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Dynamic beach response to changing storminess of Unst, Shetland: implications for landing places exploited by Norse communities

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Abstract

We present major new findings on the stability of Norse landing places on the island of Unst, Shetland using a combination of geomorphology, OSL dating, fetch analysis and sediment transport modelling. Islanders needed reliable access to the sea, and exploited sandy beaches as safe landing places. The persistence of beaches was important for long-term continuity of settlement and could be threatened by stormy conditions. Sediment modelling undertaken on two embayments on Unst, Lunda Wick and Sandwick, reveals major differences in the ability of sandy beaches to reform in these embayments after the onset of persistent stormy conditions; sandy beaches can endure under these conditions at Sandwick, but not at Lunda Wick. OSL dating of blown sands at Lunda Wick reveals a history of sand blow events pointing to large scale depletion of beach material throughout the Little Ice Age (beginning circa 1250 CE). This correlates with known sand blows at Sandwick, but here the beach could be replenished from the nearshore environment, something that was more problematic at Lunda Wick. These findings agree with the emerging picture of increased environment pressure from blown sands

on communities throughout the North Atlantic and identifies different models of related beach persistence and change.

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). Beaches on these mobile coastlines have been extensively utilised by people, particularly those found in sheltered headland bays, which 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 episodic; waxing and waning through time. This may reflect 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., 2014). There are, for example, numerous historical and archaeological examples of the impact of drifting beach sands on coastal communities throughout British Isles, with its variable 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 the crossing of climatic thresholds (Lamb, 1972) 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; Stewart et al., 2017) affecting the Norse community of Unst, 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 exploited both terrestrial and marine resources, the loss of reliable landing places and the compromised access to marine environments would have produced 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., 2018). 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., 2018). 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 burying structures; beaches can be removed, either gradually or rapidly as a result of a single large storm. Sandy beaches may be preferred landing sites, but rocky coasts can also, and were indeed used by small boats as long as weather and sea conditions are favourable. Nausts were found on both sandy and shingle beaches throughout Shetland (Tait, 2012), and these types of beaches were used as places to dry fish, by either lying them directly on the shingle or on an 'ayr' on sandy beaches. If no ayr or shingle beach was available, fish was either transported wet and dried elsewhere or consumed fresh (Goodlad, 1971). Small Norse boats, such as a *faering* (4-man boat) were fragile craft, and it was important to have the safest landing places possible, particular in the face of storms, as mentioned by Morrison (1978): ""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." While these craft may well have been able to withstand rough landings on cobble and rock coasts on occasion, it would have been a more dangerous proposition than a softer landing on sandy beaches.

Storms that remove sandy beach material 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 indeed 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. While generally negative for coastal communities, some impacts of beach instability can be positive, 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 on both settlement history and the formation of an archaeological record.

The overall aim of this paper is therefore 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.

Approaches and methods

The research in this paper is guided by the following research questions related to beach stability:

- 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 optically stimulated luminescence (OSL) analysis, by employing new in-situ dating methods, 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.

Study sites

We chose the island of Unst (Figure 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 to 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). Numerous 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 there is current settlement.

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 1).

Unst has varied bedrock geology and a coastline of rocky headlands, geos (small inlet), 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 confirmed remains of the Norse settlement on Unst date to the 10^{th} and 11^{th} centuries (Turner and Owen, 2013), although excavations at Norwick have yielded evidence for a Viking age settlement dated between the 7^{th} and the early 10^{th} century AD (Smith, 2007). There is scant evidence that the Vikings subjugated or destroyed the Pictish inhabitants of Unst and it is more likely that co-habitation of the island occurred but the Norse culture eventually dominated (Turner & Owen, 2013). The Viking Unst Project recorded some 30 structures definitely identified as longhouses and 20 more that were possible longhouses, and this is the highest concentration of longhouses known outside of Norway, pointing to Unst's importance 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). On Unst, as in the rest of Shetland, fishing was an important activity. Artefactual evidence from excavations undertaken at longhouse sites at Lunda Wick and Hamar discovered line sinkers and hook-sharpening artefacts (Bond, 2007), indicative of fishing. Midden excavations at Sandwick revealled a mix of fish bones and shellfish (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, however, 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 S1 in supplementary information) and Sandwick (Figure S2 in supplementary information).

Lunda Wick

Lunda Wick is a twin embayment on the south west coast of Unst (Figure 1). It faces north, and is partially sheltered from the open ocean by an outcrop of land 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 side of the bay to the west 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 18th (Canmore ID 64). More recent farms such as Lund House (Canmore ID 216963) are nearby, although some of these 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 indicate a changeable pattern of local coastal and potential landing places. There is less evidence of blown sands in Zones 1 and 3 which are partially sheltered by headlands, and more in Zone 2 which is 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 ridge at the inland margin. No evidence of recent blown sand is present behind the beach, although small exposures beneath 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, 1972).

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 formed by 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, found 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 uncovered the remains of a boat shelter at Burga Wick (Canmore ID 88166), not far from the (lower) Norse farmstead (**Error! Reference source not found.**) (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 high resolution 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 (1967) stated that it may originally have hosted a boat up to 5.5 m in length. Although there was no direct dating evidence, Small (1967) 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. This was most likely to convert it into a sawpit for processing driftwood. Small (1967, pg. 242)confirmed this interpretation ("A layer of rotting sawdust on sand inches above the roughly cobbled floor") and also suggests that this secondary use was fairly recent. According to Tait (2012, pg. 112), saw pits only became a part of the Shetland vernacular in the 19th century and often made use of existing structures.

Today, the noost is located on top of a backshore step with a 2-3m high drop to the beach that would make their use as a boat shetler impractical. 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.

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 S2 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. It appears to have a more consistent history of inhabitation through time than Lunda Wick. 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 occupied between the 11th to the 13th centuries 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 **Error! Reference source not found.**, 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.

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 2). 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 3), and 1 from the church section (Figure 4). During fieldwork, all sediment samples collected were immediately appraised for their luminescence behaviour using a SUERC portable OSL reader (Sanderson & Murphy, 2010). 44 sediment samples were examined in this phase of the investigations. From this initial analysis, plots of IRSL and OSL signal intensities versus depth were generated, in addition, stratigraphic variations in IRSL and OSL depletion indices, and the IRSL/OSL ratio were considered. This findings from the initial analysis informed the positioning of samples for OSL dating. All samples were sealed and immediately made light-safe for later 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 1 documents the OSL samples taken, their context and archaeological/geomorphological significance within the sections.

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

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 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 changing 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. **Error! Reference source not found.** shows an idealised schematic of the function of MIKE21.

Model domain

Bathymetry data for Sandwick was derived from the MEDIN (Marine Environmental Data and Information Network) database (MEDIN, 2018). 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 (**Error! Reference source not found.**).

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 2 lists the initial conditions for these model runs.

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).

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 other factors such as shoaling, wave refraction, bottom friction and currents (e.g. Holthuijsen, 1998), fetch on an open sea 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 exposed to high waves are also prone to erosion, while sheltered areas may see a higher degree of sedimentation. Measuring the fetch also allows us 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 Intermap (2009), 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.

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 a mean m/m gradient (Figure S6 in supplementary information). 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.

To provide a wider context, 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.

Results

Luminescence chronology

The analysed OSL sand samples presented in Table 3 reveal a complex picture of environmental change at Lunda Wick. Four profiles were sampled in Zone 3, the Noost section (Figure 3). 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 sediment at the same time as the others. In P3, OSL6 gives a date of 1540 ± 320 CE 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 19^{th} century, the end of this range being in line with the later date suggested above (Figure 11a).

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 CE and thus confirms that the noost was probably 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 here. These dates represent the first known OSL dating of noosts' and further archaeological cut-back and resampling may provide further tightening of the date range.

Within Zone 1 of the church section (Figure 4), 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 (approximately 20 surveyed visually in the field) can be seen throughout the profile, interspersed with sand-rich 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 that change to 1320 ± 50 CE. The age for OSL9 (1500 ± 40 CE) puts this sample point within the LIA proper, with significant sand deposits (derived from offshore, due to high shell content) 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 known 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 18^{th} century, and represents the time when the sand influx reduces and brown soil formation begins in earnest once again (Figure 11b).

Modelling results

Lunda Wick

Modelling results for Lunda Wick (Figure 7) 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 there is a more complex offshore environment in terms of nearshore platforms and skerries (details not captured in the model), thus small scale, very localised nearshore currents and eddies , 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 S8 in supplementary information).

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.

Sandwick

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 6). 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 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 are consistent with observed bed conditions. Admiralty charts marking sand banks approximately 800 m north of Ham Ness, are roughly in 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 reveals bed conditions through shallow water also records limited patches of sandy bed conditions in small embayments north of the large south western embayment, which is 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 S7 in supplementary information).

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, which is unable to transport sediment to 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 local sediment supply.

Offshore slope

Measured 1 km from the shoreline, 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. 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*). Our modelling results are consistent with this slope analysis.

Figure 8 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.

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.

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 beaches, 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 in the vicinity of Sandwick Bay. 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. This may be reflected in the settlement patterns pointing to a more persistent occupation of land adjacent to Sandwick Bay.

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 10 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 most favourable conditions for persistent beach formation are in Zone 3, evidenced by several remains of settlements from prehistory through to the Norse period (e.g., the Broch, the nausts, and the Norse farmsteads inshore). 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, as well as the general trend towards storminess in the British Isles understood at this time (e.g. Lamb, 1972; Lamb & Frydendahl, 1991; Burbidge et al., 2001; Sommerville, 2007; 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 CE), 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 within 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 coincident with a general shift towards increased storminess as experienced in other areas of the North Atlantic as the LIA progressed (Lamb, 1972).

The units of blown sand contain shell, which show that 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 rejuvenation of the beach, and thus its continuity as a landing site. Loss of Lunda Wick as a landing site may have forced the users to potentially rely on shingle-based beaches nearby (such as Colvadale to the north), however, as discussed, these were not as safe to use, particularly in light of storm action. Overland portages to more stable beaches, such as those at Norwick, Sandwick or the comparative shelter of Baltasound harbour may have been required in these instances, a non-trivial task for small, subsistence-based communities.

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, despite potential beach removal. 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. A fragment of pumice was 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, Iceland; 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.

Differences in the average offshore slopes are likely to be a key difference which is likely drive contrasting geomorphological responses between Lunda Wick and Sandwick. 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 offshore 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 S8 (supplementary information) 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. Settlement patterns do not necessarily reflect these offshore slope patterns of sandy beaches, with successful settlements, such as Baltasound and Uyeasound, enduring through from Norse times to the modern day without access to a nearby sandy beach. However, the relatively low relief of Unst may have made immediate access to a sandy beach for some communities unnecessary. Yet it is notable that both Baltasound and Uyeasound served as larger ports on the island for international shipping (with Uyeasound serving as a Hansa port from the 15th century onwards), thus these ports may have thrived from deeper draft ships bringing supplies and anchoring offshore, unable to land on the rocky shorelines of these harbours.

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. Nearshore 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.

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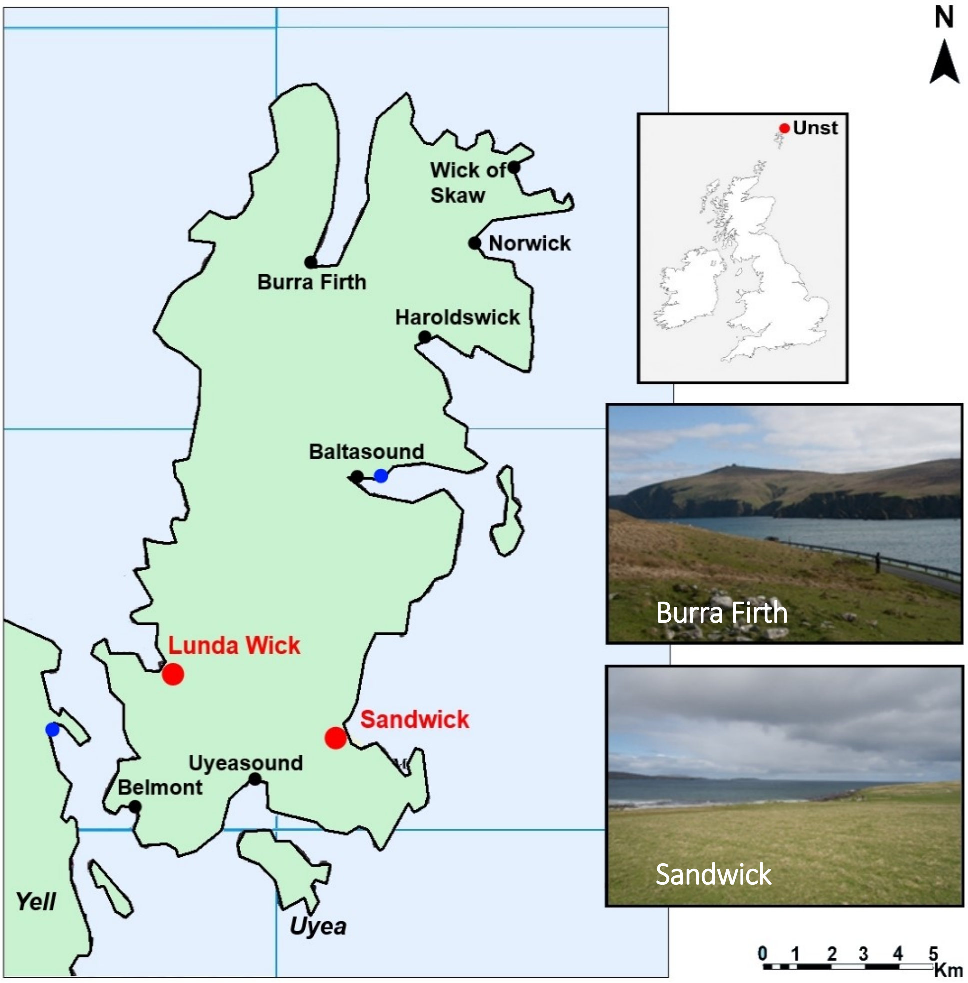


Figure 1 – Location map of Unst, with names of large embayments marked. Location of tide tables used in numerical modelling marked with blue dots.

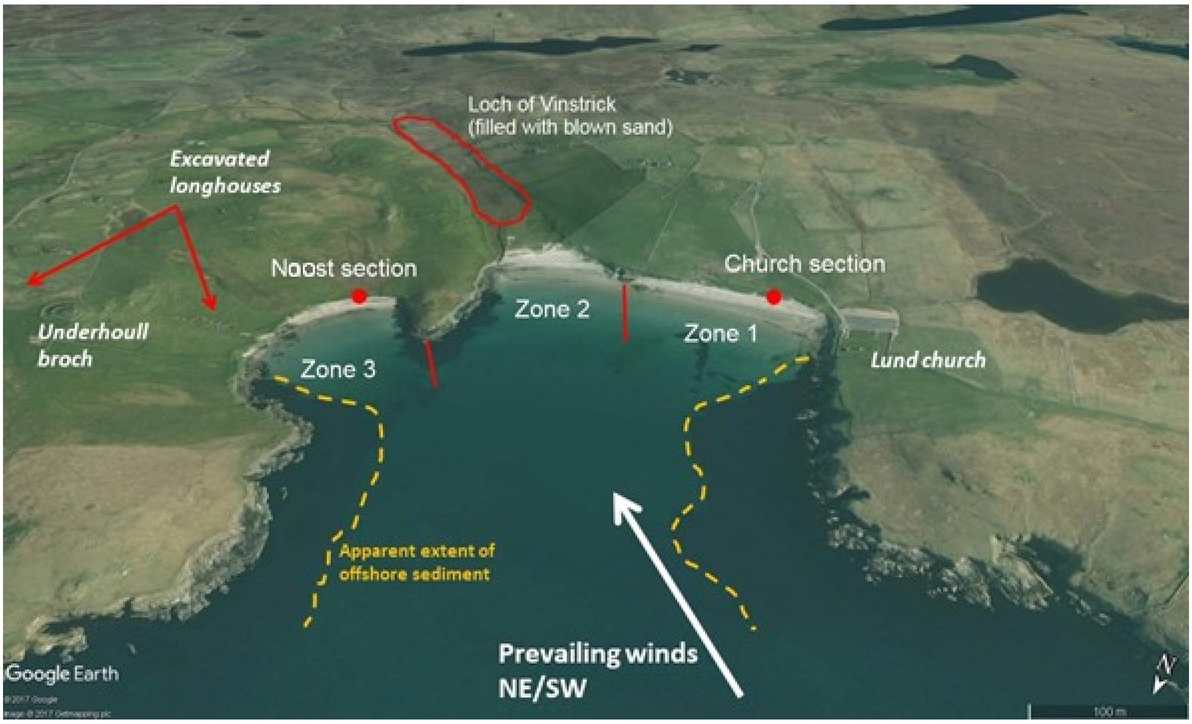
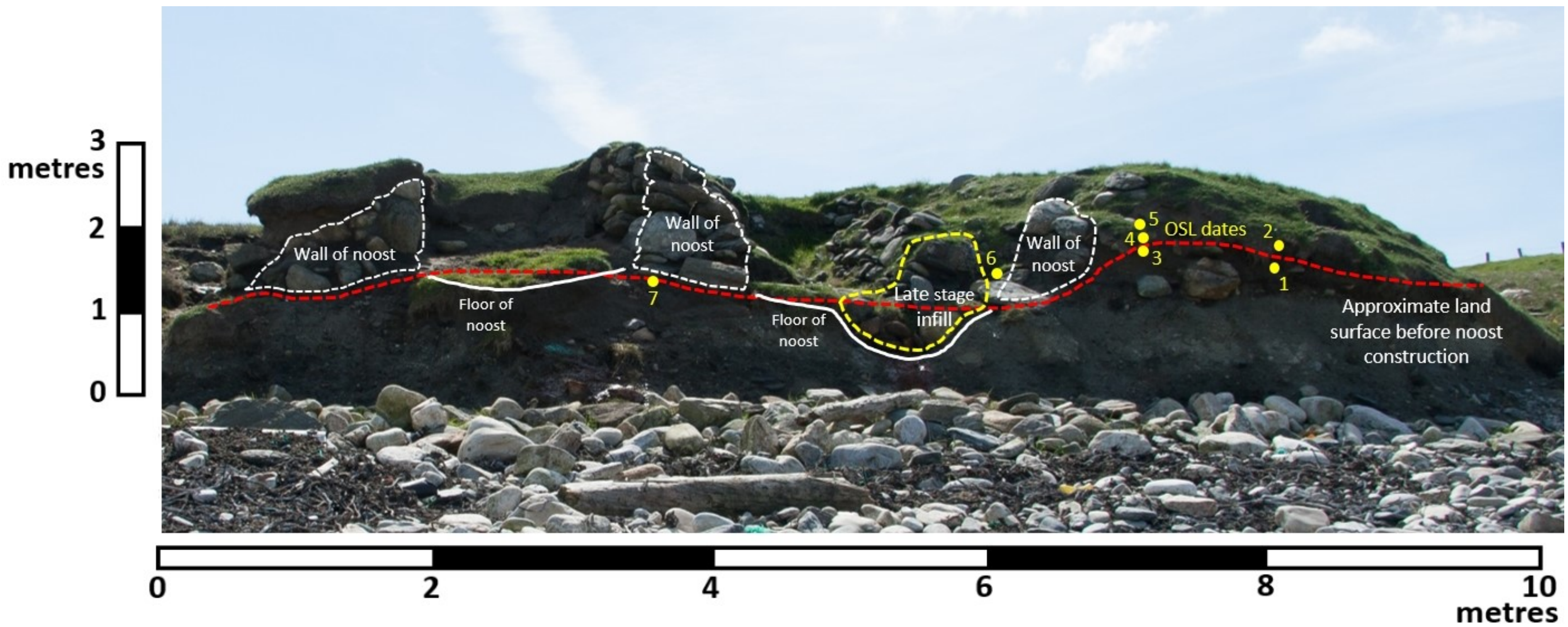


Figure 2 - Isometric view of Lunda Wick, facing south. OSL sample sections and geomorphic zones indicated. (Source: Google Earth)

a)



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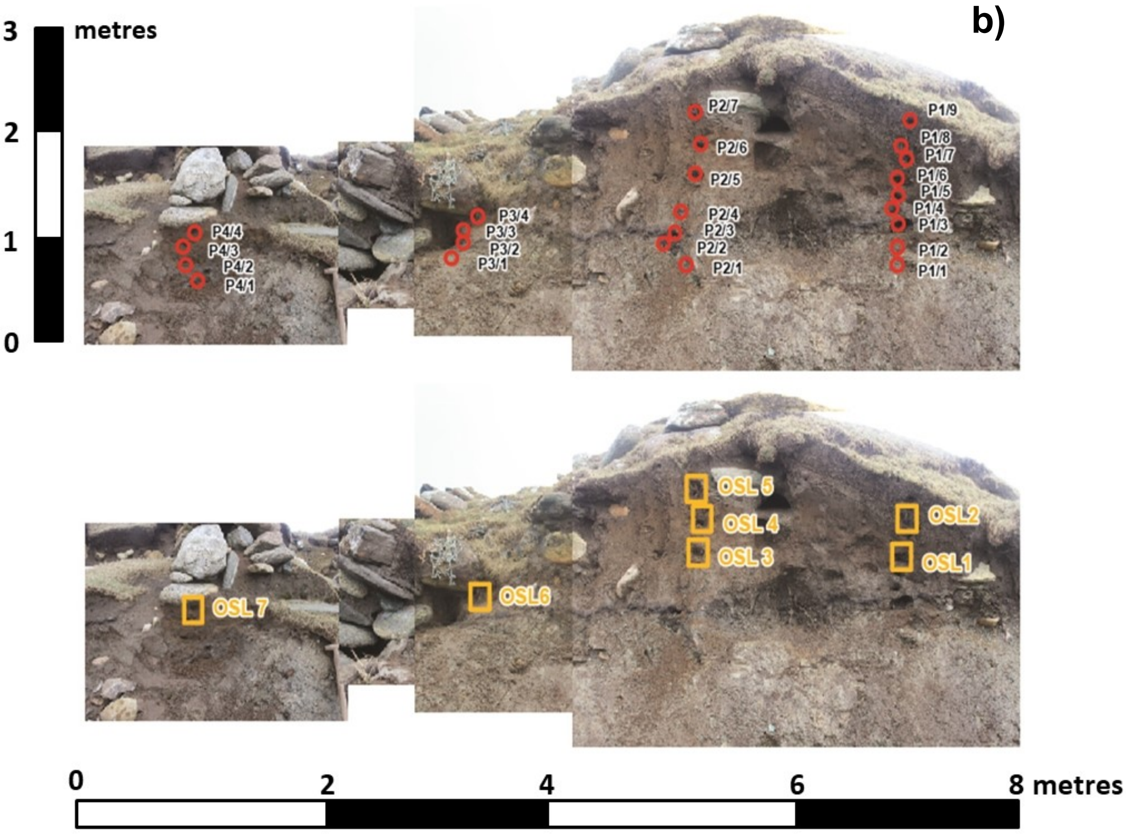

Figure 3 – a) setting of the noost section, with major section features marked. Numbered yellow dots represent SAR sample locations, marked in more detail in b) IRSL/OSL (red) and SAR (yellow) dating sample positions.

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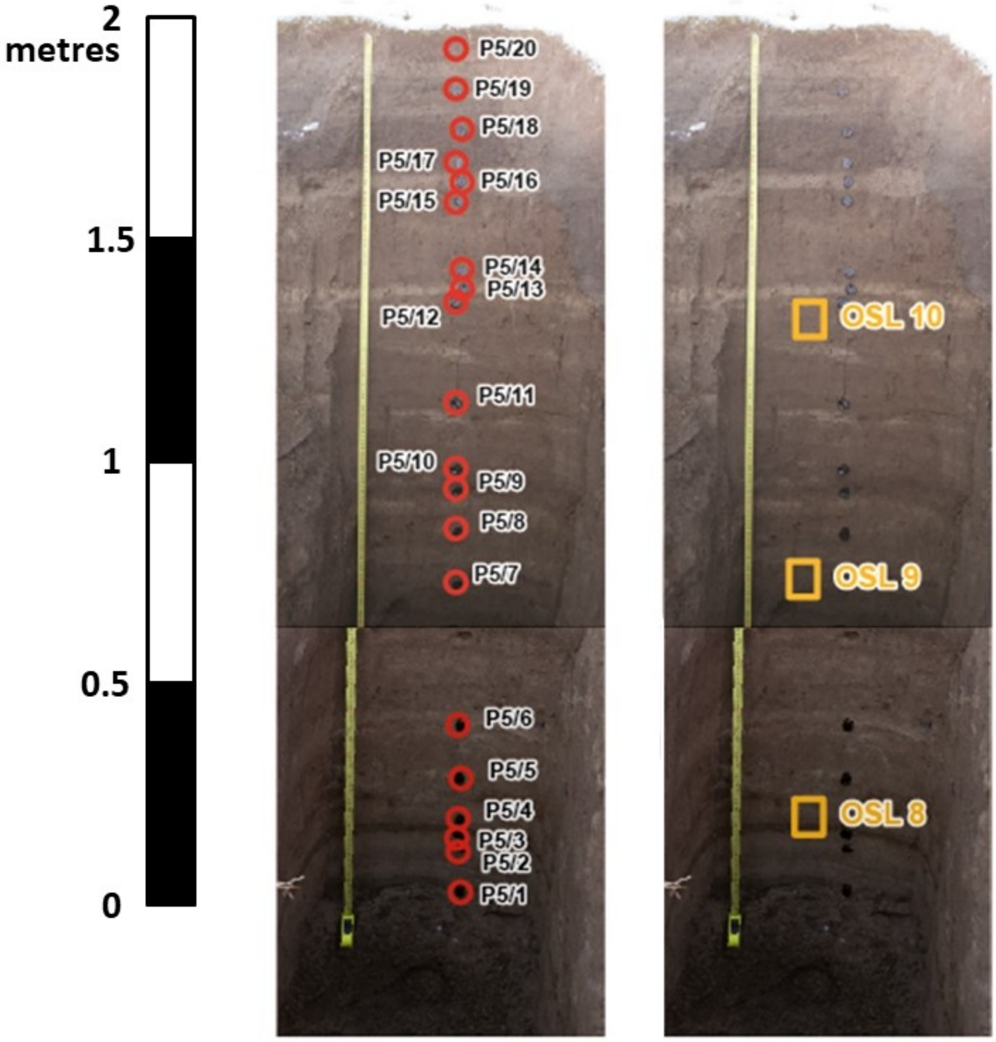

892 Figure 4 - IRSL/OSL dating samples and SAR dating samples, church section. Section 2.15 m from turf.

893

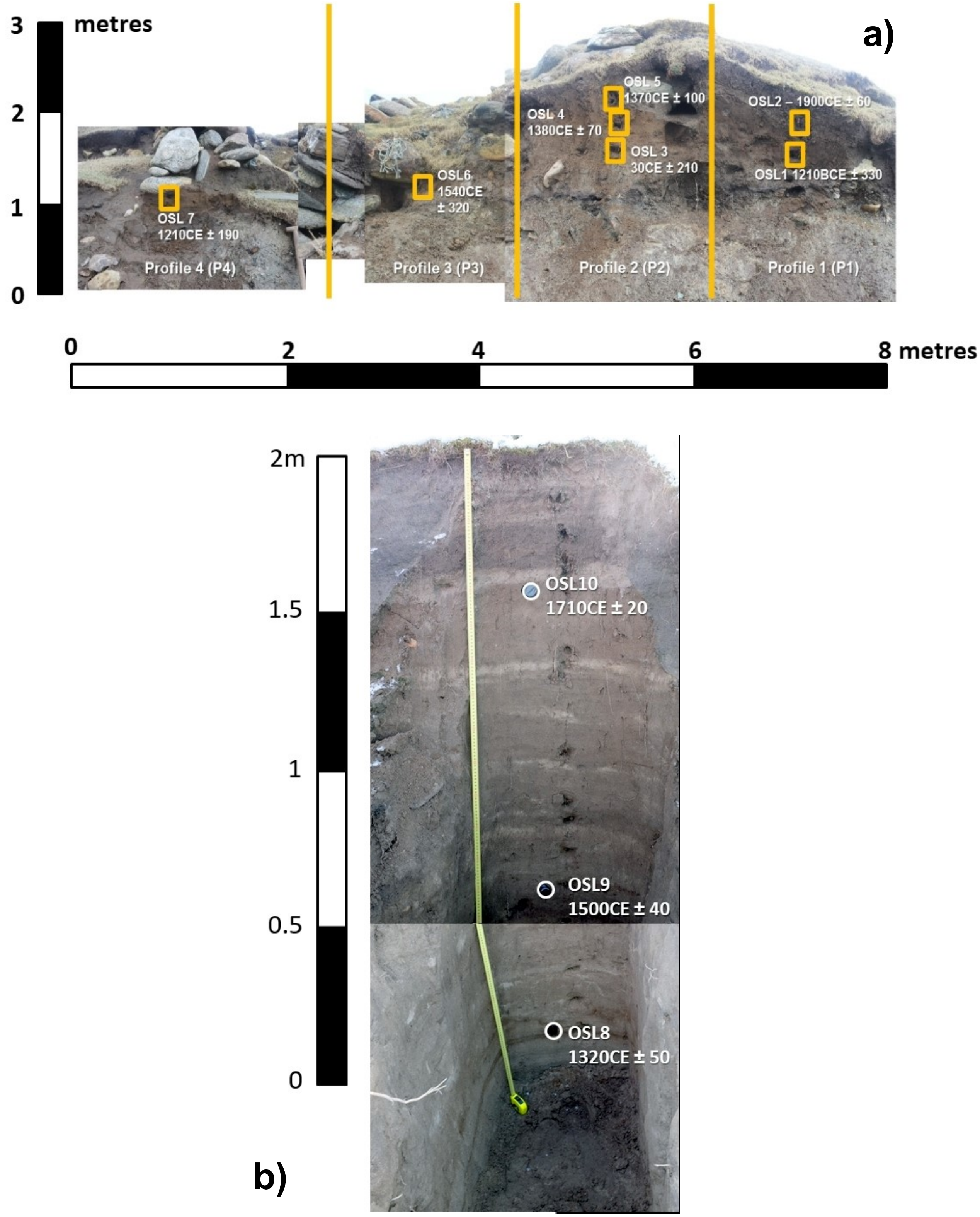

Figure 5 – a) Noost section OSL samples with calendar years, b) Zone 1 section OSL samples with calendar years.

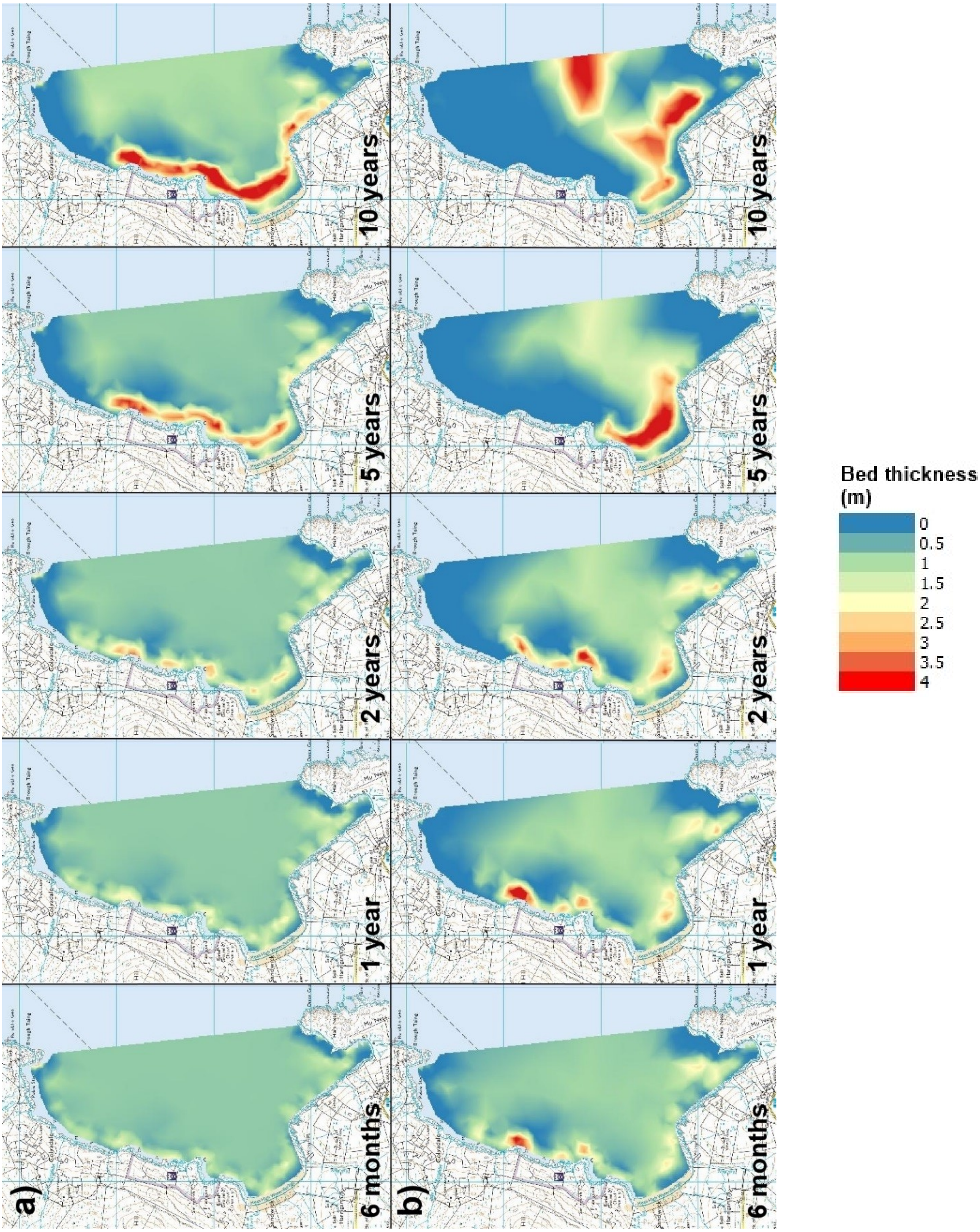

Figure 6 - Bed thickness after 10 years of model simulation at Sandwick, a) moderate wind conditions, b) stormy wind condition. Contains OS data © Crown copyright and database right (2018)

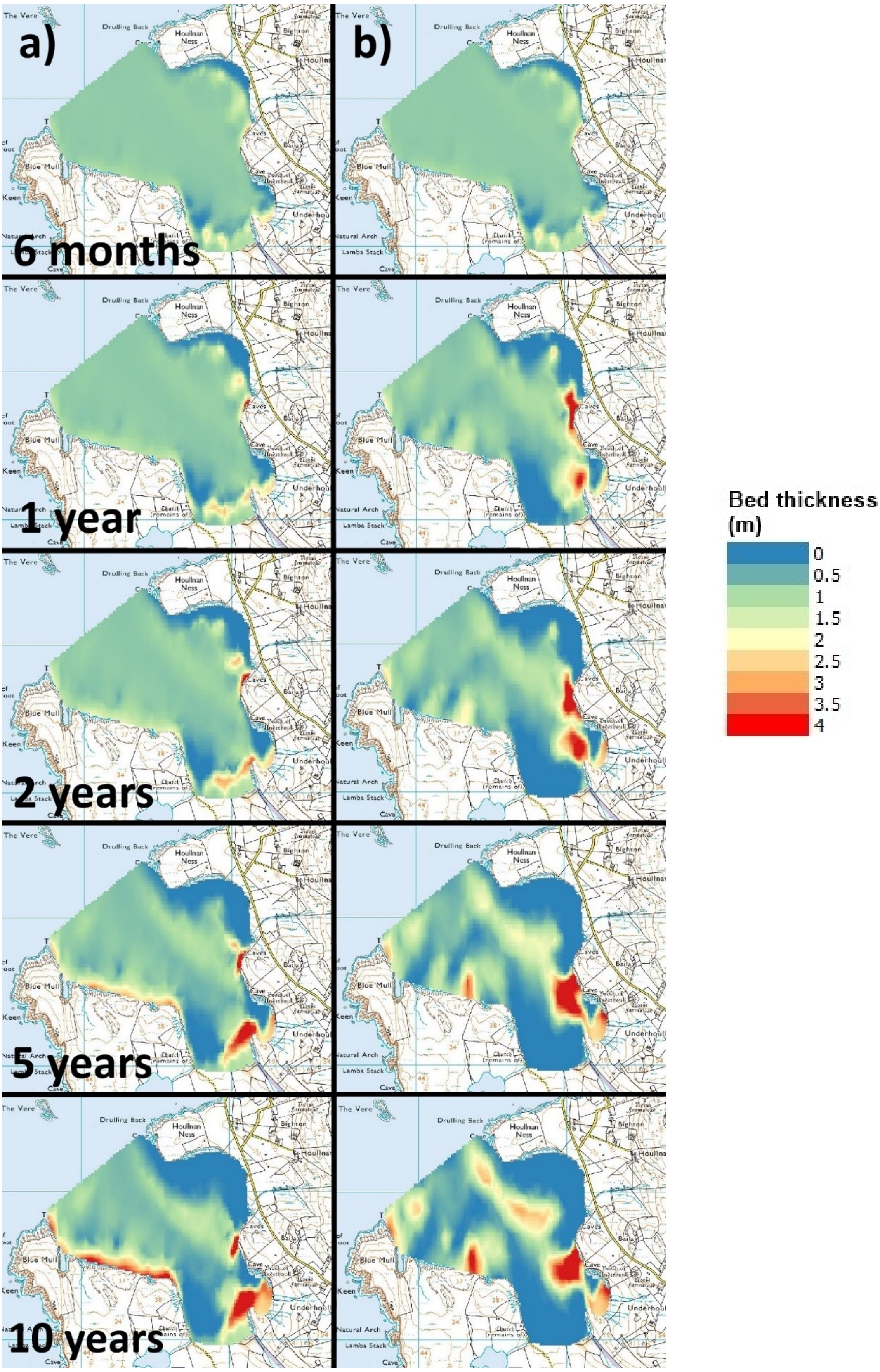

Figure 7 - Bed thickness after 10 years of model simulation at Lunda Wick, a) moderate wind conditions, b) stormy wind condition. Contains OS data © Crown copyright and database right (2018)

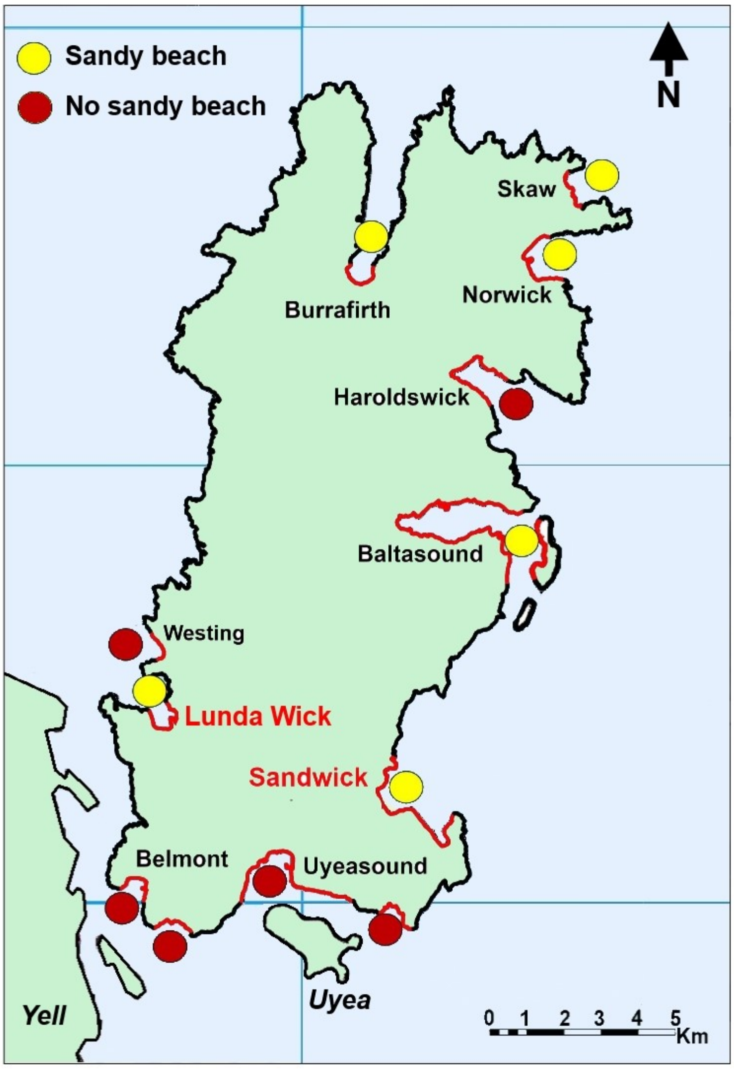

Figure 8 - Map of Unst coastline as a function of average offshore slope with embayment names marked. Red coastline indicates coastline with <0.025 m/m average offshore slope. Red and yellow circles indicate the existence of an extant sandy beach.

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 1 - Description of OSL SAR dating samples taken across profiles. Initial interpretation of archaeological significance is stated. See Kinnaird et al. (2017) for further context.

Parameter	Description
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/m³ (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 2 – Parameters used for the sediment transport modelling.

	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 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.