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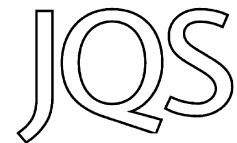
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Lateglacial and Holocene relative sea-level changes and first evidence for the Storegga tsunami in Sutherland, Scotland



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ABSTRACT: We reconstruct one of the longest relative sea-level (RSL) records in north-west Europe from the north coast of mainland Scotland, using data collected from three sites in Loch Eriboll (Sutherland) that we combine with other studies from the region. Following deglaciation, RSL fell from a Lateglacial highstand of +6–8 m OD (Ordnance Datum = ca. mean sea level) at ca. 15 k cal a BP to below present, then rose to an early Holocene highstand and remained at ca. +1 m OD between ca. 7 and 3 k cal a BP, before falling to present. We find no evidence for significant differential Holocene glacio-isostatic adjustment between sites on the north-west (Lochinver, Loch Laxford), north (Loch Eriboll) and north-east (Wick) coast of mainland Scotland. This suggests that the region was rapidly deglaciated and there was little difference in ice loads across the region. From one site at the head of Loch Eriboll we report the most westerly sedimentary evidence for the early Holocene Storegga tsunami on the Scottish mainland. The presence of the Storegga tsunami in Loch Eriboll is predicted by a tsunami wave model, which suggests that the tsunami impacted the entire north coast of Scotland and probably also the Atlantic coastline of north-west Scotland. Copyright © 2016 The Authors. *Journal of Quaternary Science* Published by John Wiley & Sons Ltd

KEYWORDS: glacio-isostatic adjustment; relative sea level; Storegga landslide; Storegga tsunami; tsunami.

Introduction

The north coast of the Scottish mainland is an important area for studying Lateglacial and Holocene relative sea-level (RSL) changes and for testing and developing different models of ice sheet history and glacio-isostatic adjustment (GIA). Recent offshore mapping of glacial landforms on the continental shelf has identified a series of recessional moraines that record the north-eastward retreat of the British and Irish Ice Sheet (BIIS) towards Shetland following the Last Glacial Maximum (LGM) (Clark *et al.*, 2012) (Fig. 1). However, there is debate regarding the thickness of this ice sheet and its retreat pattern. For example, one GIA model that uses a thermodynamical ice sheet model to define ice load history predicts ice that was 500–750 m thicker in the north-east of Scotland compared to that in the north-west of Scotland (Kuchar *et al.*, 2012). Such a contrast would be expected to cause significant west–east differential GIA movements across the northern Scottish mainland that would be observable in Lateglacial and Holocene RSL records. In contrast, other GIA studies that use a prescribed ice load history which is tuned to RSL observations and known ice margin histories predict only modest differences in ice load across the region, and hence limited differential GIA movements (e.g. Brooks *et al.*, 2008; Bradley *et al.*, 2011). These latter models broadly agree with isobase maps developed from field observations of the altitude of the Main Postglacial Transgression, a sea-level highstand attained in the early to mid-Holocene, that suggest the north mainland sits on the same shoreline isobase (e.g. Smith *et al.*, 2011) (Fig. 2).

There are few RSL studies and no published RSL curve for the north coast (discussed below). This may reflect the high-energy nature of this coast, which is typified by steep-sided sea lochs that front onto the North Atlantic

Ocean. Much of the coast is rocky, with many sand or gravel-dominated beaches and only infrequent areas of finer-grained sedimentation, often restricted to the loch heads, providing limited scope for preservation of archives of former sea level.

The aims of this study are two-fold. First, we seek to develop the first Lateglacial and Holocene RSL curve for the mainland north coast of Scotland (Loch Eriboll, Sutherland; Fig. 2). By combining this with previous studies, we seek to define the regional trend in RSL across the mainland coast of northern Scotland and examine the implications for our understanding of the history of the BIIS in the region. Our second aim is to reconstruct patterns of coastal change within Loch Eriboll, including the potential existence of deposits associated with the Storegga tsunami, which struck Scotland during the early Holocene, but which has not previously been reported from this part of north-west Scotland (Smith *et al.*, 2004).

Previous work

Along the north coast of Scotland, King and Wheeler (1963) mapped raised beaches, rock shelves or platforms backed by degraded cliffs, and wave-cut platforms at a range of elevations between 0 and +26 m OD. Some of these higher features probably date from the Lateglacial as RSL initially fell following deglaciation, but none is directly dated and they have received scant attention since their identification. An extensive raised platform at the head of Loch Eriboll (ca. +8 to +14 m OD) is mapped as belonging to the Ullapool Gravel Formation, a suite of low-lying and coastal glaciofluvial deposits in north-west Scotland, which decrease in height from west to east (+40 to +15 m OD) (Bradwell and Stoker, 2010), thought to have been deposited in association with higher than present Lateglacial sea level (Stoker *et al.*, 2009). Other examples of raised coastal gravel sheets belonging to this formation occur at Loch Laxford and the Kyle of Durness

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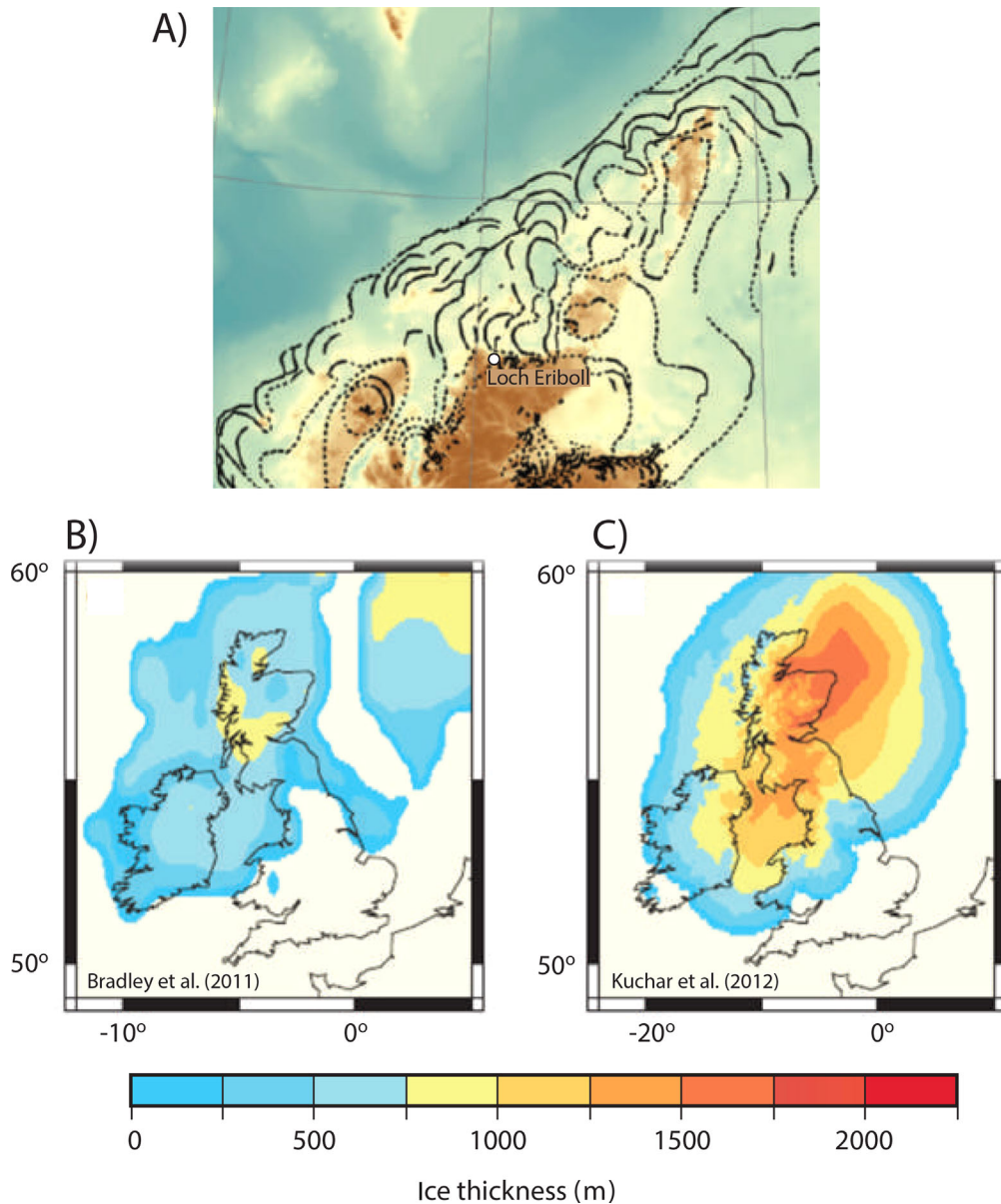


Figure 1. Ice sheet history the British and Irish Ice Sheet (BIIS) at the Last Glacial Maximum: (A) moraines of the BIIS mapped in northern Scotland (Clark *et al.*, 2012), (B) the preferred BIIS reconstruction at 21 k cal a BP (Brooks *et al.*, 2008) that is used by Bradley *et al.* (2011), and (C) the minimal BIIS reconstruction from Hubbard *et al.* (2009) at 20 k cal a BP, which best fits the relative sea-level observations used in Kuchar *et al.* (2012). B and C are modified from Kuchar *et al.* (2012).

(Fig. 2), but these raised deposits have also received limited detailed study (Bradwell and Stoker, 2010).

The nearest Lateglacial and Holocene RSL record to Loch Eriboll is from south Eddrachillis Bay, 10 km north of Lochinver (Fig. 2), where Hamilton *et al.* (2015) reconstruct RSL fall from the local marine limit (ca. +6 m OD, ca. 14 k cal a BP) to below present at ca. 12.5 k cal a BP, before rising above present again at ca. 10 k cal a BP. There are no data from this site during the rest of the Holocene. In north-east Scotland, the closest mainland RSL data are from the lower Wick River valley (Fig. 2) (Dawson and Smith, 1997). Here, early Holocene sea level rose to an initial highstand during the 'Main Postglacial Transgression' at ca. 6.8 k cal a BP (Smith *et al.*, 2011), and then fluctuated within 1 m or so of present during the rest of the Holocene.

Isobase maps for the Main Postglacial Shoreline predict that much of the north coast of Scotland lies on the same (0 m) contour (Fig. 1) (Smith *et al.*, 2011). A later Holocene shoreline (the Blairdrummond, dated to ca. 5.8–3.6 k cal a BP) is predicted to overlap the Main Postglacial Shoreline in peripheral areas of northern Scotland, including all the north mainland coast, where it is predicted to record the Holocene maximum sea level (Smith *et al.*, 2000, 2004, 2011). The

Blairdrummond isobase has a predicted elevation of +1 to +2 m OD along the north mainland coast (Fig. 1).

The study site

The north mainland coast of Scotland is incised by several sea lochs that in the west include the 18-km-long funnel-shaped Loch Eriboll (Fig. 2). The bedrock geology comprises Lewisian Gneiss, Torridon and Stoer Group sandstone and, locally, such as on the east side of Loch Eriboll, dolomitic limestone belonging to the Durness Group (Holdsworth *et al.*, 1997; Highton, 2002). Loch Eriboll is dominated by sandy mud in its inner portions, with extensive areas of intertidal sand flats with variable amounts of gravel. The modern spring tide range is ca. 4.3 m (Table 1).

At the LGM, the BIIS covered all of north-west Scotland and extended well onto the continental shelf (Bradwell *et al.*, 2008; Clark *et al.*, 2012). During its initial deglacial phase, the ice sheet margin retreated eastwards along the north coast of Scotland before individual glaciers became topographically constrained in south–north-trending lochs and then retreated inland. Paired bedrock and erratic terrestrial cosmogenic nuclide ages date ice-free conditions at the mouth of Loch Eriboll by ca. 17 000 years ago (Mathers, 2014), while a basal

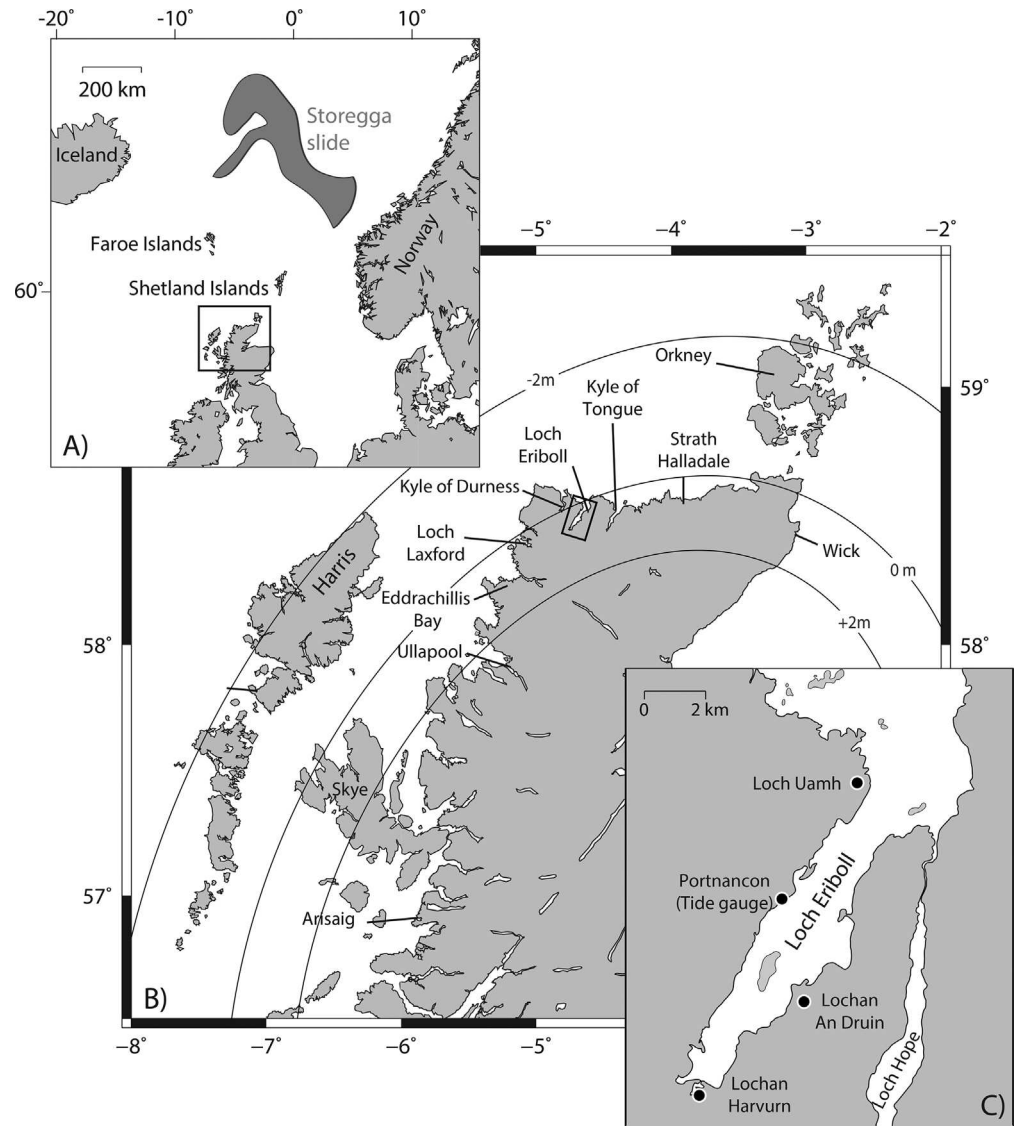


Figure 2. Location map of the study area, with field location from this study marked in C, Location of Storegga slide in A after Bondevik *et al.* (2003). The dashed lines in B denote the isobase (in m MHWST) for the Main Postglacial Shoreline (after Smith *et al.*, 2011).

calibrated radiocarbon date of ca. 15 k cal a BP from a partially infilled kettle-hole at Lochan An Druim (south-west Eriboll) provides a minimum date for ice-free conditions here (Ranner *et al.*, 2005) (Fig. 2).

We report RSL data from three study sites located on the west (Loch Uamh), south (Lochan Harvurn) and east (An Druim) shores of Loch Eriboll (Fig. 2). Loch Uamh is a low-lying freshwater loch impounded to the north by an active gravel beach with a ridge elevation of ca. +4 m OD (Fig. 3). At its southern end the lake is partially infilled by organic and mineral sediments (Dawson, 1999). Lochan Harvurn is the name of two connected tidal ponds, a beach section and associated deposits, located at the head of Loch Eriboll (Fig. 4). The tidal ponds are connected to the open coast via shallow sills of rounded boulders. A small area of salt marsh occurs at the head of the inner pond. The beach on the open

coast is made of coarse cobbles, gravel and sand, and backs onto a 2- to 4-m-high cliff that is cut into glacial and postglacial sediments. The present storm beach has an altitude of ca. +3 to +4 m OD. At our third site, termed An Druim (Fig. 5), we study a prominent raised coastal terrace and, ca. 2 km to the south of this platform, a 1- to 2-m-high coastal section of peat and sand/gravel at ca. +2 to +5 m OD that overlies a low raised beach of gravel (informally named 'Otter Beach').

Methods

We recorded the lithostratigraphy of unconsolidated sediments using a 2.5-cm-diameter gouge corer and collected sample cores using a Russian-type corer. We cut back and cleaned sediment exposures using a spade and knife and collected samples from these by pushing 0.25-m-long monolith tins into the cleaned sections and carefully digging them out. We surveyed the elevation of sample sites by levelling to a temporary benchmark established using a differential GPS and cite all altitudes with respect to Ordnance Datum [OD is the national levelling datum for the UK and the approximate height of mean sea level (MSL)]. Mean tide level (MTL) in Loch Eriboll is 0.3 m above MSL, and our RSL reconstructions use MTL as the datum.

We wrapped sediment samples in plastic and returned them to Durham where they were stored in a fridge. We

Table 1. Tidal values in metres relative to UK ordnance datum for Loch Eriboll (Portnancon).

Highest astronomical tide (HAT)	3.00
Mean high water spring tide (MHWS)	2.42
Mean high water neap tide (MHWN)	1.22
Mean tide level (MTL)	0.30
Mean low water neap tide (MLWN)	-0.58
Mean low water spring tide (MLWS)	-1.88

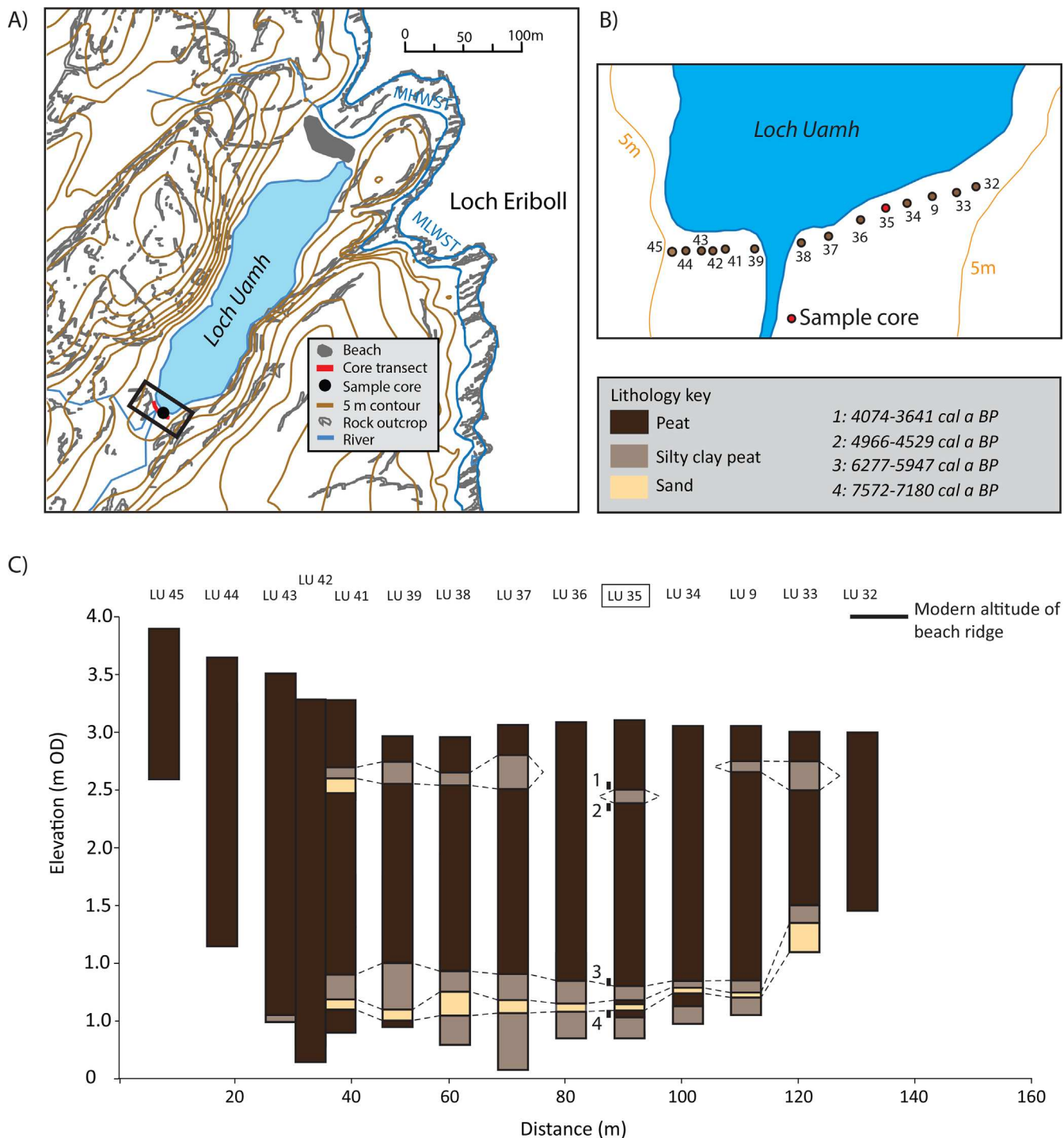


Figure 3. The Loch Uamh study site: (A) location map, (B) location of cores and (C) Loch Uamh lithostratigraphy (modified from Dawson, 1999).

prepared samples for pollen and diatom analysis using standard methods (Palmer and Abbott, 1986; Moore *et al.*, 1991). We scanned samples from two sites using the BOSCORF ITRAX non-destructive core scanner that records optical, radiographic and elemental variations (Croudace *et al.*, 2006). We measured organic content as percentage loss on ignition (LOI), burning 2–5 g of dried sediment at 550 °C for 4 h. Particle size analysis (PSA) was carried out on selected sections of the profiles, following standard methods, and analysed using a Coulter laser particle granulometer.

We establish a chronology with 15 accelerator mass spectrometry (AMS) ^{14}C dates from charcoal, plant macrofossil remains and bulk humin fractions, and (from Loch Uamh) conventional radiocarbon dating (Table 2). All radiocarbon dates are cited with a two sigma calibrated age range using

IntCal13 (Reimer *et al.*, 2013) in calendar years before present (i.e. AD 1950) (cal a BP). Our sea-level index points are mostly from transgressive or regressive contacts that we relate to a palaeo MTL using the indicative ranges that are defined by Shennan (1982). Sediment compaction can lower the altitude of sea-level index points from their original elevation, especially where thick sequences of organic-rich deposits occur. We have, in previous RSL studies in the region, assessed the impact of sediment compaction in salt marsh deposits as being very minor (Barlow *et al.*, 2014), but this process may be a cause for concern in some of the deeper peat sequences examined here, notably from Loch Uamh. We have not undertaken any geotechnical investigations as part of the current study and note that such data are also lacking from the other sites that we consider in this paper.

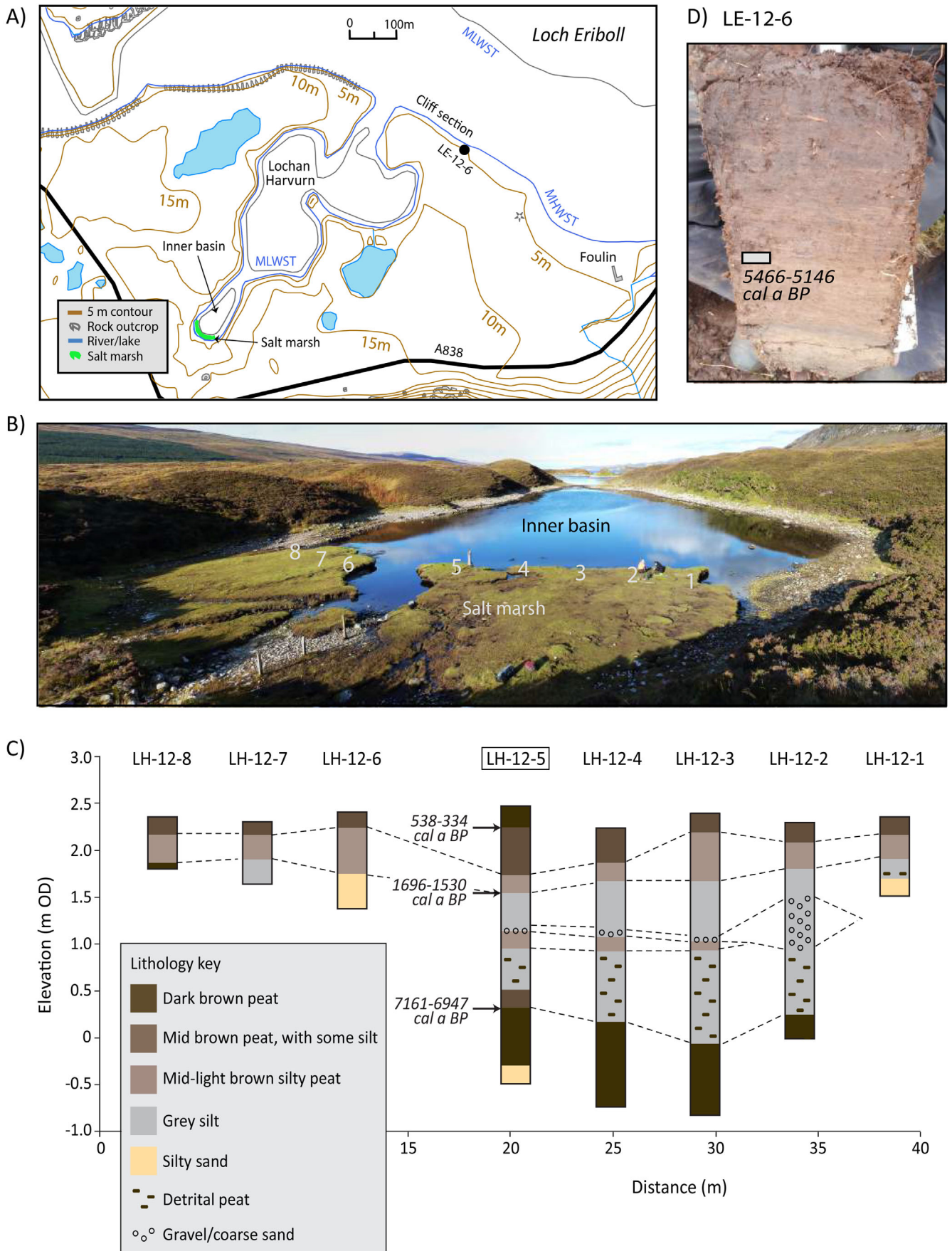


Figure 4. The Lochan Harvurn study site: (A) location map, (B) Lochan Harvurn (inner tidal basin) salt marsh core locations, (C) Lochan Harvurn salt marsh lithostratigraphy and (D) photograph of mid-Holocene salt marsh deposits sampled immediately below the present beach at LE-12-6.

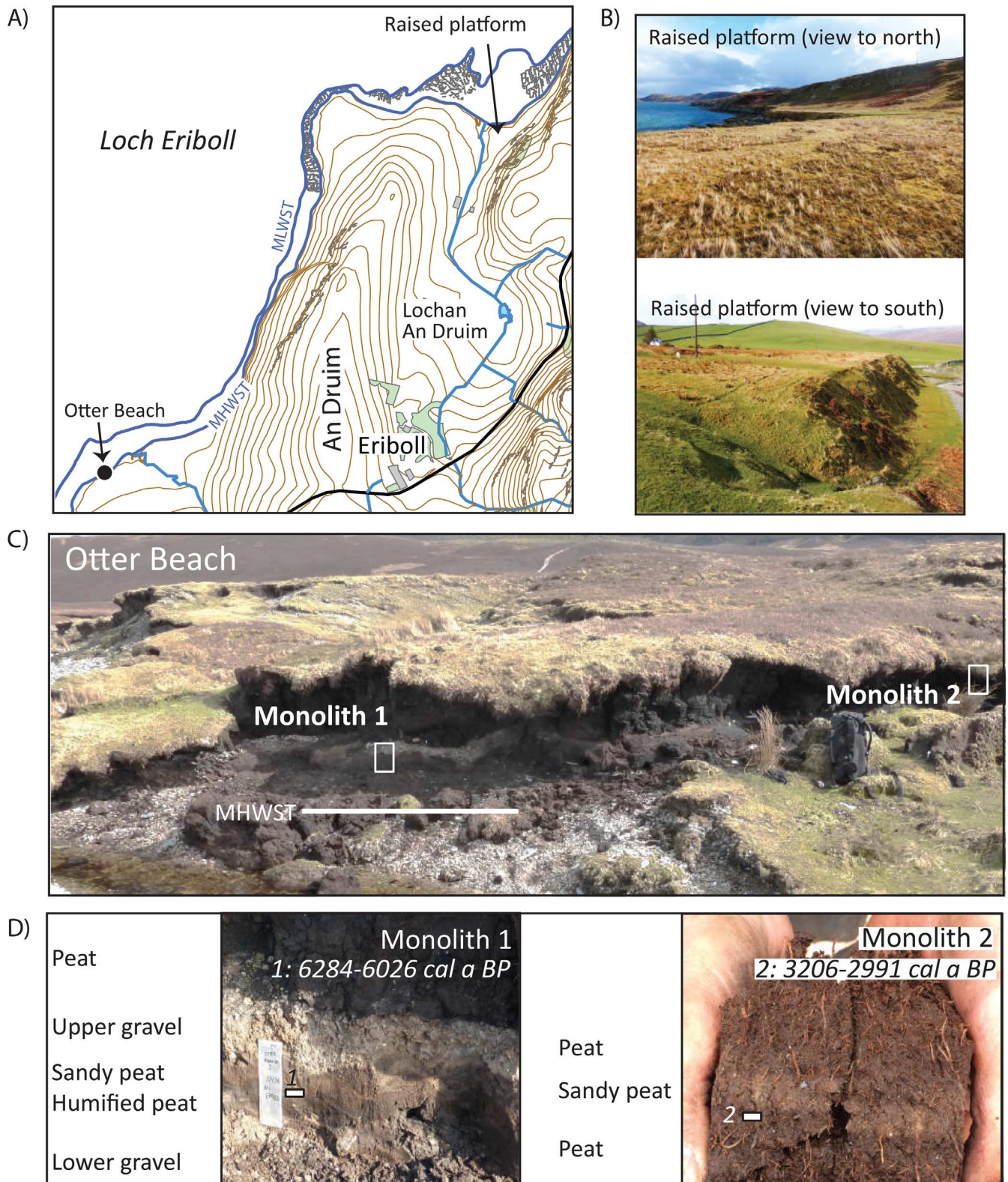


Figure 5. The An Druim study site: (A) location map, (B) the raised terrace below Eriboll Lodge, (C) Otter Beach stratigraphic section (An Druim is the hill in the background) and (D) the lithology of Monolith 1 and 2, Otter Beach.

Results

Lateglacial and Holocene RSL changes

Loch Uamh

A transect of 14 cores at the southern end of the loch shows a ca. 3-m-thick sequence of organic deposits within which are two laterally extensive minerogenic units; the lower unit is a thin sand within a silt-peat at ca. +0.9 m OD, and the higher unit is a silt-peat between ca. +2.5 and +2.8 m OD (Fig. 3).

Sample core LU35 yields four sea-level index points from transgressive and regressive contacts to each of the minerogenic units, with diatom data confirming intervals of increased and reduced marine influence, respectively (Fig. S1) (Table 2).

Lochan Harvurn

Eight cores describe the stratigraphy beneath a salt marsh located at the head of the inner tidal pond (Fig. 4). In the

Table 2. Radiocarbon dates from Loch Eriboll. Mean Tide Level is 0.3 m above MSL.

Site	Sample code	Description	Altitude of dated level (m OD)	Vertical uncertainty ± 2 SD (m MSL)	Relative sea level (m MSL)	Dating method	Radiocarbon age ± 1 SD	Comment
Loch Uamh	BETA-94749	Regressive contact	2.44	± 0.20	0.23	Conventional	3550 \pm 70	Dawson (1999)
Loch Uamh	BETA-94750	Transgressive contact	2.32	± 0.20	0.11	Conventional	4230 \pm 80	Dawson (1999)
Loch Uamh	UB 3845	Regressive contact	0.67	± 0.20	-1.54	Conventional	5380 \pm 63	Dawson (1999)
Loch Uamh	UB 3844	Transgressive contact	0.57	± 0.20	-1.35	Conventional	6482 \pm 98	Dawson (1999)
Lochan Harvurn LE-14-1	SUERC-53250	Charcoal* from base of Unit 5	4.49	None	None	AMS	4124 \pm 37	
Lochan Harvurn LE-14-1	SUERC-53251	Charcoal* from top of Unit 2	4.15	None	None	AMS	7262 \pm 39	
Lochan Harvurn LE-14-1	SUERC-53252	Charcoal* from top of Unit 2	4.12	None	None	AMS	8463 \pm 39	
Lochan Harvurn LE-14-7	SUERC-53253	Charcoal* from base of Unit 5	4.34	None	None	AMS	2625 \pm 35	
Lochan Harvurn LE-14-7	SUERC-53254	Charcoal* from top of Unit 2	4.25	None	None	AMS	7265 \pm 38	
Lochan Harvurn LE-12-5	SUERC-53658	Regressive contact (mid salt marsh)	2.22	± 0.34	0.33	AMS peat, humin fraction†	443 \pm 37	Assume deposited midway between the base of salt marsh (1.75 m OD) and the core top (2.42 m OD).
Lochan Harvurn LE-12-5	SUERC-53659	Regressive contact (low salt marsh)	1.56	± 0.34	-0.22	AMS peat, humin fraction†	1688 \pm 35	Assume deposited midway between the base of salt marsh (1.75 m OD) and the core top (2.42 m OD).
Lochan Harvurn LE-12-5	SUERC-53660	Transgressive contact	0.70	+0.80	-2.36	AMS peat, humin fraction†	6164 \pm 37	Abrupt contact – assume dated sample formed above HAT (3 m OD). Limiting date, RSL was above this level.
Lochan Harvurn LE-12-6	SUERC-53661	Regressive contact	2.32	± 0.20	0.40	AMS peat, humin fraction†	4617 \pm 35	
Otter Beach Monolith 1	BETA-414972	Regressive contact	2.93	± 0.70	0.23	AMS Juncus seeds	5390 \pm 30	Assume formed at HAT based on low frequencies of salt marsh pollen types and high organic content.
Otter Beach Monolith 2	BETA-414973	Regressive contact	3.36	± 0.70	0.56	AMS Juncus seeds	2940 \pm 30	Assume formed at HAT based on low frequencies of salt marsh pollen types and high organic content.

*Charcoal sample preparation. Samples were digested in 1 m HCl (80 °C, 30 min), washed free from mineral acid with deionized water then digested in 0.2 m KOH (80 °C, 5–15 min). The digestion was repeated using deionized water until no further humics were extracted. The residue was rinsed free of alkali, digested in 1 m HCl (80 °C, 1 h) then rinsed free of acid, dried and homogenized. The total carbon in a known weight of the pre-treated sample was recovered as CO₂ by heating with CuO in a sealed quartz tube. The gas was converted to graphite by Fe/Zn reduction.

†Humin fraction sample preparation. Samples were digested in 2 m HCl (80 °C, 8 h), washed free from mineral acid with deionized water then digested in 1 m KOH (80 °C, 2 h). The remainder of the preparation was as for charcoal samples, detailed above. Discussion of this method of preparation and its application to the salt marsh deposits of Loch Laxford (Sutherland) are given in Barlow *et al.* (2014).

deepest part is a ca. 1-m-thick woody peat that is abruptly overlain by organic silts that pass up into a salt marsh peat that extends to the surface. We use diatoms to obtain sea-level index points from the transgressive contact at the top of the woody peat and the regressive contact to the surface salt marsh peat (Fig. S2). The former is an abrupt transition and re-worked peat is common in the overlying organic silts.

On the open coast, at the head of Loch Eriboll, there are tidal flat, salt marsh and freshwater peat deposits at several sites beneath the present beach. They show that lower-energy conditions have existed here in the past, when RSL was lower and/or this stretch of coast was less exposed than present. At LE-12-6 we sampled a regressive contact ca. 0.5 m below present beach level (Fig. 4) (Table 2). Pollen from the dated level (Fig. S3) contains high frequencies of *Plantago maritima* pollen, a salt marsh plant that typically occupies the mid to upper part of coastal marshes in north-west Scotland (e.g. Shennan *et al.*, 1995).

An Druim

A stream that drains a small partially infilled kettle hole (Lochan An Druim, altitude ca. +25 m OD) enters the sea below Eriboll Lodge and dissects a prominent raised terrace (surface altitude ca. +8 m OD) that is cut in bedrock and mantled by a deposit of sands and gravels that has itself been planated (Fig. 5). We hypothesize that the planated terrace surface was formed by a higher than present sea level. We use the elevation of the terrace as a minimum estimate of sea level at or shortly after deglaciation, dated to before ca. 15 k cal a BP (Ranner *et al.*, 2005).

At Otter Beach there is a 1- to 2-m-high exposure of peat that overlies densely packed gravel at ca. +3 to +4 m OD (Fig. 5). Close to the present beach the gravel is overlain by a ca. 0.2-m-thick unit of humified peat that is in turn overlain by sand-rich peat and then a coarse, creamy-yellow sand-rich gravel. Inland, the lower gravel is overlain by peat that extends to the present surface, within which is a ca. 5-cm-thick deposit of sandy-peat that represents the landward extension of the coarser grained deposits near the present coast. Two monolith samples collected from seaward and landward locations in the section each yield a sea-level index point (Table 2). There are no diatoms in these deposits but low frequencies of halophytic pollen types and the organic-rich nature of the sediments show that each index point formed in a high salt marsh environment (Fig. S4A,B). Examination of the ITRAX geochemical data across the sand in Monolith 2 shows an increase in the occurrence of elements including K, Ca, Cr, Zr, Ti and Si coincident with the presence of the thin sand unit (Fig. S5). The upturn in the occurrence of Ca suggests a marine origin for this sediment, whereas increases in K and Cr indicate inundation by seawater (Minoura and Nakaya, 1991; Costa, 2012; Chagué-Goff *et al.*, 2015). We date high salt marsh deposits in Monolith 1 to ca. 6 k cal a BP, and an equivalent deposit in Monolith 2 to ca. 3 k cal a BP. We hypothesize that several thousand years of peat accumulation has been eroded from the site of Monolith 1 during the deposition of the overlying sandy gravel.

Lochan Harvurn: coastal cliff section

The contemporary beach sediments at the head of Loch Eriboll comprise an upper-shoreface gravel with sub-angular and sub-rounded boulders up to 50 cm in length, below which is a lower-gradient, lower-shoreface sand with some gravel. Grain size data from two surface sediment samples collected from the beach at ca. +2.5 and +1.5 m OD show

that the <2-mm fraction comprises medium sand, the former sample being moderately sorted and coarsely skewed, and the latter being poorly sorted and very coarsely skewed (Table S1).

We analysed two sediment profiles in detail (LE-14-1 and LE-14-7) (Fig. 6). The lowermost sediments exposed in the coastal cliff (Unit 1) are compact coarse sands and gravels with occasional large boulders. Overlying these deposits is a <5-cm-thick deposit of soft silt that is grey to its base and dark grey and then black to its top (Unit 2) (Fig. 6). Unit 2 is laterally extensive and broadly horizontal, occurring between ca. +4.2 and +4.4 m OD across a 100-m-wide cliff section. At LE-14-1, Unit 2 is abruptly overlain at ca. +4.15 m OD by a 5- to 20-cm-thick deposit of coarse sand with some fine gravel that fines upwards (Unit 3). Unit 3 varies in composition along the cliff section; in places it has a clear fining-upwards sequence but elsewhere the deposit is more mixed, with large boulders and cobbles (up to 0.5 m in length) at various levels within it.

Locally, Unit 2 has been reworked and mixed with Unit 3. The sediment section, upon careful cleaning, reveals distinctive sedimentary structures. These include a complex injection of 'clean' sands into the more organic sandy matrix of the unit (Fig. 7), as well as sub-rounded 2-cm-diameter sands and associated finer sediments. These are highly localized and likely to have been eroded from the underlying sediments.

Above Unit 3 is a light-grey, loosely structured, matrix-supported sand-rich gravel with frequent rounded and sub-angular cobbles (Unit 4). In some locations, such as at LE-14-7, Unit 4 is absent. Where present, Unit 4 is always overlain by peat (Unit 5) that extends to the present surface.

Two pits dug inland of LE-14-1 show that Units 2–4 extend inland from the present cliff by at least 7.5 m. Hand cores sunk in the surface peat ca. 75 m inland of the coast record an isolated, 2- to 3-cm-thick, deposit of coarse sandy gravel at ca. +4.20 m OD (LE-15-1, Fig. 6). Pollen data (Fig. S6) and clear peaks of K, Ca, Ti, Zr and Si (Fig. S6) that coincide with the sandy gravel suggest that this deposit is a landward continuation of Unit 3.

Pollen from LE-14-1 and LE-14-7 show that Unit 2 initially formed under a *Betula–Corylus* (birch–hazel) woodland (Fig. 8). Frequencies of these taxa then fall and are replaced by higher amounts of *Calluna* (heather) pollen. Charcoal fragments are common, visible in the pollen samples and to the naked eye. Taken together, the data indicate that this unit is a buried soil that developed beneath an acid-woodland that experienced some burning. Such burning could have happened due to natural processes (lightning-strike) or deliberately by Mesolithic people, as is observed at several other sites in north-west Scotland at this time (e.g. Edwards, 1990; Ohlson and Tryterud, 2000). There are no diatoms preserved in Unit 2 and no pollen indicators of marine conditions. AMS radiocarbon dates from charcoal fragments extracted from the base and top of Unit 2 in LE-14-1 yielded ages of 8463 ± 39 (9531–9436 cal a BP) and 7262 ± 39 (8170–8002 cal a BP), respectively, while charcoal fragments from the top of Unit 2 in LE-14-7 are dated to 7265 ± 38 (8170–8006 cal a BP).

There are no diatoms, foraminifera or mollusca in Unit 3. However, geochemical signatures within Unit 3 demonstrate increased counts of K and Cr, which are typically diagnostic of inundation by seawater, and Ca, which can indicate sediments of marine genesis (Minoura and Nakaya, 1991; Costa, 2012; Chagué-Goff *et al.*, 2015) (Fig. S5). The overall increase in these elements within the Unit 3 suggests a marine origin. The pollen in Unit 3 at LE-14-1 (Fig. 7) is

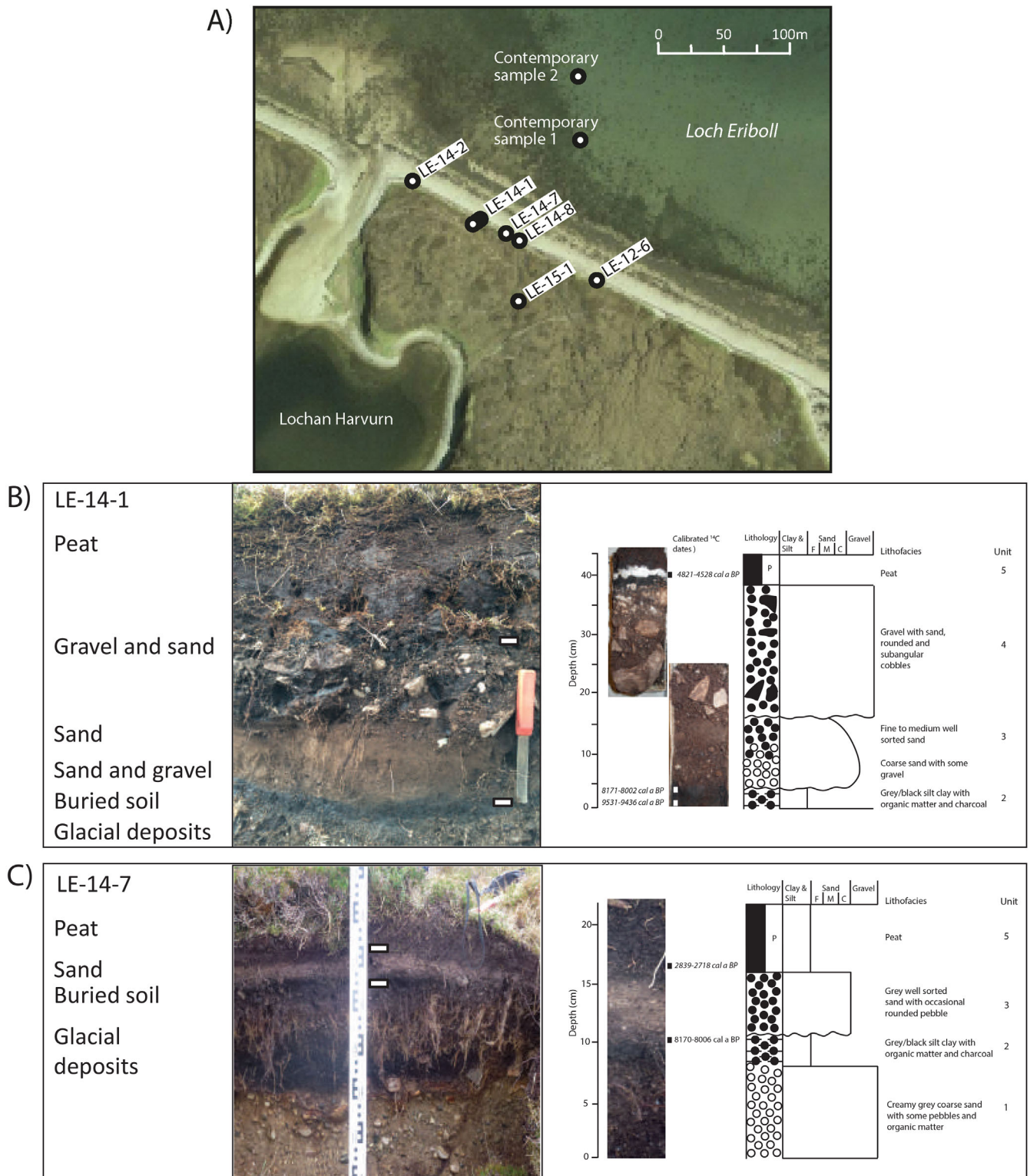


Figure 6. The Lochan Harvurn coastal cliff study site at the head of Loch Eriboll: (A) location of sample sites (image courtesy of Google Earth), (B) LE-14-1 sample profile with grain size description and lithology, and (C) LE-14-7 sample profile.

broadly similar to that in the top of Unit 2 from this site, with high frequencies of *Calluna* and, notably, *Empetrum* (Crowberry). Particle size data on the <2-mm fraction shows that the lower part of Unit 3 is a coarse, unimodal, moderately sorted sandy gravel. This closely resembles the grain size characteristics of a modern beach sand sample collected from ca. +2.5 m OD (Table S1). Overall, Unit 3 at LE-14-1 fines upwards, with two coarser sub-units within this sequence. Pollen in Unit 3 from LE-14-7 (Fig. 8) suggest a similar *Calluna*-dominated assemblage to that in LE-14-1. The sand

of Unit 3, although finer than in LE-14-1, also records an overall fining-upwards trend, in this instance with just one coarser sub-unit, and becomes better sorted up-profile.

Sand-rich gravels and cobbles (Unit 4) abruptly overlie Unit 3 at many points along the cliff section. These sediments visually resemble material on the upper part of the current beach and we interpret them as a raised beach deposit. At LE-14-1, pollen from Unit 4 suggests a birch heathland existed nearby. The Unit 4 pollen is different from that of Unit 3 (i.e. no *Empetrum* and high frequencies of *Betula*,

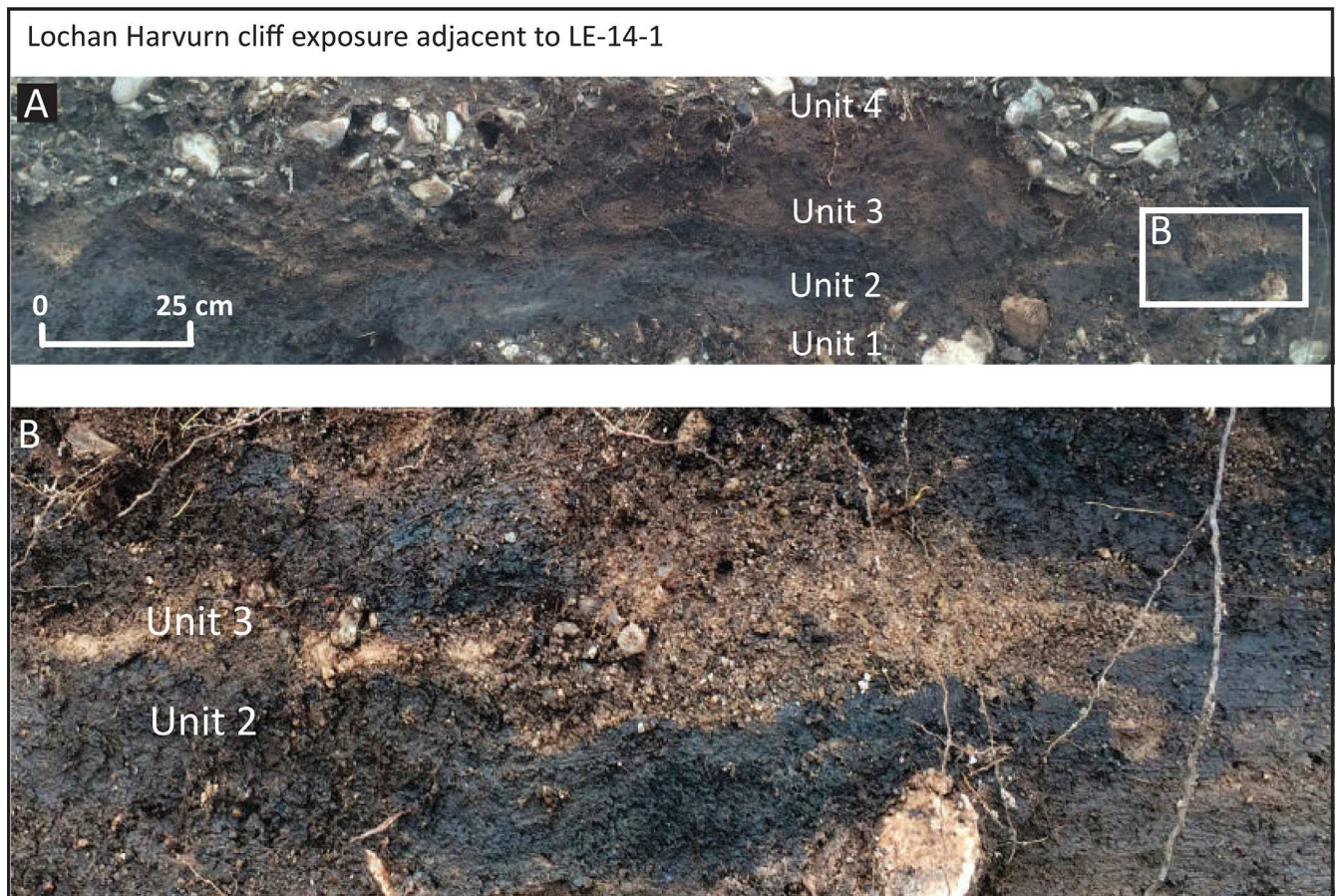


Figure 7. Stratigraphy of potential Storegga tsunami deposits (Unit 3) exposed in the cliff section at Lochan Harvurn, close to sample site LE-14-1.

lesser frequencies of *Calluna*), showing that Units 3 and 4 are distinct deposits, probably separated by a hiatus. Low *Alnus* pollen frequencies in Unit 4 show it was deposited before the regional expansion in alder. This expansion has an estimated age in the Lochan an Druim kettle hole of ca. 5800 BP (ca. 6.6 k cal a BP) (Birks, 1980, 1984), although this may be too old due to a hard water error (Ranner *et al.*, 2005). To the south-west of Loch Eriboll, near Scourie (Fig. 1), Moar (1969) reports an age for the start of the regional rise in *Alnus* pollen of 5220 ± 115 BP (6276–5736 cal a BP). Mindful of the potential hard water effect at Lochan an Druim, we use the latter age (ca. 6 k cal a BP) for the alder rise at our site and, on this basis, we conclude that Unit 4 was deposited before this date. Unit 5, the surface peat, lies unconformably above Unit 4 and, based upon our radiocarbon date from LE-14-1, began to accumulate after ca. 4.7 k cal a BP.

Discussion

Local and regional trends in Holocene RSL changes in north Scotland

We start by reconstructing RSL changes in Loch Eriboll and then compare these results to site-specific GIA model predictions (Fig. 9A). The basal kettle hole date of ca. 15 k cal a BP from Lochan An Druim provides a minimum age for the adjacent raised terrace at ca. +8 m OD. The indicative meaning of this terrace is difficult to establish, but we assume that it formed at MTL with a vertical uncertainty equal to the present tidal range (equivalent to an MTL of ca. $+6 \pm 2$ m OD). RSL fell from this level to below present during the Lateglacial and then rose again during the early Holocene, although data from this period are lacking.

Our first Holocene RSL data record the transgression of former freshwater environments at Loch Uamh (7572–7180 cal a BP) and Lochan Harvurn (7165–6957 cal a BP) as RSL rose from its lowstand. Several lines of evidence suggest that this interval of RSL rise peaked shortly after, at ca. 7–6 k cal a BP. Thus, at Loch Uamh, a removal of marine conditions dates to ca. 6.1 k cal a BP, with salt marsh replaced by freshwater peat, perhaps due to closure of the loch from the open coast by the development of the gravel beach across its northern mouth. In the Lochan Harvurn cliff section, a raised beach (Unit 4) was deposited sometime between ca. 8.1 and ca. 6 k cal a BP, while at An Druim (Otter Beach), salt marsh peat had begun to form on top of raised beach (Monolith 1) before ca. 6.1 k cal a BP, registering a gradual removal of marine conditions.

The chronology of RSL changes after ca. 6 k cal a BP is more complex, with each of our three sites experiencing different patterns of shoreline advance or retreat. At Lochan Harvurn, a regressive sequence on the foreshore (LE-12-6) records a removal of marine conditions at ca. 5.3 k cal a BP, while at Loch Uamh a transgressive/regressive cycle is dated to between ca. 4.7 and 3.8 k cal a BP. At An Druim (Otter Beach) there is a second transgression at ca. 3.1 k cal a BP (Monolith 2). The lack of chronological agreement between these sites suggests the operation of more local, site-specific processes such as changes in sediment supply or local changes in coastal configuration perhaps associated with barrier emplacement.

We now compare the Loch Eriboll RSL record with data from other sites in northern Scotland, to examine regional-scale patterns (Fig. 9B). An equivalent higher-than-present Lateglacial RSL to that observed in Loch Eriboll is recorded at Eddrachillis Bay by Hamilton *et al.* (2015). Here the local

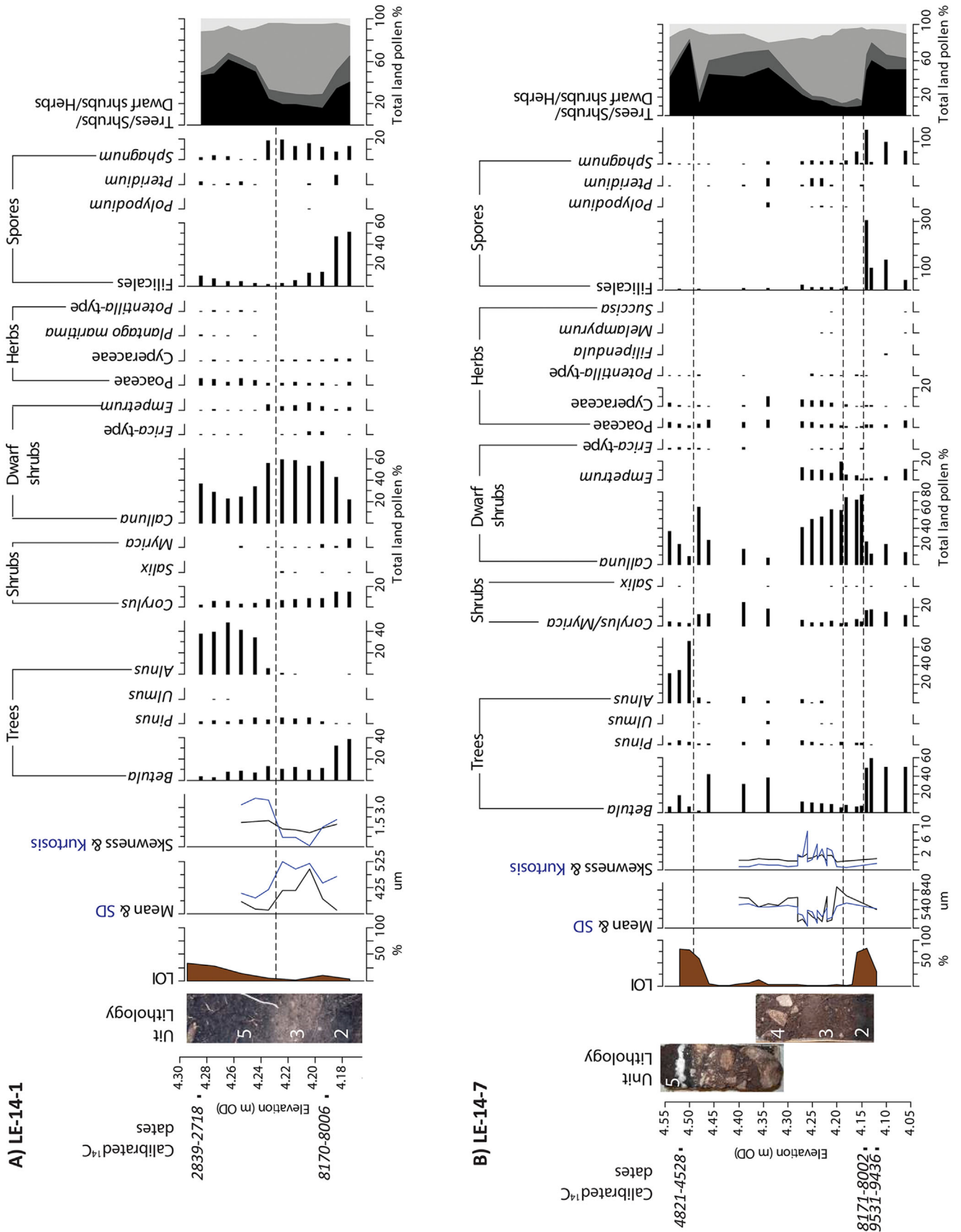


Figure 8. Pollen and grain size (<2mm) data from: (A) LE-14-1 and (B) LE-14-7.

marine limit is at ca. +6m MSL. RSL fell from this limit and isolated a low-lying tidal basin from the sea (Loch Duart Marsh, sill elevation +1.95m OD) at ca. 15–14k cal a BP. Evidence from Loch Eriboll and Loch Duart Marsh therefore supports Stoker *et al.* (2009) and Bradwell and Stoker (2010)

who argue that the raised coastal deposits of the Ullapool Formation were probably graded to a Lateglacial sea level that was higher than present.

During the Lateglacial, RSL fell below present to an undefined lowstand before rising again during the early

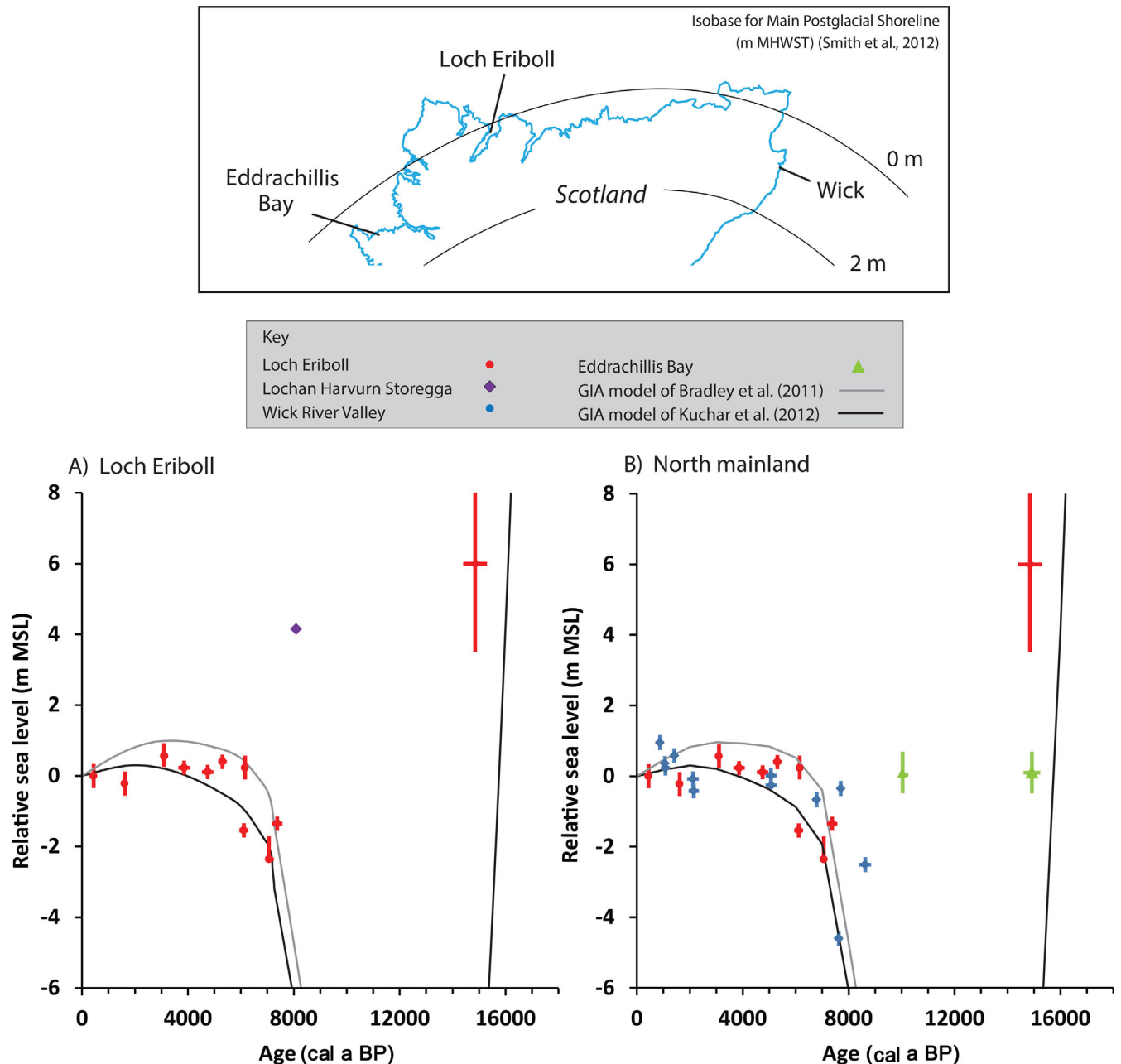


Figure 9. (A) Relative sea-level observations from Loch Eriboll, including the 'best-fit' GIA model of Bradley *et al.* (2011) and Kuchar *et al.* (2012). (B) Relative sea-level observations from the mainland coast of northern Scotland including data from Loch Eriboll (this study), the Wick River Valley (Dawson and Smith, 1997) and Eddrachillis Bay (Hamilton *et al.*, 2015).

Holocene. The details of this rise differ between studies. At the Wick River Valley (Dawson and Smith, 1997) and in Loch Eriboll (this study), early Holocene deposits of freshwater peat show that RSL was several metres below present during the early Holocene; indeed we reconstruct early Holocene RSL rise from ca. -4 m OD to reach close to present between ca. 8.6 and 6.8 k cal a BP (Fig. 9Bb). In contrast, at Eddrachillis Bay, Hamilton *et al.* (2015) interpret a single radiocarbon date from immediately below an abrupt ingress contact as evidence that RSL rose to above present by ca. 10 k cal a BP, supposedly re-flooding the Loch Duart Marsh tidal basin. They suggest that the timing of this transgression is significantly earlier than previously thought, and earlier than predicted by GIA models for the region. We suggest that the actual age of the ingress was younger than 10 k cal a BP as the early Holocene index point is from below an abrupt ingress contact and therefore provides only a minimum age for when the basin was re-flooded. Re-working and

erosion of ingress contacts is common in isolation basins, especially if, as at Eddrachillis Bay, the basin was shallow at the time of ingress (Long *et al.*, 2011).

During the mid and late Holocene, RSL data from across northern mainland Scotland suggest that RSL was broadly stable, within ca. 1 m of present. Smith *et al.* (2011) argue that the Blairdrummond shoreline should be the highest Holocene shoreline in northern Scotland, forming between ca. 5.8 and 3.6 k cal a BP, at ca. $+1$ to $+2$ m above mean high water of spring tides. At the Wick River Valley a marine transgression is dated to between ca. 5.1 and 2.1 k cal a BP, when 1 m or so of brackish marine estuarine sediments accumulated above the deposits of the Main Postglacial Transgression (Dawson and Smith, 1997). As noted above, within Loch Eriboll there is no consistency in the timing of shoreline development following the attainment of the initial early Holocene maximum and we cannot, with any confidence, attribute single-site stratigraphic features to known shorelines.

Comparison with GIA model predictions

We compare our RSL data with site-specific GIA model predictions in Fig. 9B. Our observation of a higher than present sea level in north-west Scotland during the Lateglacial supports the GIA model prediction of Kuchar *et al.* (2012) from this time, which has significantly thicker (>1 km) ice over the study area compared to that in Bradley *et al.* (2011). During the early Holocene there is a reasonable data-model agreement with both GIA models. Although the initial RSL rise happened slightly earlier than predicted, it was only by 1000 years or so. Both models predict that RSL changed little after ca. 6 k cal a BP, although Kuchar *et al.* (2012) favour a gradual RSL rise to present, whereas Bradley *et al.* (2011) suggest a slight highstand (ca. +0.5 m), and then fall to present after 3 k cal a BP. These differences largely reflect the thicker LGM ice in the Kuchar *et al.* (2012) model that results in greater mid and late Holocene subsidence due to forebulge collapse. RSL data from Loch Eriboll and the Wick River Valley show that RSL was <1 m above present for several thousand years during the mid and late Holocene before it fell to present. As such the data more closely follow the broad structure of the Bradley *et al.* (2011) model prediction during this interval.

The Bradley and Kuchar GIA models differ in their BIIS ice load history but in all other aspects they are the same. Each model has been tuned to the Arisaig RSL record (Fig. 1B), one of the longest sea-level records in north-west Europe (e.g. Shennan *et al.*, 2006). Here we have tested these models against a second, long RSL record that also stretches back into the Lateglacial. We find significant mismatches between the models and our observations, indicating that these models need to be modified. The Bradley model fails to predict the higher than present Lateglacial RSL that we observe, suggesting that the existing ice thicknesses in this model need to be increased. The absence of any strong differential GIA across our study area, at least during the Holocene, also suggests that the strong contrast in (thicker) ice loads across west and east Scotland during the LGM, as assumed by the Kuchar model, also requires revision. We hypothesize that a more uniform, thicker LGM ice load, which was removed relatively quickly during deglaciation, will result in an improved model/observation fit.

The potential Storegga tsunami deposit in Loch Eriboll

Within the coastal section at Lochan Harvurn, Unit 3 provides evidence for abrupt inundation of a terrestrial surface at ca. 8.1 k cal a BP. There are several potential depositional mechanisms for Unit 3, including terrestrial processes, storms, secular changes in RSL and a tsunami, each of which we now consider.

We suggest a terrestrial origin source for Unit 3 is unlikely because there are no immediate supplies of sand-rich sediment to the site, other than from the adjacent beach. Mesolithic human impact on the site seems likely from the charcoal and pollen data, but woodland management or natural fire would not cause the deposition of a coarse sand unit, lying as it does immediately above a buried soil. A Roman Iron Age souterrain (an underground gallery dug out and then lined with stones) and the remains of 3–5 hut circles exists to the south-east of Fouhlin (Fig. 4), but this post-dates the sediments under consideration. We therefore favour a natural origin for Unit 3, most likely from the adjacent beach.

Differentiating between a storm surge and a tsunami deposit is notoriously difficult, although there are some

potential diagnostic criteria (e.g. Chagué-Goff *et al.*, 2011). Storm deposits tend to be deposited gradually over a period with successive waves that erode the foreshore and beach, with sometimes well-developed sedimentary structures (Kortekaas and Dawson, 2007). Also, storms typically have limited return flow until after the main flood, and sediment transport is mainly by traction (Morton *et al.*, 2007). However, as discussed below, RSL was at least 6 m lower than present at ca. 8.1 k cal a BP, which would make a storm origin for Unit 3 unlikely. Additionally, we would expect to see many storms across such a high-energy coastline but there is only one significant marine unit.

Secular changes in early Holocene RSL cannot explain either the elevation or age of Unit 3. The two GIA models predict that RSL at the time of the Storegga tsunami was between ca. –4.7 and –6.1 m OD (Fig. 9A). These are approximate values, based on a single preferred Earth and ice model. Sea level was rising quickly at this time meaning that small age uncertainties in the GIA models or in our reconstructions can span several metres of RSL change. Noting these caveats, there is nevertheless a ca. 6- to 10-m height difference between the GIA estimates of RSL and the elevation of Unit 3 (ca. +4.1 to +4.7 m OD). Such a difference makes it difficult to envisage how Unit 3 could have been deposited by a secular change in RSL.

As noted above, in LE-14-1 there is a break in sedimentation that separates Unit 3 from Unit 4, and a lack of alder pollen in the latter suggests it was deposited between ca. 8.1 and 6 k cal a BP. By the latter time, our observations show that RSL had risen to close to present MTL, leading us to propose that the raised beach of Unit 4 was probably deposited by the Main Postglacial Transgression (Smith *et al.*, 2011). In contrast, exceptional conditions are required to deposit the sand of Unit 3 at its observed altitude of ca. +4.1 to +4.7 m OD.

Several other factors lend support to our attribution of Unit 3 to deposition associated with the Storegga tsunami. First, the two radiocarbon dates from charcoal in the underlying palaeosol immediately below Unit 3 are almost identical to the age of the Storegga tsunami inferred from buried moss fragments in a former tidal inlet in Norway (Rydgren and Bondevik, 2015). Second, there are several sedimentary structures in the base of Unit 3 that are common in tsunami deposits, including an abrupt (locally erosive) contact, rip-up clasts of beach sands and inclusions of reworked clasts of soft sediment balls (Fig. 7) (e.g. Dawson and Shi, 2000; Dawson and Stewart, 2007; Kortekaas and Dawson, 2007; Chagué-Goff *et al.*, 2011). This may suggest two phases of deposition, where turbulence dominates transport and is characterized by the unimodal grain size distribution. Third, the grain size data from Unit 3 in LE-14-1 and LE-14-7 reveal an overall fining-upwards sequence, which is typical of suspension deposition and a common feature of Storegga tsunami deposits in Scotland (Smith *et al.*, 2004). Fourth, the deposit is laterally continuous across the coastal section (>100 m) and can be traced ca. 75 m inland, where a distinct deposit of coarse sand with some gravel is the only interbedded minerogenic unit within peat (LE-15-1). Fifth, although there are no marine microfossils in Unit 3, grain size and ITRAX data support a marine origin for the deposit in the coastal section and inland, with the source of the sediment most likely the adjacent intertidal shoreface beach sands. Analysis of the particle size distribution of the modern intertidal sediments and the sand unit attributes both to unimodal moderately sorted gravely sand (Table S1). Lastly, the ITRAX analysis demonstrates an increased occurrence of Ti and Zr in Unit 3, which can indicate a presence of heavy minerals diagnostic of high-energy sedimentation such

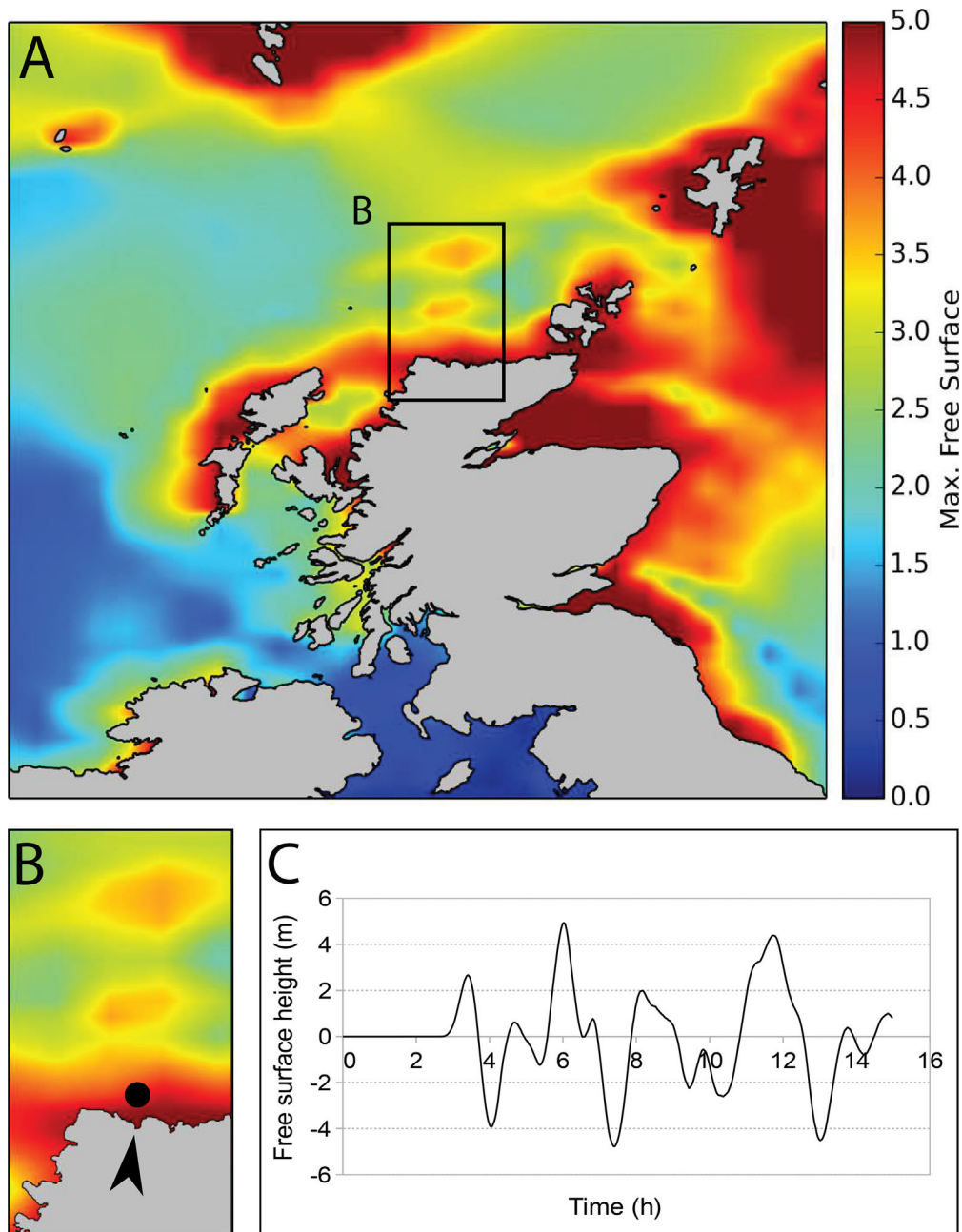


Figure 10. Modelled maximum offshore tsunami wave heights predicted using the GIA-corrected wave model of Hill *et al.* (2014). The black arrow in B marks the location used for the wave height predictions in C.

as that experienced during tsunami inundation (Chagué-Goff *et al.*, 2015).

To investigate further the possibility of Unit 3 being formed by the Storegga tsunami, we use the offshore wave heights predicted by a GIA-corrected tsunami wave model (Hill *et al.*, 2014), which incorporates realistic palaeobathymetry and covers the Loch Eriboll area with resolution of around 1 km. Using the relationship of Synolakis *et al.* (2008), the tsunami run-up height can be estimated using the peak-to-trough wave heights estimated by the model. Wave heights extracted 15 km from the coast show a maximum wave height of ca. +5.2 m (with respect to MSL) and a peak-to-trough height of ca. +6.9 m (Fig. 10, Animation S1). At the head of the loch, this relationship predicts a run-up of around +4.6 m above the palaeo-sea level. This is lower than the estimated run-up height from the field data, which suggest ca. 8–10 m run-up, depending on which GIA model is used to predict RSL. This mismatch between the model run-up heights and the empirical field evidence is also noted at other sites across Scotland especially in the Shetland Islands (Bondevik *et al.*, 2005a,b).

The two major previous modelling studies of the Storegga tsunami predict wave heights of around 3–6 m offshore the northern Scottish coast (Harbitz, 1992; Bondevik *et al.*, 2005a,b). However, both studies used bathymetric data which had 12.5-km resolution in the region [although Bondevik *et al.* (2005a,b) linearly interpolated this to 2.5 km computational grid resolution] so would have been unable to resolve the fjord-like morphology of Loch Eriboll at the time.

The palaeobathymetry used by Hill *et al.* (2014) was constructed using modern bathymetry and accounting for RSL changes due to GIA (Bradley *et al.*, 2011). However, this does not account for sediment movement or other changes in bathymetry for other reasons. The field data indicate that Loch Eriboll was a well-developed fjord around the time of the deposition of Unit 3, whereas the palaeobathymetric reconstruction of Hill *et al.* (2014) shows a relatively small bay. Funnelling of tsunamis in narrow inlets can lead to higher than expected wave heights, which may explain the difference between the modelled wave heights and those estimated from Unit 3. Nor does the model include tidal effects. The tidal amplitude in the region is around 4 m for the

mean spring tide, which could also explain some of the discrepancy. Lastly, it is also important to note that our modelled run-up estimates are sensitive to assumptions regarding the velocity of the Storegga submarine landslide. Here, we use the same slide velocity (35 m s^{-1}) to that of Harbitz (1992), who chose this velocity as it provided the best available match to geological data from northern Scotland at that time. The modelled run-up estimates for a faster/slower initial slide will be higher/lower than that predicted at present. Despite these points, which generally serve to highlight uncertainties in the tsunami model, nevertheless the modelling shows that there was clearly sufficient wave height in the region for Unit 3 to be tsunamigenic in origin.

Holocene RSL changes and tsunami preservation potential

As noted above, before this study evidence for landfall of the Storegga tsunami in northern mainland Scotland was limited to sites in the east. Moreover, although now identified within Loch Eriboll, it is only recorded at one site, causing us to reflect on why the evidence for the tsunami is so sparse in this region.

A wide range of processes can modify tsunami deposits and hence their preservation potential over different timescales. Repeat field surveys in Thailand following the 2004 Indian Ocean tsunami show that after only 4 years, the original tsunami deposit was preserved in just half of the studied sites (Szczeniński, 2012). This study concluded that the original thickness of the tsunami was key to its preservation potential, with deposits formed in areas of small run-up ($<3 \text{ m}$), which tended to be thin, unlikely to be preserved. Over longer Holocene timescales, the preservation of a tsunami deposit for 8000 years will clearly be assisted if it was deposited on and buried by peat [e.g. at Wick River Valley (Dawson and Smith, 1997) and Sullum Voe, Shetland (Bondevik *et al.*, 2003)], in fine-grained cohesive sediments that are resistant to erosion [e.g. at Maryton, Montrose (Smith *et al.*, 2004)], in subtidal lagoons where it is buried by marine clastic deposits [e.g. Strath Halladale (Dawson and Smith, 2000)] or in lakes that lie above and beyond the reach of tidal processes [e.g. on Norway's west coast (Bondevik *et al.*, 1997)].

In Loch Eriboll, the Storegga deposits at the beach section at Lochan Harvurn comprise coarse sands that were deposited on a soil and subsequently overlain by high-energy beach deposits. Inland of the coast the deposit occurs wholly within peat. Under these (not ideal) conditions, establishing unequivocal evidence that Unit 3 is a Storegga tsunami deposit has been a challenge. We attribute the lack of widespread evidence for the tsunami within Loch Eriboll to the fact that there has been widespread coastal erosion in the mid and late Holocene, as evidenced by relict cliff lines located 1–2 m above present beach level in many areas of the loch. Stable RSL, at or slightly above present for much of the Holocene, has clearly not been conducive to the preservation of the Storegga tsunami in the inner part of Loch Eriboll. That much of the north coast of mainland Scotland lies on the same shoreline isobase and experienced a similar Holocene RSL history provides a plausible explanation for the lack of reported evidence for the Storegga tsunami in the region.

Conclusions

Our objective has been to combine new field and laboratory investigations based in Loch Eriboll (Sutherland), with GIA and palaeotsunami modelling to improve understanding of

Lateglacial and Holocene RSL change and the potential impact of the Storegga tsunami along the north coast of Scotland. Our main conclusions are:

1. New RSL data obtained from three sites in Loch Eriboll establish one of the longest RSL records in North-West Europe from the north coast of Scotland. Following deglaciation, RSL fell during the Lateglacial to an undefined lowstand below present before rising again during the early Holocene to reach an initial highstand at ca. 7–6 k cal a BP, which we correlate to the Main Postglacial Transgression observed elsewhere in Scotland. During much of the mid and late Holocene RSL was at or slightly ($<1 \text{ m}$) above present. These data broadly support observations from sites located on the same isobase for the Main Postglacial Shoreline at Wick (north-east Scotland) and Lochinver (north-west Scotland).
2. We find that existing GIA models for the BIIS do not predict either the detailed local record of RSL changes that we develop from Loch Eriboll, or the regional trend in data from the north mainland coast. The simplest explanation for this mismatch is the need for a more uniform increase in the modelled ice thickness at the LGM across the study area. These differences also highlight the need for additional, long-term RSL records that extend to the Lateglacial.
3. A coastal exposure of unconsolidated sediments at the head of Loch Eriboll contains evidence for the Storegga tsunami, dated to ca. 8.1 k cal a BP. Key criteria for its identification include its age, the abrupt (locally erosive) contact to underlying deposits, rip-up structures, lateral continuity including inland extent, and geochemical and grain size data. Other potential origins for the deposit are considered (terrestrial processes, storms and secular changes in RSL) but are rejected.
4. Using a GIA-corrected tsunami wave model we predict peak offshore wave heights for the Storegga tsunami at Loch Eriboll of ca. 5 m, several metres less than is suggested by the sedimentary evidence. This difference probably reflects limitations in the tsunami model, including an under-estimation of the impact of local topographic effects in amplifying the tsunami waves as they came onshore.
5. We hypothesize that the limited evidence for the Storegga tsunami on the north coast of Scotland reflects relatively stable RSL during the mid and late Holocene which resulted in widespread coastal modification by wave energy that was restricted to a narrow vertical range. Notwithstanding these issues, our work extends our understanding of the spatial impact of the Storegga tsunami on the British Isles, confirming that it had a significant impact on much if not all the north coast of Scotland.

Supporting Information

Additional supporting information may be found in the online version of this article.

Figure S1. Diatom diagram from the lower and upper minerogenic unit recorded in the Loch Uamh lithostratigraphy, from sample core LU35.

Figure S2. Diatom profile from Lochan Harvurn (inner basin), sample core LH-12-5.

Figure S3. Pollen diagram from the foreshore peat collected from Lochan Harvurn, location LE-12-6.

Figure S4. Pollen diagram from (A) Monolith 1 and (B) Monolith 2, from Otter Beach.

Figure S5. Otter Beach geochemistry profile from Monolith 2.

Figure S6. Lochan Harvurn coastal section LE-15-1 geochemistry profile. The sample monolith was collected from the same location as LE-12-1.

Animation S1. Animation showing the modelled impact of the Storegga slide tsunami impacting the north coast of Scotland. See text for details.

Table S1. Grain size data from the present-day beach samples at Lochan Harvurn shoreface and Unit 3 (see Fig. 6A for location of samples).

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