Local and Regional Constraints on Relative Sea-Level Changes in Southern Isle of Skye, Scotland, since the Last Glacial Maximum

Isle of Skye Relative Sea-Level Changes

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Abstract

New relative sea-level (RSL) data constrain the timing and magnitude of RSL changes in southern Isle of Skye following the Last Glacial Maximum (LGM). We identify a marine limit at ~23 m OD, indicating RSL ~20 m above present *c.* 15.1 ka. Isolation basin data, supported by terrestrial and marine limiting dates, record RSL fall to 11.59 m above present by *c.* 14.2 ka. This RSL fall occurs across the time of global Meltwater Pulse 1A, supporting recent research on the sources of ice melting. Our new data also help to resolve some of the chronological issues within the existing Isle of Skye RSL record and provide details of the sub-Arctic marine environment associated with the transition into Devensian Lateglacial climate at *c.* 14.5 k cal a BP, and the timing of changes in response to Loch Lomond Stadial climate. Glacio-isostatic adjustment (GIA) model predictions of RSL deviate from the RSL constraints and reflect uncertainties in local and global ice models used within the GIA models. An empirical RSL curve provides a target for future research to address.

Keywords

Relative sea level; Isolation basins; Glacio-isostatic adjustment; palaeoenvironment; Lateglacial

Introduction and Aims

Constraining local and regional relative sea-level (RSL) changes following the Last Glacial Maximum (LGM) is critical for three key reasons: (1) to help determine the dominant drivers of RSL changes (e.g. Shennan et al., 2005); (2) to inform patterns of local to regional deglaciation and refinement of global-scale ice, Earth rheology and glacio-isostatic adjustment (GIA) models (e.g. Bradley *et al*., 2011, 2016; Kuchar *et al*., 2012; Lambeck, 1995; Shennan *et al*., 2006a, 2006b); and (3) to understand environmental and coastal evolution (e.g. Selby and Smith 2007; Smith *et al*., 2019).

Scotland has significant records of Devensian glaciation (Ballantyne and Small, 2019; Clark *et al.*, 2012; 2018) and RSL change since the LGM (Smith *et al.,* 2018). Changes in RSL record the interplay of rising global eustatic sea level due to the melting of the last ice sheets, glacio- and hydro-isostatic adjustments of the solid Earth arising from the transfer of mass from the continents to the oceans, and the gravitational effects on the ocean surface due to the changes in the distribution of mass from all these processes. The British-Irish ice sheet was sufficiently large for GIA processes to produce vastly contrasting RSL changes at different locations around the coastline of Scotland, ranging from areas beneath the thickest ice experiencing net emergence since deglaciation to more peripheral areas experiencing net submergence (Figure 1). The spatially variable pattern of GIA across Scotland also reflects the influence of Fennoscandian Ice Sheet retreat in terms of both forebulge collapse and the gravitational effect on the global geoid (Lin *et al*., 2021; Peltier, 1998; Shennan *et al.* 2018).

Spatial disparity remains in the resolution of RSL records available across Scotland (Shennan *et al*., 2018; Smith *et al*., 2019). A few areas, those close to the centre of the British-Irish ice sheet yet ice-free before the end on the Dimlington Stadial, 15 ka, and not glaciated during Loch Lomond Stadial, have the potential to produce records of Late Quaternary RSL change that are amongst the longest in the world (Shennan *et al*., 2005). While most previous RSL work on the Isle of Skye covers the Devensian Lateglacial (14.7 to 11.7 ka) and Holocene period (Selby and Smith, 2016; 2007; Selby *et al*., 2000), two lines of evidence from the south of Skye show the potential to obtain a longer record of RSL change. The Strollamus moraine, dated 15.4 +/-1 ka (Bradwell et al., 2019; Small et al., 2012), is positioned close to a raised shoreline at ~23 m OD (Walker *et al*., 1988) and an isolation basin in the Broadford River catchment, Loch Cill Chriosd, records RSL fall during the Dimlington Stadial, although the age is equivocal due to a possible hardwater effect (Shennan *et al*., 2006b).

This study builds upon these data, with three main aims: 1) determine Dimlington Stadial and Lateglacial Interstadial RSL change in the Broadford River catchment, southern Skye; 2) combine the RSL evidence from Broadford River with sites across southern Skye to present a RSL reconstruction that addresses chronological limitations of the existing RSL record; and 3) examine the implications for the refinement of GIA models. In addressing these aims we assess the compatibility of our RSL interpretations and reconstructions with the evidence of other environmental changes. Finally, we suggest some areas of future work.

Context: RSL Changes in Western Scotland

Western Scotland has the longest high-resolution record of RSL change in the British Isles, produced from isolation basins and raised tidal marshes at Arisaig (Shennan *et al.*, 1993; 1994; 1999; 2000; 2005), ~20 km south of Skye (Figure 1). Isolation basins are bedrock depressions that due to RSL changes have been connected to, and isolated from, the sea, and can record multiple phases of RSL rise and fall (Long *et al.*, 2011; Shennan *et al*., 2005). The Arisaig record provides a critical test for GIA models, yet disparity between model predictions and RSL records remain at Arisaig and at sites across the wider region, indicating the need for continued refinement of the model parameters (Figure 1; Bradley *et al*., 2011; Kuchar *et al.*, 2012; Shennan *et al.*, 2018).

Early work on Skye mapped raised shorelines, indicating former periods of higher RSL (Richards, 1971), with Selby *et al.* (2000) providing the first radiocarbon-dated sea-level index points. Existing RSL constraints extend across the Devensian Lateglacial and Holocene periods, with the majority of constraints from southern Skye (Selby and Smith, 2007; 2016; Shennan *et al*. 2006b), and supported the development of regional shoreline isobase maps (Selby and Smith, 2007; 2016).

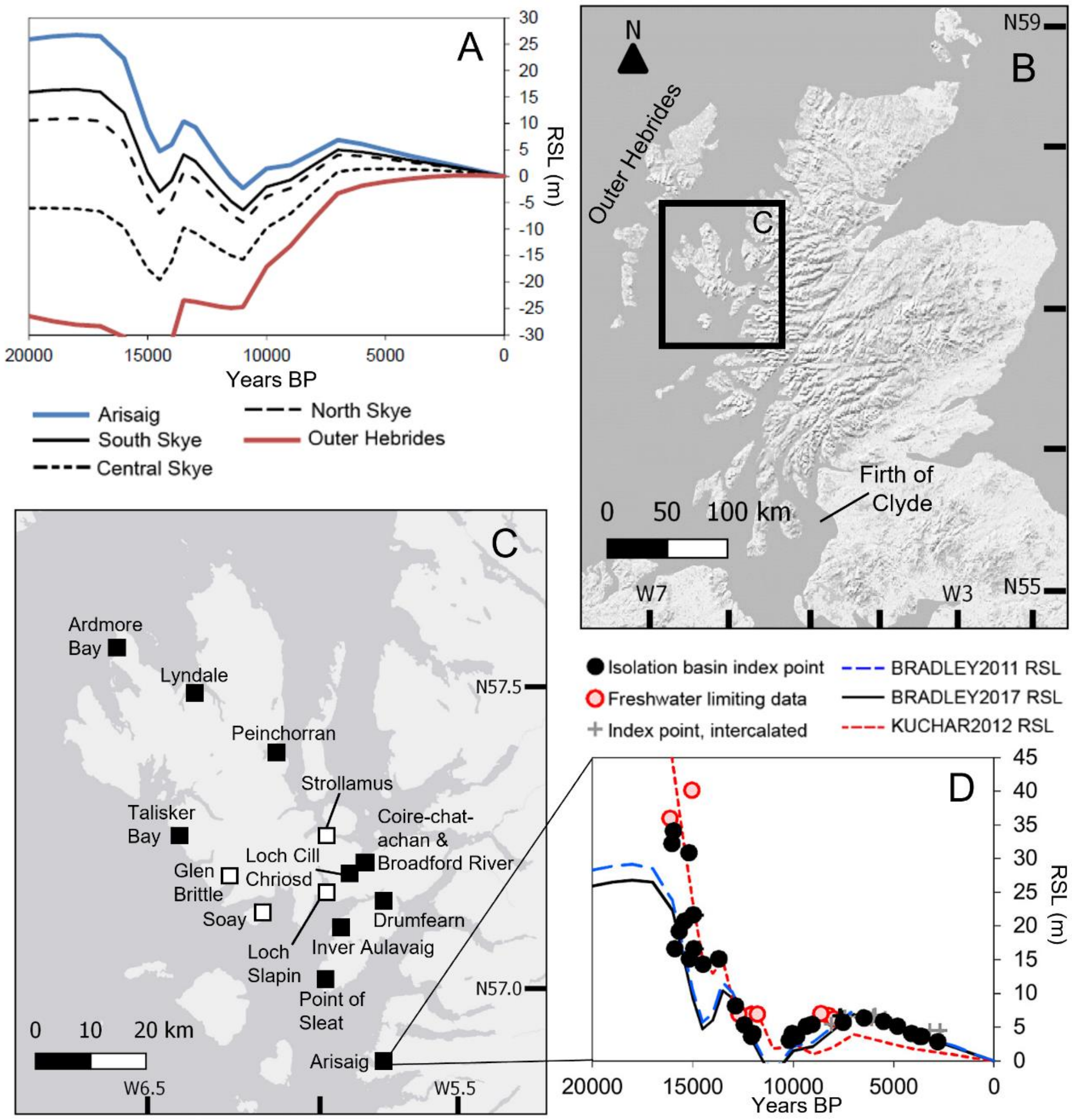

Figure 1 A) GIA model predictions of RSL for South-, Central- and Northern Skye, Arisaig and Outer Hebrides, based on the BRADLEY2017 model; B) map showing wider UK and Ireland context, denoting location of Firth of Clyde, Outer Hebrides island chain and Isle of Skye (C); C) Isle of Skye with locations mentioned in the text; black boxes indicate RSL study locations, and white boxes dated moraine deposits; and D) age elevation plot of sea-level index points, limiting data and RSL predictions for Arisaig, modified from Shennan et al. (2018); significantly, all the isolation basin index points 16-12ka BP record only RSL fall.

RSL changes following the LGM in western Scotland, including Skye, follow a similar pattern with differing magnitudes of change (Figure 1), reflecting increasing distance from the BIIS ice loading centre. Isolation basins at Arisaig record an initial fall of *c.* 30 m between *c.* 16-12 ka (Shennan *et al*., 1994; 2000; Figure 1). Following a minimum at *c.* 11 ka, RSL rises into the Holocene, reaching a mid-Holocene highstand, ~5 m above present at Arisaig, between *c.* 7-6 ka, then falling to present (Shennan *et al*., 2018; Smith *et al*., 2019; Figure 1). These RSL changes reflect the relative contributions of GIA and the global sea-level signal since the LGM. Evidence of RSL changes across western Scotland provides critical constraints on the magnitude, or presence, of the Meltwater Pulse 1A (MWP-1A) signal, as well as for deglaciation of distant ice sheets through the Lateglacial and Holocene, with distinct spatial variation in the magnitude of changes. Multiple models predict a sharp oscillation in

RSL *c.* 15-14 ka associated with MWP-1A, though no field evidence in northwest Scotland supports the predicted oscillation (Bradley *et al*., 2011; 2016; Kuchar *et al*., 2012; Shennan *et al*., 2018; Smith *et al*., 2019; Figure 1). The absence of this signal is important given that the source and magnitude of MWP-1A remains uncertain (Clark *et al*., 2002; Liu *et al*., 2016). A recently proposed solution for the absence of a MWP-1A RSL oscillation across NW Scotland is the inclusion of a significant Fennoscandinavian source for the melting ice during MWP-1A (Lin *et al.*, 2021).

Published and unpublished data from sites across southern Skye provide additional RSL and deglacial constraints (Figure 1, Table 1 and Table 2). These include a pollen record from Drumfearn, ~9 km south of Broadford (Madoc-Jones, 2014), and ^{10}Be and ^{36}Cl cosmogenic exposure ages from glacial moraines at Strollamus, Loch Slapin, Soay and Glen Brittle (Small *et al.*, 2012; 2016).

Table 1 Radiocarbon ages collected in this study. Ages calibrated as outlined in the methods with 2σ age uncertainty.

UCIAMS ID	Other ID	Material	^{14}C Age BP	^{14}C ±	Median Age (cal a BP)	Age Uncertainty a -	Age Uncertainty a +
208351	CCA17-6 378	Unidentified plant fragments	10460	60	12386	328	269
200638	CCA17-6 580	Unidentified plant fragments	11925	50	13790	184	227
208352	CCA17-6 582	Unidentified plant fragments	11380	210	13275	437	466
208222	CCA17-6 590	Shell fragments	12815	30	14394	254	351
200639	CCA17-6 605	Shell fragments	12820	35	14405	260	350
208392	CCA17-22 425	Unidentified plant fragments	11270	30	13151	53	85
219844	BR Bivalve	Shell	12905	35	14576	296	279
219843	BR Forams	Foraminifera	12875	35	14518	285	298
246215	LCC Marine	Foraminifera	13280	50	15142	234	244
246231	LCC Freshwater	Charophyte Seed Pods	13900	210	16857	609	560

Study Areas

The study area lies in the Broadford River catchment, in southern Skye, southwest of the town of Broadford and Broadford Bay (Figure 2). The local geology is predominantly sedimentary dolostone (Strath Suardal Formation), with igneous rocks to the north-west (Kilchrist Pyroclastic Rocks, Ben A Caillich Granite, Marsco Granite and Broadford Gabbro) and south-west (An Sithean Granite) (Ballantyne and Lowe, 2016). The Skye Eastern Red Hills include Beinn na Callich, 732 m OD, ~2 km from our sites, with the Loch Lomond Stadial (*c.* 12.9-11.7 ka) ice limits <1 km north of our sites. Coire Fearchair and Coire Gorm were both occupied by glaciers during the stadial (Figure 2; Bickerdike *et al*., 2018), evidenced by moraines, with the former also experiencing a significant Lateglacial rockfall or rockslide event (Ballantyne, 2013).

Table 2 RSL database for southern Skye. Table separated into those with ^{14}C dates and those with alternative dating methods. ^{14}C ages calibrated as outlined in the methods with 2σ age uncertainty; Strollamus age has 1σ uncertainty, as presented in Table 2. The indicative meanings (the position in relation to the tide level that a sample represents) for this study are assigned based upon the litho- and biostratigraphy, following Shennan et al. (2018).

Sample Code	Site	^{14}C Age BP	^{14}C Uncertainty ±	Median Age (cal a BP)	Age Uncertainty a -	Age Uncertainty a +	Sample elevation (m OD)	Vertical Error ± (m)	Sample indicative meaning	RSL (m)	Notes	Source
Be105028	Inver Aulavaig	3160	40	3386	131	70	5.1	1	Author defined RWL (m OD)	3.22	Isolation contact	Selby *et al.* 2000
Be92168	Inver Aulavaig	3280	60	3504	123	177	5.1	1	((HAT+MHWS)/2) - 0.2 m	2.72	Isolation contact	Selby *et al.* 2000
Be92170	Inver Aulavaig	8850	150	9918	372	317	5.1	1	MHWS	2.72	Isolation contact	Selby *et al.* 2000
Be105029	Inver Aulavaig	5440	50	6236	222	151	5.1	1	Author defined RWL (m OD)	3.22	Isolation contact	Selby *et al.* 2000
Be92166	Inver Aulavaig	7640	240	8480	512	605	5.1	1	Author defined RWL (m OD)	3.22	Isolation contact	Selby *et al.* 2000
Be113152	Inver Aulavaig	3070	60	3274	197	168	5.1	1	MHWS	2.72	Isolation contact	Selby *et al.* 2000
Be92167	Inver Aulavaig	12590	290	14861	986	933	5.1	1	MHWS	2.72	Isolation contact; possible hardwater effect	Selby *et al.* 2000
Be92169	Inver Aulavaig	10110	140	11700	456	746	5.1	1	Author defined RWL (m OD)	2.14	Terrestrial limiting	Selby *et al*. 2000
Beta93813b	Point of Sleat	2850	100	2986	228	249	4.13	0.6	MHWS	1.75	Isolation contact; possible hardwater effect	Selby & Smith 2007
Beta098612	Point of Sleat	3830	60	4236	221	179	4.13	0.6	MHWS	1.75	Isolation contact; possible hardwater effect	Selby & Smith 2007
Beta93990	Point of Sleat	12570	70	14930	480	273	4.13	1.34	(HAT-MTL)/2	2.51	Isolation contact; possible hardwater effect	Selby & Smith 2007
Beta098613	Point of Sleat	10460	50	12433	332	187	4.13	0.6	MHWS	1.75	Isolation contact; possible hardwater effect	Selby & Smith 2007
AA44938	Loch Cill Chriosd	15410	160	18703	422	272	19.5	0.71	MHWS	16.85	Isolation contact; possible hardwater effect	Shennan *et al.* 2006b
UCIAMS246231	Loch Cill Chriosd	13900	210	16857	609	560	19.5	0.71	HAT	16.22	Terrestrial limiting; possible hardwater effect	This study
UCIAMS246215	Loch Cill Chriosd	13280	50	15142	234	244	19.5	1	MHWN	18.25	Marine limiting	This study
UCIAMS208351	Upper CCA	10460	60	12386	328	269	14.24	0.41	HAT	10.96	Terrestrial limiting	This study
UCIAMS200638	Upper CCA	11925	50	13790	184	227	14.24	0.41	HAT	10.96	Terrestrial limiting	This study
UCIAMS208352	Upper CCA	11380	210	13275	437	466	14.24	0.41	HAT	10.96	Terrestrial limiting	This study
UCIAMS208392	Lower CCA	11270	30	13151	53	85	10.78	2	HAT	7.5	Terrestrial limiting; gravel barrier; RWL top of limus +/-2	This study
UCIAMS208222	Upper CCA	12815	30	14394	254	351	14.24	1	MHWN	12.99	Marine limiting	This study
UCIAMS200639	Upper CCA	12820	35	14405	260	350	14.24	1	MHWN	12.99	Marine limiting	This study
UCIAMS219844	Broadford River	12905	35	14576	296	279	1.78	2	MLWS	4.03	Marine Limiting	This study
UCIAMS219843	Broadford River	12875	35	14518	285	298	1.68	2	MLWS	3.93	Marine limiting	This study

Sample Code	Site	Median Age (a)	Age Uncertainty a -	Age Uncertainty a +	Sample elevation (m OD)	Vertical Error ± (m)	Sample indicative meaning	RSL (m)	Notes	Source
CCA17-6 Age Model	Upper CCA Isolation	14171	424	309	14.24	0.41	MHWS	11.59	Isolation contact; modelled age	This study
Drumfearn Pollen	Drumfearn	16000	2000	2000	23.53	0.4	HAT	20.25	Terrestrial limiting; estimated age based upon pollen analysis	Madoc-Jones 2004
STRmean	Strollamus	15400	1000	1000	23.25	1	HAT	19.97	Terrestrial limiting; raised shoreline estimated elevation and mean moraine cosmogenic exposure age	Walker *et al*. 1988; Small *et al*. 2012; Bradwell et al. 2019

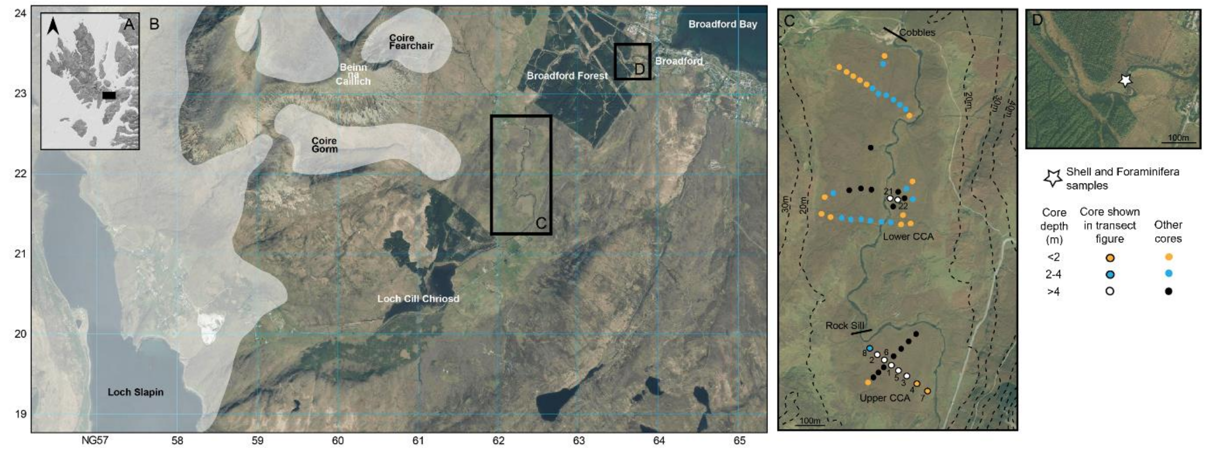

Figure 2 Study site overview A) location on Isle of Skye; B) study site locations (insets C and D), with former Loch Lomond Stadial ice extents shaded (Bickerdike et al., 2018); C) coring locations at Coire-chat-achan (Upper CCA and Lower CCA); and D) shell and foraminifera sampling location at Broadford River Section. Area shown in D lies below the 10 m OD contour. Cores shown in the transect (Figure 3) taken with a Russian corer, other cores with either a Russian or gouge corer. Aerial imagery © Getmapping Plc.

We identify two low lying (< 20 m OD) basins at Coire-chat-achan (CCA): Upper CCA and Lower CCA (Figure 2; NG6221 and NG6222), and sediment outcrops along the river and on the riverbed of the Broadford River (Broadford River Section) downstream from the basins, <10 m OD (Figure 2; NG 63 23). Upper CCA is immediately downstream of Loch Cill Chriosd, an isolation basin that records RSL at 16.85 m above present dated to c. 18.7 k cal a BP; however, this age is considered an overestimate due to a possible hardwater effect (Shennan *et al*., 2006b).

Following preliminary surveys, we collected a series of 10 Russian cores in September 2017 to provide a detailed stratigraphy of CCA, with sediment description following the Tröels-Smith (1955) scheme. In Upper CCA, the coring transect of 8 cores ran southeast to northwest across the peat bog; in Lower CCA, we collected 2 cores from the deepest part of the basin as revealed by preliminary surveys (Figure 2). We use a representative core from each basin, cores CCA17-6 and CCA17-22, for laboratory analysis. At the Broadford River Section we collected a sediment block for foraminiferal analysis and an exposed paired bivalve, in growth position, for dating. We surveyed the core locations, basin and sill morphologies, and outcrop elevations to Ordnance Datum Newlyn (m OD) using a Leica Automatic Optical Level and a Leica 1200 differential GPS in reference to an Ordnance Survey benchmark (NG62472138). The sill elevation includes a vertical levelling error for the minimum height identified.

An additional single core was collected from Loch Cill Chriosd (LCC19-01) in order to re-date the units thought to be impacted by a hardwater effect (Shennan *et al*., 2006b). We also dated material from the marine unit to minimise the hardwater effect. The isolation in LCC19-01 followed the biostratigraphy of Shennan *et al*. (2006b) (Table S1).

We use foraminifera to identify marine sedimentation (Edwards and Horton, 2006), and diatoms for the detailed identification of marine-, brackish- and freshwater conditions (Vos and De Wolf, 1988). We took subsamples throughout the cores in the laboratory for microfossil analysis, with subsequent higher resolution sampling across the identified diatomological isolation contact, the point at which the former sediment-water interface became fresh (Kjemperud, 1986). Foraminifera and diatom sample preparation followed standard methods (Palmer and Abbott, 1986; Scott and Medioli, 1980). We identified a minimum of 200 diatom valves, with taxonomy after Hartley et al. (1996) and classified species into salinity groups using the Halobian classification scheme (Hartley *et a*l., 1996; Vos and De

Wolf, 1988). Foraminifera were identified following Murray (1971; 1978) and Horton and Edwards (2006), with a minimum of 150 tests identified where possible.

Ten samples were submitted for radiocarbon analysis at the University of California Irvine Keck Carbon Cycle AMS Facility (Table 1). CCA17-6 605 and 590 ages came from shell fragments, and Broadford River Section ages from bivalve and foraminifera samples from the top of the sediment block. The remaining ages from CCA17-6 and CCA17-22 are from unidentified stem and leaf plant fragments, wet picked using a binocular microscope. Ages for sample CCA17-22 425 came from fine-grained organic material "floated" from the inorganic sediments in deionized water. Foraminifera were picked from the marine unit in LCC19-01, and charophyte seed pods from the post-isolation freshwater unit. Radiocarbon ages are calibrated using OxCal 4.4 (Bronk Ramsey, 2009), with the standard northern hemisphere atmospheric curve (IntCal20) for the plant samples and marine curve (Marine20) for the shell and foraminifera samples (Heaton *et al.*, 2020; Reimer *et al.*, 2020). Bayesian modelling, using the Sequence function in OxCal (Bronk Ramsey, 2008; 2009; Appendix S1), provides an age model for the isolation contact at CCA17-6.

Results

Coire-chat-achan (CCA)

The stratigraphy at Upper CCA reveals a basin upstream of a rock sill that outcrops in the bed of the Broadford River at NG62222171 at 14.24 +/- 0.05 m OD (Figures 2 and 3). The stratigraphy comprises a basal clay silt, overlain by ~1-1.5 m of clay silt containing shell fragments, then ~0.5 m of a slightly organic silt clay (Figure 3). This transitions into a laminated clay silt unit with occasional sand laminae 1-10 mm in thickness, which extends over 2 m thickness in some cores. Across most of the basin, this transitions into a ~1 m thick silty organic mud, overlain by ~2 m of herbaceous peat. Cores taken at the upstream end contain a unit of coarse silt sand with some gravel, which tapers towards the centre of the basin (Figure 3).

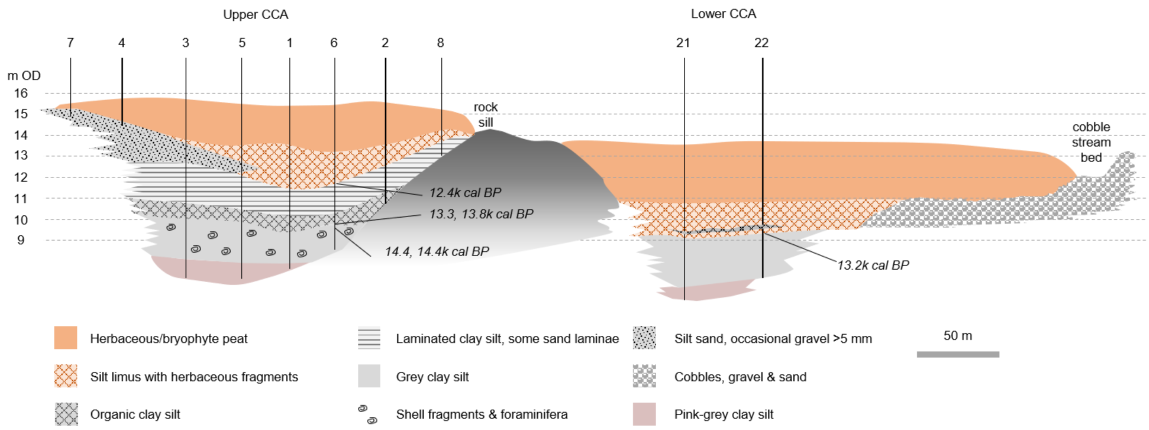

Figure 3 Simplified stratigraphic cross section across both basins with median calibrated ages (ka BP); core numbers as in Figure 2.

The lower clay silt unit contains small (<5 mm) shell fragments and calcareous foraminifera (Figure 4; Table S2). Low frequencies (≤5%) of marine diatom taxa only occur at the base of the grey clay unit (6.45 to 6.35 m), whilst foraminifera occur above this depth (Figure 4; Table S2 and S3). Fresh species dominate the diatom assemblages through the grey clay silt unit and the transition into the overlying silty organic mud, though brackish-fresh species occur in lower frequencies. The stratigraphic transition coincides with marked changes in the diatom flora, with increases in abundance of *Staurosira construens* and *Tabularia fasciculata*, with foraminifera becoming absent prior to this transition (Figure 4; Table S2 and S3). These changes indicate the diatomological and sedimentological isolation of the basin as marine water no longer crosses the sill

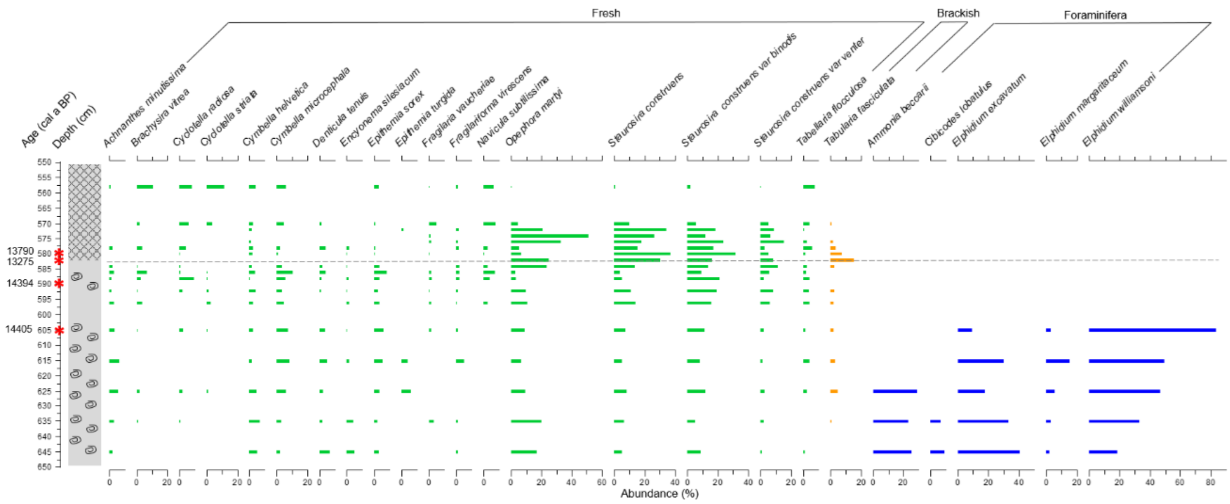

Figure 4 Litho- and biostratigraphy and ages for the lower part and isolation of core CCA17-6. Stratigraphy key follows that in Figure 3. Full radiocarbon age ranges in Table 1. Diatom and foraminifera species with abundance >5% shown.

Bayesian age modelling of five ages (Table 1), two from shell fragments below the isolation contact, two from organic material immediately above the isolation contact, and one from the organic limus directly above the laminated clay silt unit, provides a modelled age for the isolation of the basin, 14.2 ka (Figure 5; Table 1). The modelled ages display a good fit, despite the exception of UCIAMS208352, offering some confidence in the isolation age.

Lower CCA also has a basal clay silt unit, overlain by ~2 m of grey clay silt with some sand and occasional fine angular (<10 mm) gravel; this transitions into ~1.5 m of silty organic mud, then 2.5-3 m of herbaceous peat (Figure 3). In deeper parts of the basin, a <0.1 m thick organic clay silt unit occurs within the lower part of the silty organic mud. The northern part of Lower CCA shows only peat overlying a silt, sand and cobble unit, with cobbles exposed on the bed of the stream confluence; there is a distinct break in slope at the north and north-western edge of the basin, with a shift in surface elevation of up to 0.5 m (Figure 6). No sill for the basin was identified, and no shell fragments or foraminifera were identified within any of its units.

Broadford River Section

A dark grey clay silt, with broken and unbroken shells and calcareous foraminifera, occurs below the water level in the lower tract of the Broadford River. The river levee is at ~3.55 m OD, and the sediment surface in the base of the river, with the collected shell sample and sediment block, is 1.78 m OD. The ages from the bivalve and foraminifera are in close agreement (Table 1). The paired bivalve specimen

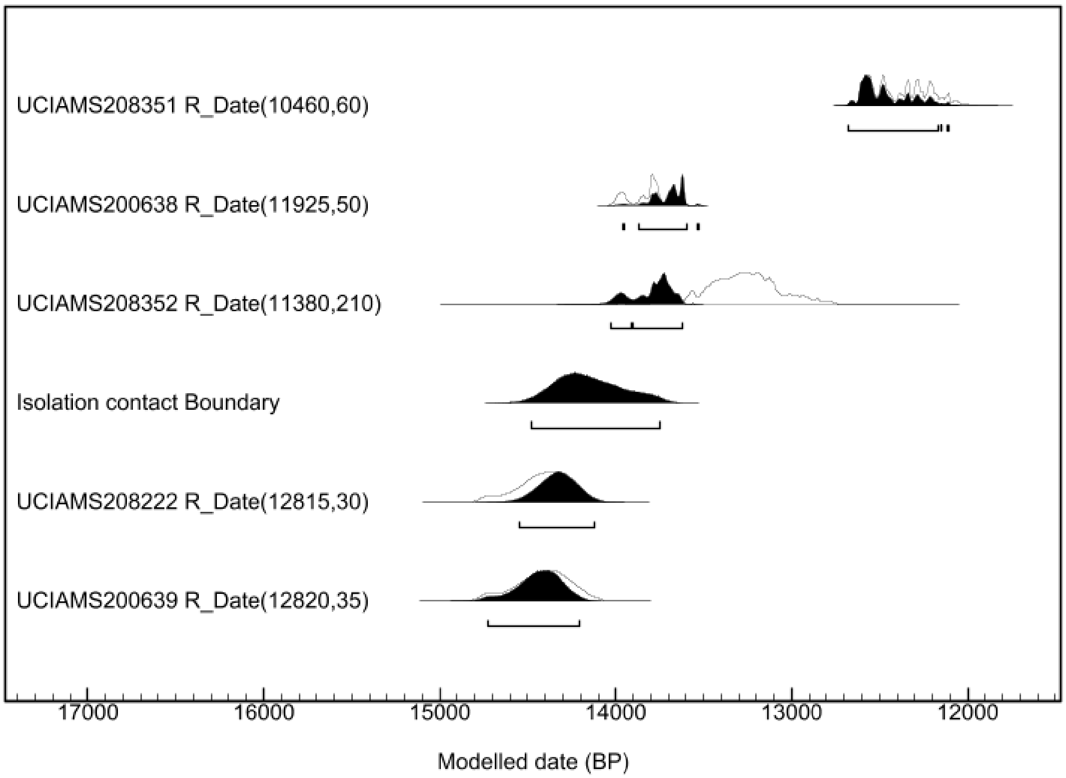

Figure 5 Age model for core CCA17-6, showing model input, calibrated radiocarbon ages (unshaded), probability density functions (shaded) and 95.4% ranges from Bayesian modelling for each sample and the isolation contact.

is *Arctica islandica* (Figure 7), and the top of the sediment block has abundant benthic foraminifera (Table S4), particularly *Elphidium excavatum* (21.4%) and *E. excavatum f. clavata* (33.3%).

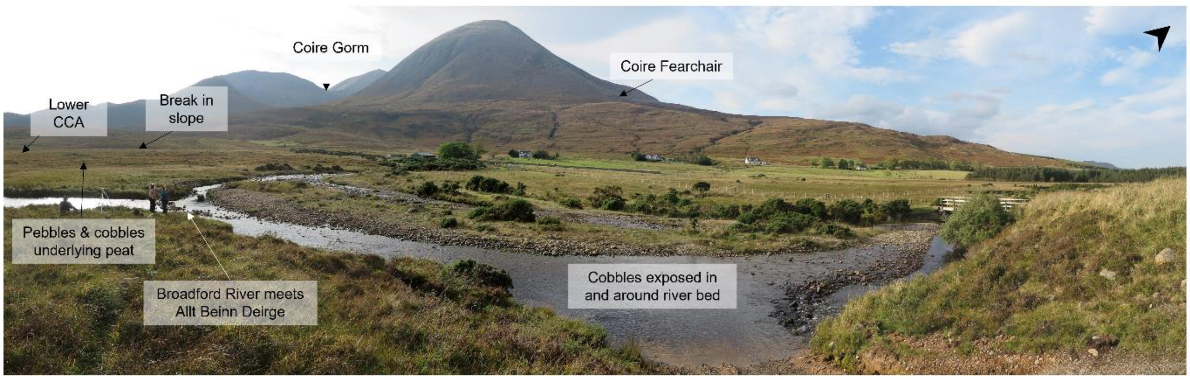

Figure 6 Cobble debris across the northern extent of Lower CCA, with some key features labelled. Image taken facing northwest at location of cobbles marked on Figure 2C.

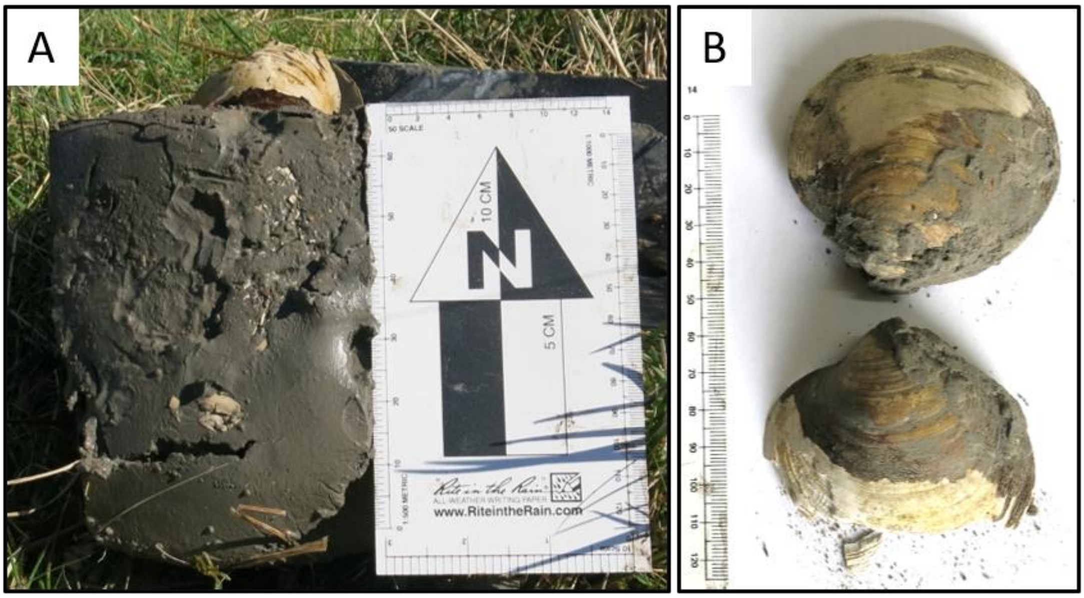

Figure 7 A) Sediment block retrieved from Broadford River Section, with paired bivalve specimen in situ; B) extracted bivalve specimen, Arctica islandica.

Discussion

Loch Lomond Stadial Environmental Change

Environmental change in response to Loch Lomond Stadial climate varies over short distances, from the growth and retreat of glaciers to changes in the type and amount of sediment movement and storage down a catchment, merging in some situations with records of RSL change. The presence of Loch Lomond Stadial glaciers has long been recognised on Skye (Ballantyne 1989; Bickerdike *et al*., 2018; Sissons, 1977) and beyond the ice limits the stadial typically appears as part of a distinct tripartite stratigraphy (Ballantyne *et al*., 2016; Lowe and Walker, 1977).

The Upper CCA sediments present a tripartite sequence, with the thick laminated silt-clay unit, associated with the Loch Lomond Stadial, between two more organic units, with isolation from the sea occurring well before the stadial (Figure 3 and 5). A similar sequence occurs upstream at Loch Cill Chriosd (Hunter, 2000; Shennan *et al.*, 2006b). In Lower CCA, the thin inorganic unit represents the Loch Lomond Stadial, with the underlying age of 13.2 k cal a BP corresponding to a pre-stadial age (Figure 3). The thin nature of this unit compared to Upper CCA and Loch Cill Chriosd is not unexpected given the downstream position in the catchment, with eroded clastic materials becoming trapped in the upstream basins. In Upper CCA, the transition from the Loch Lomond Stadial unit into increasingly organic material, at 12.4 k cal a BP, would appear to suggest an early climate amelioration prior to the rapid warming associated with the end of the stadial at 11.7 ka.

A debris fan extends across the northern portion of Lower CCA and covers any rock sill that may have controlled the seaward connection of the basin (Figures 3 and 6). Given the proximity to former LGM and Loch Lomond Stadial ice, this fan probably represents outwash from former glaciers within Coire Fearchair and Coire Gorm, and rock slope failures in Coire Fearchair, with exposure ages confirming the Loch Lomond Stadial age of the Coire Fearchair moraines (Figures 2 and 6; Ballantyne *et al*., 2016). The 12.4 k cal a BP age of post-Loch Lomond Stadial organic sedimentation in Upper CCA is consistent with the hypothesis of the surface exposure ages at Coire Fearchair representing a potentially early glacier retreat and rock slope failures occurring before glacier formation (Ballantyne *et al*., 2016).

However, the range limits of the ages obtained by both methods could support an alternative interpretation (i.e. established Loch Lomond Stadial termination chronology and rock slope failure during glacier expansion). Earlier termination of the Loch Lomond Stadial in Scotland has previously been suggested and challenged (*cf*. Bromley *et al*., 2014; Lowe *et al.*, 2019; Small and Fabel, 2016) and demonstrates the significance of continued research around the extent of the Loch Lomond Stadial in Scotland, not least to help test and reconcile discrepancies that exist between radiocarbon and cosmogenic exposure ages from the same locations (Bromley *et al*., 2014; Lowe *et al.*, 2019; Small and Fabel, 2016).

RSL change on the Isle of Skye since the LGM

Constraints on RSL change on Skye cover the period 18.7-3.0 k cal a BP, with the majority from isolation basins in southern locations (Figure 1, Table 2). Additional indicators of RSL change come from barrier systems in northern and central Skye (Peinchorran, Ardmore Bay, Lyndale, Talisker Bay; Selby and Smith, 2007; 2016). Due to differential GIA between sites across Skye (Figure 1), these central and northern sites are not incorporated into further discussion.

We now present a more refined record of RSL change since the LGM for southern Skye (Figure 8; Table 2). An infilled lake basin at ~24 m OD at Drumfearn provides an integral constraint (Madoc-Jones, 2014), with diatoms indicating freshwater conditions throughout, with no marine phase, providing a terrestrial limiting point. From the Loch Lomond Stadial tripartite stratigraphy and the pollen assemblages, we estimate an age of *c.* 16 +/- 2 ka. The Strollamus moraine, dated 15.4 +/-1 ka (Table 3; Bradwell et al., 2019; Small et al., 2012), is positioned close to a raised shoreline at ~23 m OD (Walker *et al*., 1988), and is used as a maximum age for the shoreline. Assuming the age of moraine deposition approximates the age of shoreline deposition, the Strollamus and Drumfearn sites provide a good constraint on the timing and altitude of the marine limit in southern Skye (Figure 8A).

Loch Cill Chriosd is the oldest and highest isolation basin on Skye, with RSL at 16.85 m above present. However, the age of c. 18.7 k cal a BP is considered to be an overestimate due to the calcareous bedrock geology in the catchment (Shennan *et al.*, 2006b). This suggestion seems reasonable when considered against the ages of deglacial features in southern Skye (Figure 8E; Table 3; Bradwell *et al*., 2019; Small *et al*., 2012; 2016). Indeed, our new marine limiting constraint for Loch Cill Chriosd indicates isolation must be younger than *c.* 15.1 k cal BP (Table 2; Figure 8A), suggesting the isolation age is overestimated by *c.* 3.5 ka. As the charophyte seed pods used to date the post-isolation unit (Table 1) demonstrate the hardwater effect, the marine limiting age is the most reliable age constraint for Loch Cill Chriosd as the mixing with marine water should minimise any hardwater effect.

The isolation sequence and rock sill at Upper CCA provide a sequence of constraints indicating RSL fall, with the isolation contact indicating RSL at 11.59 m modelled to 14.2 ka (Table 2; Figure 8A). The dominance of brackish-fresh diatom species in the lower silt-clay units, with minor presence of marine diatom flora, coinciding with the presence of calcareous foraminifera, suggests a salinity stratification of the water body prior to complete isolation (Figure 4). As marine influence becomes more restricted in an isolation basin, denser saline waters can become trapped, with freshwater input potentially maintaining a density gradient and reduced mixing of the water column, despite RSL exceeding the basin threshold (Balascio *et al.*, 2011).

Absence of an identifiable sill in Lower CCA prevents the determination of a precise isolation basin index point; instead, the age at the stratigraphic transition into limus provides a terrestrial limiting age, with RSL below the site at 13.2 k cal a BP (Table 2). Whilst the site must have been inundated by

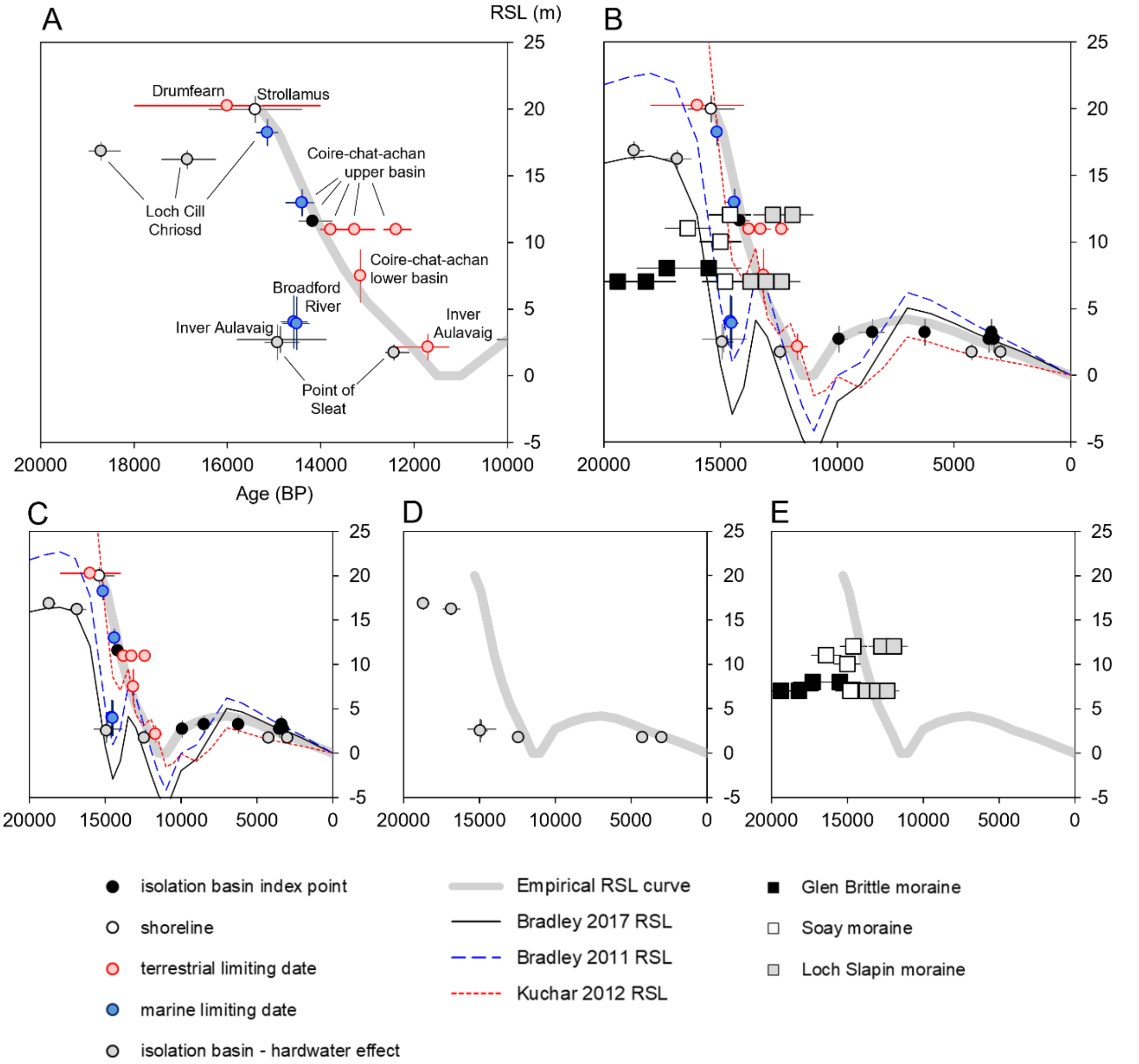

Figure 8 Age elevation plots of RSL and deglacial data for southern Skye: A) RSL data for the period 20-10 ka with locations labelled; B) all data combined; C) index points and RSL predictions; D) isolation index points with hardwater effects suggested by their original authors, and E) moraine ages.

the sea due to its lower elevation than Loch Cill Chriosd and Upper CCA, the presence of large cobbles and the debris fan probably buried any sill and/or blocked the drainage route (Figure 6).

Table 3 Published ^{10}Be and ^{36}Cl exposure ages from moraine deposits in the southern Skye (locations in Figure 1). Three Isle of Soay ages excluded by Small et al. (2016) are not included. Limiting RSL based on indicative meaning of (HAT+MHWS)/2.

Location	Sample	Elevation (m OD)	Age (a)	1 σ Age Uncertainty (±)	Source	Limiting RSL (m)
Glen Brittle	BRI01	10	18200	1300	Small et al 2016	7.04
Glen Brittle	BRI02	11	17300	1300	Small et al 2016	8.04
Glen Brittle	BRI03	10	19400	1700	Small et al 2016	7.04
Glen Brittle	BRI04	11	15500	1400	Small et al 2016	8.04
Isle of Soay	SOAY1	13	15000	900	Small et al 2016	10.04
Isle of Soay	SOAY2	14	16400	1000	Small et al 2016	11.04
Isle of Soay	SOAY6	10	14800	1000	Small et al 2016	7.04
Isle of Soay	SOAY7	15	14600	900	Small et al 2016	12.04
Loch Slapin	SLAP-1	10	13720	890	Ballantyne et al 2016 (recalculated from Small et al, 2012)	7.04
Loch Slapin	SLAP-2	10	13040	930	Ballantyne et al 2016 (recalculated from Small et al, 2012)	7.04
Loch Slapin	SLAP-3	10	12380	810	Ballantyne et al 2016 (recalculated from Small et al, 2012)	7.04
Loch Slapin	SLAP-4	15	12760	850	Ballantyne et al 2016 (recalculated from Small et al, 2012)	12.04
Loch Slapin	SLAP-5	15	11920	900	Ballantyne et al 2016 (recalculated from Small et al, 2012)	12.04

Around the time of Upper CCA isolation, marine limiting data from the Broadford River Section indicate RSL was above ~4 m at *c.* 14.5 k cal a BP (Figure 8A; Table 2). Abundant cold water foraminifera and *Arctica islandica* in the section indicate a shallow subtidal sub-Arctic environment. Similar sub-Arctic assemblages associated with the transition into the Devensian Lateglacial occur in offshore sediments around western Scotland (Peacock *et al*., 2012), with similar ages to that obtained at the Broadford River Section. The stratigraphies of the unit appear similar to the homogeneous marine clayey silt unit of the Clyde Beds identified at sites to the south near the Firth of Clyde (Figure 1), indicating a subtidal environment *c.* 14 ka (Peacock, 1999; Rose, 1980). *Arctica islandica* within the Clyde Beds indicates clearer waters following deglaciation (Peacock, 1981). The ages from Broadford River Section are consistent with the southern Skye deglacial chronology, being younger than the deglaciation ages at Strollamus, Glen Brittle and Soay (Figure 8). Marine sediments and the Clyde Beds provide important indicators of changing palaeo-climate and oceanography following deglaciation in Scotland (Peacock, 1989; 1996; 1999; Peacock *et al.*, 2012). The Broadford River Section site indicates the presence of an ice-free, sub-Arctic marine environment at the transition into the Devensian Lateglacial in southern Skye.

The Upper CCA and Broadford River Section data support the assertion that the ages from Inver Aulavaig and Point of Sleat are overestimates likely due to hardwater effects (Figure 8A; Selby, 2004; Selby and Smith, 2007; Selby *et al.*, 2000). The terrestrial limiting point from Lower CCA constrains the continuing RSL fall, below ~7.5 m at *c.* 13 k cal a BP. By *c.* 12 k cal a BP, an isolation basin and terrestrial limiting point provide similar elevations of RSL, ~2 m (Figure 8A). Despite a possible hardwater effect (Selby *et al.*, 2000), this isolation basin index point fits relatively well with the other constraints, and may not be a large overestimate.

We present a new empirical RSL reconstruction for southern Skye based upon the revised database (Figure 8). This reconstruction fits, within the 2σ error terms, all the sea-level index points from isolation basins and the shoreline at Strollamus, lies at or below all the terrestrial limiting data and at or above all the marine limiting data points. It indicates a late Dimlington Stadial RSL maximum ~20 m above present, and a continuous fall in RSL through the Devensian Lateglacial. There is no evidence of an oscillation in RSL associated with MWP-1A, supporting the recent work of Lin *et al.* (2021) calling for a significant Fennoscandinavian contribution to MWP-1A. These data have important implications for our understanding of RSL, MWP-1A, deglaciation and GIA across the region.

The elevation of RSL minimum shown 12 to 11 ka (Figure 8) is unconstrained by current data, whereas isolation basin data show a Holocene RSL highstand. The broad pattern is consistent with that from Arisaig, always at lower elevations (Figure 1), reflecting their positions with respect to the reconstructions of the British-Irish ice sheet (Clark *et al.*, 2012; 2018).

Local and Regional Constraints of Change: RSL, Deglaciation and GIA Predictions

Full understanding of the rate and magnitude of RSL changes requires integration of the local and regional evidence of environmental change, coastal landforms, RSL and deglaciation, and ultimately their incorporation into GIA models. For example, the marine limit indicating RSL ~20 m above present fits the constraints from Drumfearn and the Strollamus raised shoreline, and the deglaciation chronologies for both the Minch Ice Stream and the Hebrides Ice Stream (Bradwell *et al.*, 2019; 2021; Small *et al.*, 2012; 2016). In contrast, the previously established age for the isolation of Loch Cill Chriosd is not consistent with these constraints, with the new constraints suggesting it must be younger (Figure 8).

The RSL record indicates that Loch Slapin moraines were deposited at or above RSL while the Soay and Glen Brittle moraines were sub-tidal (Figure 8E). This has implications for the deglacial chronology, as those deposited sub-tidally would have underestimated ages. The role of coastal and oceanic forcing mechanisms on marine ice-sheet, ice stream and deglaciation dynamics are potentially significant to the BIIS (Chiverrell *et al*., 2013; Scourse *et al*., 2018; Small *et al*., 2016). A model of RSL and tidal amplitudes highlights the important potential contribution of these drivers to deglaciation in the western ice stream sectors of the BIIS (Scourse *et al.*, 2018). Such models, however, rely on GIA model predictions of RSL, and thus the need for local constraints to test the validity of GIA models remains.

Distinct differences between model predictions of former RSL and the geological evidence of RSL change in northwest Scotland are evident (Figures 1 and 8). The BRADLEY17 model predicts a lower magnitude Lateglacial RSL fall and MWP-1A oscillation than BRADLEY11, both of which differ from the KUCHAR12 model estimates (Bradley *et al.*, 2011; Kuchar *et al.*, 2012). The BRADLEY17 predictions follow the same Earth model parameters as BRADLEY11 but employ a higher grid resolution, resulting in lower RSL estimates for Skye (Figure 8). Kuchar *et al*. (2012), modifying the Bradley *et al*. (2011) GIA model with the Hubbard *et al*. (2009) numerical glaciological model, have thicker ice in Scotland than the BRADLEY11 model. The KUCHAR12 model predictions show a better fit with RSL observations 15-12 ka from Skye (Figure 8), Arisaig (Figure 1) and Assynt (Hamilton *et al*., 2015). The much higher predicted RSL pre-15 ka, with no index points in support, requires corroboration with evidence of local deglaciation of marine-based ice at the same time as the RSL constraints from index points and limiting dates at multiple locations, and remains a challenge for future research (Shennan *et al*., 2018).

The KUCHAR12 model performs less well than the other models for the Holocene (Figure 8). Given the similarity in the Earth and distant ice sheet models used across the different GIA models, the parameterisation of the local ice component, and resolution, is important for refining the RSL predictions, and reveals a strong dependency on the GIA models used (Hamilton *et al*., 2015; Shennan *et al*., 2018). At present, there is no unique model solution, whether at the scale of Skye, western Scotland or the whole of Britain and Ireland. Continued research into the RSL record and the extent, thickness and timing of glaciation and deglaciation on local and regional scales is therefore necessary. The continued contribution of findings from the BRITICE-CHRONO project will be significant in this regard (Bradwell *et al*., 2021; 2019; Clark *et al*., 2018; Small *et al*., 2017).

Evaluating the presence or absence of a MWP-1A signal in the region requires further empirical field data (Figure 8). The GIA models in Figure 8 have the same global ice models, so the source and magnitude of MWP-1A is critical. As debates continue on the source and magnitude of MWP-1A (Lin *et al.*, 2021; Liu *et al*., 2016) and global ice-volume equivalent sea level in the Lateglacial and Holocene (Bradley *et al.*, 2016; Simms et al., 2019; Yokoyama *et al.*, 2018), refinements in local ice models and RSL data from Scottish near-field locations provide critical constraints on global sea level, complementing evidence from far-field locations (Lin *et al.*, 2021; Shennan *et al.*, 2018). This applies equally to the Holocene, with misfits between RSL observations and model predictions for the early Holocene RSL rise, and the duration and height of the mid-Holocene highstand (Figure 8). These are not unique to Skye (Shennan *et al.*, 2018) and demonstrate the need for further work at near- and far-field locations to refine and model the contribution of different ice-sheets to global ice-volume equivalent sea-level change from the LGM to the late Holocene.

Conclusion

The data presented provide new insights into RSL changes in southern Skye since the LGM, and help to resolve some of the chronological issues within previous RSL records. We identify a marine limit indicating RSL ~20 m above present, though the age is rather poorly constrained based upon the 15.4 +/-1 ka age of the Strollamus moraine. New evidence, comprising isolation basins, marine and terrestrial limiting dates lead to a RSL curve for southern Skye which differs from all currently available GIA model predictions and provides a target for future research to address. The evidence for RSL at the time of MWP-1A shows no oscillation in RSL in contrast to several GIA models, adding support to the recent work of Lin et al. (2021) that proposes a significant Fennoscandinavian contribution to MWP-1A.

Despite the new evidence, several questions remain unanswered. We suggest that future work establishing RSL constraints from Skye could focus on three key areas: 1) an absolute age of the early deglacial marine limit at multiple sites; 2) the MWP-1A event, and 3) the timing and magnitude of early Holocene RSL changes. These areas will provide critical limits not only of RSL, but also constraints to validate GIA models, and insights into the defining parameters of models with local (e.g. ice thickness and deglacial chronology) to global (e.g. meltwater source) scale implications. As constraints of RSL and glacial extents and dynamics advance, further refinements in our understanding of changes since the LGM can be made.

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Supporting information:

Appendix S1 OxCal model specification used for the CCA17-6 age model

Table S1 Raw diatom counts for Loch Cill Chriosd core LCC19-01

Table S2 Raw foraminifera counts for Upper CCA core CCA17-6

Table S3 Raw diatom counts for Upper CCA core CCA17-6

Table S4 Raw foraminifera counts for Broadford River Section.