computational modelling are an important tool for future research into coastal archaeological settings.

9.3 Opportunities for future research

For the study presented in Chapters 4 and applied in Chapter 5, the theory of beach formation and persistence as a function of average nearshore slope can be further advanced by a combination of computational sediment transport modelling using different initial conditions, and long-term field monitoring campaigns in headland-dominated high energy shorelines. Modelling can constrain further the specific physical processes acting upon these embayments, and predict which embayments, based on current theory, will recover and which will not recover. A long-term field monitoring campaign, using techniques such as time-lapse cameras, could record real-time instances of beach destruction and recovery in the face of storms. This data can then be used to further refine computational modelling and further tested against real coastlines.

As mentioned in Chapter 2.2, a limitation of computational sediment transport modelling only allows *probable* changes in coastline to be interpreted from model results, and thus cannot be used to state definitively coastlines changes that would have led to harbour abandonment.

For the study presented in Chapter 6, a long-term tidal gauge, beyond the 15 days of data gathered initially, to constrain the tidal range further could be installed to add resolution to the shoreline reconstruction. A sea level core taken adjacent to Igaliku could also improve the accuracy of the reconstruction and give a definitive map of the morphological evolution of the harbour at Garðar throughout Norse settlement times in Greenland.

For the study presented in Chapter 7, the plausible delta progradation model may be experimentally tested by an extensive field campaign of large-scale sediment coring at Gásir (e.g. Delile et al., 2014; Faisse et al., 2017), and potentially OSL dating methods and tephrochronology to determine the age of landslides. Combined hydrological and fluvial sediment transport models could model the evolution of the delta and show if sediment pulses from landslides had a significant impact on the progradation of the delta. An extensive field campaign to date landslide deposits using tephrochronology can also constrain which particular events may have impacted sediment flux in the channel.

9.4 Concluding remarks

The geomorphology of Viking and Medieval Harbours in the North Atlantic played a crucial role in the long-term survival chances of these harbours. Diverse forces acting upon coastline created multiple challenges for the seafarers who exploited them. Some of these challenges were manageable with the requisite competence and technology available. Some geomorphic forces, however, exceeded the limits of adaptation and thus led to the abandonment of landing places and harbours both small and large. This had profound impacts on the evolution of settlement patterns and centres of population in the North Atlantic region we see today.

10 References

Aagaard, T., and Hughes, M. G. 2017. Equilibrium shoreface profiles: A sediment transport approach. *Marine Geology* DOI:10.1016/j.margeo.2016.12.013

Aagaard, T., Davidson-Arnott, R., Greenwood, B., Nielsen, J., 2004. Sediment supply from shoreface to dunes: linking sediment transport measurements and long-term morphological evolution. *Geomorphology* 60, 205–224. https://doi.org/10.1016/j.geomorph.2003.08.002

Aagaard, T., Orford, J., & Murray, A. S. 2007. Environmental controls on coastal dune formation; Skallingen Spit, Denmark. *Geomorphology*, *83*(1), 29-47.

Amorosi, T., Buckland, P. C., Edwards, K. J., Mainland, I., McGovern, T. H., Sadler, J. P., & Skidmore, P. 1996. They did not live by grass alone: the politics and palaeoecology of animal fodder in the North Atlantic region. *Environmental Archaeology*, *1*(1), 41-54.

Angus, S. 1994. The conservation importance of machair systems of the Scottish islands, with particular reference to the Outer Hebrides. *The islands of Scotland: a living marine heritage*, 95-120.

Anthony, E.J., Vanhee, S., Ruz, M.-H., 2006. Short-term beach–dune sand budgets on the north sea coast of France: Sand supply from shoreface to dunes, and the role of wind and fetch. Geomorphology 81, 316–329. https://doi.org/10.1016/j.geomorph.2006.04.022

Arnalds, O. 2015. *The soils of Iceland*. Dordrecht, The Netherlands: Springer.

Arneborg, J. 2003. Landnám in Greenland. *CONTACT, CONTINUITY, AND COLLAPSE*, 163.

Arneborg, J. 2006: Saga trails - Brattahlið, Garðar, Hvalsey Fjord's Church and Herjolfsnes: four chieftain's farmsteads in the Norse settlement of Greenland. A visitor's guidebook. National Museum of Denmark, Nanortalik Museum, Narsaq Museum and Qaqortoq Museum.

Arneborg, J., Larsen, F., Clemmensen, N.-C., 2009. The "Dairy Farm" of the Hvalsey Fjord Farm. Journal of the North Atlantic 24–29. https://doi.org/10.3721/037.002.s205

Arneborg, J., Lynnerup, N., & Heinemeier, J. 2012. Human diet and subsistence patterns in Norse Greenland C. 980— c. 1450: archaeological interpretations. *Journal of the North Atlantic*, *3*, 119-133.

Ashmore, P., Griffiths, D., 2011. Aeolian archaeology: the archaeology of sand landscapes in Scotland. *Aeolian Archaeology: the Archaeology of Sand Landscapes in Scotland*, 1.

Ashton, A., Murray, A.B., Arnoult, O., 2001. Formation of coastline features by large-scale instabilities induced by high-angle waves. Nature 414, 296–300. https://doi.org/10.1038/35104541

Ashton, A. D., & Murray, A. B. 2006. High-angle wave instability and emergent shoreline shapes: 1. Modeling of sand waves, flying spits, and capes. *Journal of Geophysical Research: Earth Surface*, *111*(F4).

Ashton, A.D., Murray, A.B., 2006b. High-angle wave instability and emergent shoreline shapes: 2. Wave climate analysis and comparisons to nature. Journal of Geophysical Research: Earth Surface 111.

Aunan, K., Romstad, B., 2008. Strong Coasts and Vulnerable Communities: Potential Implications of Accelerated Sea-Level Rise for Norway. Journal of Coastal Research 242, 403–409. https://doi.org/10.2112/07A-0013.1

Austin, M., Masselink, G., O'Hare, T., Russell, P., 2009. Onshore sediment transport on a sandy beach under varied wave conditions: Flow velocity skewness, wave asymmetry or bed ventilation? Marine Geology 259, 86–101. https://doi.org/10.1016/j.margeo.2009.01.001

Bagnold, R. A. 1966. *An approach to the sediment transport problem from general physics*. US government printing office.

Bampton, M., Kelley, A., Kelley, J., Jones, M., & Bigelow, G. 2017. Little Ice Age catastrophic storms and the destruction of a Shetland Island community. *Journal of Archaeological Science*, *87*, 17-29.

Barkwith, A., Hurst, M. D., Thomas, C. W., Ellis, M. A., Limber, P. L., & Murray, A. B. 2014. Coastal vulnerability of a pinned, soft-cliff coastline, II: assessing the influence of sea walls on future morphology. *Earth Surface Dynamics*, *2*(1), 233.

Barlow, L. K., Sadler, J. P., Ogilvie, A. E., Buckland, P. C., Amorosi, T., Ingimundarson, J. H., ... & McGovern, T. H. 1997. Interdisciplinary investigations of the end of the Norse Western Settlement in Greenland. *The Holocene*, *7*(4), 489-499.

Barnard, P.L., Warrick, J.A., 2010. Dramatic beach and nearshore morphological changes due to extreme flooding at a wave-dominated river mouth. Marine Geology 271, 131–148. https://doi.org/10.1016/j.margeo.2010.01.018

Barrett, J. H., & Oltmann, J. 1998. A report on mammal, bird and fish-bone from excavations at Sandwick North, Unst, Shetland, 1995. *Department of Anthropology, University of Toronto, unpublished report*.

Barrett, J.H., Beukens, R.P., Nicholson, R.A., 2001. Diet and ethnicity during the Viking colonization of northern Scotland: evidence from fish bones and stable carbon isotopes. Antiquity 75, 145–154. https://doi.org/10.1017/S0003598X00052844

Bennike, O. & Weidick, A. 2001. Late Quaternary history around Nioghalvfjerdsfjorden and Jøkelbugten, North-East Greenland. Boreas 30, 205_/227.

Bennike, O., Bjorck, S. & Lambeck, K. 2002. Estimates of South Greenland late-glacial ice limits from a new relative sea-level curve. Earth and Planetary Science Letters 197, 171 -186.

Berendsen, H.J.., Stouthamer, E., 2000. Late Weichselian and Holocene palaeogeography of the Rhine–Meuse delta, The Netherlands. Palaeogeography, Palaeoclimatology, Palaeoecology 161, 311–335.

Berkes, F., Colding, J., & Folke, C. 2000. Rediscovery of traditional ecological knowledge as adaptive management. *Ecological application*

Bever, A.J., Harris, C.K., 2014a. Storm and fair-weather driven sediment-transport within Poverty Bay, New Zealand, evaluated using coupled numerical models. Continental Shelf Research, Event Sediment Transport and Sedimentation: Insights from Measurement and Modeling 86, 34–51. https://doi.org/10.1016/j.csr.2013.07.012

Bigelow, G. 1985. Late Norse Shetland Economy'. *Shetland Archaeology.* In Shetland Archaeology: New Work in Shetland in the 1970s. *B. Smith, ed*, 95-127.

Bigelow, G. F. 1989. Life in medieval Shetland: An archaeological perspective. *Hikuin*, *15*, 183-192.

Bigelow, G. F., Ferrante, S. M., Hall, S. T., Kimball, L. M., Proctor, R. E., & Remington, S. L. 2005. Researching catastrophic environmental changes on northern coastlines: a geoarchaeological case study from the Shetland Islands. *Arctic anthropology*, *42*(1), 88-102.

Birks, H. H. (Ed.). 1988. *The cultural landscape: past, present and future*. Cambridge University Press.

Bluck, B.J., 1998. Clast assembling, bed-forms and structure in gravel beaches. Earth and Environmental Science Transactions of the Royal Society of Edinburgh 89, 291–323. https://doi.org/10.1017/S026359330000242X

Bond, J. 2007. Viking Unst Project: Excavations at Hamar and the upper house, Underhoull: Field season 2007 Interim Report no. 2. *Shetland Amenity Trust and University of Bradford, Bradford, UK*.

Bond, J.M. and Dockrill, S.J. 2013. Excavations at Upper House, Underhoull. In Turner, V.E., Bond, J.M. and Larson, A.-C. (eds.). Excavation and Survey in

Northern Shetland 2006-2010. Viking Unst. Lerwick: Shetland Heritage Publications. 156-165.

Bowen, A. J. 1984, Simple models of nearshore sedimentation; beach profiles and longshore bars, *The Coastline of Canada* SB McCann. Pap. Geol. Surv. Can, 80-10.

Bromhead, E. N., & Ibsen, M. L. 2006. A review of landsliding and coastal erosion damage to historic fortifications in South East England. *Landslides*, *3*(4), 341.

Brown, A.G., Carey, C., Erkens, G., Fuchs, M., Hoffmann, T., Macaire, J.-J., Moldenhauer, K.-M., Walling, D.E., 2009. From sedimentary records to sediment budgets: Multiple approaches to catchment sediment flux. Geomorphology 108, 35–47. https://doi.org/10.1016/j.geomorph.2008.01.021

Buckland, P. C., Edwards, K. J., Panagiotakopulu, E., & Schofield, J. E. 2009. Palaeoecological and historical evidence for manuring and irrigation at Garðar (Igaliku), Norse Eastern Settlement, Greenland. *The Holocene*, *19*(1), 105-116.

Bühler, O. and Jacobson, T.E., 2001. Wave-driven currents and vortex dynamics on barred beaches. *Journal of Fluid Mechanics 449*: 313-339.

Buscombe, D. and Masselink, G., 2006. Concepts in gravel beach dynamics. *Earth-Science Reviews*, *79*(1), pp.33-52.

Buttler, S. , 1988. Steatite in Norse Shetland. *Hikuin*, *15*, 193-206.

Butzer, K.W., 2012. Collapse, environment, and society. PNAS 201114845. https://doi.org/10.1073/pnas.1114845109

Carmona, P., Ruiz, J.M., 2008. Geoarchaeological study of the Phoenician cemetery of Tyre-Al Bass (Lebanon) and geomorphological evolution of a tombolo. Geoarchaeology 23, 334–350. https://doi.org/10.1002/gea.20202

Cayocca, F., 2001. Long-term morphological modeling of a tidal inlet: the Arcachon Basin, France. Coast. Eng. 42, 115–142. https://doi.org/10.1016/S0378-3839(00)00053-3

Chaaban, F., Darwishe, H., Battiau-Queney, Y., Louche, B., Massont, E., Khattabi, J.E., Carlier, E., 2012. Using ArcGIS® Modelbuilder and Aerial Photographs to Measure Coastline Retreat and Advance: North of France. Journal of Coastal Research 28, 1567–1579. https://doi.org/10.2112/JCOASTRES-D-11-00054.1

Chou, Yi-Ju, et al. 2015. Three-dimensional wave-coupled hydrodynamics modeling in South San Francisco Bay. *Computers & Geosciences* 85: 10-21.

Christensen, A. E. 1982. Viking age ships and shipbuilding. *Norwegian Archaeological Review*, *15*(1), 19-28.

Church, M. J., Dugmore, A. J., Mairs, K. A., Millard, A. R., Cook, G. T., Sveinbjarnardóttir, G., Ascough, P. A., Newton, A.J and Roucoux, K., 2007 'Timing and mechanisms of deforestation of the settlement period in Eyjafjallsveit, southern Iceland. Radiocarbon 49(2): 659-672.

Ciavola, P., Ferreira, O., Dongeren, A.V., Vries, J.V.T. de, Armaroli, C., Harley, M., 2014. Prediction of Storm Impacts on Beach and Dune Systems, in: Quevauviller, P. (Ed.), Hydrometeorological Hazards. John Wiley & Sons, Ltd, pp. 227–252.

Clark, C. D., Hughes, A. L., Greenwood, S. L., Jordan, C., & Sejrup, H. P. 2012. Pattern and timing of retreat of the last British-Irish Ice Sheet. *Quaternary Science Reviews* 44: 112-146.

Collins, A.L., Walling, D.E., 2004. Documenting catchment suspended sediment sources: problems, approaches and prospects. Progress in Physical Geography 28, 159–196. https://doi.org/10.1191/0309133304pp409ra

Cooper, J. A. G., Jackson, D. W. T., Navas, F., McKenna, J., & Malvarez, G. 2004. Identifying storm impacts on an embayed, high-energy coastline: examples from western Ireland. *Marine Geology 210*(1): 261-280.

Coquin, J., Mercier, D., Bourgeois, O., Cossart, E., & Decaulne, A. 2015. Gravitational spreading of mountain ridges coeval with Late Weichselian deglaciation: impact on glacial landscapes in Tröllaskagi, northern Iceland. *Quaternary Science Reviews*, *107*, 197-213.

Cowell, P.J., Roy, P.S., Jones, R.A., 1995. Simulation of large-scale coastal change using a morphological behaviour model. Marine Geology 126, 45–61. https://doi.org/10.1016/0025-3227(95)00065-7

Cruden, D. M., & Varnes, D. J. 1996. Landslides: investigation and mitigation. Chapter 3-Landslide types and processes. *Transportation research board special report*, (247).

Crumlin-Pedersen, O. 1978. The ships of the Vikings. *The Vikings*, *335*, 32-41.

Crumlin-Pedersen, O. 1991. Ship types and sizes 800–1400. *Aspects of Maritime Scandinavia 200*, *1200*, 69-82.

Crumlin-Pedersen, O. 1997. *Viking-age ships and shipbuilding in Hedeby/Haithabu and Schleswig* (Vol. 2). Viking Ship Museum/National Museum of Denmark.

Crumlin-Pedersen, O. 2000. To be or not to be a cog: the Bremen Cog in perspective. *International Journal of Nautical Archaeology*, *29*(2), 230-246.

Crumlin-Pedersen, O. 2009. Boat And Boat House. The Conceptional Origins Of Clinker Boats And Boat-Shaped Halls Of The Fourth To Eleventh Centuries In

Scandinavia. In *Creating Shapes in Civil and Naval Architecture* (pp. 194-213). Brill.

Crumlin-Pedersen, O., Bondesen, E., & Olsen, O. 2002. *The Skuldelev ships I: topography, archaeology, history, conservation and display*. Viking Ship Museum.

Cunliffe, B. W. 2001. Facing the ocean: the Atlantic and its peoples, 8000 BC-1500. Oxford University Press

da Silva, G.V., Toldo, E.E., Klein, A.H.D.F., Short, A.D. and Woodroffe, C.D., 2016. Headland sand bypassing—Quantification of net sediment transport in embayed beaches, Santa Catarina Island North Shore, Southern Brazil. *Marine Geology 379*: 13-27.

Dahl, M. P., Mortensen, L. E., Veihe, A., & Jensen, N. H. 2010. A simple qualitative approach for mapping regional landslide susceptibility in the Faroe Islands. *Natural Hazards and Earth System Sciences*, *10*(2), 159-170.

Danish Hydrological Institute (DHI), 2014. MIKE21 User Manual, Agem Alle 5, DK-2970 Hersholm, Denmark (mikebydhi.com)

Davidson, D. A., & Carter, S. P. 1998. Micromorphological evidence of past agricultural practices in cultivated soils: the impact of a traditional agricultural system on soils in Papa Stour, Shetland. *Journal of Archaeological Science*, *25*(9), 827-838.

Davidson, H. R. E. 1964. *Gods and myths of northern Europe*. Penguin UK.

Dawson, A. G., Hickey, K., Mayewski, P. A., & Nesje, A. 2007. Greenland (GISP2) ice core and historical indicators of complex North Atlantic climate changes during the fourteenth century. *The Holocene*, *17*(4), 427-434.

Dawson, H. 2013. *Mediterranean voyages: The archaeology of island colonisation and abandonment* (Vol. 62). Left Coast Press.

Dawson, S., Smith, D. E., Jordan, J., & Dawson, A. G. 2004. Late Holocene coastal sand movements in the Outer Hebrides, NW Scotland. *Marine Geology*, *210*(1), 281-306.

Dawson, S., Dawson, A. G., Jordan, J. T., Street, P., & Coventry, C. V. 2011. North Atlantic climate change and Late Holocene windstorm activity in the Outer Hebrides, Scotland. *Aeolian Archaeology: the Archaeology of Sand Landscapes in Scotland*, 25.

Dawson, S., Powell, V.A., Duck, R.W. and McGlashan, D.J., 2013. Discussion of Rennie, AF and Hansom, JD 2011. Sea level trend reversal: Land uplift outpaced by sea level rise on Scotland's coast. Geomorphology, 125 (1), 193-202. Geomorphology, 197, pp.185-186.

Dawson, T. 2013. Erosion and coastal archaeology: Evaluating the threat and prioritising action. *Ancient Maritime Communities and the Relationship between People and Environment along the European Atlantic Coasts*.

Dean, R.G., Dalrymple, R.A., 1991. Water Wave Mechanics for Engineers and Scientists. Advanced Series on Ocean Engineering vol. 2. World Scientific, River Edge, NJ, pp. 193.

Decaulne, A., Cossart, E., Mercier, D., Feuillet, T., Coquin, J., & Jónsson, H. P. 2016. An early Holocene age for the Vatn landslide (Skagafjörður, central northern Iceland): Insights into the role of postglacial landsliding on slope development. *The Holocene*, *26*(8), 1304-1318.

Delile, H., Mazzini, I., Blichert-Toft, J., Goiran, J. P., Arnaud-Godet, F., Salomon, F., & Albarède, F. 2014. Geochemical investigation of a sediment core from the Trajan basin at Portus, the harbor of ancient Rome. *Quaternary Science Reviews*, *87*, 34-45.

Diamond, J. 2005. *Collapse: How societies choose to fail or succeed*. Penguin.

Dietrich, W.E., Perron, J.T., 2006. The search for a topographic signature of life. Nature 439, 411–418.

Dixon, J. B. 1998. Roles of clay and oxide minerals in soils. In *Environmental interactions of clays* (pp. 37-53). Springer Berlin Heidelberg.

Duczko, W. 2004. Viking Rus: Studies on the Presence of Scandinavians in Eastern Europe. Leiden: Brill.

Dugmore, A.J., Church, M.J., Buckland, P.C., Edwards, K.J., Lawson, I., McGovern, T.H., Panagiotakopulu, E., Simpson, I.A., Skidmore, P. and Sveinbjarnardóttir, G., 2005. The Norse landnám on the North Atlantic islands: an environmental impact assessment. *Polar Record*, *41*(1), pp.21-37.

Dugmore, A.J., Borthwick, D.M., Church, M.J., Dawson, A., Edwards, K.J., Keller, C., Mayewski, P., McGovern, T.H., Mairs, K.A., and Sveinbjarnardóttir, G. 2007a The role of climate in settlement and landscape change in the North Atlantic islands: an assessment of cumulative deviations in high-resolution proxy climate records.' *Human Ecology* 35, 2, 169-178

Dugmore, A.J., Church, M.J., Mairs, K.-A., McGovern, T.H., Perdikaris, S., Vésteinsson, O., 2007b. Abandoned Farms, Volcanic Impacts, and Woodland Management: Revisiting Þjórsárdalur, the “Pompeii of Iceland.” Arctic Anthropology 44, 1–11. https://doi.org/10.2307/40316682

Dugmore, A. J., Keller, C., & McGovern, T. H. 2007c. Norse Greenland settlement: reflections on climate change, trade, and the contrasting fates of human settlements in the North Atlantic islands. *Arctic anthropology*, *44*(1), 12-36.

Dugmore, A. J., Keller, C., McGovern, T. H., Casely, A. F., & Smiarowski, K. 2009. Norse Greenland settlement and limits to adaptation. *Adapting to Climate Change: Thresholds, Values, Governance. Cambridge University Press, Cambridge*, 9.

Dugmore, A. J., Casely, A. F., Keller, C.and McGovern, T.H. 2010 'Conceptual modelling of seafaring, climate and early European exploration and settlement of the North Atlantic Islands' In Anderson, A. Barrett, J.H. and Boyle, K.V. (eds.) *Global Origins and Development of Seafaring*, Monograph Series Macdonald Institute, University of Cambridge 213-229

Dugmore, A. J., McGovern, T. H., Vésteinsson, O., Arneborg, J., Streeter, R., & Keller, C. 2012. Cultural adaptation, compounding vulnerabilities and conjunctures in Norse Greenland. *Proceedings of the National Academy of Sciences*, *109*(10), 3658-3663.

Dyer, C., Outram, J., Turner, V. E. 2013. Gazetteer of Longhouses in Unst. *In* Viking Unst: Excavation and Survey in Northern Shetland 2006 – 2010. Lerwick: Shetland Heritage Publications. 109 - 121.

Edwards, T. W., Hammarlund, D., Newton, B. W., Sjolte, J., Linderson, H., Sturm, C., Nilsson, A. L. 2017. Seasonal variability in Northern Hemisphere atmospheric circulation during the Medieval Climate Anomaly and the Little Ice Age. *Quaternary Science Reviews*, *165*, 102-110.

Engelund, F., & Fredsøe, J. 1976. A sediment transport model for straight alluvial channels. *Hydrology Research 7*(5): 293-306.

Etting, V. 2009. The Rediscovery of Greenland During the Reign of Christian IV. *Journal of the North Atlantic*, *2*, 151-160.

Everest, J. D., Bradwell, T., Stoker, M., & Dewey, S. 2013. New age constraints for the maximum extent of the last British–Irish Ice Sheet (NW sector). *Journal of Quaternary Science*, *28*(1), 2-7.

Faïsse, C., Mathé, V., Bruniaux, G., Labussière, J., Cavero, J., Jézégou, M. P., Sanchez, C. 2017. Palaeoenvironmental and archaeological records for the reconstruction of the ancient landscape of the Roman harbour of Narbonne (Aude, France). *Quaternary International*.

Falqués, A. and Calvete, D., 2005. Large-scale dynamics of sandy coastlines: Diffusivity and instability. *Journal of Geophysical Research: Oceans*, *110*(C3).

Faulkner, D., 1999. Flood estimation handbook Volume 2: rainfall frequency estimation [WWW Document].

Feeley, F.,2012. *Mammal Consumption at the Medieval Fishing Station at Gufuskálar* (No. 62). NORSEC Zooarchaeology Laboratory Report.

Feuillet, T., Coquin, J., Mercier, D., Cossart, E., Decaulne, A., Jónsson, H. P., & Sæmundsson, Þ. 2014. Focusing on the spatial non-stationarity of landslide predisposing factors in northern Iceland: Do paraglacial factors vary over space?. *Progress in Physical Geography*, *38*(3), 354-377.

Fitton, J. M., Hansom, J. D., Rennie, A. F. 2016. A national coastal erosion susceptibility model for Scotland. *Ocean & Coastal Management 132*: 80-89.

Fitzhugh, W. W., & Ward, E. I. (Eds.). 2000. *Vikings: The North Atlantic Saga* (pp. 1-432). Washington, DC: Smithsonian Institution Press.

Fleming, K., Lambeck, K., 2004. Constraints on the Greenland Ice Sheet since the Last Glacial Maximum from sea-level observations and glacial-rebound models. Quaternary Science Reviews 23, 1053–1077. https://doi.org/10.1016/j.quascirev.2003.11.001

Fojut, N. 2006. *Prehistoric and Viking Shetland*. Shetland Times Limited.

Forbes, D.L., Parkes, G.S., Manson, G.K. and Ketch, L.A., 2004. Storms and shoreline retreat in the southern Gulf of St. Lawrence. *Marine Geology 210*(1):169-204.

Fredsoe, J., Andersen, O. H., & Silberg, S. 1985. Distribution of suspended sediment in large waves. *Journal of Waterway, Port, Coastal, and Ocean Engineering 111*(6): 1041-1059.

Frei, K. M., Coutu, A. N., Smiarowski, K., Harrison, R., Madsen, C. K., Arneborg, J., ... & Hartman, S. 2015. Was it for walrus? Viking Age settlement and medieval walrus ivory trade in Iceland and Greenland. *World Archaeology*, *47*(3), 439-466.

Funder, S., Hansen, L., 1996. The Greenland ice sheet—a model for its culmination and decay during and after the last glacial maximum. *Bulletin of the Geological Society of Denmark*, *42*(2), 137-152.

G. J. Marcus , "Hafvilla: A Note on Norse Navigation," *Speculum* 30, no. 4. Oct., 1955: 601-605.

Gad, F. 1970. A History of Greenland, Vol. 1. Hurst and Co., London.

Gallagher, E.L., Elgar, S., Guza, R.T., 1998. Observations of sand bar evolution on a natural beach. J. Geophys. Res. 103, 3203–3215. https://doi.org/10.1029/97JC02765

Garrett, B.L., 2011. Assaying history: creating temporal junctions through urban exploration. Environment and Planning D: Society and Space 29, 1048–1067. https://doi.org/10.1068/d18010

Gehrels, W.R., Marshall, W.A., Gehrels, M.J., Larsen, G., Kirby, J.R., Eiríksson, J., Heinemeier, J., Shimmield, T., 2006. Rapid sea-level rise in the North Atlantic Ocean since the first half of the nineteenth century. The Holocene 16, 949–965. https://doi.org/10.1177/0959683606hl986rp

Gehrels, W.R., 2010. Late Holocene land- and sea-level changes in the British Isles: implications for future sea-level predictions. Quaternary Science Reviews, Climate Variability of the British Isles and Adjoining Seas 29, 1648–1660. https://doi.org/10.1016/j.quascirev.2009.09.015

Goosse, H., Guiot, J., Mann, M. E., Dubinkina, S., & Sallaz-Damaz, Y. 2012. The medieval climate anomaly in Europe: Comparison of the summer and annual mean signals in two reconstructions and in simulations with data assimilation. *Global and Planetary Change*, *84*, 35-47.

Gopalakrishnan, S., Smith, M.D., Slott, J.M. and Murray, A.B., 2011. The value of disappearing beaches: a hedonic pricing model with endogenous beach width. *Journal of Environmental Economics and Management 61*(3): 297-310.

Gordon, E. V. 1981. An Introduction to Old Norse.

Graham, A. 1969. *Archaeological notes on some harbours in Eastern Scotland*. National Museum of Antiquities.

Graham, E., Hambly, J., & Dawson, T. 2017. Learning from Loss: Eroding Coastal Heritage in Scotland. *Humanities*, *6*(4), 87.

Griffiths, D. 2015. Medieval Coastal Sand Inundation in Britain and Ireland. *Medieval Archaeology*, *59*(1), 103-121.Guttesen, R. 1992. New Geographical and Historical Information from Lucas Janz Waghenaer's Faroe-chart. *Geografisk Tidsskrift-Danish Journal of Geography*, *92*(1), 22-28.

Groen, P. & Dorrestein, R., 1976. *Zeegolven*. KNMI Opstellen op oceanografisch en maritiem meteorologisch gebied 11. Koninklijk Nederlands Meteorologisch Instituut.

Guðmundsson, G. J. 2009. Greenland and the wider World. *Journal of the North Atlantic*, *2*(sp2), 66-73.

Günther, F., Overduin, P.P., Sandakov, A.V., Grosse, G., Grigoriev, M.N., 2013. Short and long-term thermo-erosion of ice-rich permafrost coasts in the Laptev Sea region. Biogeosciences Discussions 10, 2705–2765. https://doi.org/10.5194/bgd-10-2705-2013

Hadley, D. 2006. *The Vikings in England: settlement, society and culture*. Manchester University Press.

Haine, T. 2008. “What Did the Viking Discoverers of America Know of the North Atlantic Environment?” Weather 63: 60–5

Hall, R. 2005. *Exploring the World of the Vikings*. Thames and Hudson

Hansen, S. S. 1991. Toftanes: a Faroese Viking age farmstead from the 9–10th centuries . *Acta Archaeologica*, *61*, 44-53.

Hansen, S. S. 2000. Viking settlement in Shetland. *Acta Archaeologica*, *71*(1), 87-103.

Harley, M. D., Turner, I. L., Short, A. D., & Ranasinghe, R., 2011. Assessment and integration of conventional, RTK-GPS and image-derived beach survey methods for daily to decadal coastal monitoring. *Coastal Engineering*, *58*(2), 194-205.

Harrison, R., Roberts, H. M., & Adderley, W. P. 2008. Gásir in Eyjafjörđur: International Exchange and Local Economy in Medieval Iceland. *Journal of the North Atlantic*, *1*(1), 99-119.

Harrison, R. 2010. Gásir Hinterlands Project 2009 Midden Prospection and Excavation. *FSÍ (Fornleifastofnun Íslands/Icelandic Archaeological Institute), Reykjavík and NORSEC, New York, FS440-06384*.

Harrison, R., Robots, H. M., 2014, Preliminary Field Report of the 2013 Skuggi and Staðartunga Excavations in Hörgárdalur, Eyjafjörður, FS538-06384, FSÍ, Reykjavík and CUNY NORSEC, New York

Harrison, R. 2014. Connecting the land to the sea at Gásir. *Long-term Human Ecodynamics in the North Atlantic: An Archaeological Study, Lexington Publishers, Lanham, Maryland*, 117-136.

Heath, B. 2005. *Discovering the Great South Land*. Rosenberg Pub Pty Limited.

Hewitt, K., 2006. Disturbance regime landscapes: mountain drainage systems interrupted by large rockslides. Progress in Physical Geography 30, 365–393. https://doi.org/10.1191/0309133306pp486ra

Holthuijsen, L. 1998. Waves in shallow water. In: World Meteorological Organization, Guide to wave analysis and forecasting (Geneva ^{2}1998): 81–88

Houser, C., 2013. Alongshore variation in the morphology of coastal dunes: Implications for storm response. *Geomorphology*, *199*: 48-61.

Houser, C., Hapke, C., Hamilton, S., 2008. Controls on coastal dune morphology, shoreline erosion and barrier island response to extreme storms. Geomorphology 100, 223–240. https://doi.org/10.1016/j.geomorph.2007.12.007

Hovius, N., Stark, C.P., Allen, P.A., 1997. Sediment flux from a mountain belt derived by landslide mapping. Geology 25, 231–234. https://doi.org/10.1130/0091-7613(1997)025<0231:SFFAMB>2.3.CO;2

Hubbard, A., Bradwell, T., Golledge, N., Hall, A., Patton, H., Sugden, D., Cooper, R. and Stoker, M., 2009. Dynamic cycles, ice streams and their impact on the extent, chronology and deglaciation of the British–Irish ice sheet. *Quaternary Science Reviews*, *28*(7-8), pp.758-776.

Hurst, M. D., Barkwith, A., Ellis, M. A., Thomas, C. W., & Murray, A. B., 2015. Exploring the sensitivities of crenulate bay shorelines to wave climates using a new vector-based one-line model. *Journal of Geophysical Research: Earth Surface*, *120*(12), 2586-2608.

Hurst, M.D., Rood, D.H., Ellis, M.A., Anderson, R.S. and Dornbusch, U., 2016. Recent acceleration in coastal cliff retreat rates on the south coast of Great Britain. *Proceedings of the National Academy of Sciences*, p.201613044.

Imsen, S. (Ed.). 2010. *The Norwegian Domination and the Norse World, C. 1100-c. 1400* (Vol. 3). Tapir Academic Press.

Inglis, J. (Ed.). 1993. *Traditional ecological knowledge: concepts and cases*. IDRC.

IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

ISOR, 2017, Iceland GeoSurvey Geological Web Map, http://jardfraedikort.is/index_enska.html, accessed 01/09/2016.

Iverson, R. M. 2000. Landslide triggering by rain infiltration. *Water resources research*, *36*(7), 1897-1910.

Jackson, D.W.T., Cooper, J.A.G. and Del Rio, L., 2005. Geological control of beach morphodynamic state. *Marine Geology 216*(4): 297-314.

Jones, O.P., Simons, R.R., Jones, E.J.W., Harris, J.M., 2006. Influence of seabed slope and Coriolis effects on the development of sandbanks near headlands. J. Geophys. Res. 111, C03020. https://doi.org/10.1029/2005JC002944

Jónsson, S., & Ágústsson, K. 2005. Landslides in Iceland Studied using SAR Interferometry. In *Envisat & ERS Symposium*(Vol. 572).

Keen, T.R., Beavers, R.L., Howd, P.A. and Hathaway, K., 2003. Shoreface sedimentation during a northeaster at Duck, North Carolina, USA *Journal of Coastal Research* 19(1):24-40.

Kemp, A.C., Horton, B.P., Donnelly, J.P., Mann, M.E., Vermeer, M., Rahmstorf, S., 2011. Climate related sea-level variations over the past two millennia. Proceedings of the National Academy of Sciences 108, 11017–11022.

Kendall, A. 2014. Material Culture and North Atlantic Trade in Iceland and Greenland. *Human Ecodynamics in the North Atlantic: A Collaborative Model of Humans and Nature through Space and Time*, 101.

Kennedy, D.M., Milkins, J., 2015. The formation of beaches on shore platforms in microtidal environments. Earth Surf. Process. Landforms 40, 34–46. https://doi.org/10.1002/esp.3610

Kidmo, D. K., Danwe, R., Doka, S. Y., & Djongyang, N. 2015. Statistical analysis of wind speed distribution based on six Weibull Methods for wind power evaluation in Garoua, Cameroon. *Revue des Energies Renouvelables 18*(1): 105-125.

Kinnaird, T. C., Sanderson, D. C., & Bigelow, G. 2014. Luminescence Dating of Windblown Sands from Archaeological Sites in Shetland (Early Modern Farmstead, Broo Peninsula; Norse settlement, Sandwick South, Unst).

Kinnaird, T.C., Sanderson, D.C.W., Bigelow, G.F., 2015. Feldspar SARA IRSL dating of very low dose rate aeolian sediments from Sandwick South, Unst, Shetland. Quaternary Geochronology, LED14 Proceedings 30, Part B, 168–174. https://doi.org/10.1016/j.quageo.2015.02.019

Kinnaird, T. C., Sanderson, D. C. W., Preston, J., Dugmore, A. J., & Newton, A. J. 2017. Luminescence dating of sediments from Lunda Wick and Lund, Unst, Shetland. *University of Glasgow EnLighten Publications*.

Kirkbride, M. P., & Dugmore, A. J. 2005. Late Holocene solifluction history reconstructed using tephrochronology. *Geological Society, London, Special Publications*, *242*(1), 145-155.

Koch, L. (1945). *The east Greenland ice*. CA Reitzels Forlag.

Kraus, N. C., Larson, M., & Wise, R. A. 1998. *Depth of closure in beach-fill design* (No. CETN-II-40). Army Engineer Waterways Experiment Station Vicksburg MS Coastal and Hydraulics Lab.

Krogh, K. J., 1982. Erik den rødes Grønland. Nationalmuseets Forlag.

Krzewińska, M., Bjørnstad, G., Skoglund, P., Olason, P.I., Bill, J., Götherström, A. and Hagelberg, E., 2015. Mitochondrial DNA variation in the Viking age population of Norway. *Phil. Trans. R. Soc. B*, *370*(1660), p.20130384.

Kuijpers, A., Abrahamsen, N., Hoffmann, G., Hühnerbach, V., Konradi, P., Kunzendorf, H., Weinrebe, W. 1999. Climate change and the Viking-age fjord environment of the Eastern Settlement, South Greenland. *Geology of Greenland Survey Bulletin-Review of Greenland Activities*, *183*, 61-67.

Lamb, H. H. 1965. The early medieval warm epoch and its sequel. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *1*, 13-37.

Lamb, H. H. (1982). The climatic environment of the Arctic Ocean. In *The Arctic Ocean* (pp. 135-161). Palgrave Macmillan, London.

Lambeck, K. (1995). Late Devensian and Holocene shorelines of the British Isles and North Sea from models of glacio-hydro-isostatic rebound. *Journal of the Geological Society*, *152*(3), 437-448.

Lassen, S. J., Kuijpers, A., Kunzendorf, H., Hoffmann-Wieck, G., Mikkelsen, N., & Konradi, P. 2004. Late-Holocene Atlantic bottom-water variability in Igaliku Fjord, South Greenland, reconstructed from foraminifera faunas. *The Holocene*, *14*(2), 165-171.

Lauer, M., & Aswani, S. 2009. Indigenous ecological knowledge as situated practices: understanding fishers' knowledge in the western Solomon Islands. *American Anthropologist*, *111*(3), 317-329.

Laxness, H. 2009. *Independent people*. Vintage.

Lazarus, E.D., Murray, A.B., 2007. Process signatures in regional patterns of shoreline change on annual to decadal time scales. Geophysical Research Letters 34. https://doi.org/10.1029/2007GL031047

Leach, H.M., 1999. Intensification in the Pacific: A Critique of the Archaeological Criteria and Their Application. Current Anthropology 40, 311–340. https://doi.org/10.1086/200021

Lim, D.I., Choi, J.Y., Jung, H.S., 2009. Sea-cliff Erosion and Retreat in Semi-enclosed Macrotidal Embayment: Hampyung Bay, West Coast of Korea. Journal of Coastal Research 732–736.

Lim, M., Rosser, N.J., Allison, R.J., Petley, D.N., 2010. Erosional processes in the hard rock coastal cliffs at Staithes, North Yorkshire. Geomorphology 114, 12–21. https://doi.org/10.1016/j.geomorph.2009.02.011

Lim, M., Rosser, N.J., Allison, R.J., Petley, D.N., 2010. Erosional processes in the hard rock coastal cliffs at Staithes, North Yorkshire. Geomorphology 114, 12–21.

Limber, P.W., Murray, A.B., 2011. Beach and sea-cliff dynamics as a driver of long-term rocky coastline evolution and stability. Geology 39, 1147–1150. https://doi.org/10.1130/G32315.1

Lindow, J. 2002. *Norse Mythology: A Guide to Gods, Heroes, Rituals, and Beliefs*. Oxford University Press.

Liu, X., Dong, Z., Wang, X., 2006. Wind tunnel modeling and measurements of the flux of wind-blown sand. Journal of Arid Environments 66, 657–672. https://doi.org/10.1016/j.jaridenv.2005.11.010

Lloyd, J.M., Norðdahl, H., Bentley, M.J., Newton, A.J., Tucker, O., Zong, Y., 2009. Lateglacial to Holocene relative sea-level changes in the Bjarkarlundur area near Reykhólar, North West Iceland. J. Quaternary Sci. 24, 816–831. https://doi.org/10.1002/jqs.1272

Lloyd, J.M., Zong, Y., Fish, P., Innes, J.B., 2013. Holocene and Lateglacial relative sea-level change in north-west England: implications for glacial isostatic adjustment models. J. Quaternary Sci. 28, 59–70. https://doi.org/10.1002/jqs.2587

Long, A. J., Innes, J. B., Kirby, J. R., Lloyd, J. M., Rutherford, M. M., Shennan, I., & Tooley, M. J. 1998. Holocene sea-level change and coastal evolution in the Humber estuary, eastern England: an assessment of rapid coastal change. *The Holocene*, *8*(2), 229-247.

Long, A. J., Woodroffe, S. A., Roberts, D. H., & Dawson, S. 2011. Isolation basins, sea-level changes and the Holocene history of the Greenland Ice Sheet. *Quaternary Science Reviews*, *30*(27), 3748-3768.

Løset, J. O., 2004. Vikingskip og norske trebåter/Viking ships and Norse wooden boats (http://www.vikingskip.com/index.htm, accessed on 02/11/2017)

Lowe, C., & Boardman, S. 1998. *Coastal erosion and the archaeological assessment of an eroding shoreline at St Boniface Church, Papa Westray, Orkney*. Sutton.

Madsen, O. S., Grant, W. D. 1976. *Sediment transport in the coastal environment* (Vol. 209). Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics, Dept. of Civil Engineering, Massachusetts Institute of Technology.

Mäkiaho, J.-P., 2007. Estimation of ancient and future shoreline positions in the vicinity of Olkiluoto, an island on the western coast of Finland: The difference between Grid and TIN based GIS-approaches. Palaeogeography, Palaeoclimatology, Palaeoecology 252, 514–529. https://doi.org/10.1016/j.palaeo.2007.05.009

Mann, M. E., Jones, P. D. 2003. Global surface temperatures over the past two millennia. *Geophysical Research Letters* 30

Mann, M. E. 2002. Little ice age. *Encyclopedia of global environmental change*, *1*, 504-509.

Mann, M. E., Zhang, Z., Rutherford, S., Bradley, R. S., Hughes, M. K., Shindell, D., Ammann, C., Faluvegi, G., Ni, F. 2009. Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. *Science*, 326(5957), 1256-1260

Manson, G.K., 2012. Configuration of Mike21 for the Simulation of Nearshore Storm Waves, Currents and Sediment Transport: Brackley Bight, Prince Edward Island. *Ottawa: Geological Survey of Canada. Geological Survey of Canada Open File*, *6736*.

Manson, G.K., Davidson-Arnott, R.G.D., Forbes, D.L., 2015. Modelled nearshore sediment transport in open-water conditions, central north shore of Prince Edward Island, Canada. Can. J. Earth Sci. 53, 101–118. https://doi.org/10.1139/cjes-2015-0090

Marcus, G. T. 1960. The early Norse traffic to Iceland. *The Mariner's Mirror*, *46*(3), 174-181.

Marriner, N., Morhange, C., Boudagher-Fadel, M., Bourcier, M., & Carbonel, P. 2005. Geoarchaeology of Tyre's ancient northern harbour, Phoenicia. *Journal of Archaeological Science*, *32*(9), 1302-1327.

Marriner, N., Morhange, C., 2007. Geoscience of ancient Mediterranean harbours. *Earth-Science Reviews* 80, 137–194. https://doi.org/10.1016/j.earscirev.2006.10.003

Marriner, N., Morhange, C., Carayon, N., 2008. Ancient Tyre and its harbours: 5000 years of human-environment interactions. Journal of Archaeological Science 35, 1281–1310. https://doi.org/10.1016/j.jas.2007.09.003

Marriner, N., Morhange, C., & Goiran, J. P. 2010. Coastal and ancient harbour geoarchaeology. *Geology Today*, *26*(1), 21-27.

Martin, C. 2009. Rubh’ an Dúnain, Bracadale, Skye – Data Structure Report, September 2009, RCAHMS

Marttila, J. 2016. Resources, Production, and Trade in the Norse Shetland. *Journal of the North Atlantic*, (29), 1-20.

Maspataud, A., Ruz, M.H. and Héquette, A., 2009. Spatial variability in post-storm beach recovery along a macrotidal barred beach, southern North Sea. *Journal of Coastal Research* 1:88-92.

Masselink, G. and Short, A.D., 1993. The effect of tide range on beach morphodynamics and morphology: a conceptual beach model. *Journal of Coastal Research 9*(3): 785-800.

Masselink, G. and Pattiaratchi, C.B., 2001. Seasonal changes in beach morphology along the sheltered coastline of Perth, Western Australia. *Marine Geology 172*(3): 243-263.

McGovern, T. H. 1980. Cows, harp seals, and churchbells: Adaptation and extinction in Norse Greenland. *Human Ecology*, *8*(3), 245-275.

McGovern, T. H. 1985. The arctic frontier of Norse Greenland. *The archaeology of frontiers and boundaries*, 275-323.

McGovern, T.H. 1990. The Archeology of the Norse North Atlantic. Annual Review of Anthropology 19, 331–351. https://doi.org/10.1146/annurev.an.19.100190.001555

McGrail, S. 1998. Ancient Boats in North-West Europe. Routledge

McGrail, S. 2014. *Ancient Boats in North-West Europe: The archaeology of water transport to 1500*. Routledge.

Meeker, L. D., Mayewski, P. A. 2002 'A 1,400-year high resolution record of atmospheric circulation over the North Atlantic and Asia', *The Holocene* 12, 257–66.

Mehler, N., 2009. The perception and interpretation of Hanseatic material culture in the North Atlantic: problems and suggestions. *Journal of the North Atlantic*, *2*(sp1), pp.89-108.

Mehler, N. and Gardiner, M., 2013. On the verge of colonialism: English and Hanseatic trade in the North Atlantic islands. *Exploring Atlantic transitions*, pp.1-14.

Mehler, N., 2014. Hanse Archaeology. In *Encyclopedia of Global Archaeology* (pp. 3209-3219). Springer New York.

Mehler, N., Gardiner, M., Dugmore, A., & Coolen, J. 2015. 'The Elusive Norse Harbours of the North Atlantic: Why they were abandoned, and why they are so hard to find.' In: Schmidts, Th., & Vučetić, M. (eds.), Häfen Im 1. Millennium . Bauliche Konzepte, herrschaftliche und religiöse Einflüsse, 313–321. RGZM Tagungen 22. Mainz: Verlag des Römisch-Germanischen Zentralmuseums.

Melin, E. 2005. Kønugarðr, the Name given to Kiev in the Icelandic Sagas, with an Excursus on Kind in Place-Names. *Arkiv för nordisk filologi*, *120*, 55-68.

Mercier, D., Cossart, E., Decaulne, A., Feuillet, T., Jónsson, H.P., Sæmundsson, Þ., 2013. The Höfðahólar rock avalanche (sturzström): Chronological constraint of paraglacial landsliding on an Icelandic hillslope. *Holocene* 23, 432–446. https://doi.org/10.1177/0959683612463104

Meyer, M., Harff, J., 2005. Modelling Palaeo Coastline Changes of the Baltic Sea. Journal of Coastal Research 213, 598–609. https://doi.org/10.2112/04-703A.1

Meyer, M., Harff, J., Gogina, M., Barthel, A., 2008. Coastline changes of the Darss–Zingst Peninsula — A modelling approach. Journal of Marine Systems 74, Supplement, S147–S154. https://doi.org/10.1016/j.jmarsys.2008.03.023

Mikkelsen, N., Kuijpers, A., Lassen, S., & Vedel, J. 2001. Marine and terrestrial investigations in the Norse Eastern Settlement, south Greenland. *Geology of Greenland Survey Bulletin*, *189*, 65-69.

Miot da Silva, G., Siadat Mousavi, S.M., Jose, F., 2012. Wave-driven sediment transport and beach-dune dynamics in a headland bay beach. Marine Geology 323–325, 29–46. https://doi.org/10.1016/j.margeo.2012.07.015

Moreno-Chamarro, E., Zanchettin, D., Lohmann, K., Jungclaus, J.H., 2015. Internally generated decadal cold events in the northern North Atlantic and their possible implications for the demise of the Norse settlements in Greenland. *Geophys. Res. Lett.* 2014GL062741. https://doi.org/10.1002/2014GL062741

Murray, A.B., 2007. Reducing model complexity for explanation and prediction. *Geomorphology* 90, 178–191. https://doi.org/10.1016/j.geomorph.2006.10.020

Naimo, A., 2014. A Novel Approach to Generate Synthetic Wind Data. Procedia - Social and Behavioral Sciences, Operational Research for Development, Sustainability and Local Economies 108, 187–196. https://doi.org/10.1016/j.sbspro.2013.12.830

NASA Landsat Program, Landsat 4 (1984-1993), Landsat 5 TM (1984-2012), Landsat 7 ETM+ (1999-2013), Landsat 8 OLI (2013-2016), courtesy of the U.S. Geological Survey, Sioux Falls.

Naylor, L.A., Stephenson, W.J., Trenhaile, A.S., 2010. Rock coast geomorphology: Recent advances and future research directions. Geomorphology, Rock Coast Geomorphology 114, 3–11. https://doi.org/10.1016/j.geomorph.2009.02.004

Neal, A., 2004. Ground-penetrating radar and its use in sedimentology: principles, problems and progress. Earth-Science Reviews 66, 261–330.

Neill, S.P., Scourse, J.D., 2009. The formation of headland/island sandbanks. Continental Shelf Research 29, 2167–2177. https://doi.org/10.1016/j.csr.2009.08.008

Nitter, M., Elvestad, E., Selsing, L., 2013. Maritime Site Protection and the Fetch Method: an example from Rogaland, Norway. International Journal of Nautical Archaeology 42, 87–102. https://doi.org/10.1111/j.1095-9270.2012.00365.x

Norðdahl, H., Pétursson, H.G., 2005. 3. Relative sea-level changes in Iceland: new aspects of the Weichselian deglaciation of Iceland, in: C. Caseldine, A.R., J. Harđardóttir and Ó. Knudsen (Ed.), Developments in Quaternary Sciences, Iceland — Modern Processes and Past Environments. Elsevier, pp. 25–78.

O'Brien, S. R., Mayewski, P. A., Meeker, L. D., Meese, D. A., Twickler, M. S., & Whitlow, S. I. 1995. Complexity of Holocene climate as reconstructed from a Greenland ice core. *Science*, *270*(5244), 1962-1964.

O'Connor, M., Cooper, J.A.G., Jackson, D.W.T., 2007. Morphological behaviour of headland embayment and inlet-associated beaches, northwest Ireland. *Journal of Coastal Research*, *SI 50 (Proceedings of the 9th International Coastal Symposium*): 626 – 630.

O'Rourke, M.J., 2017. Archaeological Site Vulnerability Modelling: The Influence of High Impact Storm Events on Models of Shoreline Erosion in the Western Canadian Arctic. *Open Archaeology*, *3*(1), pp.1-16.

Ogawa, H., Dickson, M.E., Kench, P.S., 2015. Hydrodynamic constraints and storm wave characteristics on a sub-horizontal shore platform. Earth Surf. Process. Landforms 40, 65–77. https://doi.org/10.1002/esp.3619

Ogilvie, A. E. (1984). The past climate and sea-ice record from Iceland, Part 1: Data to AD 1780. *Climatic Change*, *6*(2), 131-152.

Ogilvie, A. E., & Jónsson, T. 2001. "Little Ice Age" Research: A Perspective from Iceland. *Climatic Change*, *48*(1), 9-52.

Ólafsdóttir, R., Schlyter, P., & Haraldsson, H. V. 2001. Simulating icelandic vegetation cover during the holocene implications for long-term land degradation. Geografiska Annaler: Series A, Physical Geography, 83(4), 203-215.

Paphitis, D., 2001. Sediment movement under unidirectional flows: an assessment of empirical threshold curves. *Coastal Engineering 43*(3):227-245.

Parker, C., Thorne, C. R., & Clifford, N. J. 2015. Development of ST: REAM: a reach-based stream power balance approach for predicting alluvial river channel adjustment. *Earth Surface Processes and Landforms*, *40*(3), 403-413.

Parteli, E. J., Durán, O., Tsoar, H., Schwämmle, V., & Herrmann, H. J. 2009. Dune formation under bimodal winds. *Proceedings of the National Academy of Sciences*, *106*(52), 22085-22089.

Patterson, W.P., Dietrich, K.A., Holmden, C. and Andrews, J.T., 2010. Two millennia of North Atlantic seasonality and implications for Norse colonies. *Proceedings of the National Academy of Sciences*, *107*(12), pp.5306-5310.

Perdikaris, S., & McGovern, T. H. 2007. Cod fish, walrus, and chieftains: Economic intensification in the Norse North Atlantic. *Seeking a Richer Harvest*, *3*, 193-216.

Peters, S. E., & Loss, D. P., 2012. Storm and fair-weather wave base: A relevant distinction? *Geology*, *40*(6), 511-514.

Pétursson, H. G., 1999. The geology and environmental changes in the Gásir area. In A. Christophersen & A. Dybdahl (ed.): Gásir - en internasjonal handelsplass i Nord-Atlanteren. Senter for middelalderstudier, Skrifter nr. 9, pp 65-70.

Ragin, C. C., 1987. The Comparative Method. Moving beyond qualitative and quantitative strategies. Univ. of California Press.

Ragin, C. C., 2000. Fuzzy-Set Social Science. University of Chicago Press.

Rasch, M., Holm Jakobsen, B. & Nielsen, N. 1997a. Geomorphology and sedimentary record of three cuspate forelands as indicators of late Holocene relative sea-level changes, Disko, West Greenland. Danish Journal of Geography 97, 33_/46.

Rasch, M. & Jensen, J. F., 1997b. Ancient Eskimo dwelling sites and Holocene relative sea-level changes in southern Disko Bugt, central West Greenland. Polar Research 16, 101_/115.

Rasch, M., 2000. Holocene relative sea-level changes in Disko Bugt, West Greenland. *Journal of Coastal Research* 16, 306/315.

Ratliff, K. M., & Murray, A. B. 2014. Modes and emergent time scales of embayed beach dynamics. *Geophysical Research Letters 41*(20): 7270-7275.

Reniers, A.J.H.M., Roelvink, J.A., Thornton, E.B., 2004. Morphodynamic modeling of an embayed beach under wave group forcing. Journal of Geophysical Research: Oceans 109, n/a–n/a. https://doi.org/10.1029/2002JC001586

Rennie, A.F., Hansom, J.D., 2011. Sea level trend reversal: Land uplift outpaced by sea level rise on Scotland's coast. Geomorphology 125, 193–202. https://doi.org/10.1016/j.geomorph.2010.09.015

Roesdahl, E. 1998. *The Vikings*. Penguin UK.

Rohweder, J., Rogala, Johnson, B., Anderson, D., Clark, S., Chamberlin, F., Potter, D. & Runyon, K. 2012: *Application of Wind Fetch and Wave Models for Habitat Rehabilitation and Enhancement Projects – 2012 Update.*

Ross, M. C. 1998. *Prolonged echoes: Old Norse myths in medieval Northern society* (p. 146). Odense University Press.

Rosser, N.J., Brain, M.J., Petley, D.N., Lim, M., Norman, E.C., 2013. Coastline retreat via progressive failure of rocky coastal cliffs. Geology 41, 939–942. https://doi.org/10.1130/G34371.1

Sahlins, M. D. 1963. *Culture and environment: The study of cultural ecology*. Voice of America, US Information Agency.

Sallenger Jr., A.H., Krabill, W., Brock, J., Swift, R., Manizade, S., Stockdon, H., 2002. Sea-cliff erosion as a function of beach changes and extreme wave runup during the 1997–1998 El Niño. Marine Geology 187, 279–297. https://doi.org/10.1016/S0025-3227(02)00316-X

Salvioli, J. 2006. Stockton Beach coastal processes study : final report : stage 1 - sediment transport analysis and description of on-going processes. Chatswood, N.S.W. : DHI Water & Environment, 2006.

Samaras, A.G., Koutitas, C.G., 2014. Comparison of three longshore sediment transport rate formulae in shoreline evolution modeling near stream mouths. Ocean Engineering 92, 255–266. https://doi.org/10.1016/j.oceaneng.2014.10.005

Sanderson, D.C.W., Murphy,S., 2010, Using simple portable OSL measurements and laboratory characterisation to help understand complex and heterogeneous sediment sequences for luminescence dating, Quaternary Geochronology 5, 299-305

Sandison, C., 1954, *The Sixareen and her racing descendents*. Lerwick .

Sandweiss, D. H., & Kelley, A. R. 2012. Archaeological contributions to climate change research: the archaeological record as a paleoclimatic and paleoenvironmental archive. *Annual Review of Anthropology*, *41*.

Sanjaume, E., Tolgensbakk, J., 2009. Beach ridges from the Varanger Peninsula (Arctic Norwegian coast): Characteristics and significance. Geomorphology 104, 82–92. https://doi.org/10.1016/j.geomorph.2008.05.029

Screen, J.A., Simmonds, I., 2010. The central role of diminishing sea ice in recent Arctic temperature amplification. Nature 464, 1334–1337.

Serreze, M.C., Francis, J.A., 2006. The Arctic Amplification Debate. *Climatic Change* 76, 241–264.

Shennan, I., & Horton, B. 2002. Holocene land-and sea-level changes in Great Britain. *Journal of Quaternary Science*, *17*(5-6), 511-526.

Sherman, D. J., Jackson, D. W., Namikas, S. L., & Wang, J. 1998. Wind-blown sand on beaches: an evaluation of models. *Geomorphology*, *22*(2), 113-133.

Shetland Islands Council, 2011. Shetland in Statistics. *Economic Development Unit, Shetland Islands Council 38th Edition*

Shields, A., 1936. Application of similarity principles and turbulence research to bed-load movement. *Soil Conservation Service.(translation from original, accessed at https://repository.tudelft.nl/islandora/object/uuid:a66ea380-ffa3-449b-b59f-38a35b2c6658/datastream/OBJ, 11/03/2017)*

Ship's Business. 2010. http://shipsbusiness.com/shallow-water-navigation.html, accessed 17th October 2017

Short, A.D., 1996. The role of wave height, period, slope, tide range and embaymentisation in beach classifications: a review. *Revista Chilena de Historia Natural 69*(4):589-604.

Short, A.D, Masselink, G., 1999. Embayed and structurally controlled beaches. *Handbook of beach and shoreface morphodynamics 1*(999):230-249.

Siegle, E., Huntley, D. A., Davidson, M.A., 2004. Physical controls on the dynamics of inlet sandbar systems. *Ocean Dynamics 54*(3-4):360-373.

Sigurdsson, J. V. 2010. The Norse Community. In *The Norwegian Domination and the Norse World, C. 1100-c. 1400*, *3*, 59.

Simões, F.J., 2014. Shear velocity criterion for incipient motion of sediment. *Water Science and Engineering 7*(2): 183-193.

Simpson, I. A., Guðmundsson, G., Thomson, A. M., & Cluett, J. 2004. Assessing the role of winter grazing in historic land degradation, Mývatnssveit, northeast Iceland. *Geoarchaeology*, *19*(5), 471-502.

Sines, R. 2015. *Norse in the North Atlantic: A comparison of the Norse settlements and societies of Iceland and Greenland during the Middle Ages*. University of Nebraska at Kearney.

Slott, J. M., Murray, A. B., Ashton, A. D., & Crowley, T. J. 2006. Coastline responses to changing storm patterns. *Geophysical Research Letters*, *33*(18).

Small, A., 1968, Excavations at Underhoull, Unst, Shetland. : Proceedings of the Society of Antiquaries of Scotland, v. 98.

Smith, B. B. 2007. Norwick: Shetland's first viking settlement?. In *West over Sea* (pp. 285-298). Brill.

Solli, B., 2014. Medieval Harbours in Norway: on a newly discovered jetty and possible ship-blockage on Veøy in Romsdal. International Journal of Nautical Archaeology 43, 66–75. https://doi.org/10.1111/1095-9270.12031

Sommerville, A. A., Hansom, J. D., Housley, R. A., & Sanderson, D. C. W. 2007. Optically stimulated luminescence (OSL) dating of coastal aeolian sand accumulation in Sanday, Orkney Islands, Scotland. *The Holocene*, *17*(5), 627-637.

Soulsby, R. L., & Clarke, S. 2005. Bed shear-stresses under combined waves and currents on smooth and rough beds. *HR Wallingford, Report TR137*.

Sparrenbom, C.J., Bennike, O., Björck, S., Lambeck, K., 2006. Holocene relative sea-level changes in the Qaqortoq area, southern Greenland. Boreas 35, 171–187. https://doi.org/10.1111/j.1502-3885.2006.tb01148.x

Steenstrup, K.J.V., Kornerup., A. 1881. Expeditionen til Julianehaabs distrikt i 1876. Meddelelser om Grønland 2: 1–41.

Steffen, H., Wu, P., 2011. Glacial isostatic adjustment in Fennoscandia—A review of data and modeling. *Journal of Geodynamics* 52, 169–204. https://doi.org/10.1016/j.jog.2011.03.002

Stephenson, W.J., Kirk, R.M., 2000a. Development of shore platforms on Kaikoura Peninsula, South Island, New Zealand: Part One: The role of waves. Geomorphology 32, 21–41.

Stephenson, W.J., Kirk, R.M., 2000b. Development of shore platforms on Kaikoura Peninsula, South Island, New Zealand: II: The role of subaerial weathering. *Geomorphology* 32, 43–56. https://doi.org/10.1016/S0169-555X(99)00062-8

Stewart, H., Bradwell, T., Bullard, J., Davies, S. J., Golledge, N., & McCulloch, R. D. (2017). 8000 years of North Atlantic storminess reconstructed from a Scottish peat record: implications for Holocene atmospheric circulation patterns in Western Europe. *Journal of Quaternary Science*, *32*(8), 1075-1084.

Streeter, R., **Dugmore**, A. J., Lawson, I. T., Erlendsson, E., Edwards. K. J., 2015. The onset of the palaeoanthropocene in Iceland: Changes in complex natural systems. *The Holocene*, 2015, 25, 10. 1662-1675

Stylegar, F. A., & Grimm, O. (2005). Boathouses in northern Europe and the north Atlantic. *International Journal of Nautical Archaeology*, *34*(2), 253-268.

Surge, D., & Barrett, J. H. 2012. Marine climatic seasonality during medieval times (10th to 12th centuries) based on isotopic records in Viking Age shells from Orkney, Scotland. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *350*, 236-246.

Swindles, G. T., Galloway, J., Outram, Z., Turner, K., Schofield, J. E., Newton, A. J., Dugmore, A.J., Church, M. J., Watson, E. J., Batt, C., Bond, J. 2013. Re-deposited cryptotephra layers in Holocene peats linked to anthropogenic activity. *The Holocene*, *23*(10), 1493-1501.

Thaden, E. 2001. State and people in the history of northern Norwegians and White Sea and Kola Russians. *East European Quarterly*, *35*(2), 129.

Thomas, C. W., Murray, A. B., Ashton, A. D., Hurst, M. D., Barkwith, A. K., & Ellis, M. A. 2016. Complex coastlines responding to climate change: do shoreline shapes reflect present forcing or" remember" the distant past?. *Earth Surface Dynamics*, *4*(4), 871.

Tong, X., Shi, L., Xia, X., n.d. Shoreline Evolution and Stability Analysis of Headland-Bay Beach of Huangcheng. Proceedings of the Twenty-fourth. 2014 International Ocean and Polar Engineering Conference Busan, Korea, June 15-20, 2014 1100–1104.

Townend, M. 2002. *Language and history in Viking Age England: linguistic relations between speakers of Old Norse and Old English* (Vol. 6). Brepols Publishers.

Trenhaile, A. S. 2001. Modeling the effect of weathering on the evolution and morphology of shore platforms. *Journal of Coastal Research*, 398-406.

Trenhaile, A.S., 2002. Rock coasts, with particular emphasis on shore platforms. Geomorphology, 29th Binghamton Geomorphology Symposium: Coastal Geomorphology 48, 7–22. https://doi.org/10.1016/S0169-555X(02)00173-3

Trenhaile, A.S., 2004. Modeling the accumulation and dynamics of beaches on shore platforms. Marine Geology 206, 55–72. https://doi.org/10.1016/j.margeo.2004.03.013

Trenhaile, A.S., 2011. Predicting the response of hard and soft rock coasts to changes in sea level and wave height. Climatic Change 109, 599–615. https://doi.org/10.1007/s10584-011-0035-7

Tuller, S. E., & Brett, A. C. 1984. The characteristics of wind velocity that favor the fitting of a Weibull distribution in wind speed analysis. *Journal of Climate and Applied Meteorology 23*(1): 124-134.

Turki, I., Medina, R., Coco, G., Gonzalez, M., 2013a. An equilibrium model to predict shoreline rotation of pocket beaches. Marine Geology 346, 220–232. https://doi.org/10.1016/j.margeo.2013.08.002

Turki, I., Medina, R., Gonzalez, M., Coco, G., 2013b. Natural variability of shoreline position: Observations at three pocket beaches. Marine Geology 338, 76–89. https://doi.org/10.1016/j.margeo.2012.10.007

Turner, V. E. 2012. Location, Form and Function in Shetland's Prehistoric Field Systems.

Turner, V.E., Owen, O. 2013. The Legacy of Viking Unst. *In* Viking Unst: Excavation and Survey in Northern Shetland 2006 – 2010. Lerwick: Shetland Heritage Publications. 233 - 252.

Udo, K., Kuriyama, Y., & Jackson, D. W. 2008. Observations of wind-blown sand under various meteorological conditions at a beach. *Journal of Geophysical Research: Earth Surface*, *113*(F4).

Unger, R. W. 1980. *The ship in the medieval economy, 600-1600*. McGill-Queen's Press-MQUP.

Van Donk, S.J., Wagner, L.E., Skidmore, E.L. and Tatarko, J., 2005. Comparison of the Weibull model with measured wind speed distributions for stochastic wind generation. *Transactions of the ASAE*, *48*(2): 503-510.

van Rijn, L.C., Walstra, D.J.R., Grasmeijer, B., Sutherland, J., Pan, S., Sierra, J.P., 2003. The predictability of cross-shore bed evolution of sandy beaches at the time scale of storms and seasons using process-based Profile models. Coast. Eng. 47, 295–327. https://doi.org/10.1016/S0378-3839(02)00120-5

Vicinanza, D., Contestabile, P. and Ferrante, V., 2013. Wave energy potential in the north-west of Sardinia (Italy) *Renewable Energy 50*: 506-521.

Viles, H.A., Goudie, A.S., 2003. Interannual, decadal and multidecadal scale climatic variability and geomorphology. Earth-Science Reviews 61, 105–131. https://doi.org/10.1016/S0012-8252(02)00113-7

Vilhjalmsson, T. 1997. Time and travel in the old norse society. *Disputatio*, *2*, 89-114.

Vinther, B. M., Jones, P. D., Briffa, K. R., Clausen, H. B., Andersen, K. K., Dahl-Jensen, D., & Johnsen, S. J. 2010. Climatic signals in multiple highly resolved stable isotope records from Greenland. *Quaternary Science Reviews*, *29*(3), 522-538.

Vitousek, S., Barnard, P.L., Limber, P., 2017. Can beaches survive climate change? J. Geophys. Res. Earth Surf. 2017JF004308. https://doi.org/10.1002/2017JF004308

Walkden, M.J.A., Hall, J.W., 2005. A predictive Mesoscale model of the erosion and profile development of soft rock shores. Coastal Engineering 52, 535–563. https://doi.org/10.1016/j.coastaleng.2005.02.005

Watt, J. A. 1998. *The church in medieval Ireland* (Vol. 5). Univ College Dublin Press.

Weidick, A., Kelly, M. & Bennike, O. 2004. Late Quaternary development of the southern sector of the Greenland Ice Sheet, with particular reference to the Qassimiut lobe. Boreas 33, 284 - 299.

Westley, K., Quinn, R., Forsythe, W., Plets, R., Bell, T., Benetti, S., McGrath, F. & Robinson, R. 2011. Mapping submerged landscapes using multibeam bathymetric data: a case study from the north coast of Ireland. *International Journal of Nautical Archaeology*, *40*(1), 99-112.

Wilken, D., Wunderlich, T., Majchczack, B., Andersen, J. and Rabbel, W., 2015. Rayleigh-wave Resonance Analysis: a Methodological Test on a Viking Age Pit House. *Archaeological Prospection*, *22*(3), pp.187-206.

Wilson, J. F., Weiss, D. A., Richards, M., Thomas, M. G., Bradman, N., & Goldstein, D. B. 2001. Genetic evidence for different male and female roles during cultural transitions in the British Isles. *Proceedings of the National Academy of Sciences*, *98*(9), 5078-5083.

Woodroffe, S.A., Long, A.J., Lecavalier, B.S., Milne, G.A., Bryant, C.L., 2014. Using relative sea-level data to constrain the deglacial and Holocene history of southern Greenland. Quaternary Science Reviews, APEX II: Arctic Palaeoclimate and its Extremes 92, 345–356. https://doi.org/10.1016/j.quascirev.2013.09.008

World Meteorological Organization (WMA), 1998. Guide to Wave Analysis and Forecasting. Second Edition WMO-No. 702

Wunderlich, T., Wilken, D., Andersen, J., Rabbel, W., Zori, D., Kalmring, S. and Byock, J., 2015. On the ability of geophysical methods to image medieval turf buildings in Iceland. *Archaeological Prospection*, *22*(3), pp.171-186.

Young, N. E., Schweinsberg, A. D., Briner, J. P., & Schaefer, J. M. 2015. Glacier maxima in Baffin Bay during the Medieval Warm Period coeval with Norse settlement. *Science advances*, *1*(11), e1500806.

Zaruba, Q., & Mencl, V. 2014. *Landslides and their control* (Vol. 31). Elsevier.

Zhang, K., Douglas, B.C. and Leatherman, S.P., 2004. Global warming and coastal erosion. *Climatic Change 64*(1-2): 41-58.

Zhang, W., Harff, J., Schneider, R., Meyer, M., Wu, C., 2011. A Multiscale Centennial Morphodynamic Model for the Southern Baltic Coast. Journal of Coastal Research 890–917. https://doi.org/10.2112/JCOASTRES-D-10-00055.1

Zilmer, K. 2005. *He drowned in Holmr's sea-His cargo-ship drifted to the sea-bottom, only three came out alive'.* Records and representations of Baltic traffic in the Viking Age and the Early Middle Ages in early Nordic sources.

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