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Holocene paleo-geographic reconstructions of the Ramore Head area, Northern Ireland, using geophysical and geotechnical data: paleo-landscape mapping and archaeological implications.

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ABSTRACT

We present early to mid-Holocene paleo-geographic reconstructions for the Ramore Head area (Northern Ireland). This coastal area is characterised by Mesolithic occupation (c. 10–6 ka) and preserved early–mid Holocene peats both on- and offshore. This paper improves on previous reconstructions by employing a backstripping methodology which removes accumulated recent deposits from identified buried paleo-landsurfaces instead of using modern topography as an analogue to the past landscape. Paleo-landsurfaces are identified offshore from seismic profiles supplemented by cores, and onshore through legacy borehole records. The paleo-landsurface can be traced offshore to depths of -2 to -19 m and is buried by <5 m of modern sediment. It extends onshore under the coastal town of Portrush and is buried <2.5–10 m below modern ground level. The identified paleo-landsurface is combined with sea-level curves from recent Glacio-Isostatic-Adjustment models to reconstruct marine transgression during the early–mid-Holocene. Comparison is also made with reconstructions based on modern topography. Together, the identified paleo-landsurfaces and revised reconstructions can assist future site prospection on- and offshore and delimit high potential areas for heritage management. Revised reconstructions also allow placement of extant archaeology into a more accurate context of landscape change and help develop insights into local-scale site location patterns.

INTRODUCTION

Paleo-geographic reconstructions play a crucial role in archaeological research by providing the essential physical backdrop against which to study past societies. The positioning of topography, coastlines, water courses and other physical features would have strongly influenced archaeological site locations and past peoples' actions as they sought to maximize the advantages of their surrounding landscape. The ability to undertake paleo-geographic reconstruction is particularly important for prehistoric coastal archaeology, since the relevant landscapes have often been transformed by Pleistocene and Holocene sea-level change; for instance converting presently coastal environments to inland ones or inundating and submerging formerly terrestrial landscapes (Westley & Dix, 2006; Hijma et al., 2012; Sturt, Garrow, & Bradley, 2013). The need for accurate reconstructions is therefore important on multiple levels including site prospection on the basis of former landscape use (e.g. Vos, De Kleine, & Rutten, 2012; Ward et al. 2013), interpreting past human action/strategies within their landscape context (e.g. Sturt, 2006; Athanassas et al., 2012) or identifying areas of high archaeological potential to enable effective management (e.g. Peeters, Murphy, & Flemming, 2009; TRC Environmental, 2012).

For coastal areas, reconstructing paleo-geography can be done using a variety of techniques and data sources, the choice of which is ultimately dependent on data quality and availability. The simplest technique relies on varying sea-level (derived from a global eustatic curve, local relative sea-level (RSL) curve or Glacio-Isostatic-Adjustment (GIA) model depending on availability) over the modern seabed/land surface and assuming that this represents a reasonable analogue for the past landscape (e.g. Fisher et al., 2010; Westley et al., 2011; Micallef et al., 2013). Given the ready accessibility of topographic and bathymetric Digital Elevation Models (DEMs) alongside GIS software, this is the fastest and easiest method of paleo-geographic reconstruction. However, it will always lead to less accurate reconstructions where there has been significant erosion or deposition (Westley, Dix, & Quinn, 2004). In such situations; a better alternative is to 'backstrip' the modern landscape of accumulated sediment by identifying an interpreted paleo-landsurface, generally from seismic profiles constrained by core samples offshore or borehole samples onshore. This then forms the surface over which sea-level can be varied (e.g. Bates, Bates, & Dix, 2009; Athanassas et al., 2012; Sonnenburg, Boyce, & Suttak, 2012). Although this improves on using modern topography/bathymetry, it is only effective where the paleo-landscape has been buried rather than eroded and where sufficient subsurface data exist to allow its identification. Further improvements are possible if the landforms making up the paleo-landsurface can also be identified, reconstructed and dated; for example coastal landforms, fluvial channels, lagoons, peat or dunes (Berendsen, Cohen, & Stouthamer, 2007; Gaffney, Thomson, & Fitch, 2007; Marriner, Morhange, & Carayon, 2008; Pavlopoulus et al., 2010; Hijma et al., 2012; Stanley & Bernasconi, 2012; Vos, De Kleine, & Rutten, 2012). This level of analysis arguably provides the most accurate reconstruction as it is based on direct physical evidence of the paleo-landscape rather than an interpreted topographic horizon flooded by a changing sea-level. However, it requires sufficient accurate interpreted evidence of the relevant paleo-environmental signatures based on scientific analysis, for example micropaleontology, sedimentology, micromorphology and/or geophysics (Bates, Bates, & Whittaker, 2007; Marriner, Morhange, & Carayon, 2008; Pavlopoulus et al., 2010; Vos, De Kleine, & Rutten, 2012) which may not always be available particularly where the data in question were not collected for scientific purposes (e.g. engineering boreholes).

In the following study, we adopt a backstripping methodology to paleo-geographic reconstruction and apply it to Ramore Head on the north coast of Northern Ireland. We have chosen the backstripping method because the quality of much of the extant data, specifically legacy geotechnical logs, is insufficient to allow detailed identification and mapping of paleo-environmental signatures or landforms relating to paleo-geographic change. However, it should provide more accurate reconstructions than previous attempts based on modern bathymetry and topography (Pollard, 2011; Westley et al., 2011).

The study area has been chosen because it has been identified as a locus of coastal Mesolithic activity, one of only a handful of such sites along Ireland's north coast (Woodman, 1978). It has also been identified as having potential for the preservation of submerged prehistoric landscapes offshore (Westley et al., 2011). Studies of such landscapes around Ireland are still in their infancy (Bell, O'Sullivan, & Quinn, 2006; Westley, 2013), compared with similar research in NW Europe, particularly the Baltic and North Seas (Benjamin et al., 2011). Therefore, there is a clear need to better understand them, in terms of their location, archaeological significance and preservation potential in order to enable effective study and management. Conversely, Ireland has benefitted from an ever-increasing pool of high-resolution marine geophysical data thanks to national seabed mapping programs such as the INFOMAR Program and the Joint Irish Bathymetric Survey (JIBS) (Quinn et al., 2010; Dorschel et al., 2011), and also increasing commercial development of the continental shelf. The study area is well-covered by these data including high-resolution multibeam bathymetry and seismic profiles. It therefore represents a useful test case in verifying the effectiveness of these datasets for improving paleo-geographic reconstruction in an Irish context.

The aims of this paper are twofold:

1. We identify preserved remnants of the paleo-landscape both onshore and offshore of Ramore Head using extant geophysical and geotechnical data.
2. We identify backstripped paleo-landsurfaces from these data and combine them with extant models of relative sea-level (RSL) change to produce a series of local-scale (<5 km) paleo-geographic reconstructions.

We then discuss how accurate reconstructions, based on offshore and onshore evidence of buried relict landscapes, can assist archaeological and paleo-environmental prospection and help define areas for heritage management. We also explore whether the revised reconstructions provide new insights into the effect of paleo-geographic change on the local Mesolithic population in terms of the positioning of known sites within the landscape and the possible locations of unrecorded ones.

STUDY AREA

Geology & Physical Geography

Ramore Head is a bedrock peninsula, occupied by the modern town of Portrush, which separates two sandy beaches; Mill Strand – bounding the West Bay, and Curran Strand – bounding the East Bay (Figure 1). Both beaches and the peninsula are backed by extensive mid–late Holocene dune systems although only the East Bay dunes are currently visible, as the West Bay system has been built over (Wilson, McGourty, & Bateman, 2004). Underlying geology comprises a sequence of Jurassic clays (Lias) overlain by flint-bearing Cretaceous chalk and Paleogene basalt. A NW-SE oriented fault (the Portrush fault) runs through the West Bay. East of the fault the full bedrock sequence occurs above sea-level with chalk cliffs exposed at the shoreline. Conversely, only basalt is visible west of the fault and forms a line of cliffs and platforms. Ramore Head itself is a Paleogene dolerite intrusion (a sill) that is more erosion-resistant than the older surrounding Lias and chalk. It extends northeast to form the Skerries; a chain of small islets sheltering the East Bay (Wilson & Manning, 1978).

Local topography is highly variable. The modern town is bounded on the west by 20–25 m high basalt cliffs. To the east, the complex topography of the East Bay dunes gives way to 50–60 m high chalk cliffs. Ramore Head itself has sheer 20 m high cliffs on its western side but dips eastward to only 4–5 m high. The historic core of Portrush was situated on the Head itself but has since expanded to occupy the shallow depression (6–10 m above sea-level) immediately inland.

Coastal processes are high energy and wave-dominated with a spring tidal range of 1.7 m (Pintado, 2007). Mean significant wave heights offshore (35 m depth) average 1.35 m and can exceed 10 m during winter storms (Backstrom, Jackson, & Cooper, 2009). Interpretation of coincident high-resolution multibeam bathymetry and backscatter data shows a largely featureless seabed primarily composed of sand with some patches of mixed (sand, gravel and shell) sediment in the East Bay and stoney or bedrock reef fringing Ramore Head and the Skerries (Plets et al., 2012). Relief in the East Bay is relatively low except for an elongated triangular channel-like feature extending east from Ramore Head and the Skerries. In the West Bay, relief is restricted to the rocky cliffs on its fringes and large sandwaves at c. 20–25 m depth (Plets et al., 2012). At face value, the high-energy conditions do not appear conducive to preservation of submerged archaeological landscapes. However, the protection afforded by the Skerries to the East Bay, and preservation of early–mid-Holocene intertidal and subtidal peat in the West Bay suggest that it is possible (see below; Westley et al., 2011; Wilson et al., 2011).

Archaeology

Archaeological finds suggest that Portrush was an important focus for Mesolithic settlement. Unfortunately, most finds were uncovered by building work and antiquarians in the 19th Century, so the precise chronology, nature and location of the settlement are poorly defined (Knowles, 1888–91; Simpson, 1888–91; Gray, 1888/9). Much of the collected material does not appear to have survived and that which has survived, or was documented, has proved difficult to assign to a specific location. Based on the antiquarian reports and the known lithic material, Woodman (1978) concluded that there were at least two

Mesolithic (c. 9800–6000 cal BP in Ireland: Woodman, 2012) sites under Portrush town; at least one of which is Earlier Mesolithic (c. 9800–8400 cal BP: Woodman, 2012) based on the presence of diagnostic flake axes, narrow blades and narrow blade cores. The key findspots are located close to the historic centre on Ramore Head: a flint-bearing layer of peaty soil, underlying a beach deposit revealed by sand removal (Springhill) and another deposit close to the railway station also buried under sand (Railway Rd) (Figure 1).

At Mill Strand, Patterson (1896) reported a cache of lithics embedded in an exposed peat face underlying the dunes, which are typologically suggestive of the Later Mesolithic (8400–6000 cal BP: Woodman, 1978). A handful of lithic finds have also been reportedly washed onto the beach (Hewson 1935; McAllister, personal communication, 2013) though their precise cultural affinity is uncertain. Most recently, Pollard (2011) described finds from several disturbed sites in the general area (Ballyreagh, Ramore Hill, Dhu Varren). Though none are securely dated, they were assigned Mesolithic ages on the basis of typology or proximity to dated contexts. If genuinely Mesolithic, when taken in association with the antiquarian sites, they provide an indication of a general Mesolithic presence in the wider area (Figure 1).

Sea-level and Paleo-environmental Change

The main driver of Late Pleistocene to Holocene paleo-geographic change in the study area was relative sea-level (RSL) change. Owing to differential isostatic adjustment caused by late Pleistocene glaciation, RSL change here is complex and, due to a lack of well-dated sea-level index points and limits, still heavily debated (Edwards et al., 2008; McCabe, 2008). The extant data and modeled RSL from Glacio-Isostatic-Adjustment (GIA) models both suggest an initial RSL highstand immediately following deglaciation (c. 16–20 ka cal BP), followed by a fall to a lowstand and then a rise to a mid-Holocene highstand (Figure 2; Carter, 1982; McCabe, Cooper, & Kelley, 2007; Brooks et al., 2008). Estimates of lowstand timing and depth range from -30 m at c. 13.5 ka cal BP (based on undated potentially wave-cut submarine features: Kelley et al., 2006) to -16 to -13 m at c. 14.5 ka cal BP (based on GIA models: Brooks et al., 2008; Bradley et al., 2011).

Sparse evidence of RSL change within the immediate 20–30 km consists of submerged and intertidal peat (Figure 2). Peat dredged from the Bann Estuary (7 km west) indicates that RSL was below c. -6 to -7 m at 9.7–10.3 ka cal BP (Carter, 1982). This is supported by another submerged peat from Lough

Foyle (20 km west), from a depth of c. -2.3 to -2.6 m and dated to 9.4–8.7 cal ka BP (Westley, 2013). At Portrush itself, a subtidal (-3 m) peat sample from the West Bay was dated to 9.3–8.9 ka cal BP (Westley, 2013) (Figure 3; Table 1).

Within the study area, more detail comes from intertidal and coastal peat sections in the West Bay examined by Jessen (1949). Jessen's (1949) interpretation was that the peat represented the remains of fens or swamp woods which formed in sand dune hollows as rising sea-level impeded drainage. Peat growth was subsequently terminated by the mid-Holocene marine transgression, inferred on the basis that the peat was underlain by ridges of fine stone- and shell-free sand (interpreted as blown sand) and overlain by laminated sand with rounded pebbles and cobbles (interpreted as a raised beach). Recent work has constrained the timing of the highstand to c. 6.9–6.5 cal ka BP and at least 4 m elevation based on additional dates from the intertidal (Mill Strand) and inland (Dhu Varren) sections of the peat (Wilson et al., 2011) (Figure 3; Table 1).

In short, there is enough evidence to show RSL below present during the early–mid-Holocene and rising during the mid–late Holocene, but not enough to accurately constrain the precise timing and depth of the lowstand and subsequent highstand (Figure 2). It also appears that while the dated evidence broadly supports the pattern modeled by Brooks et al. (2008) and Bradley et al. (2011), in this area at least, it fits better with the former given that most of the dated peat samples represent maximum limits on past RSL and hence should plot above the modeled RSL curve (see Figure 2). Consequently, the Brooks et al. (2008) model will be used throughout the rest of this paper.

METHODOLOGY

Marine Geophysical Data

Offshore bathymetry is provided by a high-resolution (1 m) multibeam echo-sounder (MBES) dataset collected in 2008 by the Joint Irish Bathymetric Survey (JIBS). This covers the entirety of the offshore portion of the study area except for the shallowest nearshore zone (Quinn et al., 2010; Plets et al., 2012) (Figure 4). Sub-bottom profile data are from two sources (Figure 4). Firstly, Chirp seismic surveys were undertaken by the University of Ulster in the late 1990s (Cooper et al., 2002). Fifteen lines were collected in the study area including single transects in the West Bay and a loose grid (200–500 m spacing) in the East Bay. Secondly, a grid of Boomer seismic lines (50 m spacing) within the West Bay was collected by METOC Plc/Titan Surveys in advance of the installation of a submarine telecommunications cable. For analysis, all seismic data were input into *IHS Kingdom* software for horizon picking, and identification and interpretation of acoustic units. Three-dimensional topographic surfaces were created by first converting the identified 2D acoustic horizons from two-way-travel-time (TWT) to depth using a constant velocity value of 1600 m/s, gridding them in *IHS Kingdom* using the flex gridding algorithm (cell sizes of 100m and 20m for the Chirp and Boomer data respectively) and finally exporting them to *ESRI ArcGIS* for integration with other spatial data. Flex gridding is a component of *IHS Kingdom* and combines minimum curvature and minimum tension algorithms. It was chosen because it is the software's suggested option for rapid interpolation capable of dealing with both dense and sparse data (compare the survey line spacing for the East and West bays) while also honoring the original data points.

Geotechnical Data

Geotechnical boreholes undertaken for engineering works dating from 1968–2003 were obtained from the archive of the Geological Survey of Northern Ireland (GSNI). These were supplemented by four recent (2009) boreholes taken through the West Bay/Mill Strand beach and dunes by METOC Plc as part of the aforementioned cable installation (Figure 4). Positional information for the archive boreholes was generally good and supplied as maps, grid coordinates or addresses. However, elevation information was lacking on occasion and, where missing, was based on the LPS 10 m-resolution Digital Elevation Model (DEM). Offshore sampling is limited to 14 short (<1 m) hand-driven percussion cores from the West Bay taken by the UK National Facility for Scientific Diving (NFSD) (Quinn et al., 2010). Scanned hardcopy borehole logs were input into *Rockworks* software for display and interpretation. The recorded lithostratigraphic sequence for each log was interpreted in the context of local paleo-environmental change (see below for interpretation) and transformed into stratigraphic units which best represent the evolution of the paleo-landscape. Stratigraphic surfaces were gridded within *Rockworks* using the Kriging algorithm (with additional polynomial interpolation) at a 50 m cell size and exported to *ArcGIS* for integration with the offshore data, analysis and paleo-geographic reconstruction. Kriging was chosen because it is an established technique in terrain modelling capable of dealing with irregularly spaced datapoints (boreholes in this case) while also attempting to express directional trends in the data. For both on- and offshore areas, paleo-geographic reconstructions were created by reshading/re-coloring the gridded surface (i.e. the reconstructed paleo-landsurface) within *ArcGIS* to reflect the height of past RSL as inferred from the GIA model of Brooks et al. (2008).

Datums

Key to accurate integration of offshore and onshore data is the use of a common vertical datum (Bates, Bates, & Dix, 2009). The former data are referenced to chart datum (CD) while the latter are referenced to Ordnance Datum (Belfast) (OD(B)) which, in the study area, is 1.24 m above CD. Bathymetric and seismic data were therefore corrected to OD(B). However, there were some vertical mismatches (up to c. 2 m) between the seismic and MBES datasets relating to tidal and navigational (e.g. layback) corrections for each survey and the period elapsed between surveys (10 years between the Chirp and MBES and 1 year between the Boomer and MBES) during which time bathymetry has naturally varied on the order of c. 1-2 m (Backstrom, Jackson, & Cooper, 2009). Given the coarse nature of the datasets and interpretation below, we feel that these margins of error are acceptable within the context of the project but must be made clear before proceeding.

RESULTS

The following sections describe the results obtained from examination of the above datasets. The majority of the seismic data discussed is resultant from the West Bay Boomer survey as this has never been analysed for scientific purposes. The East Bay Chirp profiles are only discussed briefly and to highlight their key characteristics given that they were previously interpreted by Cooper et al. (2002) and Kelley et al. (2006) and a full discussion can be found therein.

West Bay Boomer Profiles

Unit 1 (U1)

U1 represents the lowest unit imaged by the seismic data. Its upper surface is a discontinuous reflector [R1] of varying amplitude (low to high) which dips both in a seaward direction and towards the north-east. The north-eastward dip is enhanced in the inshore part of the bay by a distinct break in slope which becomes less apparent further offshore. Penetration through U1 is poor and internal reflectors are rarely imaged. Where visible, they consist either of point reflectors or low frequency, low to moderate amplitude discontinuous and contorted horizons (Figure 5).

Unit 2 (U2)

U2's upper boundary consists of a distinct moderate to high amplitude reflector which itself consists of the convergence of two horizons [R2a; R2b] running broadly horizontal in a shore-parallel direction, but dipping seaward (Figure 5). U2 appears massive with little structure beyond occasional discontinuous internal reflectors which consist either of localized pockets of point reflectors or individual subparallel low amplitude horizons (Figure 5). U2 appears to lie conformably over U1, though this cannot be completely verified as there is limited penetration though U2 and the underlying contact with U1 is not always imaged.

Unit 3 (U3)

U3 is a roughly wedge-shaped acoustic unit which lies conformably over U2 and separated from it by R2a (Figure 6). It is found only in water depths of <c. 20 m and is clearest in the southwestern part of the bay. U3 is divided into 2 sub-units. U3a, the lower sub-unit, is massive with a few discontinuous low amplitude reflectors. U3b above it, conversely, is characterized by discontinuous, high frequency, moderate to high amplitude chaotic reflectors (Figure 6). A single moderate amplitude dipping internal reflector cuts down across both sub-units. U3 is capped by a distinct high amplitude horizon [R3] which dips seaward to also form the upper boundary of Unit 4 (see below). A discontinuity is consistently present along the inshore (c. 10 m water depth) part of R3, with the inner part of it overlying the chaotic facies of U3b, but the outer part overlying the massive facies of U3a and U4 (Figure 6). The inner section of R3 often appears of greater negative amplitude than the outer part (i.e. it appears as a bright white reflector).

Unit 4 (U4)

U4 is a wedge-shaped acoustic unit overlying U2 and is located immediately seaward of U3, being only present in water depths between c. 15–25 m (Figure 5). It is separated from both U2 and U3 by R2b, and appears to downlap onto U2, either offlapping or truncating the seaward edge of U3 (Figure 6).

Internally, U4 is acoustically transparent and generally structureless with occasional low amplitude sub-parallel reflectors (Figure 5). Like U3, U4 is present in the southwestern part of the bay and pinches out towards the northeast.

Unit 5 (U5)

U5 is present across the entire study area and directly overlies U2, U3 or U4 depending on whether they are present (Figure 5). Internally, U5 comprises high frequency, moderate to high amplitude reflectors which tend to be subparallel in shallow water before becoming more chaotic or hummocky in water depths >c. 20 m. U4's contact with the underlying units appears erosional, clearly truncating R2b and planing the tops of U3 and U4 to form a single consistent surface capped by R3.

East Bay Chirp Profiles

Both Cooper et al. (2002) and Kelley et al. (2006) identified at least three main acoustic units, differentiated by variations in internal reflectors and clear intervening horizons. All bar one of the mapped reflectors are relatively smooth and continuous; the exception is a chaotic high-amplitude reflector with apparently channel-like features located on the eastern edge of the East Bay (Figure 7). The reduced penetration and wide line spacing however, compared to the Boomer, means that is more difficult to precisely map the spatial extent of the various units and identify smaller sub-units within the East Bay.

Geotechnical Data

Eighty-one onshore borehole records are supplemented by 14 small (<1 m) diver-collected (percussion) hand cores offshore. The boreholes range between 1.2–27 m in length and are distributed unevenly across the study area with clusters in the south, southwest and east (Figure 4). They show that the uppermost deposit beneath Portrush consists of a layer of 1–6 m thick sand with the thickest deposits over the dunes backing the East and West Bays.

On Ramore Head, the sand forms a thin (<1–2 m) veneer directly over the bedrock. However, landward of the peninsula, a distinct layer of peat is detectable running from the subtidal zone in the West Bay to the sand dunes of the East Bay (Figures 4 & 8). This ranges from 0.2–5.5 m thick and is located at heights ranging from -3 to +9.8 m OD. The thickest (up to 5.5 m) peat is located at Dhu Varren and the West Bay (Figure 3) and the thinnest (<0.5 m) in the southern part of Portrush, where the peat is also at its highest elevation (c. +7–10 m OD). The large dunes of the East Bay have not been sampled to any great extent. Two sets of boreholes on their southern margin suggest the peat is present; however, on their western side, immediately adjacent to the town, the peat was not sampled. Whether this relates to its absence (either naturally or by anthropogenic removal) or insufficient borehole penetration is uncertain. Underlying the peat are deposits of clay, gravel, silt or sand with the bedrock situated up to several metres below the present ground level and, in many places, not actually reached (Figure 8). Ramore Head is the only area where bedrock is consistently reached because the overburden is thin.

INTERPRETATION

Mapping and Identification of Offshore Paleo-landsurfaces

A descriptive summary of the acoustic units and interpretation can be found in Table 2. The deepest acoustic units pre-date the lowstand terrestrial landscape. Within the East Bay, Cooper et al. (2002) identified bedrock overlain by glacial till and glaciomarine sediment on the basis of the acoustic character of the mapped units. In the West Bay the stratigraphic succession is probably similar. U1 is interpreted either as bedrock, or bedrock overlain by a drape of glacial sediment (owing to a general lack of penetration and similar depths to bedrock sampled in adjacent onshore boreholes). U2 is interpreted as sediment of glacial origin. Adjacent onshore boreholes sample a thick (10–12 m) layer of sandy clayey gravelly silt with cobbles and some boulders overlying the bedrock at a similar depth to the mapped inshore extent of U2 (Figure 3). Given the environmental history of the study area, glacial action is the most plausible explanation for deposition of such a thick deposit of mixed sediment.

From an archaeological perspective, the key horizon is the former terrestrial surface created when sea-level fell from the post-glacial highstand, which was later inundated, and may now be buried and preserved offshore. This would have been the landsurface exposed and available for Mesolithic settlement. In the West Bay, this is interpreted as the top of U3b. The reflector bounding its upper surface [R3] was ground-truthed by hand coring and found to be peat dating to 8.9–9.3 ka cal BP (Westley, 2013) (PRW8_1: Figure 3), which supports this interpretation. Attribution of peat is also supported by the often strong negative amplitude of R3, particularly its inshore section. Such acoustic signatures have previously been identified as indicative of submerged peats (Plets et al., 2007). Effectively, therefore U3a is interpreted as a regressive formation created as RSL fell from the postglacial highstand with a vegetated landscape developing on its uppermost surface (U3b and R3) during the lowstand. This follows the sequence of changes described by Cooper et al. (2002) and Kelley et al. (2006) for the study area.

Nonetheless, this does not mean that the entirety of R3 represents a preserved peat-covered landsurface. It is apparent that there are discontinuities along the horizon (e.g. Figure 6) and strongly negative amplitudes are not always present. A more plausible explanation is that R3 represents a transgressive unconformity running over the former landsurface which is now buried by <5 m of modern sand (Figure 9b). The unconformity interpretation is supported by the fact that R3 clearly truncates R2b (Figure 6). The former landsurface meanwhile has been preserved in places particularly where consolidated peat deposits have proved resistant to erosion. This mirrors the current situation in the West Bay intertidal zone where outcrops of compact peat resist erosion in contrast to the surrounding mobile sand. Thus, we adopt a conservative position and limit the interpreted extent of the peaty paleo-landsurface to the inner part of R3 (i.e. shoreward of the discontinuity indicated on Figure 6 at depths of c.-2 to -9 m) where it has been ground-truthed and more frequently displays a strong negative amplitude (Figure 9a).

Given that R3 also extends seaward to cap U4, this could therefore indicate that the latter is also a remnant of the former landscape. However, given the limited ground-truthing to date and uncertainties in the lateral continuity of R3 described above we have less confidence in the attribution of peat to its upper boundary. Moreover, since we still do not know the precise depth of the lowstand (e.g. -30 m: Kelley et al., 2006; -16 m: Brooks et al., 2008), it is not certain that U4 was even subaerially exposed, in which case it could represent a shallow water/nearshore deposit. Finally, U5 is interpreted as modern/post-transgression sand produced by modern reworking of pre-existing deposits. This has been ground-truthed by cores and surface samples as loose fine-medium sand.

In the East Bay, the key landsurface is the chaotic channelized horizon located in the east of the study area at a depth of -3 to -19 m and presently buried by <2.5 to 5 m of modern sediment (Figures 7 and 9). This follows the interpretation of Cooper et al. (2002) who interpreted it as peat partly covering a sandy landsurface created during RSL regression. Kelley et al. (2006) attempted ground-truthing and, on this basis, revised the interpretation to beach gravel rather than peat. However, their core was taken on the extreme margin of this horizon and, when combined with inaccuracies in vessel positioning, could mean that the actual target horizon was not sampled. Therefore, given that peat is present in the same stratigraphic position in West Bay, its presence in the East Bay should not entirely be ruled out. As in the West Bay therefore, the transgressive unconformity corresponds to the first continuous acoustic horizon buried beneath the seabed. This is generally buried by <5 m of modern sand, except for areas around the triangular channel on the modern seabed extending off the Skerries. Here, the interpolated surface lies above the modern seabed because the acoustic horizon is not present in the channel and the gridding process has extrapolated it based on its position within the channel banks (Figure 9b).

Mapping and Identification of Onshore Paleo-landsurfaces

The majority of the boreholes examined were collected for engineering rather than scientific purposes and consequently only provide reliable information on major transitions in lithology – e.g. peat versus sand versus bedrock. Borehole lithostratigraphy indicates a general upward pattern of bedrock, mixed sediment (clays, silts, sand and gravels), peat, sand and finally made ground, with one or more of the deposits absent on occasion. Of these, the surface most relevant to archaeology and paleo-geographic reconstruction is the thick peat layer given its Mesolithic date (Figure 3). A summary of the basic lithology and assigned stratigraphic units can be found in Table 2.

Based on the boreholes, the peat is located in a band running from the West Bay under the low-lying area south of Ramore Head and into the modern dunes of the East Bay (Figures 4, 8 and 9a). However, detailed paleo-environmental work has not been done on the borehole-sampled peat and radiocarbon dates are limited to 5 samples, all from around Mill Strand (Table 1; Wilson et al., 2011). Therefore, there is no independent confirmation that the peat is a spatially and temporally continuous deposit. The assumption of continuity is made on the basis of its relatively consistent height across the study area and its consistent stratigraphic position above mixed deposits containing silts, sand, gravel and clays, and below sand. For the reconstructions, the peat has been classified as the stratigraphic unit ‘Early-Mid Holocene peat’ and is interpreted to be buried at a depth of between <2.5 to 10 m below modern ground level (Figure 9b).

Borehole information is insufficiently detailed to subdivide the thick clays, silts, sands and gravels which underlie the peat. These most likely have a strong glacial component, based on their stratigraphic position and frequently poorly sorted nature. However, separating out, for instance, subglacial till from raised glaciomarine sediment (such as are exposed 7 km to the east: McCabe, Carter, & Haynes, 1994) or even identifying Jessen's (1949) inferred blown sand/relict dunes immediately under the peat is not possible. Therefore these poorly sorted sediments have been classified as a unified '(Post)glacial undifferentiated' stratigraphic unit (Figure 8).

The same is true of the unit overlying the peat, which theoretically should comprise late Holocene aeolian sand (Wilson, McGourty, & Bateman, 2004), sometimes resting above mid-Holocene highstand marine sediment. In reality, the extent of the latter deposit is uncertain as most of the boreholes report just sand or gravel above the peat with no indication as to whether it is rounded (i.e. water-lain) or contains shells indicative of marine or intertidal conditions. Consequently, this unit has been classified simply as 'Mid–Late Holocene' (Figure 8).

Peat is absent from Ramore Head itself where the 'Mid–Late Holocene' unit forms a thin veneer over bedrock. It is possible that conditions were not suitable for peat formation here or that it was removed during construction. That the latter is the case for at least parts of the peninsula is suggested by Simpson (1888-91) who described a layer of dark brown to black 'peaty soil' buried beneath blown sand close to the town centre which was revealed by construction work. Given this possibility, and the heavy anthropogenic modification of the Ramore Head, we have chosen to use the bedrock surface as a proxy for the past landscape as it marks the most continuous and likely unmodified layer recorded by the boreholes (Figure 8). Nonetheless, we recognize that it marks only the minimum possible elevation of the paleo-landsurface on the peninsula. Interpolation of the borehole records suggest that the bedrock lies <5 m below the modern landscape across most of Ramore Head. Some areas however, appear to have bedrock interpolated as lying above it, generally by <5 m (Figure 9b). This stems from the relatively coarse 50m cell size used in the interpolation procedure which cannot replicate the irregular topography particularly on the peninsula's coastal fringes.

Paleo-geographic Reconstruction

In order to create the paleo-geographic reconstructions, we assume the following:

1. Brooks et al. (2008) provides a reasonable estimate of past RSL change. This results in a lowstand of -16 m at 14.5 ka cal BP, early Mesolithic (10-9 ka cal BP) RSL of -9 to -6 m and a late Mesolithic/mid-Holocene (6 ka cal BP) highstand of +3 m.
2. Identified offshore acoustic horizons and onshore stratigraphic layers represent the best approximation of the paleo-landscape. In the West Bay, this is the inshore section of horizon R3. In the East Bay, this is the first buried horizon under the seabed including the chaotic channel-like reflector to the east. Onshore, this is the peat horizon inland of Ramore Head, while for the Head itself, it is the bedrock surface (Figure 9b).

The reconstructed Mesolithic paleo-geography of Portrush is depicted in Figures 10 and 11 which respectively model lower and higher RSL than present. Each figure also provides a comparison between reconstructions created using the modeled paleo-landsurfaces (referred to as backstripped) and modern bathymetric/topographic surfaces (referred to as modern-based).

Regarding lower RSL, the immediate impression is that there is relatively little difference between using the modern-based and the backstripped reconstructions (Figure 10). This seems particularly true of the -16 m lowstand where the triangular elongated channel feature in the East Bay is still apparent, though with potentially less land exposed to the east if the backstripped reconstruction is accepted (Figure 10a, b). By the early Mesolithic (10–9 ka), differences become more apparent. This however is truer of the East Bay than the West, where Ramore Head forms a more prominent peninsula and less land is exposed in the backstripped reconstruction, with a difference in shoreline position of up to 500 m (Figure 10c, d). The backstripped reconstruction also suggests that after 9 ka, the paleo-shoreline had migrated to a position close to the present shoreline whereas the modern-based counterpart has it clearly seaward of the present shore (Figure 10e,f). The reconstructed landscape of the West Bay is reasonably similar regardless of which surface is used, with measured differences between backstripped and modern-based shorelines ranging up to 100–150 m. This stems from the relatively shallow (<2.5–5 m: Figure 9) burial of the interpreted paleo-landsurface beneath the seabed. Nonetheless, for both bays, given that peat compaction and erosion may have occurred during transgression, it is possible that actual paleo-landsurface was higher than the modeled one, and hence a more accurate reconstruction could lie somewhere between the backstripped and modern-based examples.

During the late Mesolithic (6 ka), RSL is predicted to have risen to +3 m. For the modern-based reconstruction, the impact is minimal, with only a narrow fringe around the modern beaches and intertidal rock platforms of Ramore Head inundated (Figure 11b). Using the backstripped paleo-landsurface, the impacts are not appreciably different beyond a little extra flooding in the West Bay and southeast corner of Ramore Head (Figure 11a). Regarding this latter area, note that there is no data for the western side of the Curran Strand dunes (Figure 11a) which may have differed significantly in elevation from the past landsurface. Flooding may therefore have been more extensive than depicted.

More significant impacts are visible if we attempt to account for the effect of tides and waves. For instance, given that spring tidal range is 1.7 m and storm waves can reach heights of up to 5 m (Pintado, 2007), a maximum surge of up to c. 6 m is theoretically possible. Under a mid-Holocene highstand, such a surge could therefore be as high as 8.9 m (i.e. 3 m highstand + 0.9 m spring tide + 5 m storm wave). This, combined with a backstripped paleo-landsurface, is modeled to affect all but the southeastern-most extent of the peat and the central raised bedrock area of Ramore Head and results in separation of the peninsula from the mainland (Figure 11c). By contrast, under the modern-based reconstruction, Ramore Head remains connected to the mainland despite extensive flooding on its flanks (Figure 11d). In reality, this is a maximal situation assuming that the peat has not suffered compaction or erosion, or that neither it nor the bedrock had any overlying deposits (e.g. blown sand). Nonetheless, even if RSL is reduced to an arbitrary level of 6 m to account for these factors or perhaps to model a less extreme storm surge, major flooding may still have prevailed in the low ground at the neck of Ramore Head and the low-lying area where the bulk of the peat layer is situated (Figure 11e). Thus, while we cannot say for certain on the basis of the extant evidence whether Ramore Head was an island during the Later Mesolithic (as suggested by Woodman, 1978), the models imply that the area between the Head and the mainland was at best low-lying, wet and susceptible to storms.

DISCUSSION

We recognize that assumptions are required to produce these maps and reconstructions. Onshore, we can confidently detect the peat even through relatively crude legacy data. However, mapping continuous paleo-landsurfaces between individual borehole records is less certain and requires the assumption that each one does indeed sample the same surface. Offshore, the reverse is true; the seismic data allow more confident correlation of surfaces and their continuity, however, we are less confident about their assignation due to a lack of ground-truthing. This is a classic example of the problems identified by Bates, Bates, & Dix (2009) in their discussion of onshore-offshore correlation of paleo-geographic reconstructions, and one which cannot be reconciled from the available data at present. That said, even though the resulting maps are admittedly crude, we demonstrate below that they can still help to refine our local-scale understanding of archaeological potential and paleo-geographic change.

Mapping Archaeological Potential

Improved mapping aids heritage management in that identified areas of potential can be protected accordingly, either through avoidance or through appropriate mitigation. Thus, the inshore portion of the West Bay between the intertidal zone and -9 m where there is ground-truthed evidence of paleo-landscape preservation (peat) is the highest potential zone. The easternmost section of the East Bay between depths of -3 to -19 m may have similar potential, but this would need to be confirmed by ground-truthing (Figure 9). In comparison, previous attempts to identify archaeological potential on the basis of bathymetric data alone could not go beyond defining the entirety of both West and East Bays as high potential (Westley et al., 2011).

Regarding the onshore, the low-lying area inland of Ramore Head contains a buried relict prehistoric landsurface (Figure 9). The lack of peat on the Head, possibly caused by destruction through building work, implies that few surviving remnants remain. Interestingly, the official draft Area Plans for Portrush identify the only historic core around the harbor as the most archaeologically important, largely on the basis of potential for medieval and post-medieval remains (Dept. of Environment, 2005). We suggest that from a purely preservation-driven perspective (i.e. notwithstanding biases caused by human preferences for site location – see below) the inland areas may also be important for prehistoric material.

Improved mapping will also assist submerged site prospection since targeted surveys on identified high potential hotspots will reduce survey times, and thus expense. In this case, our analysis suggested that large parts of East Bay may not preserve paleo-landscapes, compared to the potentially richer West Bay. The data analysed can also help plan prospection surveys and determine appropriate methods of investigation given that water and burial depth place constraints on methods used. Since the water depths over the high potential areas are relatively shallow (<20 m), they are within reach of conventional SCUBA; however, their depth of burial (>2.5–5 m: Figure 9) means that archaeological test pitting/excavation would be difficult and systematic coring may be a more appropriate means of investigation. The shallower burial depth of the West Bay deposits and the known high mobility of the overburden (e.g. Backstrom, Jackson, & Cooper, 2009), do suggest that it may be periodically exposed and therefore repeat monitoring surveys by divers to examine naturally exposed peat patches could be feasible. The greater depth of the East Bay deposits (maximum depths of -19 m vs -9 m) also suggests that it may preserve older Late Pleistocene land-surfaces compared to the West Bay. This would not be unexpected, given that there are known instance of such paleo-environmental deposits preserved elsewhere in northeast Ireland, albeit in the intertidal zone rather than offshore (e.g. Prior, Holland, & Cruikshank, 1981; Whitehouse, Watson, & Turney, 2008).

Revised Paleo-geographic Reconstructions

The revised paleo-geographic reconstructions allow us to develop insights into site location patterns on a local scale. The most immediately obvious is that Ramore Head stands out as a peninsula under both high and low RSL. Backstripping and lowered RSL also accentuate its vertical aspect relative to the surrounding bays. This contrasts with previous reconstructions which imply a more linear coastline and less peninsularity (e.g. Pollard, 2011: Figure 5; Westley et al., 2011: Figure 7). During the Earlier Mesolithic, Ramore Head therefore formed an accessible peninsula standing out from an otherwise linear coastline with views to the east, west and north. The surrounding lower-lying land would also have formed a convenient access point to the sea given the dominant chalk and basalt cliffs to either side, and had the further advantage of shelter behind the Skerries. The general location is also advantageous given the nearby flint-bearing chalk (Pollard, 2011), and its position equidistant (7 km) between the major salmon rivers of the Bann and Bush, of which the former has confirmed Earlier Mesolithic use, and the latter, potential occupation (Woodman, 1978). There is therefore little reason why Portrush and the surrounding landscape would not have been an important focus of settlement during this early period.

Under high sea-level during the Later Mesolithic, major periodic flooding during storms and high tides may have affected the low-lying areas joining Ramore Head to the mainland. It is therefore interesting that the richest hotspots of Mesolithic material (the Springhill and Railway Rd sites) were found on the Head itself, and (assuming that the rough antiquarian locational references are correct), along the central bedrock ridge which is modeled to have sat above the maximum storm surge (+8.9 m). Supporting evidence for this comes from Simpson (1889–91:77) who stated that the level of the artifact-bearing layers at Springhill were 'at least forty feet [12m] above present sea-level', though his account also implied that beach deposits were present above the artifact-bearing layer, hence suggesting that storm waves could have occasionally reached even higher than modeled.

We cannot distinguish at present which of the Ramore Head findspots were Earlier or Later Mesolithic, but the reconstructions would imply that there were certainly good reasons for its occupation, namely as a viewpoint and accessible location to the sea in all periods and a relative high point safe from storm waves during the later highstand. For the surrounding area, activity and occupation would have been feasible during the Earlier Mesolithic lowstand (Figure 10c-f), but might now be buried beneath the compact peat layer onshore or within the peat offshore given the current dates for the respective areas (see Figure 3). For the Later Mesolithic, periodic inundation and general wetness of the surrounding low-lying ground could explain the relative lack of material found within the onshore peat despite the extensive preserved paleo-landscape (Figure 11; Hewson, 1935). It may not have been amenable to long-term settlement; particularly as RSL and groundwater levels rose, though it could instead preserve evidence of other short-term activities. These could include for example, shore access for fishing, shellfish collection and boat launching or the exploitation of coastal marsh or woodland for plant collection, hunting or fowling (see McCartan (2002) and Bell (2007) for examples of coastal Mesolithic activity from northeast Ireland and western Britain respectively).

Wider Significance

The approach described above is methodologically is similar to Bates, Bates, & Dix, (2009) in terms of the underlying aim (production of contiguous on- and offshore paleo-geographic reconstructions), datasets (boreholes) and software (*Rockworks* and *ArcGIS*). The main difference lies in attempting to progress from using backstripped bedrock as an analogue for the palaeo-landsurface (Bates, Bates, & Dix, 2009) to identifying an intermediate horizon interpreted as best representative of the paleo-landsurface (this study). Progression has been aided by the availability of tight grids of seismic offshore and a clear identifiable paleo-landscape onshore (intertidal peat) on which to base the interpretation. An alternative approach, demonstrated by Sonnenburg, Boyce, & Suttak (2012) for a Canadian lakebed, is to backstrip down to a level calculated from sedimentation rates, in their case derived from dated and isostatically adjusted core samples. Taken together, this shows that there are multiple approaches to creating backstripped paleo-geographic reconstructions which can be adopted depending on data quality and availability. For example, Sonnenburg, Boyce, & Suttak (2012) lacked seismic data, but had well-dated core samples, enabling accurate calculation of sedimentation rates. By contrast, this study had access to offshore seismics, which were more conducive to tracing spatially extensive buried potential paleo-landsurfaces.

In comparison with reconstructions based on modern land/seabed surfaces, backstripping methods are undoubtedly an improvement because they theoretically give a more accurate picture of paleo-geography, with the caveat that the interpreted paleo-landsurface is indeed accurate and the disadvantage that they are more difficult and time-consuming to produce. This is not to say that modern-based reconstructions have no purpose. In areas of little/low sedimentation, the paleo-landscape may be reasonably close to the modern one and modern-based reconstructions can provide useful insights (e.g. Bates et al. (2013) for the bedrock-dominated Orkney Isles). They are also better suited for broad-scale reconstructions where the difference made by backstripping will be largely invisible and indeed, may not even be possible at the relevant scale (e.g. Sturt, Garrow, & Bradley (2013) for the British Isles).

Arguably though, backstripping falls short of approaches, such as exemplified by Vos, De Kleine, & Rutten (2012), which aim to identify landforms (e.g. fluvial channels, dunes, floodplains) within the paleo-landscape and thus develop more complex and accurate reconstructions than simply the flooding/exposure of interpreted landsurfaces. This ‘stepped’ approach begins with a preliminary geological model of potential paleo-landsurfaces and then improves on this through increasingly high resolution investigations of successively smaller areas of archaeological potential. Crucially, each step integrates information from multiple newly collected datasets from sources such as MBES, seismic profiles, scientifically analysed (e.g. ^{14}C dating, pollen, micropalaeontology) cores and cone penetration tests. Its effectiveness to date is demonstrated by identification of buried high potential landforms, namely river dunes in a fluvio-deltaic environment, which have been successfully sampled for Mesolithic remains (Weerts et al., 2012). Nevertheless, in the absence of this quantity of data and level of analysis, backstripping methods, as shown here or by Sonnenburg, Boyce, & Suttak (2012), can provide a solution intermediate between it and the use of modern landsurfaces, and/or alternatively provide the initial stage of the stepped approach described by Vos, De Kleine, & Rutten (2012).

CONCLUSION

We have presented here identified and mapped Holocene paleo-landsurfaces for the Ramore Head area of Northern Ireland based on the integration of offshore geophysical and onshore geotechnical datasets and used these to produce revised paleo-geographic reconstructions. We recognize that there are limitations with the approach used here particularly with regard to data density and quality, but feel that the analysis and reconstructions presented here can still make useful contributions to archaeological research and management. In this study, our analysis has shown that possible remnants of the preserved paleo-landscape exist offshore in both the West and East Bays and also onshore where they underlie much of the southern part of the town. Knowing these locations, both in terms of spatial extent and depth of burial will help future attempts to prospect for submerged archaeological evidence and to delimit it for management purposes, both on- and offshore. The revision of paleo-geographic reconstructions to incorporate presently buried landsurfaces has allowed us to place our extant archaeology within a more accurate paleo-landscape context and in doing so, has helped develop insights into local-scale site location patterns.

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FIGURE CAPTIONS

Figure 1. Map of study area showing key place names and reported Mesolithic sites. Size of black circles is indicative of the potential area over which lithic material was collected. None of the material is from a securely dated context and Mesolithic attribution is on the basis of lithic typology (Woodman, 1978; Pollard, 2011). 1: Ramore Hill; 2: Railway Rd; 3: Springhill; 4: Mill Strand (lithic material and intertidal peat); 5: Dhu Varren; 6: Ballyreagh. Onshore topography is from the 10 m-resolution Land and Property Services DEM; offshore bathymetry is from the 1 m-resolution Joint Irish Bathymetric Survey (JIBS) DEM. White areas have no DEM coverage. All contour depths/elevations are in metres OD(B).

Figure 2. GIA-modeled RSL curves for the study area (Brooks et al., 2008; Bradley et al., 2011). Superimposed is a composite RSL curve (McCabe, Cooper, & Kelley, 2007; Kelley et al., 2006). Also shown are radiocarbon dated upper and lower limits on RSL (Brooks & Edwards, 2006) supplemented by recently dated samples (Wilson et al., 2011; this paper). Datapoints mentioned in text are labeled, those in italics are submerged or intertidal peats.

Figure 3. Core and borehole logs for the West Bay and Mill Strand showing early–mid-Holocene peat. Radiocarbon dates in uncalibrated years are plotted alongside the logs. Insert aerial photograph shows core locations as well as the intertidal peat exposure on Mill Strand (see Table 1 for calibrated dates; Wilson et al., 2011).

Figure 4. Location of seismic profiles, onshore boreholes and offshore hand cores. Thick lines offshore indicate seismic profiles shown in Figures 5 and 7; dashed lines onshore show borehole stratigraphic sections in Figure 8. Borehole/core symbols have been color-coded to show which sampled Holocene peat.

Figure 5. Shore normal Boomer line from the West Bay shown uninterpreted (top) and with interpreted acoustic units. Note the complicated stratigraphy in Unit 3, with at least two possible sub-units – U3a and U3b. See Figure 6 for closeup view of the inshore section of the line.

Figure 6. Close-up view of inshore section of Boomer line shown in Figure 5. Note the division of Unit 3 into the overlying chaotic U3b sub-unit and the underlying massive U3a sub-unit. Note also the truncation of R2b by R3 and the discontinuity in R3.

Figure 7. Chirp line from the East Bay with interpretation (Cooper et al., 2002) superimposed.

Figure 8. Interpreted stratigraphic sections based on borehole logs. See Figure 4 for section locations.

Figure 9a) Location and elevation relative to OD(B) of areas intepreted as having potential preserved paleo-landcape remains (onshore peat, submerged peat and channelized horizons). These have been interpolated on the basis of seismic data for offshore, and borehole records for onshore. b) Interpolated backstripped topographic surface used for paleo-geographic reconstruction. This represents a combination of horizons interpreted as best representing the paleo-landsurface: R3 (West Bay), first buried horizon and channelized horizon (East Bay), peat and bedrock (onshore). Surface have been shaded to show the difference in elevation between the backstripped surface and modern bathymetry/topography with lighter shades indicating where the backstripped surface is interpolated to lie above the modern landsurfaces and darker shades where it is interpolated below the modern landsurface.

Figure 10. Comparative lowstand paleo-geographic reconstructions for Ramore based on (left) backstripped seismic horizons and (right) the modern seabed surface. White areas have no data coverage.

Figure 11. Comparative highstand and storm surge (+6 m and +8.9 m) paleo-geographic reconstructions for Portrush based on (left) backstripped horizons (right) the modern terrestrial DEM. For the backstripped reconstructions, note that the modelled topographic surfaces only cover Ramore Head and the land immediately to the south. Areas to the west and north east (indicated on 11a) have no boreholes and therefore are still based on the modern DEM. However, thearea west of Ramore Head comprises 20 m high

bedrock cliffs and would therefore never have flooded, even under maximum surges. East of Ramore Head, there is more uncertainty given that the landscape presently comprises Late Holocene dunes (zone north of dashed line on 11a).

TABLE CAPTIONS

Table 1. Radiocarbon dates from the Holocene peat at Portrush (Dhu Varren, Mill Strand and West Bay.) See Figure 3 for locations and Wilson et al., (2011) for further discussion. Dates calibrated with Calib 6.0.1 and the IntCal 2009 calibration curve (Reimer et al., 2009).

Table 2. Summary table showing on- and offshore evidence for paleo-environmental changes discussed in the text and offshore acoustic and onshore stratigraphic units assigned to each phase.

Figures

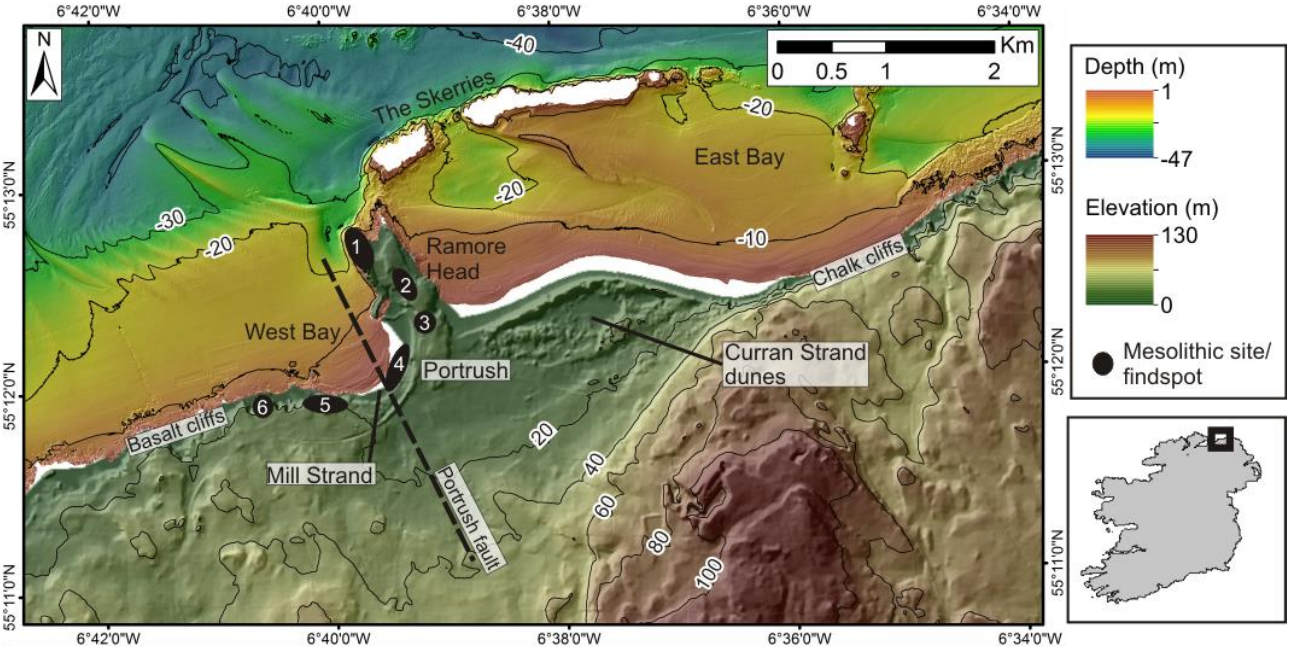


Figure 1.

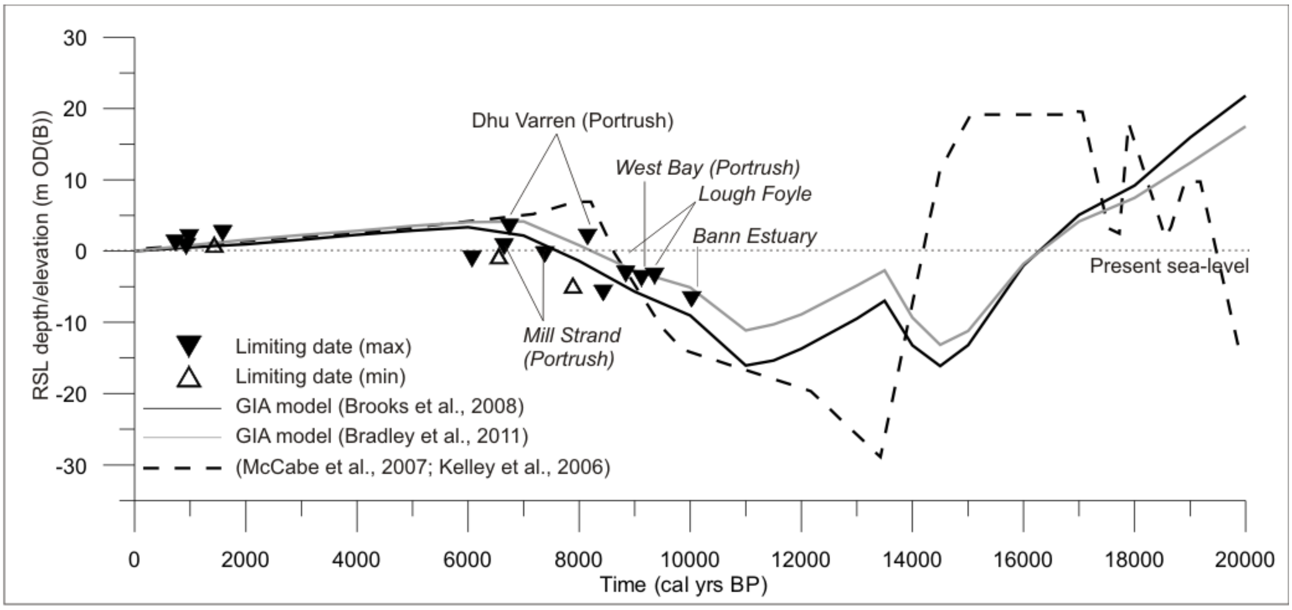
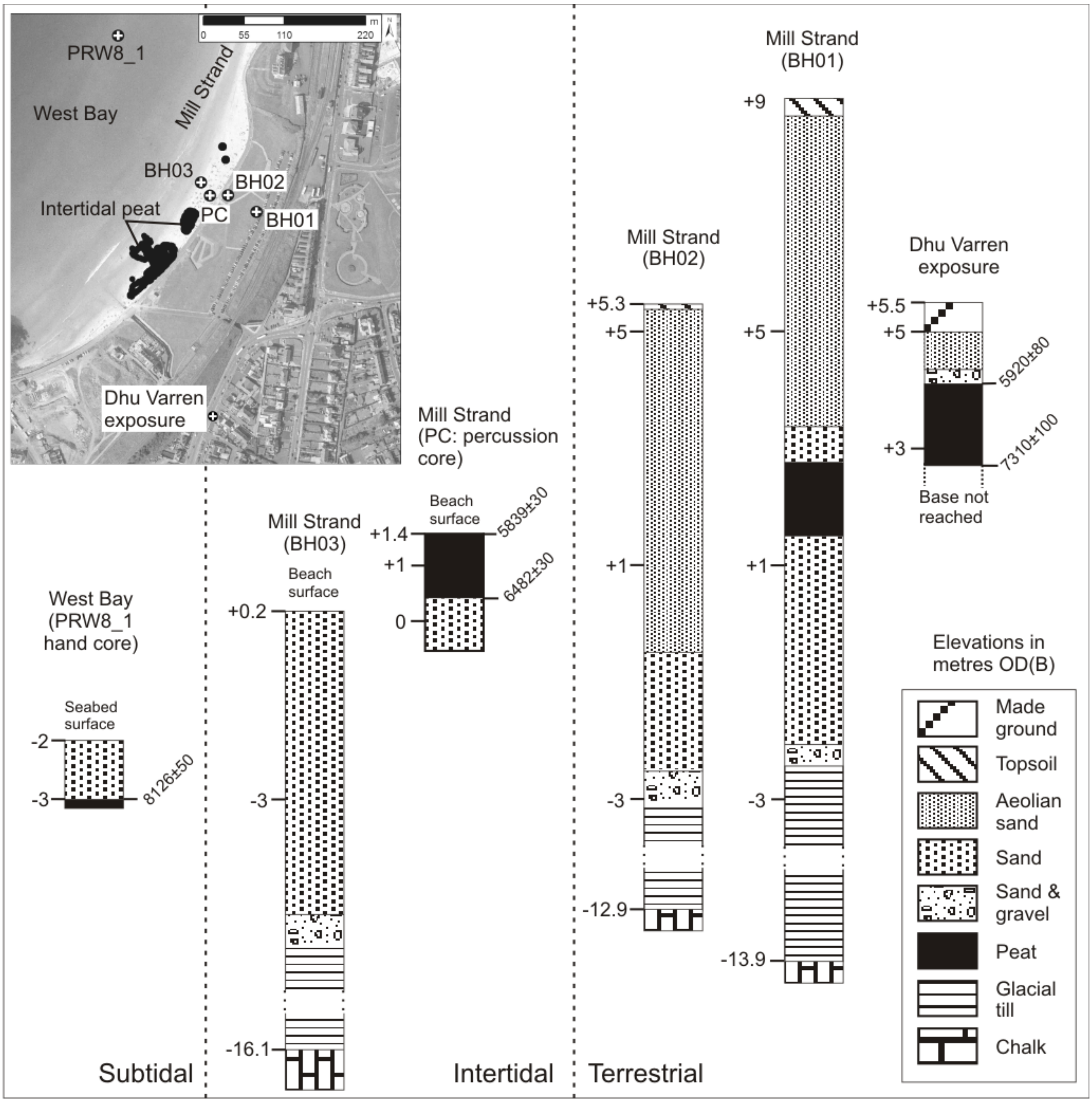
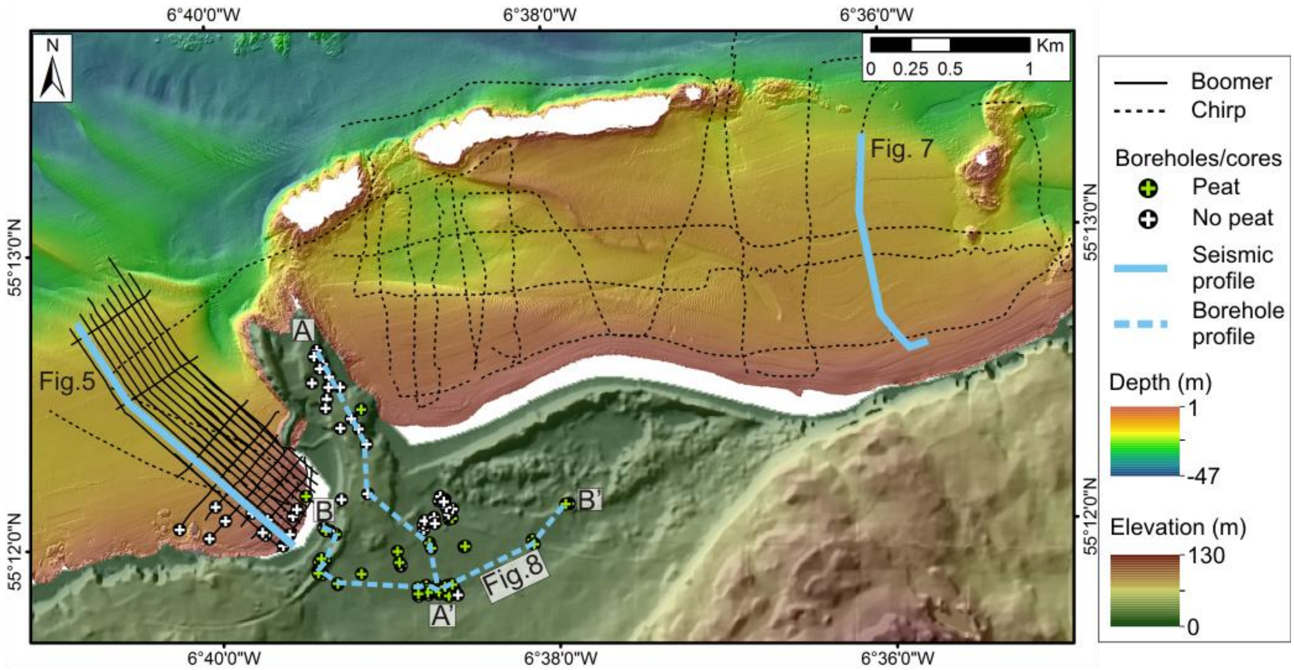


Figure 2.



PRW8_1
West Bay
Mill Strand
BH03
BH02
Intertidal peat
PC
BH01
Dhu Varren exposure
0 55 110 220 m
Mill Strand (BH01)
+9
+5
+1
-3
-13.9
Mill Strand (BH02)
+5.3
+5
+1
-3
-12.9
Dhu Varren exposure
+5.5
+5
+3
5920±80
7310±100
Base not reached
Mill Strand (PC: percussion core)
Beach surface
+1.4
+1
0
5839±30
6482±30
Mill Strand (BH03)
Beach surface
+0.2
-3
-16.1
West Bay (PRW8_1 hand core)
Seabed surface
-2
-3
8126±50
Elevations in metres OD(B)
Made ground
Topsoil
Aeolian sand
Sand
Sand & gravel
Peat
Glacial till
Chalk
Subtidal
Intertidal
Terrestrial

Figure 3.



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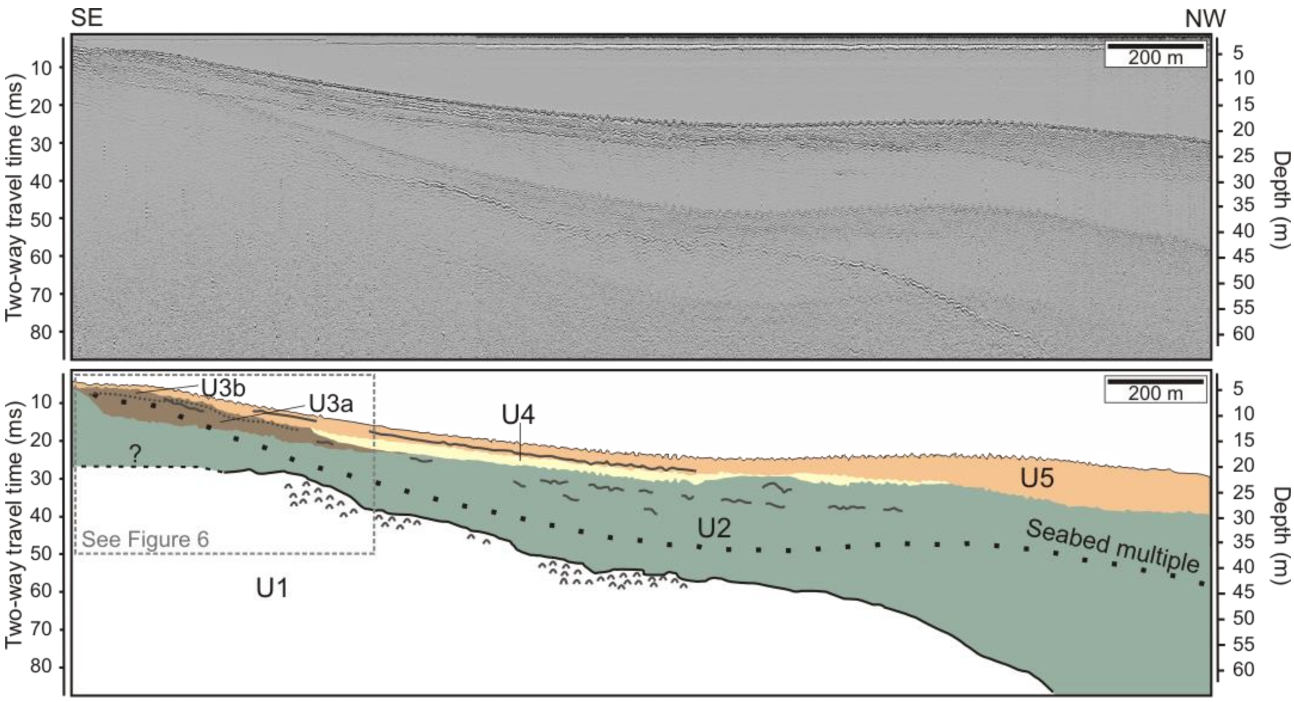

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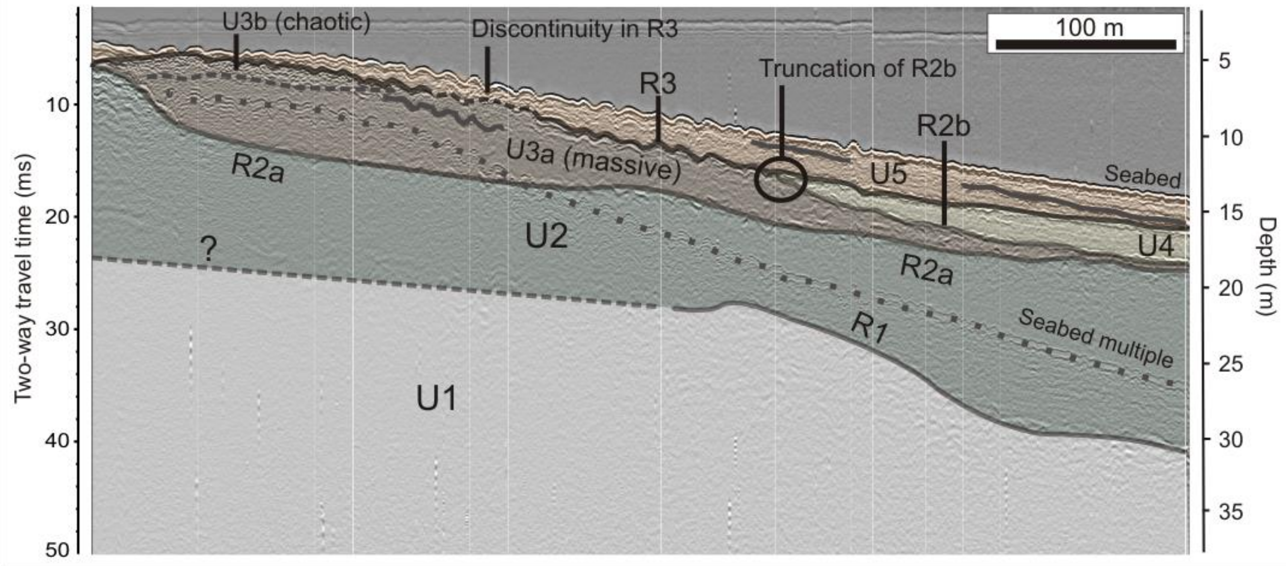

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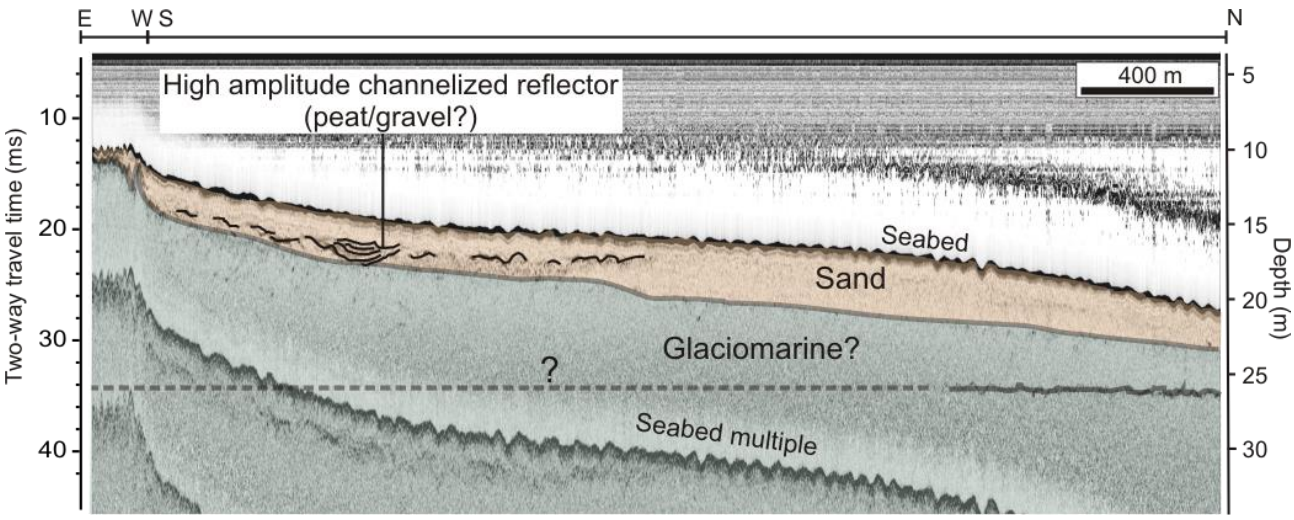
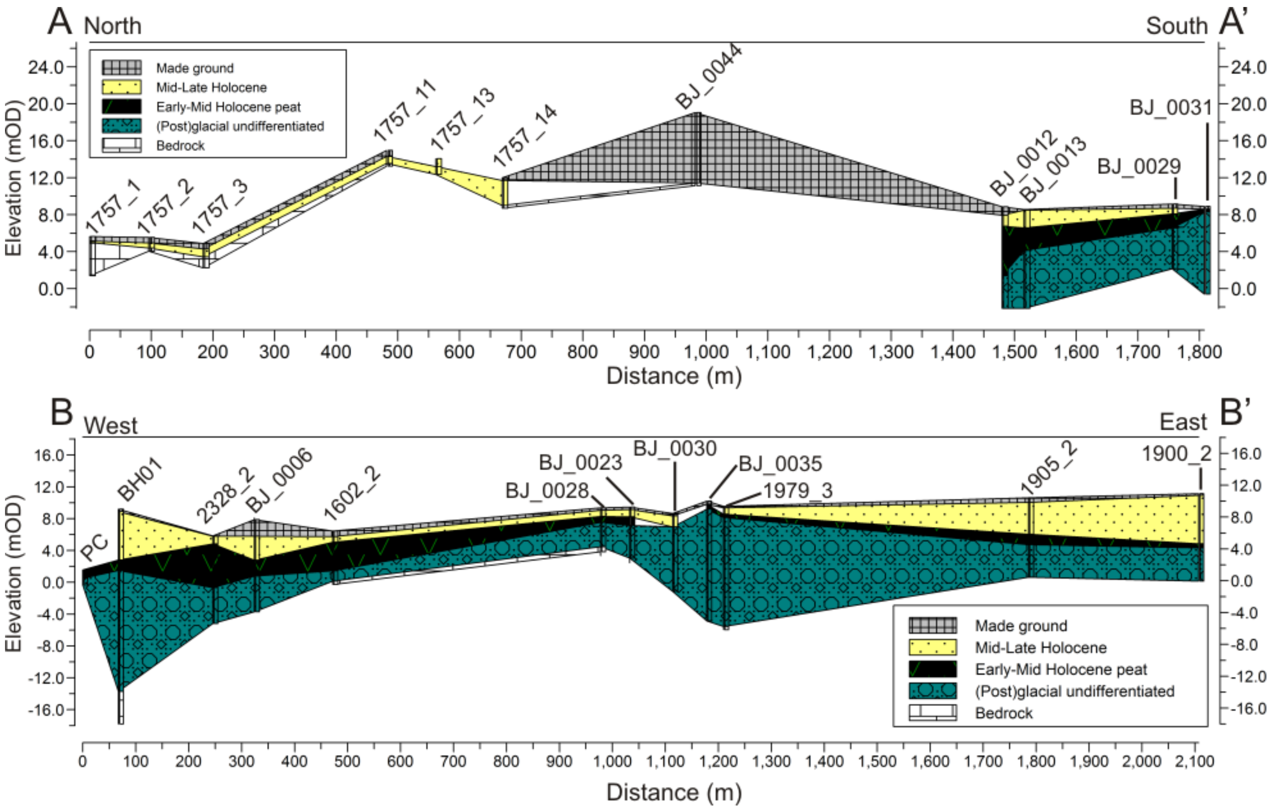
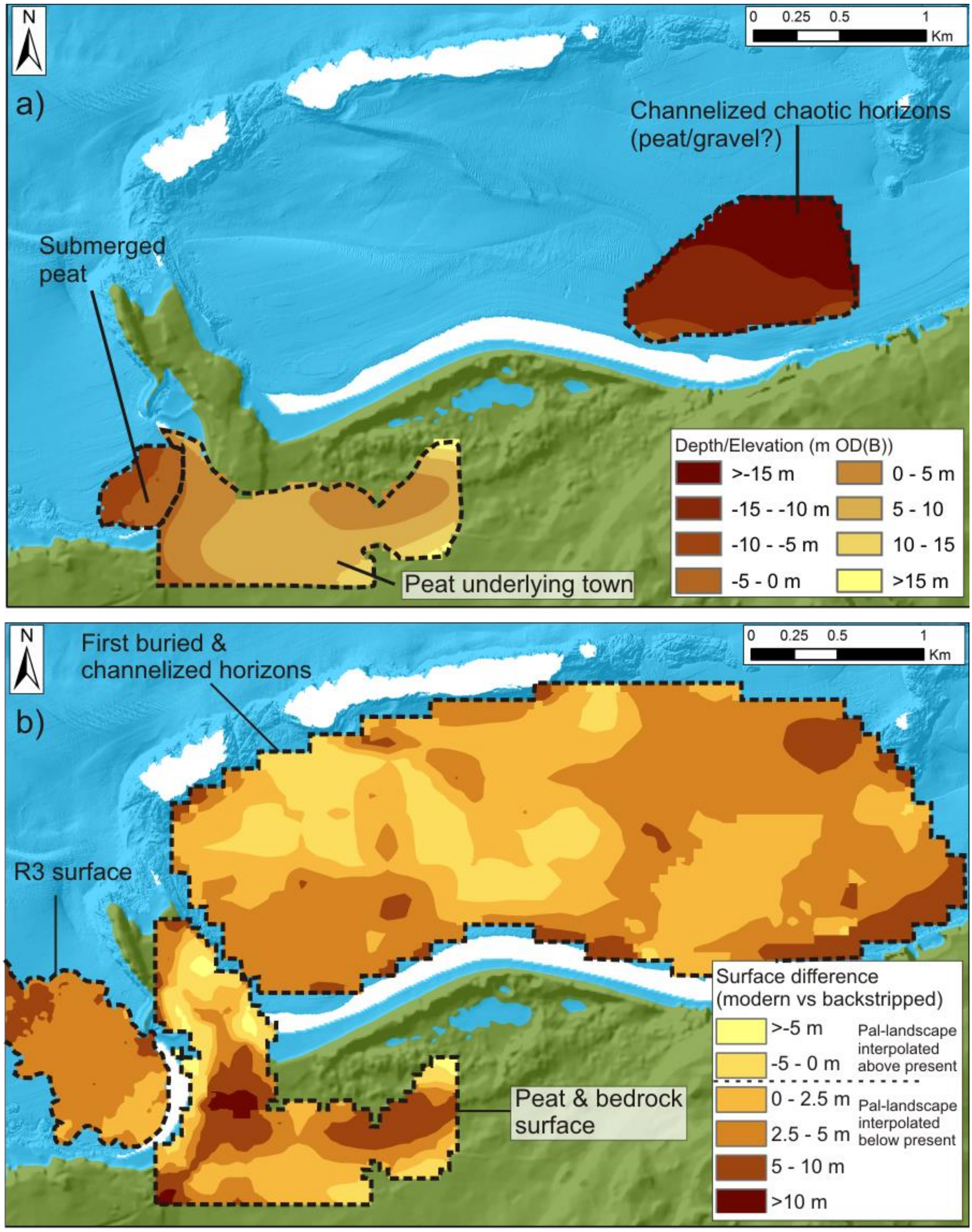


Figure 7.



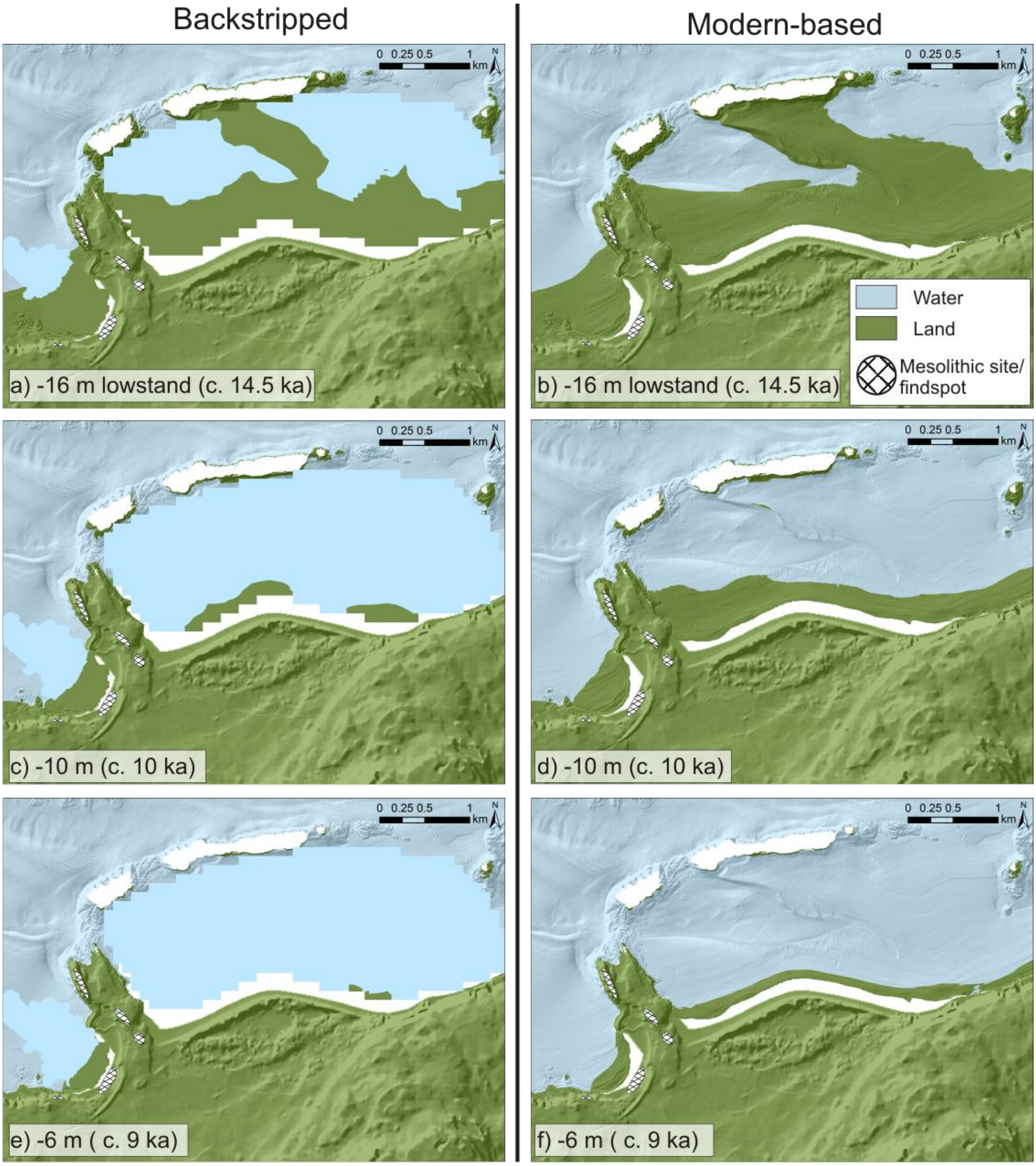
A North
South A'
Made ground
Mid-Late Holocene
Early-Mid Holocene peat
(Post)glacial undifferentiated
Bedrock
Elevation (mOD)
Distance (m)
1757_1
1757_2
1757_3
1757_11
1757_13
1757_14
BJ_0044
BJ_0012
BJ_0013
BJ_0029
BJ_0031
B West
East B'
PC
BH01
2328_2
BJ_0006
1602_2
BJ_0028
BJ_0023
BJ_0030
BJ_0035
1979_3
1905_2
1900_2

Figure 8.



N
0 0.25 0.5 1
Km
a)
Channelized chaotic horizons
(peat/gravel?)
Submerged
peat
Peat underlying town
Depth/Elevation (m OD(B))
>-15 m
-15 - -10 m
-10 - -5 m
-5 - 0 m
0 - 5 m
5 - 10
10 - 15
>15 m
N
0 0.25 0.5 1
Km
b)
First buried &
channelized horizons
R3 surface
Peat & bedrock
surface
Surface difference
(modern vs backstripped)
>-5 m
-5 - 0 m
Pal-landscape
interpolated
above present
0 - 2.5 m
2.5 - 5 m
5 - 10 m
>10 m
Pal-landscape
interpolated
below present

Figure 9.



Backstripped
Modern-based
0 0.25 0.5 1 km
N
a) -16 m lowstand (c. 14.5 ka)
b) -16 m lowstand (c. 14.5 ka)
Water
Land
Mesolithic site/
findspot
c) -10 m (c. 10 ka)
d) -10 m (c. 10 ka)
e) -6 m (c. 9 ka)
f) -6 m (c. 9 ka)

Figure 10.

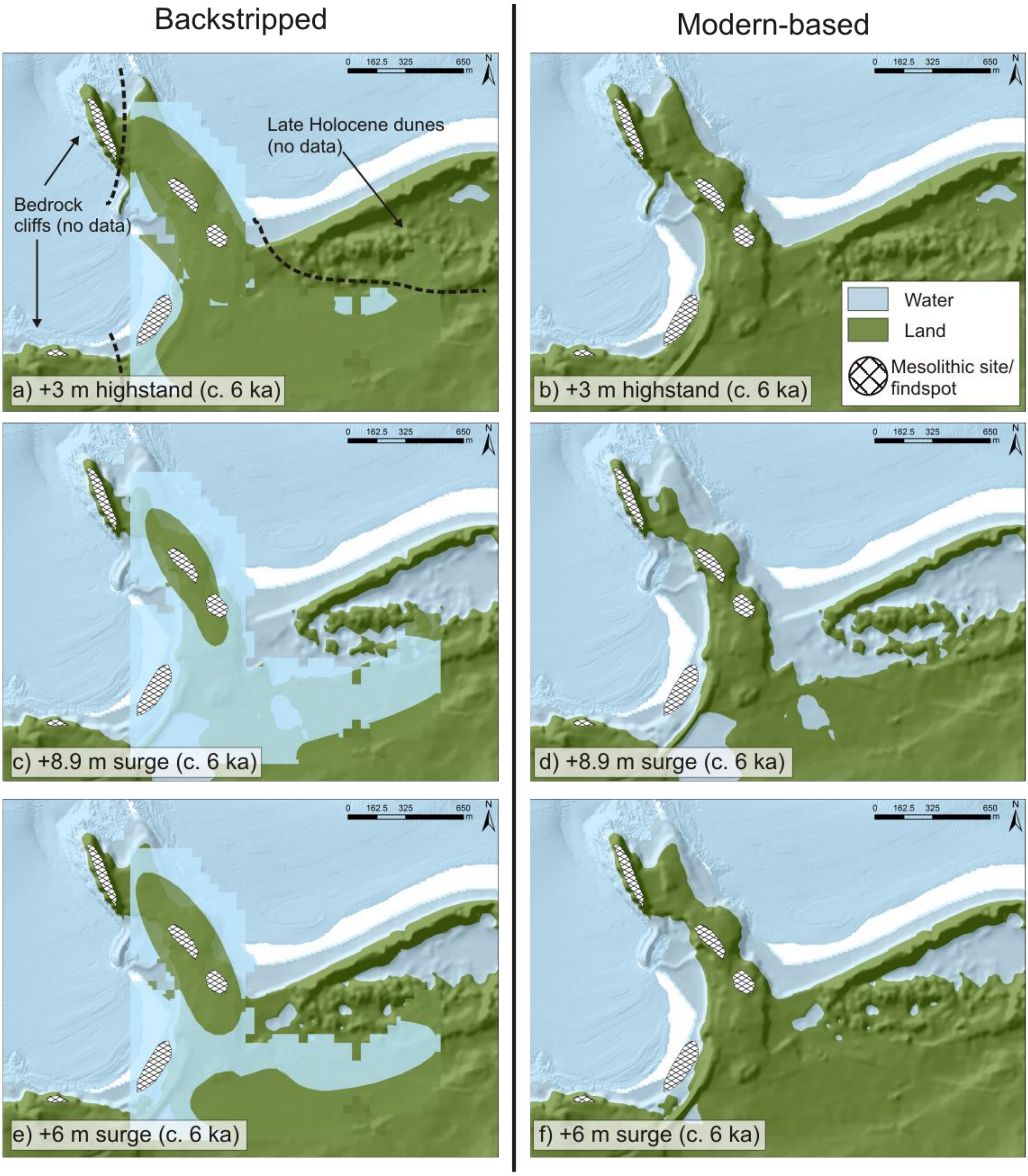

Backstripped
Modern-based
0 162.5 325 650 m
N
Late Holocene dunes (no data)
Bedrock cliffs (no data)
a) +3 m highstand (c. 6 ka)
b) +3 m highstand (c. 6 ka)
Water
Land
Mesolithic site/ findspot
c) +8.9 m surge (c. 6 ka)
d) +8.9 m surge (c. 6 ka)
e) +6 m surge (c. 6 ka)
f) +6 m surge (c. 6 ka)

Figure 11.

Sample location	Lab code	Material	Elevation (mOD)	14C age (yr BP)	$\delta^{13}C$ (‰)	Cal Age (yr BP)
Dhu Varren exposure (top)	Beta-36943	Bulk peat	4.1	5920±80	-25.0*	6540-6949
Dhu Varren exposure (base)	Beta-36944	Bulk peat	2.8	7310±100	-25.0*	7959-8341
Mill Strand percussion core (top)	UBA-14416	Bulk peat	1.4	5839±30	-27.8	6562-6736
Mill Strand percussion core (base)	UBA-14417	Plant macrofossil	0.3	6482±30	-34.1	7319-7439
West Bay hand core PRW8_1 (top)	UBA-21209	Bulk peat	-3	8126±50	-31.7	8992-9253

*Estimated value.

Table 1.

Offshore		Onshore		Interpreted paleo-environmental change
Acoustic Unit	**Description (seismic and hand core)**	**Stratigraphic Unit**	**Description (boreholes)**	
U5	Seismic : high frequency moderate–high amplitude reflectors; sub-parallel in shallow water, chaotic in deeper water. Ground-truth: sand	Mid–Late Holocene	Sand/gravel	Mid-Holocene highstand and RSL fall to present
R3	Seismic: generally continuous high amplitude horizon truncating underlying units and horizons. Ground-truth: peat (c. 9 ka cal BP)	Early–Mid Holocene peat	Peat (c. 6–7 ka cal BP)	Early Holocene RSL rise
U3a, U3b, U4	Seismic: Wedge-shaped acoustic units. Offshore unit: generally massive with discontinuous low amplitude subparallel reflectors. Inshore unit: generally massive with discontinuous low amplitude reflectors at base, high frequency high amplitude chaotic reflectors at top.	(Post)glacial undifferentiated	Poorly sorted sediment (clay to boulder range)	Late Pleistocene–Early Holocene lowstand
U3a	Seismic: generally massive with discontinuous low amplitude reflectors	(Post)glacial undifferentiated	Poorly sorted sediment (clay to boulder range)	Isostatic uplift and RSL fall
U2, R2a, R2b	Seismic: generally massive with occasional low–moderate amplitude point/sub-parallel reflectors bounded by continuous moderate-high amplitude reflector	(Post)glacial undifferentiated	Poorly sorted sediment (clay to boulder range)	Deglaciation and postglacial highstand
U1, R1	Seismic: Discontinuous low frequency contorted/point reflectors bounded by discontinuous low–moderate amplitude reflector	(Post)glacial undifferentiated	Poorly sorted sediment (clay to boulder range) over bedrock	Deglaciation and postglacial highstand

Table 2.