Late Glacial to Holocene relative sea level change in Assynt, northwest Scotland, UK

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Abstract

Relative sea-level change (RSL), from the Late Glacial through to the late Holocene, is reconstructed for the Assynt region, northwest Scotland, based on bio- and lithostratigraphical analysis. Four new radiocarbon-dated sea-level index points help constrain RSL change for the Late Glacial to late Holocene. These new data, in addition to published material, capture the RSL fall during the Late Glacial and the rise and fall associated with the mid-Holocene highstand. Two of these index points constrain the Late Glacial RSL history in Assynt for the first time, reconstructing RSL falling from 2.47 ± 0.59 m OD to 0.15 ± 0.59 m OD at *c.* 14000 – 15000 cal. BP These new data test model predictions of glacial isostatic adjustment (GIA), particularly during the early deglacial period which is currently poorly constrained throughout the British Isles. While the empirical data from the mid- to late-Holocene to present matches quite well with recent GIA model output, there is a relatively poor fit between the timing of the Late Glacial RSL fall and early Holocene RSL rise. This mismatch, which is also evident elsewhere in northwest Scotland, may result from uncertainties associated with both the global and local ice components of GIA models.

Introduction

The United Kingdom has been the focus of sea-level research for a number of decades (e.g. Tooley 1982; Devoy 1982; Shennan et al. 2005; Shennan et al. 2006a). The British and Irish Ice Sheet (BIIS) provides a compact case-study suitable for disentangling the relative contributions of eustasy, deformation of the ocean geoid, isostasy and local processes to regional records of post-Last Glacial Maximum (LGM) relative sea-level (RSL) change (Flemming, 1982; Shennan, 1989). The pattern of RSL change in Scotland is of particular interest as it is dominated by a complex spatial pattern of glacial isostatic adjustment (GIA) caused by the proximity of the centre of the LGM BIIS, and the peripheral effects of the Fennoscandian ice sheet (Peltier, 1998). As a consequence, post LGM records of RSL change in Scotland have the potential to refine, both the ice sheet history and Earth rheology components of GIA models. The Arisaig sea-level curve from western Scotland, which is currently the longest and most complete RSL archive for the British Isles (Shennan et al. 1996; Shennan et al. 2005), is a particularly important test of GIA models (e.g. Shennan et al. 2006a; Bradley et al. 2011). Many other locations, particularly those close to the centre of the LGM BIIS, currently have very limited records of past sea level, particularly covering the Late Glacial period, with spatially and temporally disparate sea level index points. The aim of this paper is to develop new records of past sea level for the understudied Assynt region of northwest Scotland (Figure 1), extending the current record, from Coigach (Shennan et al. 2000), beyond the mid-Holocene. Offshore geological records from northwest Scotland show that this region consisted of a series of LGM ice streams which channelled ice offshore towards the continental shelf off northwest Scotland (Stoker & Bradwell 2005; Bradwell et al. 2007; Bradwell et al. 2008a; Bradwell 2008b). New sea level data from this region will contribute to refining the next generation of ice sheet and GIA models which have the potential to reconstruct dynamic ice sheet processes (Kuchar et al., 2012) at a time when trimlines, previously identified as indicators of maximum ice thickness (McCarroll et al., 1995; Ballantyne et al., 1998), are being reinterpreted as englacial thermal boundaries, constraining minimum ice elevation (Ballantyne and Hall, 2008; Ballantyne, 2010; Fabel et al., 2012).

Existing relative sea level data from northwest Scotland

Raised beaches, coastal geomorphology, buried peats and salt marshes have all been used to develop post-LGM and Holocene records of past sea level. The most widely employed approach in northwest Scotland involves isolation basins which, in this region of isostatic uplift, are preserved above current sea level and record phases of marine transgression and regression (e.g. Shennan et al. 1994; 1995a; 1995b; 1996; 1999; 2000; 2005; 2006b; Selby & Smith 2007). The successful application of this approach in the Morar region of western Scotland, resulted in the reconstruction of a 16,000 year, near continuous RSL record at Arisaig (Figure 1A) (Shennan et al., 2005). By comparison, records further north typically comprise only a few Holocene data points limiting the interpretation of regional post LGM RSL change in northwest Scotland. Existing sea-level index points from the Assynt region are restricted to Coigach, 20 km northwest of Ullapool (Figure 2), and extend from the early through to the late Holocene (Shennan et al. 2000). Diatom, foraminifera and pollen assemblages preserved in sediment sequences from Dubh Lochan (isolation basin), Loch Raa (tidal marsh) and Badentarbet (wetland and barrier) (Figure 1A) indicate a RSL rise to a mid-Holocene highstand of c. 2.6 m OD followed by a RSL fall (Shennan et al. 2000). In addition, raised shorelines have been identified in the Assynt region at Achnahaird Bay (rock platform at c. 5.2 m OD) (Shennan et al. 2000) and Stoer Beach (raised beach at 6.47 m OD). Although the timing of these sea level highstands is unknown, the position of mean sea level can be reconstructed assuming fossil shore platforms and beaches such as these formed between Mean Tide Level (MTL) and Mean High Water Spring Tide (MHWST) (Shennan et al. 2000). This indicates a water level between 3.1-5.2 m OD at Achnahaird Bay and 4.37-6.47 m OD at Stoer Beach. The altitudes of these raised platforms however contradicts the regional reconstructions of the Main Postglacial Shoreline (-2 m OD) and the Blairdrummond Shoreline (-2 m OD), determined from a Gaussian quadratic trend surface model of raised beaches around Scotland (Smith, 2005). Salt marsh RSL records from Loch Laxford and Kyle of Tongue (Figure 1A) indicate a RSL fall in line with GIA models of late Holocene isostatic uplift in the region (Barlow et al., 2014).

Study sites

The Assynt region extends along the Scottish northwestern coastline from Loch Broom (Ullapool) to Eddrachillis Bay (Figure 1A). The fjordic landscape has been sculpted by past glacial cycles resulting in 'knock-and-lochan' topography, dominated by ice-scoured rock outcrop covered by peat and is well suited to lake-basin development (Lawson, 1995; Gillen, 2003). Sediment sequences from isolation basins at Duart Bog, Loch Duart Marsh and Oldany, on the north coast of the Assynt region (Figure 1A), were investigated in November 2013. Basins inundated during part of the tidal cycle accumulate brackish or marine sediments, whilst those above Highest Astronomical Tide (HAT) accumulate freshwater sediments; changes in sedimentary units correspond with the isolation or ingression of the basin therefore reflecting its position in relation to sea level (Lloyd, 2000; Lloyd and Evans, 2002). Duart Bog is located along the western shoreline of Loch Nedd, a sea loch (Figure 1B). This low-lying, sediment-filled basin is sheltered by surrounding deciduous woodland with steep topography of Lewisian Gneiss ascending to the south west of the basin. Loch Duart Marsh is accessed through the woodland encircling Duart Bog (Figure 1B) and is a small, largely infilled basin, c. 53 x 23 m with fringing salt marsh, connected to Loch Nedd at high tide via the adjacent tidal pond. A bedrock sill with overlying boulders, separates Loch Duart Marsh, at low tide, from the tidal pond which is also isolated from Loch Nedd during part of the tidal cycle. Oldany is a large infilled basin lying just below 10 m OD and sheltered by the surrounding steep topography of Lewisian Gneiss bedrock outcrop.

Methods

Methods follow established approaches to reconstructing past sea level from isolated basin sediments (Shennan et al., 2015). Gouge-coring transects across each basin documented stratigraphic changes and the depth of the basin's sill, where buried. Sediments were logged using the Tröels-Smith (1955) descriptive scheme. Material was collected for laboratory analysis using a Russian corer, with the samples wrapped in plastic and stored in a fridge on return to Durham. Core location, altitudes and the elevation of each basin's sill were surveyed using a Sokkia Set 6 Total Station and levelled to Ordnance Datum (m OD) using the flush bracket benchmark 12125, located on the south side of Clashnessie Bridge (Figure 1A) (NC 0557 3080).

Palaeoenvironmental reconstruction through cores from each basin is based upon diatom analysis, supported by pollen identification and sediment organic content. The strong relationship between diatom taxa and salinity accurately enables marine, brackish-water and freshwater phases of the isolation process to be characterised (Kolbe, 1927; Hustedt, 1953; Vos and De Wolf, 1988). Diatom sample preparation followed the standard method summarised by Palmer & Abbott (1986) and Battarbee (1986). An alternative methodology, designed by Scherer (1994) to determine the absolute abundances of diatoms, was used at the base of LDM-13-1 (200 cm to 220 cm) because of poor diatom preservation and a high clay content. This settling method produces slides with an even distribution of valves with minimal clumping (Maddison, 2005). A minimum of 250 valves were counted where possible with diatom species identification following Hustedt (1953), Hartley et al. (1996), Haworth (1976) and Robinson (1982). Species are grouped according to salt tolerance using the Halobian classification scheme (Kolbe, 1927; Hustedt, 1953; Hemphill-Haley, 1993) and plotted as greater than 5 % of the total diatom valves counted, using C2 (Juggins, 2003). Diatoms are zoned based on stratigraphically constrained cluster analysis using Tilia's constrained incremental sum of squares (CONISS) software (Grimm, 1987). Percentage loss on ignition (LOI) provides an indication of the organic content through the cores to complement the diatom analysis and is determined by combustion of material for 30 minutes at 850 °C following drying of the material at 105 °C overnight (Heiri et al., 2001).

AMS radiocarbon dating of bulk sediment samples from the organic unit adjacent to a palaeoenvironmental transition, as identified by the diatom assemblages, provides chronological control for the periods of marine ingression and regression. Radiocarbon measurements were conducted by the ^{14}C CHRONO Centre for Climate, the Environment, and Chronology and Beta Analytic and calibrated using CALIB REV7.0 and IntCal13 calibration curve (Reimer et al., 2013) with the 2 sigma age range reported in Table 1. Pollen analysis was used to complement the radiocarbon chronology. Pollen preparation followed the standard methodology outlined by Moore et al. (1991). Most of the pollen analysis is qualitative, for the purpose of providing a relative age for the isolation and ingression contacts identified rather than for palaeoenvironmental reconstruction. Counts for qualitative analysis exceeded 66 grains. Full counts (100-200 grains) however are given for Duart Bog (index point 1) as the radiocarbon date for this index point is considered unreliable, and these are presented in Figure 5.

Results

Duart Bog (58°14.70'N, 5°10.67'W): Sill altitude 4.77 m OD

The lithostratigraphy at Duart Bog documents a transitional sediment sequence from clay (430 cm to 425 cm) to silty clay (425 cm to 408 cm) overlain by organic limus (408 cm to 380 cm) and an upper peat unit (380 cm to surface; Figure 3). Three zones can be identified in the diatom assemblages in core DuB-13-3 (Figure 3). Brackish species dominate at the base of the core (zone 1), indicating a marine influence in the basin during initial clay sedimentation probably via its connection with Loch Nedd (Figure 1B). There is an abrupt change in diatom flora to predominantly freshwater species at 425 cm, marking the zone 1-2 boundary. This reflects a reduction in marine influence caused by isolation of the basin. This transition to freshwater conditions, which persist through zone 2 and 3, coincides with a change from clay to organic rich silty clay and an associated increase in organic content as suggested by the loss on ignition results (Figure 3). This is followed by a steady increase in organic content up-core. Pollen analysis above the zone 1-2 boundary indicates that this regression at 425m probably dates to the early part of the Late Glacial Interstadial due to the dominance of *Empetrum*. AMS ^{14}C dating of the regressive contact constrains it to 12580-12840 cal. BP, therefore reconstructing RSL fall to before the Loch Lomond Stadial (12.9 – 11.7 ka).

Loch Duart Marsh (58°14.78'N, 5°10.79'W): Sill altitude 1.95 m OD

Core LDM-13-1 from Loch Duart Marsh consists of four main sediment units: a lower silty clay unit (220 cm to 200 cm) overlain by an organic rich silty clay deposit (200 cm to 158 cm) where rootlets are abundant; a silty clay unit between 158 cm and 60 cm with a 10 cm thick shell layer (152 cm to 142 cm); and a gradual transitional increase in organic material to the upper unit of modern salt marsh peat. The organic content increases from 4 to 41 %, between 220 cm and the surface, with minor peaks above the overall trend at 164 cm (31 %) and 28 cm (72 %) (Figure 4).

Based on the diatom flora and lithostratigraphy seven zones were identified using CONISS. The diatom flora is dominated by marine species in zone 1, indicating marine influence in the basin at the base of the sequence. The transition to zone 2 is characterised by a shift in diatom flora to freshwater species, indicating a reduction in marine influence and isolation of the basin from the sea by 202 cm. An AMS ^{14}C date just above this isolation contact provides an age of 14610-15240 cal. BP indicating a Late Glacial age (Table 1). The age of this transition is supported by qualitative pollen analysis which identified *Artemisia*, Cyperaceae, Poaceae and *Empetrum* (Supplementary Table 1).

There is an abrupt change in the diatom flora at 158 cm from the freshwater assemblage of zone 4, to the mixed marine and freshwater flora in zone 5 (Figure 4). This transition is indicative of a marine ingression into the basin. Qualitative pollen analysis indicates this inundation dates to the early-mid Holocene and this is confirmed by the AMS ^{14}C date immediately below the transition at 160 cm (9890-10180 cal. BP; Table 1). This dated contact therefore constrains the timing of the RSL rise during the earliest part of the Holocene.

Marine conditions persist through zones 5 and 6 until a gradual change from approximately 65 cm across the boundary between zone 6 and zone 7. This transition is characterised by a reduction in marine diatoms and an increase in freshwater species, though the assemblage is still mixed water flora (Figure 4). The AMS ^{14}C date above this transition at 40 cm (310-480 cal. BP) illustrates that this decline in marine influence occurred during the Late Holocene, constraining the RSL fall to present following the mid-Holocene highstand. The lithostratigraphy supports the diatom assemblage; increases in organic matter correspond with the isolation and partial isolation of the basin by 202 cm and 40 cm respectively whilst increases in the inorganic content correlates with periods of stronger marine influence.

Oldany (58°14.47’N, 5°14.50’W): Sill altitude 8.10 m OD

Coring at Oldany recovered organic sediment overlying bedrock at all locations. The depth of organic accumulation ranged from 2 m to 6.5 m. Diatom analysis demonstrates that a freshwater environment (Supplementary Figure 1), recorded by the dominance of oligohalobian-indifferent species and the occurrence of halophobous species, persists throughout the core. This indicates that MSL did not exceed 6 m OD at Oldany (calculated as sill altitude minus the difference between MHWST and MTL: 8.1 – 2.1 = 6 m OD), providing a limiting altitude for post-LGM RSL in Assynt.

Discussion

The diatom flora and lithostratigraphy of the cores studied show clear fluctuations in RSL in the Assynt region. These changes in RSL have been dated using AMS ^{14}C and pollen stratigraphy to allow the generation of four sea-level index points (Table 2). The new index points, along with published data from Coigach, allow the generation of a new RSL curve for the Assynt area (Figure 6). The significance of this new sea-level curve is discussed in detail in the following sections.

Post-Last Glacial Maximum relative sea-level change in Assynt

The new sea-level index points (Table 2) from Duart Bog (index point 1) and Loch Duart Marsh (index point 2) extend the published RSL record from Assynt (Shennan et al. 2000) back to the Late Glacial (Figure 6). The new limiting elevation from Oldany, where the freshwater diatom assemblage suggests the marine limit following regional post-LGM ice retreat was less than +6 m OD, also constrains the altitude of Late Glacial RSL (Figure 6). This is compatible with the altitude of raised shorelines in the Assynt region (Shennan et al. 2000). The sea level index points from Coigach (Shennan et al. 2000) and the new points from Duart provide constraints on the post-glacial- Holocene RSL.

Loch Duart Marsh index point 2 (negative tendency) constrains RSL to -0.15 ± 0.59 m OD at 14610-15240 cal. BP, an age supported by the pollen flora (Supplementary Table 1). A Late Glacial fall in sea level is also supported by index point 1 (negative tendency) from Duart Bog. However the chronological control from Duart Bog is less well constrained. Duart Bog (index point 1; negative tendency) places RSL at +2.47 ± 0.59 m OD and is radiocarbon dated to 12580-12840 cal. BP. However, this age is not supported by the pollen data close to the regressive contact at 425 cm, which suggests the index point is considerably older (Figure 5). Discrepancies between the relative elevation of the Loch Duart Marsh and Duart Bog sites also suggest that the radiocarbon date for index point 1 may be erroneously young. For example, if the index point 1 radiocarbon date were to be correct, a 2.82 m rise in RSL would be required following the isolation of Loch Duart Marsh and before the isolation of Duart Bog (Figure 6) due to differences in sill altitude for each site. Of the two sites, Loch Duart Marsh is at a lower altitude and therefore should record two marine intervals at the base of the core, rather than one, if the radiocarbon date for index point 1 was correct (Figure 4). Equally, because of the difference in elevation, Duart Bog should record the regression earlier than Loch Duart Marsh, rather than later, if both basins are recording the same RSL fall (Figure 6). The most likely explanation for these discrepancies is that the AMS ^{14}C date from the Duart Bog core is incorrect, contaminated by younger carbon, sourced perhaps from the downward reworking of humic acid or rootlets (Balesdent, 1987). As the radiocarbon date for the regression contact at Duart Bog seems younger than expected based upon its elevation relative to Loch Duart Marsh, full pollen percentage counts were made above the regressive contact at 425 cm (Figure 5). Counts from 418.5 and 415 cm are dominated by *Empetrum*, with lesser frequencies of Cyperaceae and *Artemisia*. At 408.5 cm, however, Cyperaceae has become the most abundant pollen taxon, with reduced *Empetrum* and increased *Rumex*. Pollen analysis at nearby Lochan an Druim, 37 km north east at Eriboll (Birks, 1984), and elsewhere in northern Scotland (Pennington et al., 1972), has identified similar *Empetrum*-dominated pollen zones near the start of the Late Glacial Interstadial, followed by an analogous switch to Cyperaceae (Supplementary Figure 2). The *Empetrum* pollen zone in northern Scotland associated with the Late Glacial Interstadial, like the Duart Bog sample, is also dominated by sedge pollen. The virtual absence of *Juniperus* in the Duart Bog samples is also very similar to the early Interstadial data from Lochan an Druim, and means that these Duart Bog levels cannot equate to late Loch Lomond Stadial/early Holocene age, when *Juniperus* was abundant locally. By analogy with the pollen and radiocarbon data from Lochan an Druim, therefore, the Duart Bog pollen must indicate a time early in the Lateglacial Interstadial, by interpolation about c.14,400 cal. BP (Supplementary Figure 2). This demonstrates that the ^{14}C date for index point 1 is erroneously young. The regression visible at the base of the Duart Bog core is therefore likely to be similar to index point 2 recorded in the Loch Duart Marsh core.

Sea-level index points from both Loch Duart Marsh (index point 3) and Coigach (Shennan et al. 2000) provide constraint on the RSL rise before the mid-Holocene highstand (Figure 6). The new index point from Loch Duart Marsh shows that RSL rose earlier than previously thought to -0.15 m OD at 9890-10180 cal. BP (Figure 6). Based on the index points from Coigach, sea level then rose to above 2.17 m OD at 8250-8370 cal. BP (Shennan et al. 2000). Freshwater diatom and pollen flora from Loch Raa, Coigach provides a limiting altitude for the mid-Holocene highstand at 2.6 m OD (Shennan et al. 2000). The persistence of freshwater conditions following the marine ingression at the base of DuB-13-3 supports this by providing a further limiting point, constraining the altitude of the mid-Holocene highstand to below +2.47 ± 0.59 m OD.

Following the mid-Holocene highstand, a series of index points from Coigach (Shennan et al. 2000) constrain a RSL fall (Figure 6). Index point 4 which marks the onset of Loch Duart Marsh isolation provides a further constraint on this falling sea level with a RSL of +1.05 ± 1.21 m OD, between 310 -480 cal. BP. This index point is compatible with recent records of RSL change from salt marshes at Loch Laxford and Kyle of Tongue (18 km and 49 km north east of Duart respectively), which indicate a gradual fall in RSL over the last 2000 years in northwest Scotland (Barlow et al., 2014).

Fit with glacial isostatic adjustment models

By extending the existing RSL curve for the Assynt region back to the Late Glacial it is now possible to compare recent GIA model outputs for the region with data from both the earlier part of the deglacial sequence and the late Holocene. There is a clear mismatch with the Bradley et al. (2011) GIA model output during the Late Glacial, as the model under predicts the sea-level elevation recorded at Duart Bog and Loch Duart Marsh by over 10 m (Figure 6). Some of this discrepancy (c. 2 m) may be resolved by adopting the palaeo-tidal correction modelled for MHWST by Neill et al. (2010) for Arisaig. Changes in tidal amplitude, since the LGM, have rarely been taken into account despite the significant impact on the interpretation of isolation basin records. Neill et al. (2010), however, predicted that MHWST has decreased by 2.6 m since 16 ka, with around 2 m of this decline occurring during the Late Glacial period.

The marine limit elevation, from Oldany (6 m OD), as well as the raised shoreline evidence from the wider Assynt region, fits reasonably well with the Bradley et al. (2011) model prediction of maximum post LGM sea level of c. 5 m OD (Shennan et al. 2000). Although these geomorphological features are not dated, comparison with the age-constrained index points indicates that they are too high to be mid-Holocene in age and are therefore likely to be a result of Late Glacial sea level. Reconstructions of RSL at both Duart (index point 3) and Coigach, lie over 5 m above the Bradley et al. (2011) model prediction of rising RSL prior to the mid-Holocene highstand, while index points constraining the mid-Holocene highstand itself (from Coigach (Shennan et al. 2000)) and the late Holocene RSL fall (from Duart-index point 4), are close to that predicted by the Bradley et al. (2011) model.

The Kuchar et al. (2012) GIA model combined a 3-D thermomechanical ice sheet model (Hubbard et al., 2009) with the Bradley et al. (2011) GIA Earth model. The Hubbard et al. (2009) ice model is driven by palaeoclimate data based on the physics of ice flow; it therefore provides a test for the interpretation of trimline data (e.g. Ballantyne & Hall 2008; Ballantyne 2010). The Kuchar et al. model prediction for the Assynt region (Figure 6) is based on the minimal ice reconstruction of the Hubbard et al. (2009) ice model. The Kuchar et al. (2012) model produces a larger isostatic response and its prediction for Arisaig fits extremely well with the RSL data from this site, in contrast with previous models (e.g. Shennan et al. 2006a; Bradley et al. 2011). Similarities between Assynt's vertical ice extent reconstructed by the Kuchar et al. (2012) model and that deduced from the region's weathering limits for the Bradley et al. (2011) ice model leads to these GIA models producing relatively similar RSL predictions from ~15 k yr BP to present (within ~1 m) (Figure 6). The region's vertical ice extent determined from weathering limits on Ben More Assynt, Conival and Canisp, for example, ranges from around 750 to 850 m (Ballantyne, 1997; McCarroll et al., 1995), greater than that reconstructed by the Kuchar et al. (2012) minimal ice model (500 to 750 m thick). Consequently, whilst the Kuchar et al. (2012) predictions produce a good fit for Arisaig, this is not the case for Assynt where the reconstructed vertical ice extent appears too conservative.

Relative sea level in northwest Scotland and implications for models of the British and Irish Ice Sheet

The combination of ice and Earth models adopted by Bradley et al. (2011) for the British Isles results in good model-data fit for the Holocene part of the 16000 year Arisaig RSL record (Shennan et al. 2005), though the model struggles to fit the oldest and highest data points. By comparison, the additional ice thickness in Hubbard et al. (2009) adopted in the Kuchar et al. (2012) GIA model (with similar Earth model parameters to Bradley et al. (2011)) provides better fit with the oldest part of the Arisaig curve. However, our new data supports the assertion (as noted by Kuchar et al. 2012) that despite additional ice thickness in the Hubbard et al. (2009) ice model over the central region, there is still poor GIA model and RSL data fit in the far northwest of Scotland during the Late Glacial and early-Holocene. The consistency of Earth model solutions (e.g. Lambeck et al. 1998; Steffen & Kaufmann 2005; Bradley et al. 2011; Kuchar et al. 2012) suggests that the misfit is most likely a consequence of the ice model: either the global melt history or underestimation of local ice thickness.

Resolving the exact timing of Antarctic melt remains a challenge (Peltier, 1998; Peltier et al., 2002; Shennan et al., 2002; Whitehouse et al., 2012). Many recent far-field RSL investigations have sought to resolve the post-LGM ‘eustatic’ record, but uncertainties associated with local processes, e.g. depositional lowering and tectonic movements in far field locations, are not always fully understood and/or quantified (e.g. Zong 2004; Horton et al. 2005; Bradley et al. 2011; Deschamps et al. 2012). Consequently, data-model misfit in northwest Scotland may be a consequence of uncertainties in the global ice model. However, as much of the misfit is during the Late Glacial, it suggests the errors may primarily be associated with the ‘local’ ice model during a time when regional isostatic processes are the most dominant component of RSL change.

Recent reassessment of palaeo-trimline data in Scotland (e.g. McCarroll et al. 1995; Ballantyne et al. 1998), based on cosmogenic-nuclide analysis of bedrock and erratic 'pairs', has resulted in their reinterpretation as englacial thermal boundaries. These features therefore, are now thought to constrain the minimum rather than maximum surface elevation of the BIIS (Ballantyne & Hall 2008; Ballantyne 2010; Fabel et al. 2012), resulting in greater ice thicknesses than in the Brooks et al (2008) ice model used by Bradley et al., (2011). This reassessment is supported by the improved fit between the deglacial RSL data from central western Scotland (for example Arisaig) and the Kuchar et al. (2012) GIA model which contains much thicker ice. However, the Kuchar et al. (2012) minimal ice model (as preferred for Arisaig) still contains LGM ice 100 m thinner than that deduced from the weathering limits in the northern sector of the ice sheet (e.g. Assynt) (McCarroll et al., 1995; Ballantyne, 1997). The reinterpreted field data constraining ice thickness and the Assynt RSL curve, suggest that the regional BIIS ice model used by Bradley et al. (2011) and Kuchar et al. (2012) is still too conservative in this region and points to the local ice model being the most likely cause of the underestimation of modelled height of RSL in Assynt (Figure 6). The issue of ice thickness and it's underestimation is not exclusive to the Scottish sector of the BIIS as similar misfits have been observed elsewhere , such as Ireland (e.g. Brooks et al. 2008; Kuchar et al. 2012).

Increased ice thickness estimates may also be complemented with improved deglacial chronologies. Cosmogenic ^{10}Be dating is extensively used to estimate the timing of deglaciation and glacial readvances, as well as reconstructions of the BIIS extent. Improvements in cosmogenic dating have resulted in a shift to the use of locally determined ^{10}Be production rates (LPR), rather than global ^{10}Be production rates which have refined the deglaciation chronology (Balco et al., 2008; Ballantyne, 2012; Ballantyne and Stone, 2012; Ballantyne et al., 2013). For example, Ballantyne (2012) recalibrated existing exposure ages using LPR for sites extending from Orkney to Beinn Inverveigh in the Scottish Highlands. Prior to recalibration, 62 % of these published ^{10}Be exposure ages for Loch Lomond Stadial ice retreat were younger than 11.7 ka. Following recalibration, 73% were within the chronological limits of the Loch Lomond Stadial (12.9-11.7 ka) (Ballantyne 2012). Revising the deglaciation chronology, based on the recalibration of erroneously young exposure ages, may also help reconcile the misfit between GIA models and the empirical data from northwest Scotland.

Conclusions

This paper presents new sea-level data for Assynt, northwest Scotland, which adds to the existing RSL data from Coigach (Shennan et al. 2000), extending the regional RSL curve back to the Late Glacial. There is good fit between the data and the GIA models of Kuchar et al. (2012) and Bradley et al. (2011) for the mid to late-Holocene; however, both models underestimate the elevation of RSL during the Late Glacial and early Holocene. Recent reassessment of trimline data has led to their interpretation as indicating the minimum surface elevation of the BIIS rather than maximum elevation (e.g. Ballantyne & Hall 2008; Ballantyne 2010). The RSL results from Assynt support this, suggesting the GIA models need to incorporate thicker ice in the northwest sector of the BIIS. Additional RSL index points from around the marine limit (c. 4-6 m) and the sea-level lowstand (c. 11-14 k yr BP) are needed to help further constrain the regional RSL history. This in turn needs to be complemented with new models of the BIIS ice sheet which include improved deglacial chronologies and estimates of ice sheet thickness.

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Table 1: New radiocarbon dates from the Duart area of Assynt from this study.

Site (index point #)	Laboratory code	^{14}C age BP (± 2σ)	Calibrated age (cal. BP)	Altitude (m OD)	Material dated/Comment
Duart Bog (1)	UBA-26502	10810 ± 82	12580 – 12840	2.52	Organics within silt clay unit, above regressive contact
Loch Duart Marsh (2)	Beta-390107	12670 ± 80	14610 – 15240	0.03	Organics within organic rich silty clay unit, above regressive contact
Loch Duart Marsh (3)	UBA-26501	8887 ± 72	9890 - 10180	0.46	Organics within organic rich silty clay unit, below transgressive contact and away from shell layer (142 cm to 152 cm)
Loch Duart Marsh (4)	UBA-26500	332 ± 68	310 - 480	1.66	Organics within limus regressive unit

Table 2: Sea-level index points for the Assynt region from Duart (this paper) and Coigach (Shennan et al. (2000)). Dating associated with Duart Bog (1*) is based on pollen evidence rather than radiocarbon material (presented in Table 1). The positive (+) or negative (-) tendency is noted for each index point whilst limiting index points (L) are also highlighted. The vertical error associated with each sea-level index point presented for Duart was determined as follows $\surd e_1^2 + e_2^2 + e_3^2 \ldots + e_n^2$, where $e_1 \ldots e_n$ are the individual sources of error (Preuss 1979; Shennan et al. 2000; Horton et al. 2000). Errors associated with levelling (index point 1-4: 0.1 m), sill elevation (index point 2-4: 0.05 m) and indicative range (index point 1-3: 0.58 m; 4: 1.20 m) were taken into account. In addition the impact of sediment compaction (0.04 m) was determined for the upper regressive sequence of LDM 13-1 associated with index point 4.

Site (index point ref.)	Laboratory code	Calibrated age (cal. BP)	Altitude (m OD)	Reference Water Level	Indicative Meaning (m OD)	Index point altitude (m OD ± error)		Tendency	Ref.
Duart Bog (1*)		13400 - 15400	4.76	MHWST	2.1	2.67	0.59	-	This paper
Loch Duart Marsh (2)	Beta-390107	14610 - 15240	1.95	MHWST	2.1	-0.15	0.59	-	
Loch Duart Marsh (3)	UBA-26501	9890 - 10180	1.95	MHWST	2.1	-0.15	0.59	+	
Loch Duart Marsh (4)	UBA-26500	310 - 480	1.95	MHWNT	0.9	1.05	1.21	-	
Loch Raa (LR96-4)	AA27222	4354 - 4804	5.09	MHWST + 0.20	2.58	2.52	0.25	-	Shennan et al. (2000)
Loch Raa (LR96-1)	AA27221	4153 - 4834	4.16	MHWST + 0.40	2.78	1.39	0.25	-	
Loch Raa (LR96-8)	AA27223	4575 - 4866	3.62	MHWST + 0.20	2.58	1.05	0.25	-	
Dubh Lochan (DHL96-17)	AA23873	4574 - 4961	3.69	MHWST	2.38	1.32	0.43	-	
Dubh Lochan (DHL96-17)	AA23874	5913 - 6192	3.69	MHWNT + 0.80	1.93	1.77	0.43	-	
Dubh Lochan (DHL96-17)	CAM38852	8135 - 8370	3.69	MHWNT + 0.40	1.53	2.17	0.43	+	
Dubh Lochan (DHL96-17)	AA23875	9661 - 10030	3.69	> HAT	2.97	0.72	0.52	L	
Badentarbat	SRR5485	5652 - 5910	0.9	MTL	0.23	0.67	1.50	-	

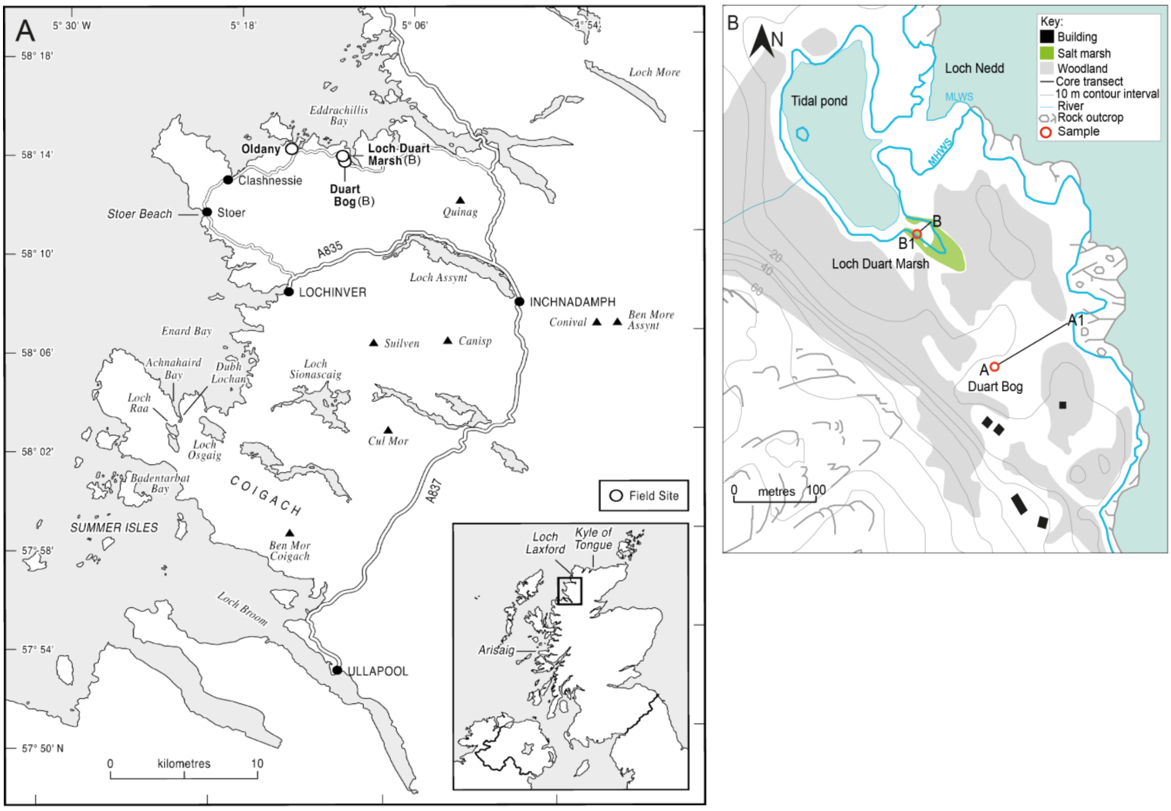

Figure 1: A. Map of the Assynt region showing the location of the field sites B. Map of the Duart Bog and Loch Duart Marsh field sites and the location of the coring and survey transects and sample core locations.

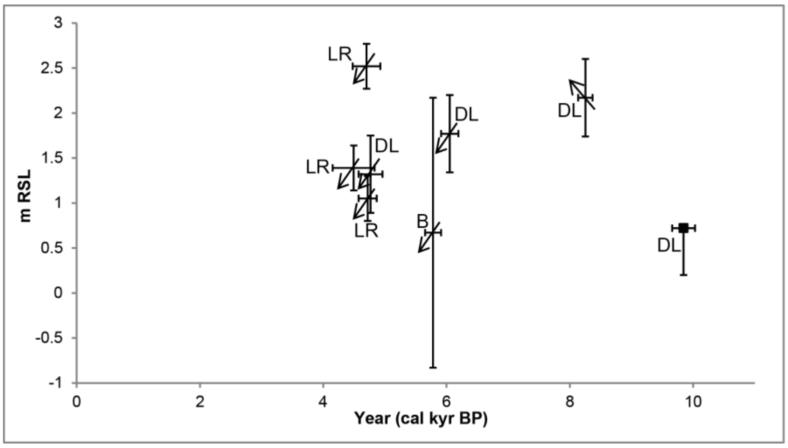

Figure 2: Published sea-level index points from Dubh Lochan (DL; isolation basin), Loch Raa (LR; tidal marsh) and Badentarbet (B; wetland and barrier) in the Coigach area of Assynt (adapted from Shennan et al. (2000)). The arrows indicate the positive or negative tendency associated with each sea-level index point whilst the limiting index point is denoted by a black square symbol.

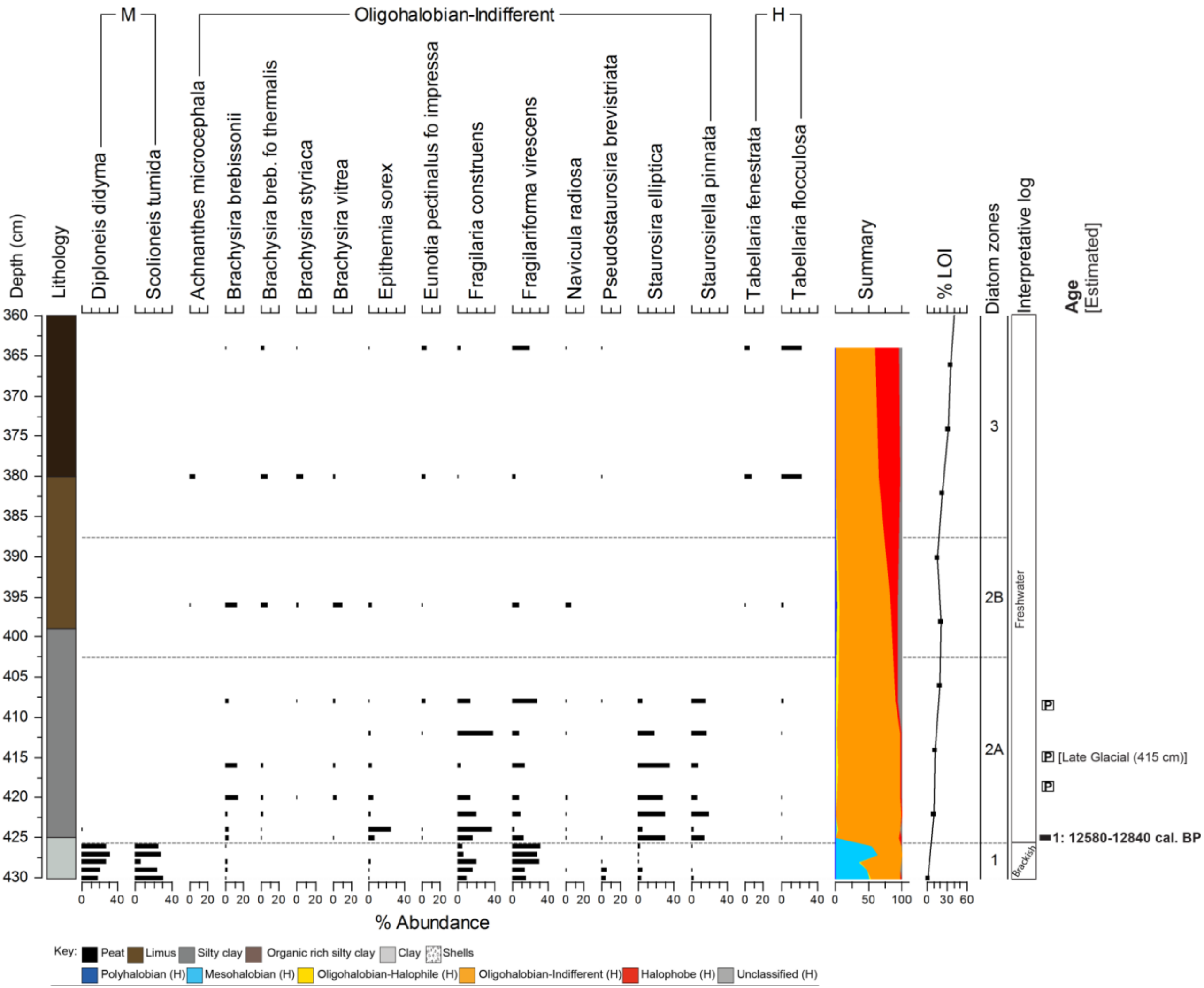

Figure 3: Summary diatom flora, lithostratigraphy and diatom assemblage (flora shown exceed 5 % of total valves counted) for Duart Bog (core DuB-13-3), illustrating the transition from brackish-dominant to freshwater conditions between zone 1 and 2A. The position and calibrated age of radiocarbon dates are shown as well as the age indicated by the supporting pollen analysis (shown by the P) (Figure 5).

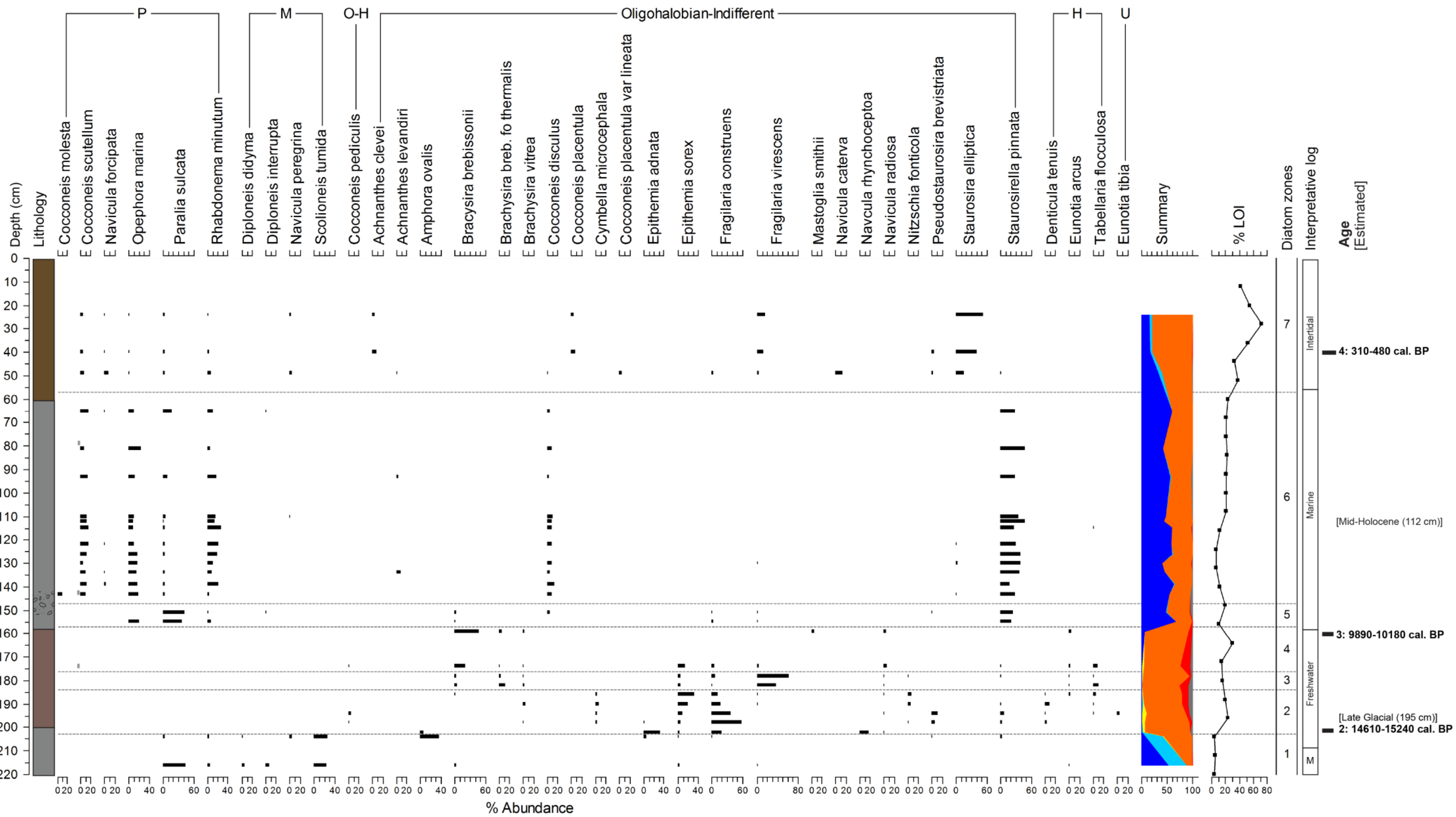

Figure 4: Summary diatom flora, lithostratigraphy (see Figure 3 for key), and diatom assemblage (flora shown exceed 5 % of total valves counted) for Loch Duart Marsh (core LDM-13-1), illustrating the transition from marine to freshwater conditions between zone 1 and 2 and zone 4 and 5. The position and calibrated age of radiocarbon dates are shown as well as the age indicated by the supporting pollen analysis (Supplementary Table 1).

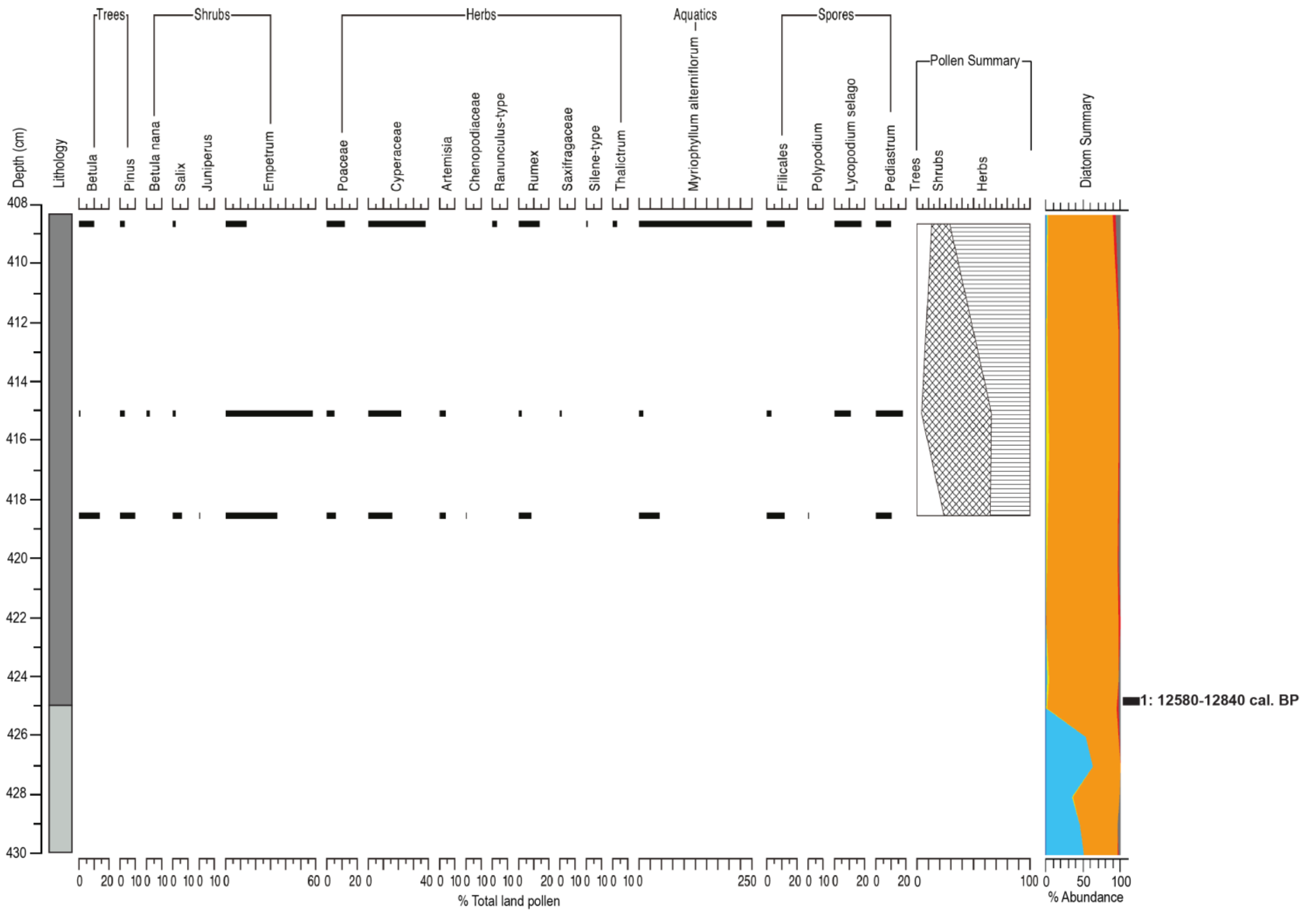

Figure 5: Summary pollen and diatom flora, lithostratigraphy (see Figure 3 for key), pollen assemblage and calibrated radiocarbon date for Duart Bog (core DuB-13-3).

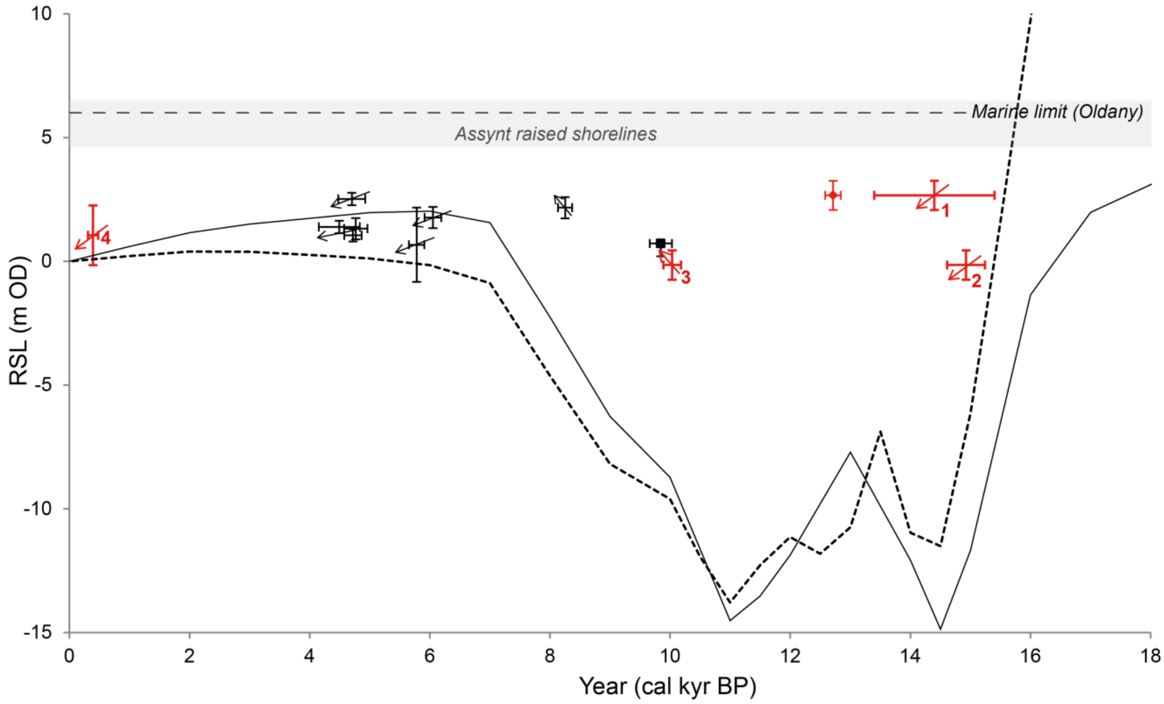

Figure 6: Bradley et al. (2011) (solid line) and Kuchar et al. (2012) (dashed line) model predictions for Assynt, including previous sea-level index points for the Assynt region from Coigach (Shennan et al. 2000), shown in black, and from Duart (this study), in red. Index point 1 (DuB-13-3) based on radiocarbon material is denoted by the red diamond symbol whilst limiting index points are denoted by a black square. The arrows indicate the positive or negative tendency associated with each sea-level index point; increasing arrow indicates RSL increase for example.

Late Glacial to Holocene relative sea level change in Assynt, northwest Scotland, UK

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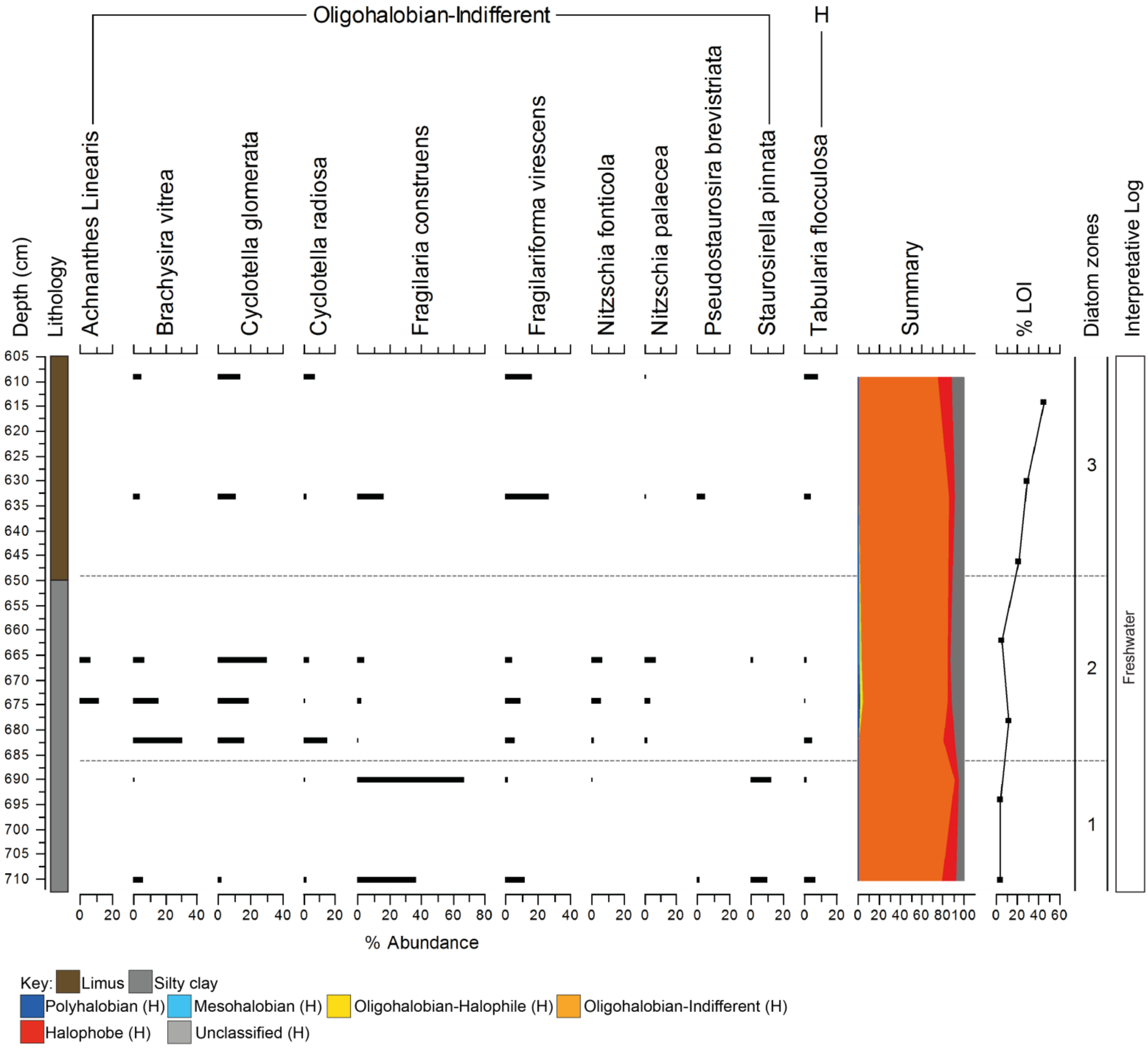
Supplementary Information

Supplementary Table 1	Qualitative pollen counts to support AMS ^{14}C radiocarbon dates from Loch Duart Marsh core (LDM-13-1).
Supplementary Figure 1	Summary diatom flora, lithostratigraphy and diatom assemblage (flora shown exceed 5 % of total valves counted) for Oldany, illustrating the freshwater conditions.
Supplementary Figure 2	Correlation of pollen zones at sites, including Duart, in northwest Scotland between the Late Glacial Interstadial and Early Holocene. Dominant pollen types are listed for each zone whilst those in brackets are less abundant, however characteristic of the zone. Calibrated radiocarbon dates are positioned at the appropriate zone boundary. Site locations are shown in the inset map.

Supplementary Table 1

Pollen	Depth (cm) 112	195
Land pollen		
Betula	27	0
Alnus	14	0
Quercus	3	0
Ulmus	1	0
Corylus	6	0
Pinus	1	0
Salix	1	0
Calluna	1	0
Cyperaceae	3	1
Poaceae	1	5
Cruciferae	1	1
Plantago maritima	7	7
Rumex	0	5
Artemisia	0	2
Empetrum	0	1
Labiatae	0	1
Equisetum	0	1
Algae and Freshwater Aquatics		
Pediastrum	0	21
Myriophyllum alterniflorum	0	130
Botryococcus	0	45
Debarya	0	1
Indicated Environment	Mid-Holocene wooded with saltmarsh indicators (coastal)	Lateglacial arctic tundra with open, cold water (deep pond)



Supplementary Figure 1

	Regional Interpretation	**Duart Bog**[1] This paper	**Lochan an Druim**[2] Birks (1984)	**Loch Sionascaig**[3] Pennington et al. (1972)	**Cam Loch**[4] Pennington (1975)	**Loch Borralan/Craggie**[5/6] Pennington et al. (1972)
Early Holocene	Expansion of locally present shrubs (e.g. *Empetrum*, *Juniperus*) together with an increase in Poaceae and herbs (e.g. *Filipendula*)		*Juniperus* *Empetrum* Poaceae **13535 ± 255 cal BP**	*Betula* Poaceae Polypodiaceae	*Juniperus* *Empetrum* Polypodiaceae	*Betula ? nana* Poaceae *Rumex*
Loch Lomond Stadial	Open grasses and sedge heaths dominated whilst *Artemisia* pollen was high in the region		Ericales undiff. Cyperaceae *Saxifraga opp./ S. aizoides*	*Empetrum* *Betula* (*Artemisia*) Compositae *Lycopodium selago*	*Empetrum* *Betula* *Artemisia* Poaceae **12355 ± 1195 cal BP**	Cyperaceae Poaceae *Artemisia*
Late Glacial Interstadial	Treeless dwarf-shrub heath, frequently dominated by *Empetrum* and sometimes *Juniperus*. Also associated with varying amounts of grasses, sedges and herb	*Empetrum* Cyperaceae	*Empetrum* Poaceae Cyperaceae	*Empetrum* Poaceae (Cyperaceae) (*Juniperus*) (*Betula*)	*Empetrum* Poaceae Cyperaceae (*Juniperus*) (*Betula*) **13870 ± 640 cal BP**	*Empetrum* Poaceae Cyperaceae Rumex (*Betula*)

Supplementary Figure 2