Postglacial relative sea-level changes in northwest Iceland: Evidence from isolation basins, coastal lowlands and raised shorelines

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Abstract Relative sea-level (RSL) data provide constraints on land uplift associated with former ice loading and can be used to differentiate between contrasting ice unloading scenarios. Isolation basin, coastal lowland and geomorphological evidence is employed to reconstruct RSL changes in northwest (NW) Iceland, which may have experienced contrasting uplift patterns. Under local (NW) uplift, highest RSL would be expected in central Vestfirðir, whereas highest RSL would be closest to the main ice-loading centre under regional (central Iceland) uplift. Four new RSL records are presented based on 16 sea-level index points and 4 limiting ages from sites principally focussed along a transect away from central Iceland. The new RSL records highlight spatial variability of Holocene RSL changes and provide constraints on deglaciation. There is an increase in marine limit elevation with proximity to the proposed principal ice loading centre in central Iceland. Highest recorded marine limit shorelines are found in Hrútafjörður-Heggstaðanes (southeast), the lowest in Hlöðuvík and Rekavík bak Látrum (north), and at an intermediate elevation in Reykjanes-Laugardalur (central Vestfirðir). Evidence from Breiðavik-Látrar records early rapid deglaciation in Breiðafjörður or a complex interplay of multiple uplift centres. RSL fell rapidly following deglaciation in several locations as a result of the quick response of the Icelandic lithosphere to unloading. The RSL data along the transect show an uplift pattern consistent with extensive regional glaciation emanating from central Iceland, which could have implications for ice sheet configuration and patterns of deglaciation, glacio-isostatic adjustment modelling and the volume of meltwater input into the North Atlantic.

Keywords

Holocene; sea level changes; Europe; Micropalaeontology, diatoms; isolation basin; Iceland

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1. Introduction

A range of evidence has been used to investigate the lateral and vertical extent of the Last Glacial Maximum (LGM) Icelandic Ice Sheet (IIS), including glacial geomorphology, striation mapping (e.g. Thorodssen, 1905-1906; Hoppe, 1968; 1982), sedimentology (e.g. Syvitski *et al.,* 1999; Andrews *et al*., 2000), seismic profiling (Egloff and Johnson, 1979), submerged feature mapping (Spagnolo and Clark, 2009), ice sheet modelling (Hubbard *et al*., 2006; Hubbard, 2006), marine limit mapping (Norðdahl and Pétursson, 2005; Norðdahl *et al*., 2008), and ocean coring (Andrews *et* al., 2000; Eiríksson *et al*. 2000). However, none of these methods have been able to unequivocally determine the most likely LGM ice loading scenario for Iceland. Relative sea-level studies have the potential to produce high-resolution data to identify the location and thickness of former ice loading through constraint of the marine limit, the establishment of deglacial timing and the patterns of Lateglacial to Holocene relative sea-level changes. In turn, these data act as important constraints for glacio-isostatic adjustment (GIA) models, which can further assist in the testing of ice loading hypotheses, lithospheric and mantle viscosity characteristics. This paper provides new relative sea level (RSL) data from northwest (NW) Iceland, which reflect post-(de)glacial loading and unloading of the crust as a result of near-equilibrium glacio-isostatic conditions during deglaciation (Norðdahl and Ingólfsson 2015). Establishing the lateral and vertical extents of the LGM IIS, associated ice volumes and patterns of deglaciation, is crucial, due to Iceland's location close to sensitive areas of deepwater formation in the Nordic Seas and northern North Atlantic (Dickson *et al*., 2002; Fig. 1).

Isolation basins have been used in a number of locations close to present and former ice sheets to develop records of RSL change, including e.g. in Antarctica (Watcham *et al.*, 2011), Canada (Hutchinson *et al.,* 2004; Smith *et al*, 2005), Finland (Eronen *et al*, 2001), Greenland (Long *et* al, 2011), Norway (Balascio *et al*, 2011), Russia (Corner *et al*, 1999), the UK (Shennan *et al*, 1994; Shennan *et al*, 1998) and Iceland (Rundgren *et al*, 1997; Lloyd *et al*, 2009). Isolation basins are rock depressions which have been connected to or isolated from the sea due to RSL changes across an impervious rock sill that controls tidal inundation (e.g. Lloyd and Evans, 2002, Long *et al*, 2011). A series of stages of basin isolation have been identified (e.g. Lloyd and Evans, 2002) and analysis of sediment and microfossil datasets allows the identification of three isolation contacts – diatomological, hydrological and sedimentological - which can subsequently be linked to positions within the tidal frame (Kjemperud, 1986). Radiocarbon dates at these isolation contacts provide constraints on the timing of RSL change and the resulting RSL curves may in turn determine patterns of postglacial land-level change (e.g. Long *et al*., 2011), allowing an assessment of former ice loading patterns.

Coastal lowlands are situated close to present sea-level and encompass the environment from mud flat to above high marsh conditions, and have the potential to record past RSL changes where sufficient accommodation space is available to record changes in environmental conditions. Coastal lowland environments may therefore encompass saltmarshes, which have previously been used in Iceland to reconstruct patterns of RSL change (e.g. Gehrels *et al*., 2006; Saher *et al*., 2015).

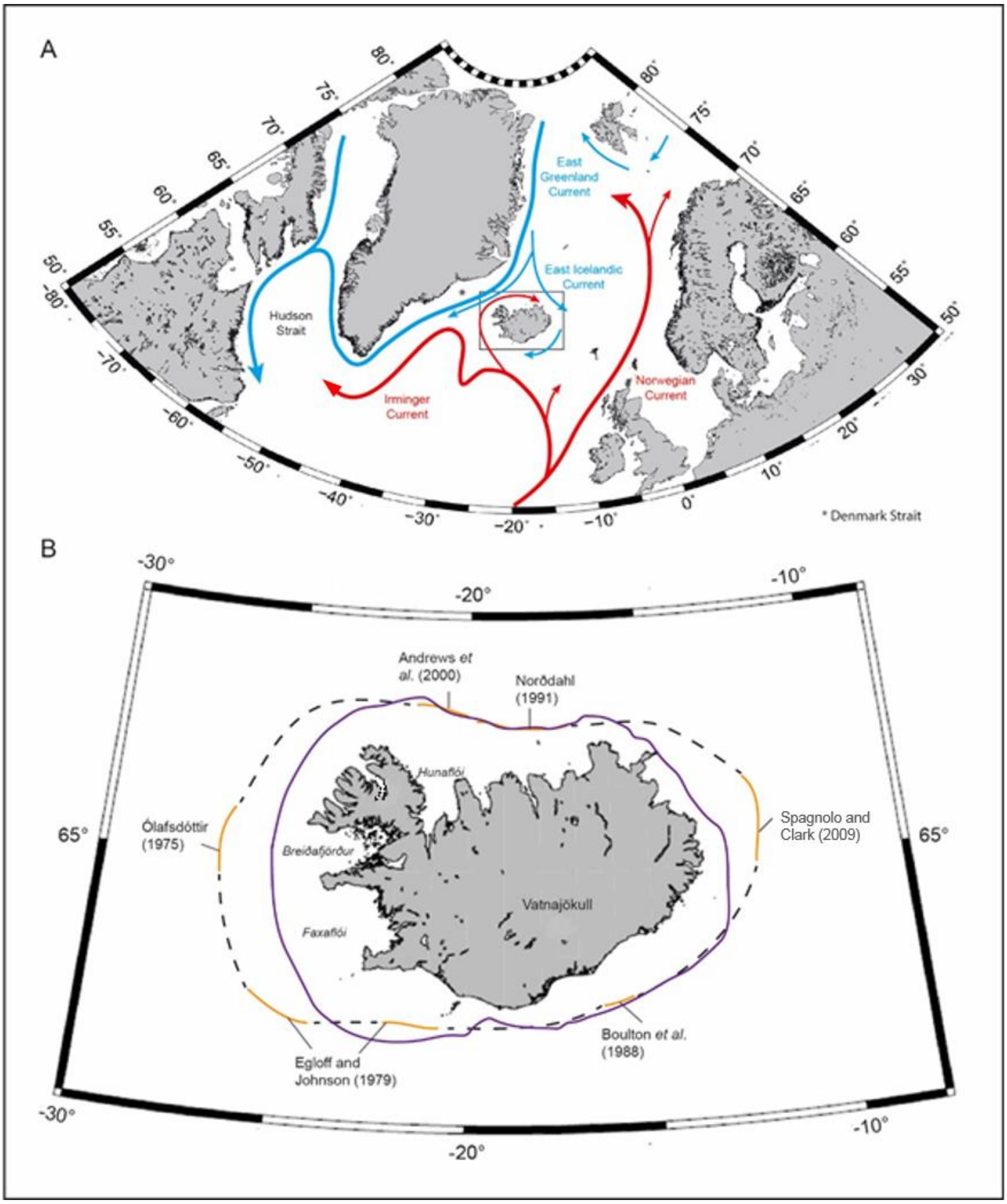

Figure 1: A: Current oceanic circulation patterns in the North Atlantic, highlighting Iceland's position close to several major currents. B: Field and modelling evidence for the lateral extent of the LGM IIS, including undated moraines (solid orange), diverse physical evidence (black dashed, Norðdahl and Pétursson, 2005, Norðdahl and Ingólfsson, 2015) and modelled extent (solid purple, Hubbard et al., 2006).

In this study, 16 new sea-level index points (SLIPs) are presented, based on diatomological, tephrochronological and radiocarbon analyses on isolation basin and coastal lowland sediments, which are combined with new and existing data derived from geomorphological indicators. The resulting new RSL curves allow an assessment of the spatial variability of former RSL in NW Iceland and thus the patterns of Lateglacial to Holocene ice loading in the region.

2. RSL change in Iceland

Until recently, RSL research in Iceland focussed on the investigation of the marine limit, which has been extensively surveyed (e.g. Ingólfsson, 1991; Norðdahl and Pétursson, 2005; Norðdahl *et al*., 2008). The marine limit is a raised shoreline which represents the highest point reached by post-deglacial RSL (Andrews, 1970) and thus varies in age and elevation due to differences in ice thickness and the style and timing of deglaciation (Ingólfsson, 1991; Jennings *et al*., 2000; Norðdahl and Ingólfsson, 2015). However, difficulties in determining the age of the marine limit in Iceland have been noted, which is key if marine limit records are to be employed as robust reconstructions of former RSL. In addition, marine limit datasets tend to produce single SLIPs, which are of limited value as constraints for glacio-isostatic adjustment models. Isolation basin studies have therefore provided additional constraints on proposed postglacial RSL changes in Iceland (Norðdahl and Pétursson, 2005; Pétursson *et al*., 2015). In the majority of cases, the principal benefit of isolation basin studies is the provision of a complete RSL curve for a location, which provides information regarding the tendency of RSL change, compared to individual SLIPs from raised shorelines. These records of RSL changes are particularly important as a test for glacio-isostatic adjustment (GIA) model outputs when exploring various ice loading scenarios (e.g. Hubbard *et al*., 2006; Patton *et al*., 2017).

Mapping of the marine limit has identified that the highest marine limits are present at Akrafjall and Stóri-Sandhóll, western Iceland, at 105 and 148 m a.s.l. (Ingólfsson and Norðdahl, 2001). Dating at Stóri-Sandhóll has revealed an age of 12,928 ± 95 ^{14}C a BP (uncalibrated; Ingólfsson and Norðdahl, 2001) or 14.7 cal. ka BP (Norðdahl and Ingólfsson, 2015). The high marine limit elevations in western Iceland are taken as evidence for rapid deglaciation (Ingólfsson and Norðdahl, 2001; Norðdahl and Ingólfsson, 2015). The pattern of marine limit elevation in NW Iceland is particularly complex, ranging from 14 m a.s.l. in northern Vestfirðir (Principato, 2008) to 85 and 95 m a.s.l. in the Breiðavík-Látrar area in the southwesternmost part of Vestfirðir (Norðdahl and Pétursson, 2005, Fig. 2).

Based on the existing data on raised marine shorelines in Iceland, Norðdahl and Pétursson (2005) were able to depict a pair of distinct and younger shorelines below the marine limit shoreline, dated to about 12.0 and 11.2 cal ka BP respectively, and both preceded by an increase in RSL (Norðdahl and Pétursson 2005; Pétursson *et al*. 2015). A number of lower-elevation raised shorelines have also been identified in Iceland, including the *Nucella* beach, which is characterised by '*Nucella'* shell deposits at ~4-5 m a.s.l. (Bárðarson, 1906, 1910a, 1910b). An estimated age for the formation of the '*Nucella* beach' in Hrútafjörður is ca. 4.5 cal. ka BP (Þórarinsson, 1956; John, 1974: John and Alexander, 1975; Hansom and Briggs, 1991), whereas Eiríksson *et al*. (1998) estimated its formation between ca. 3.2 and 5.7 cal. ka BP. In northern Vestfirðir, Principato (2008) suggested an age of ca. 3 cal. ka BP for the 5 m beach and in southern Iceland Símonarson and Leifsdóttir (2002) dated the 6 m beach there between 2.3 and 2.9 cal. ka BP (original dates; 2625 ± 40 and 3145 ± 35 ^{14}C a BP). These dates provide constraints on late Holocene RSL change in Iceland.

More recently, isolation basin studies have been completed in Iceland to produce comprehensive records of postglacial RSL changes (Rundgren *et al*., 1997; Lloyd *et al*., 2009; Brader *et al*., 2015). The first isolation basin study was undertaken on the Skagi peninsula (Rundgren *et al*., 1997), where a fall in RSL of 45 m between 13 cal. ka BP and 10.2 cal. ka BP is reported, during which there were two marine transgressions of around 5 m amplitude up to Younger Dryas and Preboreal shorelines. Isolation basin and raised shoreline evidence in southern Vestfirðir (Lloyd *et al*., 2009) and northern Snæfellsnes (Brader *et al*., 2015) have provided an insight into RSL changes on the northern and southern shorelines of Breiðafjörður, western Iceland. Lloyd *et al*. (2009) identified the local marine limit at 80 m a.s.l. (with raised shorelines between 84 and 98 m a.s.l.) and demonstrated a continuous RSL fall from ca. 14 cal. ka BP (estimated date from highest basin, 12,185 ± 100 ^{14}C a BP) to the early Holocene in southern Vestfirðir. Initial rates of RSL fall were high with a notable reduction in the rate of RSL fall during this period (Lloyd *et al*., 2009), with an intermediate elevation shoreline between 41 and 51 m a.s.l. dated to between 11.1 and 13.2 cal. ka BP. Lloyd *et al*. (2009) highlight the potential for a RSL rise during the Younger Dryas in southern Vestfirðir, although additional data are required to further test this hypothesis. An increase in RSL in Allerød/Younger Dryas times has been demonstrated in other parts of Iceland (Rundgren *et al*., 1997; Norðdahl and Pétursson, 2005; Norðdahl and Ingólfsson, 2015). Lloyd *et al*. (2009) also provide the first isolation basin evidence for a late-Holocene highstand in Iceland, which has been seen elsewhere through '*Nucella* beach' deposits.

In contrast to southern Vestfirðir, the marine limit in northern Snæfellsnes is identified as 65 – 69 m a.s.l. and limited influence of Younger Dryas ice re-advance is evident within the RSL record there (Brader *et al*., 2015). In Snæfellsnes, RSL fell below present sea level at ca. 10 cal. ka BP, occurring a few centuries later than in south west Iceland (>10.5 cal. ka BP; Ingólfsson *et al*., 1995) and Skagi (>10.2 cal. ka BP; Rundgren *et al*., 1997). There is however a clear contrast in the patterns of RSL changes over relatively short distances within the region, likely as a consequence of differences in lithospheric characteristics, the area available for ice accumulation, pattern and style of deglaciation and age of the elevated shorelines (Ingólfsson and Norðdahl, 2001; Norðdahl and Pétursson, 2005; Brader *et al*., 2015; Norðdahl and Ingólfsson, 2015).

Late Holocene saltmarsh studies have been undertaken at Viðarhólmi, Snæfellsnes, western Iceland in order to investigate more recent RSL changes (Gehrels *et al*., 2006; Saher *et al*., 2015). The diatom record from Viðarhólmi highlights variability in the patterns of recent RSL changes, possibly as a result of changes in the North Atlantic Oscillation (NAO; Saher *et al*., 2015). Deeper coring at the site also generated a series of basal SLIPs for the late Holocene (Gehrels *et al*., 2006).

In addition to terrestrial records of RSL change, additional research has been undertaken using marine records to constrain the RSL fall below present sea level in the early Holocene, including seismic profiling (e.g. Thors and Boulton, 1991), records of submerged peat (e.g. Ingólfsson *et al*., 1995) and marine core analysis (e.g. Quillman *et al*., 2010). At present, there remains uncertainty over the scale of the proposed early Holocene RSL lowstand, due to methodological limitations, conflicts between evidence from different sources and poor spatial coverage. It is important to establish the timing and magnitude of any RSL lowstand, as data constraining RSL change will be important for the testing of GIA models in Iceland. New data from marine environments, which could be combined with the new terrestrial evidence from isolation basins, coastal lowlands and raised shorelines, would better constrain this RSL lowstand and in turn allow further testing of contrasting uplift scenarios.

3. Study area

The present study is based on data collected from a number of locations on the Vestfirðir Peninsula (NW Iceland) (Fig. 2). South of the study area is the Snæfellsnes Peninsula, which is dominated by the ice-capped Snæfellsjökull Volcanic System and forms the southern coastline of Breiðafjörður. East of the study area is the Skagi Peninsula, a large peninsula in North Iceland characterized by a number of lake basins at its northernmost point (Rundgren *et al*., 1997). The peninsula forms the eastern coastline of Húnaflói, a major fjord system in North Iceland. Drangajökull glacier is situated in northern Vestfirðir. The research locations explored within this study are situated on the Vestfirðir Peninsula: Hlöðuvík and Rekavík bak Látrum (5 sites); Reykjanes-Laugardalur in Ísafjarðardjúp (10 sites); and Breiðavík-Látrar (1 site; Fig. 2). Hrútafjörður-Heggstaðanes forms the southeasternmost section of the study area (8 sites; Fig. 2).

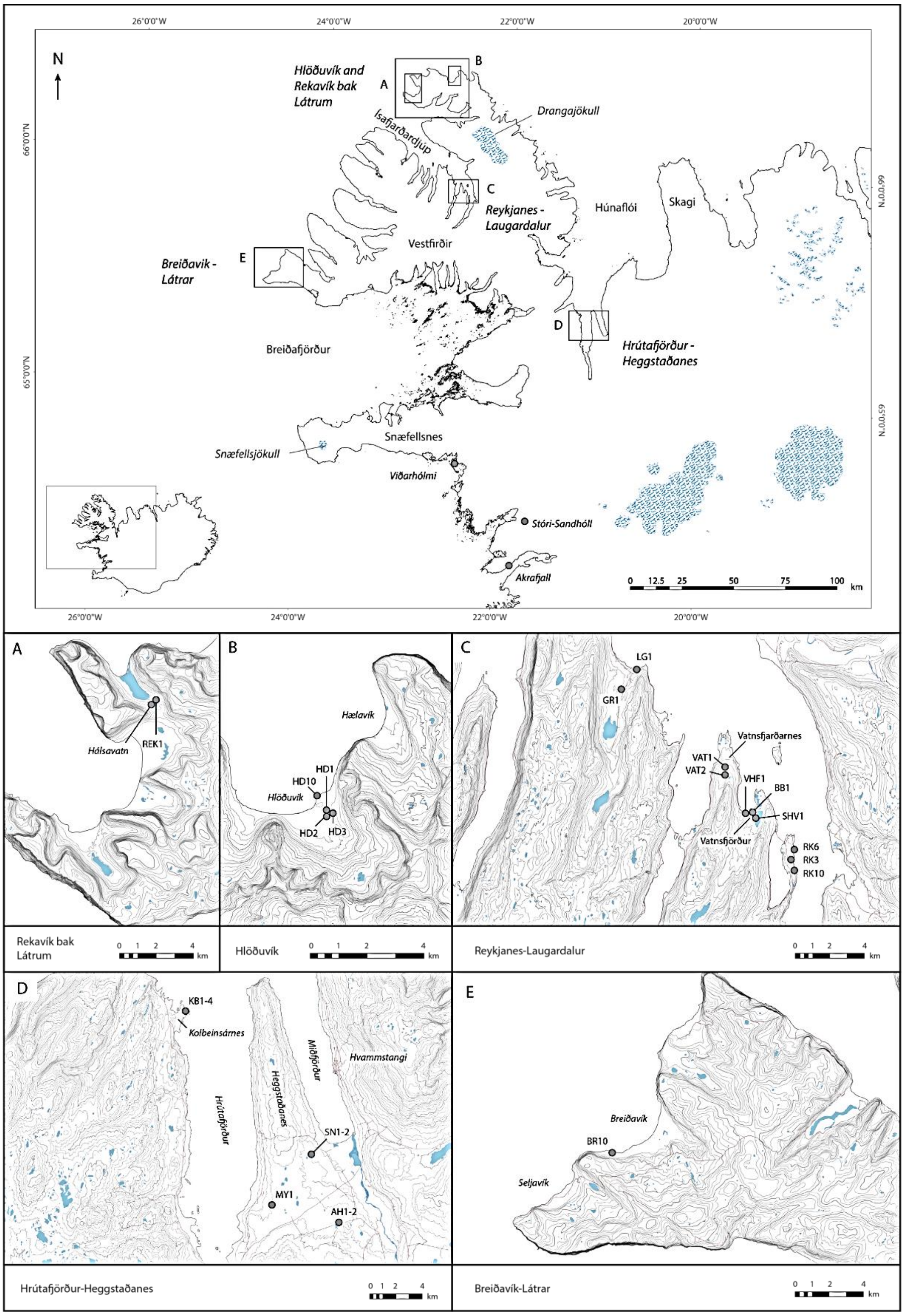

Figure 2: Study area in NW Iceland, highlighting the key research locations – A: Rekavík bak Látrum, B- Hlöðuvík, C - Reykjanes-Laugardalur, D – Hrútafjörður-Heggstaðanes, E – Breiðavík-Látrar - and sites mentioned in the text. Blue hashed areas – current glaciers, light blue – lakes. Base Map – Based on data from National Land Survey of Iceland.

4. Methods

4.1 Site Selection

The sites were chosen to exploit RSL changes across a potential former ice loading centre above Vestfirðir. The sites in Hlöðuvík and Rekavík bak Látrum, Reykjanes-Laugardalur and Hrútafjörður-Heggstaðanes form the research transect, with secondary sites at Breiðavík and Látrar at the mouth of Breiðafjörður.

Figure 3 illustrates the hypothesised patterns of RSL change at the three main sites along the transect under two glacio-isostatic uplift scenarios. Under a regional uplift scenario, with ice loading emanating from central Iceland (black line, Fig. 3), it is proposed that the marine limit elevation would increase with proximity to the former centre of unloading (and therefore uplift) in central Iceland. Alternatively, the highest marine limit elevation would be found in Reykjanes-Laugardalur under a local uplift scenario (grey dashed line, Fig. 3), due to a centre of localised ice unloading in NW Iceland.

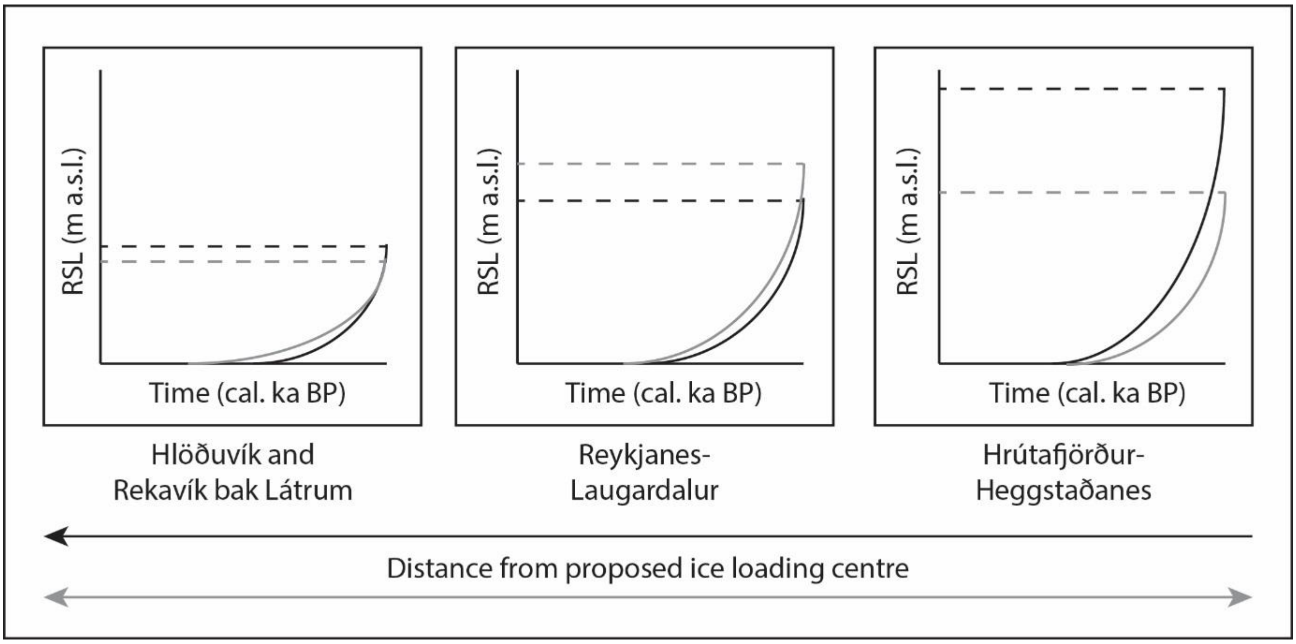

Figure 3: Hypothesised patterns of RSL change if the centre of uplift was situated in central Iceland or if there was a local centre of uplift in central Vestfirðir in each of the principal research locations – Hlöðuvík and Rekavík bak Látrum, Reykjanes-Laugardalur, and Hrútafjörður-Heggstaðanes – in northwestern Iceland. Under the central Iceland scenario (black), distance from the loading centre increases leftward, whereas distance from the loading centre increases away from Reykjanes-Laugardalur under the local scenario (grey dash). The hypothesized marine limit is denoted by the dashed lines.

4.2 RSL reconstruction

In order to assess patterns of RSL change in NW Iceland, we collected isolation basin and coastal lowland sediment samples from the marine limit to present sea level in each of the four field locations. The isolation basins were selected using the criteria outlined by Long *et al.* (2011), ensuring a suitable size (<1 km^2), depth (<10 m) and spacing of sites in each research location (see Long *et al*. (2011) for further information). Where the basin sill was covered by overlying sediments, a grid of cores established the lowest high point in the underlying bedrock. The elevation of the isolation basin sill was measured relative to mean high water spring tide (MHWST) in the field using an Electronic Distance Meter (EDM; ± 0.1 m) and subsequently corrected to mean sea level (MSL or m a.s.l.) using tide tables for the nearest tide station (Admiralty Tide Tables, 2006).

The stratigraphy of each isolation basin was established by coring perpendicular transects with a gouge corer from infilled sections or from the rear of a boat when a lake was present. Samples extracted were described using the Troels-Smith (1955) classification scheme. Following initial survey, a core was extracted from the deepest point along the transect using a Russian corer (Jowsey, 1966).

Diatom preparation followed the standard procedures outlined by Palmer and Abbott (1986) and diatoms were classified using a range of sources (e.g. Brun, 1965; Foged, 1974; Hartley, 1996). A minimum of 300 diatoms were counted per sample and subsequently grouped by halobian classification (Hustedt, 1957) as follows: polyhalobian (marine), mesohalobian (brackish), halophilous (salt tolerant), oligohalobous – indifferent (freshwater) and halophobous (salt intolerant). Summary diatom figures are given in the main text with full diatom assemblage graphs provided within Supplementary Information. Diatom zones are based on changes in taxa composition within individual assemblages. Microfossil analyses of isolation basin sediment sequences can allow the identification of three isolation contacts - the diatomological, hydrological and sedimentological contacts (Kjemperud, 1986) - which can be related to key positions within the tidal frame. Mean High Water Spring Tide (MHWST) is frequently used for the diatomological isolation contact (Long *et al*., 2011), which is characterised by predominantly freshwater conditions with a minor brackish element. The hydrological isolation contact represents entirely freshwater conditions and equates to Highest Astronomical Tide (HAT).

Chronological control of isolation contacts was established with a combination of radiocarbon and tephra analyses. Due to a lack of macrofossil material, the accelerator mass spectroscopy (AMS) radiocarbon dates were based on bulk organic sediment samples in close proximity to the isolation contact and were analysed at the NERC Radiocarbon Facility (NRCF). Tephra samples were analysed at the Tephra Analytical Unit, School of GeoSciences, University of Edinburgh using a Cameca SX100 electron microprobe. Details of the tephra analytical conditions can be found in Supplementary Information. Both radiocarbon and tephra samples underwent an acid pre-treatment prior to analysis. Radiocarbon dates are calibrated with the Radiocarbon Calibration Program (CALIB) Rev. 7.1 html (Stuiver and Reimer, 1993) with the IntCal13 data set for terrestrial material (Reimer *et al*., 2013).

In order to establish the elevation of former RSL, a correction is required based on the indicative meaning of the dated point in the diatom assemblage (see Shennan *et al*., 2015), with the error comprised of elevation uncertainty, sill determination uncertainty and the indicative range of the assemblage. Establishment of a series of SLIPs for each research location has allowed the production of a series of new RSL curves for NW Iceland. Full details of site stratigraphies, diatom assemblages and tephra geochemical results are presented as Supplementary Information.

5. Results - New sea-level index points for NW Iceland

Results of stratigraphic, diatom and chronological analyses are divided into the four principal geographical locations investigated as part of this research (Fig. 2). In total, 16 new SLIPs and 4 limiting points have been generated for NW Iceland.

5.1 Hlöðuvík and Rekavík bak Látrum (Area A and B (Fig 2); five sites)

Four lake basins and one raised shoreline were surveyed in Rekavík bak Látrum and Hlöðuvík (Fig. 2A and B). The majority of these sites are found in Hlöðuvík, where the marine limit can be traced across the mouth of the valley at about 15 m a.s.l. and at ~ 26 m a.s.l. in nearby Hælavík (Hjort *et al.*, 1985). One basin was also surveyed in Rekavík bak Látrum, close to the local marine limit at 15-25 m a.s.l. (Hjort *et al*., 1985). Sections 5.1.1 to 5.1.5 provide an overview of the stratigraphy and diatom assemblage for each site, with information for each location summarised in Fig. 4.

5.1.1 Hlöðuvík 3 (HD3) - 66°24.965' N, 22°38.857' W - Sill Elevation: 18.01 ± 0.30 m a.s.l.

HD3 is the lowest basin sampled in Hlöðuvík (Fig. 2B). The stratigraphy is characterised by a basal tephra deposit overlain by olive green limus, sandy gravel and uppermost turfa peat, with a visible tephra at the base of the analysed core (Fig. 4). Geochemical analysis of a dark grey/black tephra deposit allows identification as being part of the Saksunarvatn sequence of tephras (Fig. 5). It is now apparent that there were multiple eruptions of Grímsvötn between 9.9 cal ka BP and 10.4 cal ka BP (Jennings et al., 2014), with up to 7 eruptions responsible for tephra deposits heading north and west of Grímsvötn onto the north Iceland and SE Greenland shelves. Three of these have major element characteristics which are indistinguishable from the Saksunarvatn tephra dated to approximately 10.2 ka (Jennings et al., 2014; Lohne et al., 2014). The oldest and thickest of these has been dated to around 10380 cal BP (10284–10501 cal BP) by Kristjánsdóttir et al. (2007) and Jennings et al. (2014) suggest that a correlation to the 10252-10342 cal BP ice-core dated 'Saksunarvatn' tephra (Rasmussen et al., 2007) is likely, but cannot be confirmed. It is likely that the 'Saksunarvatn' tephra found in our cores correlates with this too, but again cannot be confirmed. Diatom analysis shows freshwater conditions dominate at the site, suggesting that RSL was lower than the sill elevation at 10.2 cal. ka BP. This also acts as a limiting age for marine limit formation.

5.1.2 Hlöðuvík 2 (HD2) - 66°25.156' N, 22°38.846' W – Sill Elevation: 18.13 ± 0.30 m a.s.l.

HD2 is a small basin situated west of HD3 (Fig. 2B). The site stratigraphy is comprised of a basal silt, overlain by olive-green limus and turfa peats. No tephra deposits were found at the site. The diatom assemblage for HD2 is dominated by freshwater conditions (Fig. 4) suggesting that the site was situated above the influence of marine conditions and thus the site acts as a limiting elevation for postglacial RSL at the location.

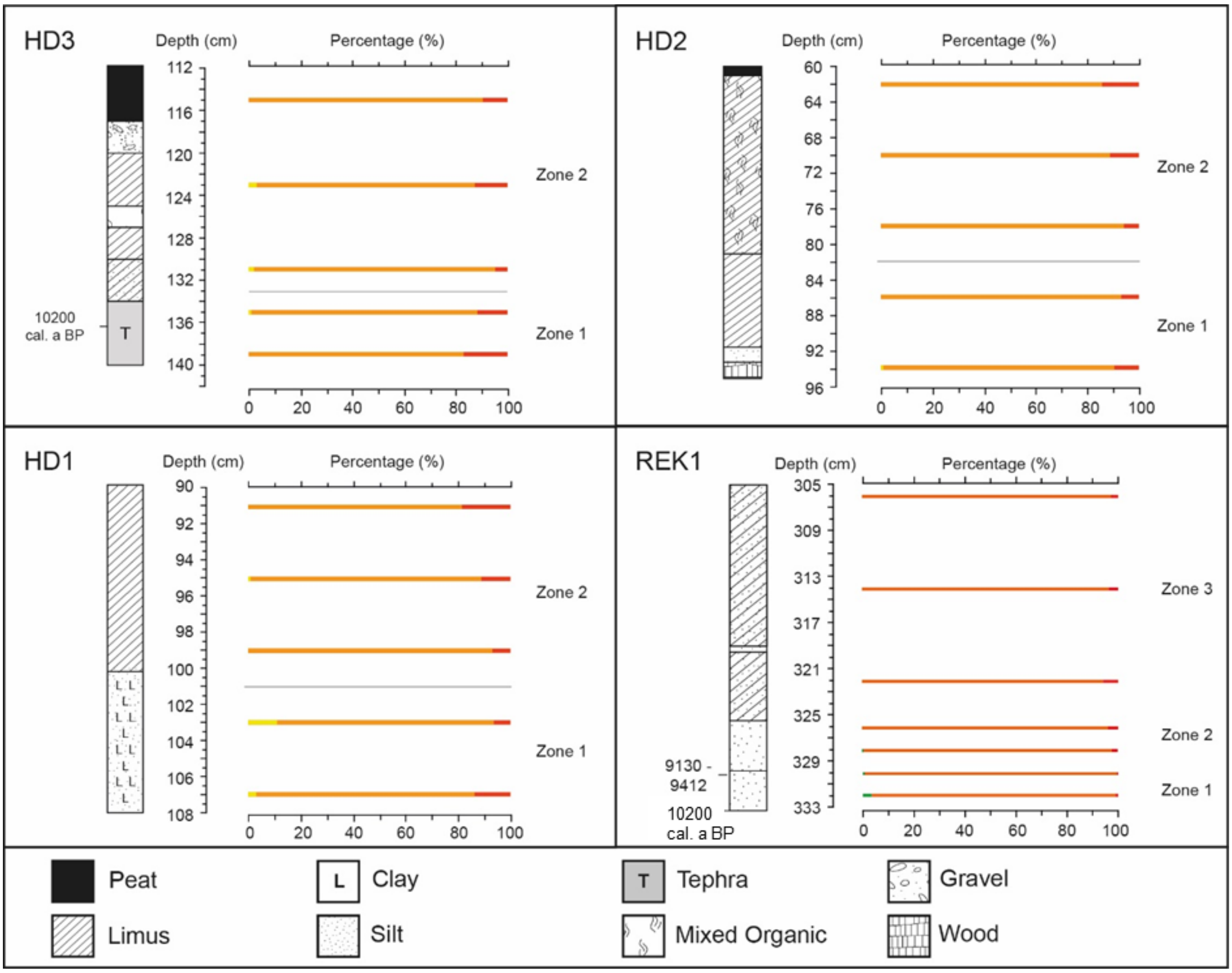

Figure 4: Summary diatom assemblages and stratigraphic profiles for sites in Hlöðuvík and Rekavík bak Látrum showing the key environmental changes recorded in each location: HD3 – Hlöðuvík 3, HD2 – Hlöðuvík 2, HD1 – Hlöðuvík 1 and REK1 – Rekavík bak Látrum 1. Diatoms are grouped by salinity: blue – marine, green – brackish, yellow – salt tolerant, orange – freshwater, red – salt intolerant. Full diatom assemblages and core stratigraphies are provided in Supplementary Information.

5.1.3 Hlöðuvík 1 (HD1) - 66°25.142’ N, 22°38.776’ W – Sill Elevation: 18.71 ± 0.30 m a.s.l.

HD1 is a small but the uppermost basin in Hlöðuvík (Fig. 2B). The site stratigraphy is characterised by a basal blue-grey clay overlain by olive-green limus. Above this layer, an organic rich layer is evident, covered by turfa peat. The diatom assemblage is dominated by freshwater taxa (Fig. 4) and therefore the site acts as a limiting elevation for former RSL.

5.1.4 Hlöðuvík Raised Shoreline (HD10) - 66°25.354’ N, 22°38.857’ W – Sill Elevation: 17.48 ± 1.00 m a.s.l.

The raised shoreline in Hlöðuvík was surveyed using an EDM in order to establish the highest postglacial RSL in the region (Fig. 2B). Surveying established the minimum elevation of the marine limit at ~18 m a.s.l., just above the value reported by Hjort *et al*. (1985, 10-15 m a.s.l.). The raised beach is characterised by a lower till deposit, overlain by marine sediments, with a subsequent upper till. There was a lack of dateable material within the proposed 'marine' sediments, meaning that it has not been possible to establish an accurate chronology for this feature. However, the discovery of the Saksunarvatn tephra (10.2 cal. ka BP) in the basins above the marine limit acts as a limiting age for feature formation.

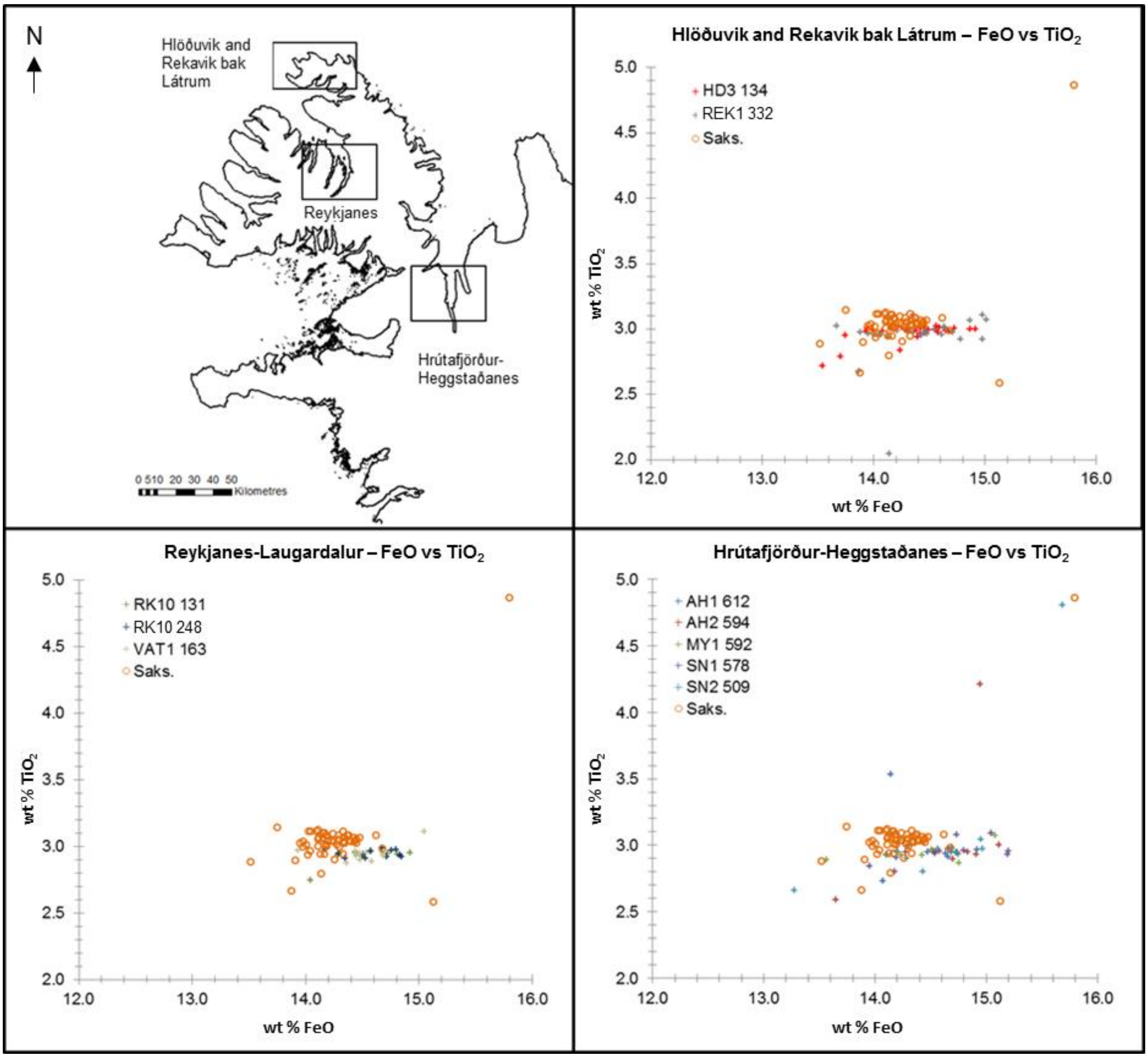

Figure 5: Geochemical results of tephra analyses on samples from Hlöðuvík and Rekavík bak Látrum, Reykjanes-Laugardalur and Hrútafjörður-Heggstaðanes. Samples are plotted against Saksunarvatn geochemistries (orange circles) sourced from Tephrabase (2015).

5.1.5 Rekavík bak Látrum (REK1) - 66°24.500' N, 23°0.441' W – Sill Elevation: 18.63 ± 0.30 m a.s.l.

REK1 is situated aside a kettle-hole lake (Hálsavatn) in Rekavík bak Látrum and represents the westernmost field site in the region (Fig. 2A). The site stratigraphy is comprised of a basal tephra-rich gravel overlain by clay rich silts, silty limus and an uppermost organic rich limus (Fig. 4). The Saksunarvatn tephra was identified at the base of the core following geochemical analysis of a black tephra deposit (10.2 cal. ka BP; Fig. 5). There is a clear dominance of freshwater conditions at the site, but the occurrence of limited numbers of brackish taxa suggests occasional inundation by highest times or storm events at the base of the core. A radiocarbon sample at 330 cm produced an age of isolation of 9130 – 9412 (9.2 k) cal. a BP (Table 1), which provides a limiting (minimum) age for marine limit formation in the region.

5.1.6 RSL curve for Hlöðuvík and Rekavík bak Látrum

The results from Hlöðuvík and Rekavík bak Látrum provide one new SLIP and one limiting point for postglacial RSL in the region (Table 1; Fig. 6). Due to the geomorphology of the region, there are limited locations with sufficient coastal lowlands to produce a large number of SLIPs. However, these new data provide valuable constraint on RSL change for the location, which is situated at the northwesternmost point of the principal research transect.

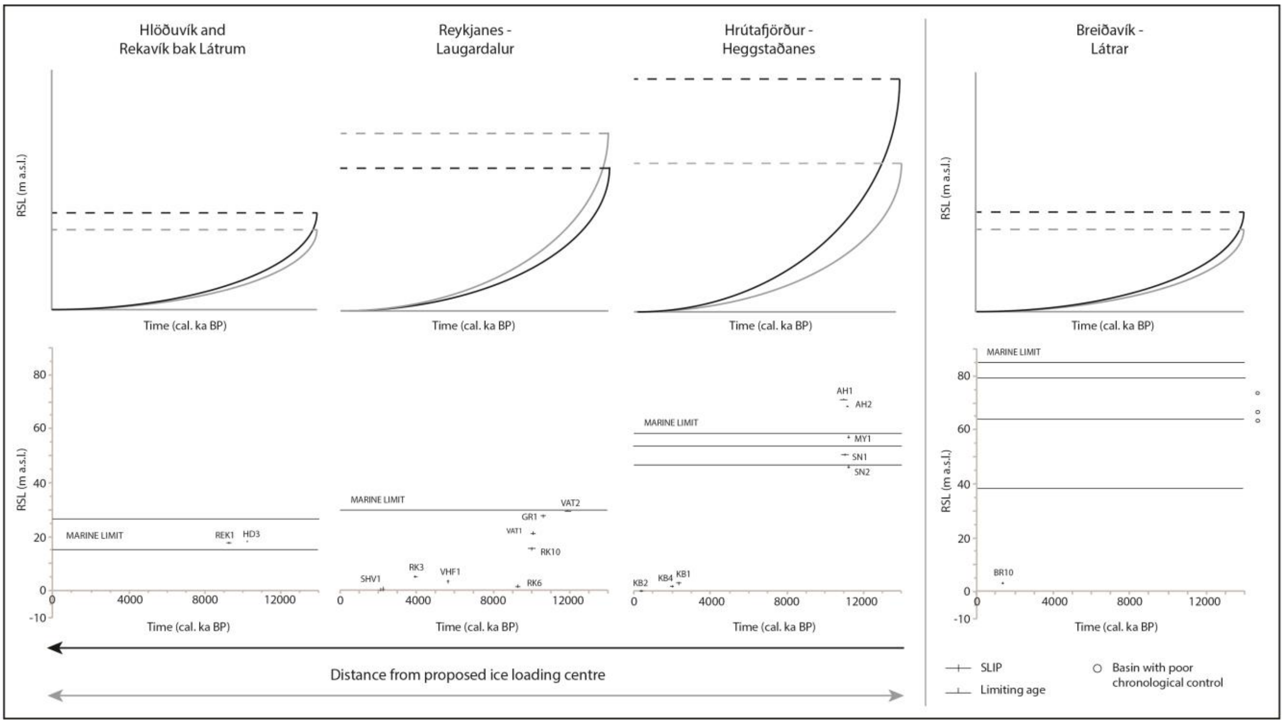

Figure 6: Hypothesised and reconstructed RSL curves for NW Iceland, based on new and existing data from the region. Hypothesised RSL curves are based on Figure 3, with grey representing localised uplift and black representing the central uplift scenario. The hypothesised RSL curve for Breiðavík-Látrar is based on its position at an extreme terrestrial location from the principal uplift centre in central Iceland. Reconstructed RSL curves are plotted along the principal research transect in NW Iceland - Hlöðuvík and Rekavík bak Látrum (NW), Reykjanes-Laugardalur (central) and Hrútafjörður-Heggstaðanes (SE) - with Breiðavík-Látrar (SW) plotted separately.

5.2 Reykjanes-Laugardalur (Area C (Fig. 2); 10 sites)

Ten sites in the Reykjanes-Laugardalur area were investigated from the marine limit to present sea level. Reykjanes-Laugardalur represents the centre-point for the research transect to evaluate contrasting glacio-isostatic uplift scenarios due to different uplift centres (Fig. 3).

5.2.1 Bólvík (BB1) - 65°56.392' N, 22°29.029' W – Sample Elevation: -0.50 ± 0.25 m a.s.l.

BB1 is a small embayment close to the farm at Vatnsfjörður, (Fig. 2C). A sample comprising basal gravel rich silt, overlain by a gravel rich turfa peat and uppermost gravel rich silt layer was collected close to the present beach (Fig. 7). Diatom analysis reveals marine dominance in the lowermost unit, with a limited (~20%) freshwater component to the diatom assemblage. Within the turfa peat, freshwater influence increases with a minor brackish component. Diatom preservation in the uppermost sediment unit was poor and provided insufficient numbers for a reliable sample for analysis. A radiocarbon date from the turfa peat (bulk sample) returned a 'modern' age for the deposit (Table 1).

5.2.2 Sveinhúsavatn (SHV1) - 65°56.210' N, 22°28.193' W – Sill Elevation: 1.24 ± 0.30 m a.s.l.

SHV1 is a relatively large lake basin close to the farm at Vatnsfjörður (Fig. 2C). The site stratigraphy comprises sandy silts with distinct shell layers. The diatom assemblage can be divided into eight distinct zones, showing the transition from brackish-marine to brackish-freshwater dominance at the site, which is still connected to the sea at present. A series of tephra layers are found through the sediment profile, which underwent geochemical analysis (Fig. 7; Anderson, personal communication, 2016). The tephra layers at 270 cm, 215 cm and 165 cm were identified respectively as the Landnám layer (the Settlement Layer) 877AD (1073 cal. a BP), Eldgjá 939AD (1011 cal. a BP) (*cf*. Schmid *et al*., 2016) and Hekla 1693AD (257 cal. a BP) tephras (*cf*. Brynjólfsson *et al*. 2015). In addition, two radiocarbon samples were analysed from 218 cm (1996 - 2299 (2.1 k) cal. a BP) and 228 cm (2158 – 2349 (2.25 k) cal. a BP), establishing a chronology for the site. Two SLIPs were generated providing constraint on late Holocene RSL changes in the region (Table 1).

5.2.3 Reykjanes 6 (RK6) - 65°55.193' N, 22°25.588' W – Sill Elevation: 2.30 ± 0.30 m a.s.l.

RK6 is a small basin, found north of the present airfield on Reykjanes (Fig. 2C). The sediment profile at RK6 comprises a basal olive green mixed organic material, overlain by a lower peat layer, olive green humified organic material and middle peat layer. Above this, is an upper olive green organic layer, overlain by an upper turfa peat layer. The diatomological isolation contact is identified at 100 cm (Fig. 7) shown by a reduction in brackish conditions at the site. A bulk organic radiocarbon sample at 100 cm produced an age for the SLIP of 9139 – 9432 (9.3 k) cal. a BP (Table 1).

5.2.4 Vatnsfjörður Home Field (VHF1) - 65°56.324’ N, 22°30.000’ W – Sample Elevation: 4.50 ± 0.30 m a.s.l.

VHF1 is situated close to an archaeological site and present farm at Vatnsfjörður (Fig. 2C). The stratigraphy is made up of a basal blue-grey sandy clay, overlain by extensive peats. A number of sediment samples were extracted through the profile. Diatom analysis shows the core dominated by freshwater conditions, with a weak brackish signal at the base (Fig. 7). A radiocarbon sample at 69 cm provides a marine limiting age of 5584 – 5711 (5.6 k) cal. a BP (Table 1).

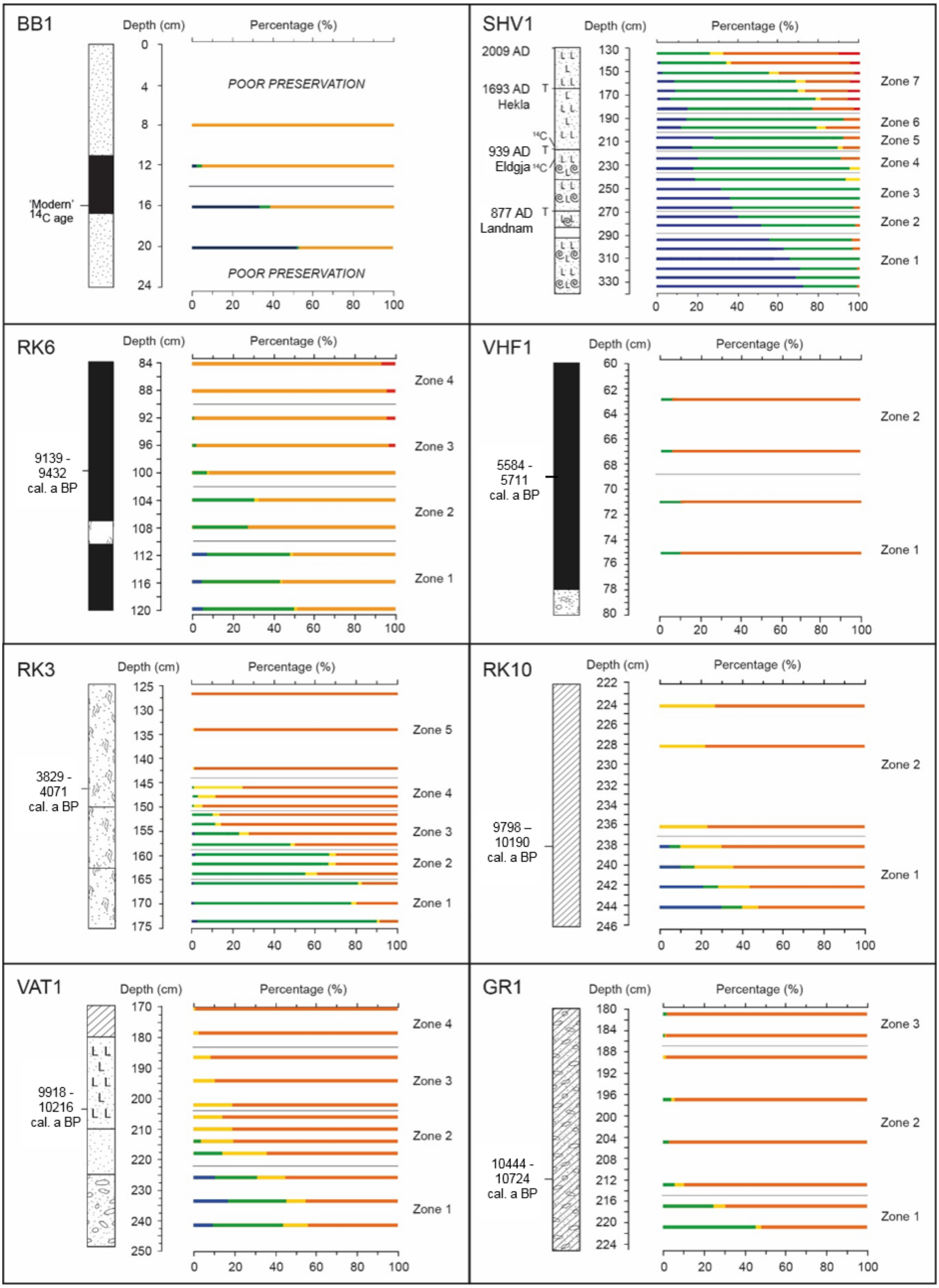

Figure 7: Summary diatom assemblages and stratigraphic profiles for sites in Reykjanes-Laugardalur showing the key environmental changes recorded in each location: BB1 – Bólvík, SHV1 – Sveinhúsavatn, RK6 – Reykjanes 6, VHF1 – Vatnsfjörður Home Field, RK3 – Reykjanes 3, RK10 – Reykjanes 10, VAT1 – Vatnsfjarðarháls 1, GR1 – Grímhólsvatn. For the key, refer to Figure 4.

5.2.5 Reykjanes 3 (RK3) - 65°54.171' N, 22°25.069' W – Sill Elevation: 6.19 ± 0.30 m a.s.l.

RK3 is situated between RK6 and RK10, south of the present airfield on Reykjanes (Fig. 2C). A sediment sample comprised a basal brown silty mixed organic material, overlain by a grey silt, brown mixed organic material and upper peat layer. The diatom assemblage shows a transitional sequence and can be divided into five zones. A radiocarbon sample at 147 cm produced a timing of isolation of 3829 – 4071 (3.9 k) cal. a BP (Fig. 7; Table 1). There is a clear reduction in marine influence at the site over the course of the diatom record (Fig. 7).

5.2.6 Reykjanes 10 (RK10) - 65°54.321' N, 22°25.184' W – Sill Elevation: 16.49 ± 0.30 m a.s.l.

RK10 is a predominantly infilled basin on the Reykjanes peninsula, situated between RK3 and the airfield (Fig. 2C). The site stratigraphy is characterised by a basal gravel, extensive limus deposits and turfa peat. Diatom analysis highlights two distinct zones (Fig. 7). The diatomological isolation contact is clearly evident at 237 cm and a bulk radiocarbon sample at 238 cm returned an age for the SLIP of 9798 – 10190 (10.0 k) cal. a BP (Table 1). In addition, the Saksunarvatn tephra was identified by geochemical analysis at 248 cm, providing a second (minimum) age of 10.2 cal. ka BP (Fig. 5). There is a clear reduction in marine influence at the site, suggesting a RSL fall at the location.

5.2.7 Vatnsfjarðarháls 1 (VAT1) - 65°57.823' N, 22°31.175' W – Sill Elevation: 22.22 ± 0.30 m a.s.l.

VAT1 is situated at the head of the Vatnsfjarðarnes peninsula (Fig. 2C). The stratigraphy was determined through a transect of 15 cores and comprises a basal gravel, grey silt, olive green limus and upper turfa peat. An extensive tephra deposit is also evident at the site, occurring shortly after the transition from silt to limus. Geochemical analysis of these dark grey deposits has identified the Saksunarvatn tephra at 163 cm (10.2 cal. ka BP; Fig. 5). The diatom assemblage from VAT1 can be divided into four distinct zones (Fig. 7). The diatomological isolation contact is identified at 204 cm from which a radiocarbon sample produces an age of 9918 – 10216 (10.1 k) cal a BP (Table 1) for the SLIP. Consequently, a weak marine phase is terminated at ca. 10.1 cal. ka BP, with the Saksunarvatn tephra (10.2 cal. ka BP) found above the section.

5.2.8 Grímhólsvatn (GR1) - 66°0.053' N, 22°39.353' W – Sill elevation: 28.52 ± 0.30 m a.s.l.

GR1 is a large basin situated close to the local marine limit at ~25 m a.s.l. in Laugardalur (Fig. 2C). The core from the northern section of the present lake basin is characterised by a basal silty brown limus overlain by an olive green limus layer. The diatomological isolation contact is identified at 212 cm, with a radiocarbon sample generating an age of 10444 - 10724 (10.6 k) cal. a BP for the SLIP indicating a reduction in marine influence of a brackish environment at the location (Fig. 7).

5.2.9 Vatnsfjarðarháls 2 (VAT2) - 65°57.553' N, 22°30.956' W – Sill Elevation: 29.59 ± 0.30 m a.s.l.

VAT2 is a large basin found above and south of site VAT1 on the Vatnsfjarðarnes peninsula (Fig. 2C). The collected core was comprised of a basal gravel, overlain by silty clay, limus and peat layers. The diatom assemblage is dominated by freshwater conditions. There is a short-lived brackish component at 428 cm, which may represent a storm event or brief marine incursion of the basin. A clear transitional sequence is not evident at the site, suggesting that the site was situated above the influence of marine conditions. A radiocarbon sample at 428 cm produced an age of 11712 – 12067 (11.9 k) cal. a BP (Table 1) for a short-lived brackish episode.

5.2.10 Laugardalur (LG1)

The raised shoreline at Laugardalur provides an elevation for the local marine limit in Reykjanes-Laugardalur (Fig. 2C). The distinctive feature is found at the mouth of Laugardalur valley and was surveyed in a number of locations using an EDM to ~25/30 m a.s.l. A lack of dateable material means that it has not been possible to directly date the feature, although diatom analysis from GR1 provides a limiting age for formation of the shoreline.

5.2.11 RSL curve for Reykjanes-Laugardalur

Eight new SLIPs and the surveyed marine limit produce a new RSL curve for the region (Fig. 6; Table 1). The new RSL curve for Reykjanes-Laugardalur shows RSL rapidly falling from the marine limit at ~25/30 m a.s.l., which may have been formed at ca. 10.6 – 11.9 cal. ka BP, to below present sea level by ca. 9.3 cal. ka BP. RSL then rose above present sea level to a mid-Holocene highstand at ~4 m a.s.l. between ca. 4 and 5.8 cal. ka BP, before falling to present sea level (Fig. 6). The regression sequences from RK6 and VHF1 mean that sea-level must have risen to or close to the elevation of these sites during the early to mid- Holocene.

5.3 Hrútafjörður-Heggstaðanes (Area D (Fig. 2); eight sites)

Eight isolation basin and coastal lowland sites were investigated in the Hrútafjörður-Heggstaðanes area, which represents the innermost research location along the principal research transect through NW Iceland (Fig. 3).

5.3.1 Kolbeinsárnes 2 (KB2) - 65°25.978’ N, 21°11.793’ W – Sill Elevation: 1.09 ± 0.30 m a.s.l.

KB2 is a lake situated on the Kolbeinsárnes peninsula on the western coastline of Hrútafjörður (Fig. 2D) inundated at high tide. A core for analysis was extracted from the infilled section to the rear of the basin, summarised as a basal grey silt, subsequent blue-grey silty clays and an overlying *Sphagnum* peat layer. No tephra layers were evident at the site. Diatom analysis reveals a gradual transition from brackish-marine dominance to an increase in freshwater taxa presence (Fig. 8). A bulk radiocarbon sample at 30 cm provides an age of 308 – 484 (0.4 k) cal. a BP for the reduction of marine influence at the site and a known position within the tidal frame (ongoing isolation).

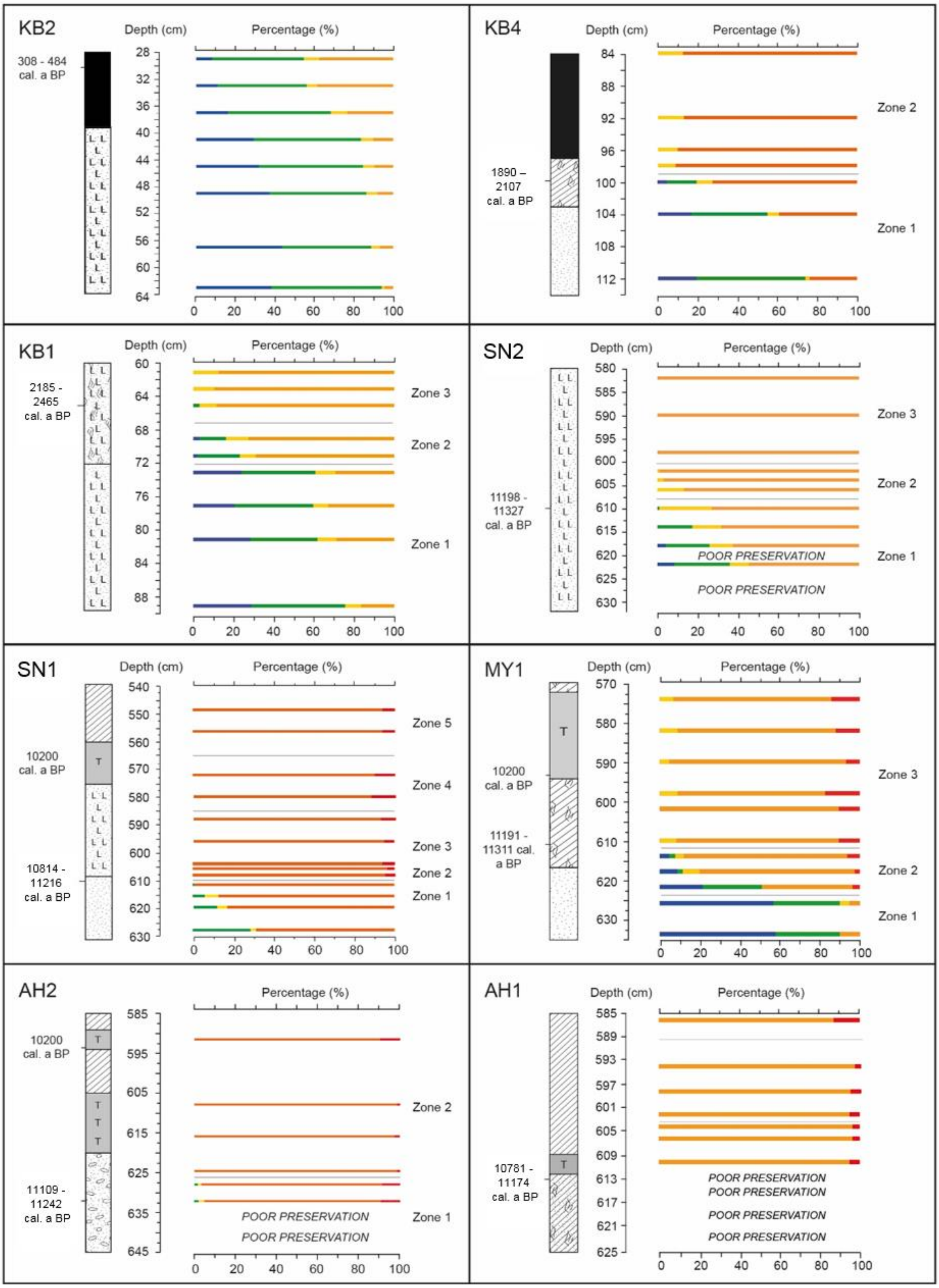

Figure 8: Summary diatom assemblages and stratigraphic profiles for sites in Hrútafjörður-Heggstaðanes showing the key environmental changes recorded in each location: KB2 – Kolbeinsárnes 2, KB4 - Kolbeinsárnes 4, KB1 - Kolbeinsárnes 1, SN2 – Sandavatn 2, SN1 – Sandavatn 1, MY1 – Mýrar 1, AH2 – Álfhóll 2, AH1 – Álfhóll 1. For the key, refer to Figure 4.

5.3.2 Kolbeinsárnes 4 (KB4) - 65°25.906’ N, 21°11.992’ W – Sill elevation: 2.24 ± 0.30 m a.s.l.

KB4 is found to the southwest of KB2 on the Kolbeinsárnes peninsula (Fig. 2D). The sediment core contains a lower silty clay, organic-rich limus and overlying turfa peat (Fig. 8). The diatom assemblage shows a transition from brackish-marine to freshwater dominance (Fig. 8). Radiocarbon dating of a bulk sediment sample at the diatomological isolation contact at 100 cm returned an age of 1890 – 2107 (2.0 k) cal. ka BP, which is employed for the SLIP. There is a clear decrease in marine influence at KB4, representing a fall in RSL below 2.24 m a.s.l. at the location.

5.3.3 Kolbeinsárnes 1 (KB1) - 65°25.984’ N, 21°11.756’ W – Sill elevation: 3.45 ± 0.30 m a.s.l.

KB1 is a small basin situated north of KB2 and northeast of KB4 (Fig. 2D). The stratigraphy comprises of a basal blue-grey clay with silt, organic rich silt, olive-green limus with abundant rootlets and a distinct uppermost olive-green limus layer (Fig. 8). The diatom assemblage represents a gradual decrease in marine influence at the site (Fig. 8). A bulk sediment sample for radiocarbon analysis from the diatomological isolation contact at 65 cm returned an age of 2185 – 2465 (2.3 k) cal. a BP for RSL falling below the SLIP.

5.3.4 Sandavatn 1 (SN1) - 65°20.249’ N, 20°59.381’ W – Sill elevation: 51.02 ± 0.30 m a.s.l.

SN1 is situated north of SN2 on the Heggstaðanes peninsula (Fig. 2D). A transect of 4 cores produced a stratigraphy comprising a basal blue-grey silt, overlying limus layer and surface turfa peat deposits. A tephra deposit was evident between the silt and limus layer at 578 cm, identified as the Saksunarvatn tephra (10.2 cal ka BP) following geochemical analysis. Diatom analysis reveals a transitional sequence from brackish to freshwater dominance (Fig. 8). A radiocarbon sample at the apparent diatomological isolation contact at 610 cm produced a minimum age of 10814 – 11216 (11.1 k) cal. a BP for the SLIP.

5.3.5 Sandavatn 2 (SN2) - 65°20.026’ N, 20°59.230’ W – Sill elevation: 46.51 ± 0.30 m a.s.l.

SN2 is a large infilled basin also situated on the eastern side of the Heggstaðanes peninsula (Fig. 2D). The site stratigraphy was established through 4 cores and is characterised as a basal silt overlain by organic rich limus containing a distinct tephra layer and an uppermost turfa peat layer. The Saksunarvatn tephra was identified within the limus deposit at 509 cm, providing an age of 10.2 cal ka BP. In addition, a radiocarbon sample from an apparent diatomological isolation contact at 610 cm (Fig. 8) gave a minimum isolation age of 11198 – 11327 (11.3 k) cal. a BP for the SLIP. There is an indication of a reduced brackish influence at the site (at 614 cm), possibly indicating a RSL lowering at the location.

5.3.6 Mýrar 1 (MY1) - 65°18.253’ N, 21°02.401’ W – Sill elevation: 57.90 ± 0.30 m a.s.l.

Mýrar is situated on the western side of the Heggstaðanes peninsula (Fig. 2D). The site stratigraphy was established by a transect of 3 cores and comprises a basal gravel with overlying blue-grey silts and clays, mixed organic sediments and uppermost peat layer. A number of individual tephra layers were identified within the sedimentary profile. The diatom assemblage can be divided into three distinct zones (Fig. 8). A radiocarbon sample was analysed from 612 cm and returned an age of 11191 – 11311 (11.2 k) cal. a BP for the SLIP shown by the transition from marine, brackish to freshwater dominance in the diatom flora. The Saksunarvatn tephra was also identified at 592 cm, providing additional chronological control for the site (10.2 cal ka BP).

5.3.7 Álfhóll 2 (AH2) - 65°17.601' N, 20°55.978' W – Sill elevation: 68.22 ± 0.30 m a.s.l.

AH2 is a small basin ~110 m west of AH1 in innermost Heggstaðanes (Fig. 2D). A basal blue-grey sand, overlain by silty clay and an olive-green limus is present within the cores. A dark grey tephra was identified as Saksunarvatn at 594 cm following geochemical analysis, providing an age of 10.2 cal ka BP (Fig. 5 and 8). Diatom samples were analysed throughout the core sample showing freshwater dominance but the lowermost samples provided insufficient diatoms to ensure a reliable count (Fig. 8). A radiocarbon sample from 632 cm provided a limiting age for the deposition of organic material and the site was therefore above RSL at 11109 – 11242 (11.2 k) cal. a BP.

5.3.8 Álfhóll 1 (AH1) - 65°17.657' N, 20°55.821' W – Sill elevation: 70.62 ± 0.30 m a.s.l.

AH1 is the highest basin investigated in Hrútafjörður-Heggstaðanes, situated to the northeast of AH2 (Fig. 2D). The sediment stratigraphy was established through a transect of 3 cores and comprises basal blue-grey clay and silty clay overlain by an olive-green limus. A dark grey tephra layer was evident at 609 – 612 cm, which was identified as the Saksunarvatn tephra following geochemical analysis, providing an age of 10.2 cal ka BP (Fig. 5 and 8). In total, nine diatom samples were analysed, although the lowermost samples failed to produce sufficient diatoms to ensure a valid count (Fig. 8). A radiocarbon sample at 613 cm produced an age of 10781 – 11174 (11.0 k) cal. a BP and acts as a limiting age for the site, although this should be treated with some caution, given the close proximity to the Saksunarvatn tephra (10.2 cal. ka BP).

5.3.9 RSL curve for Hrútafjörður-Heggstaðanes

Six new SLIPs and two limiting points have been produced in Hrútafjörður-Heggstaðanes, the innermost location along the research transect in NW Iceland. These new SLIPs have allowed the construction of a tentative new RSL curve for the region, highlighting initial RSL fall and more recent RSL changes (Fig. 6). The lack of mid-elevation sites in the region means that it has not been possible to constrain RSL changes between ca. 11200 and 2400 cal. a BP (Fig. 6). Pétursson (pers. comm, 2016) has measured the marine limit at 47 m a.s.l. in Hrútafjörður and 53 m a.s.l. in Hvammstangi (east of Heggstaðanes), which provide a similar constraint on maximum postglacial RSL as MY1 (58 m a.s.l.) where a clear transitional sequence is evident. AH1 and AH2 act as limiting RSL points, suggesting that RSL has most likely been below this level since deglaciation.

5.4 Breiðavík-Látrar (Area E (Fig. 2); one site)

A series of sites were investigated in the Breiðavík-Látrar area in order to investigate the high marine limit elevations recorded in the region. A number of higher elevation sites recorded evidence for marine influence, yet suffered from poor chronological control, and thus are not presented here. Consequently, only one site is presented here in full, from close to present sea level (Fig. 9). The elevational data from the higher sampled sites can however be seen in Fig. 6.

5.4.1 Breiðavík 10 (BR10) - 65°32.631' N, 24°25.081' W – Sill elevation: 4.40 ± 0.30 m a.s.l.

The BR10 locality is situated in Breiðavík, a large bay on the westernmost part of Iceland (Fig. 2E). The site stratigraphy can be summarised as a basal sand overlain by silt-rich limus and organic rich silts, with visible shell remains likely deposited into the basin by aeolian transport. The diatom record shows a reduction and subsequent increase in marine influence at the location, with the diatomological isolation contact therefore identified at 218 cm (Fig. 9). A bulk radiocarbon sample from 218 cm produced an age of 1301 – 1407 (1.4 k) cal. a BP.

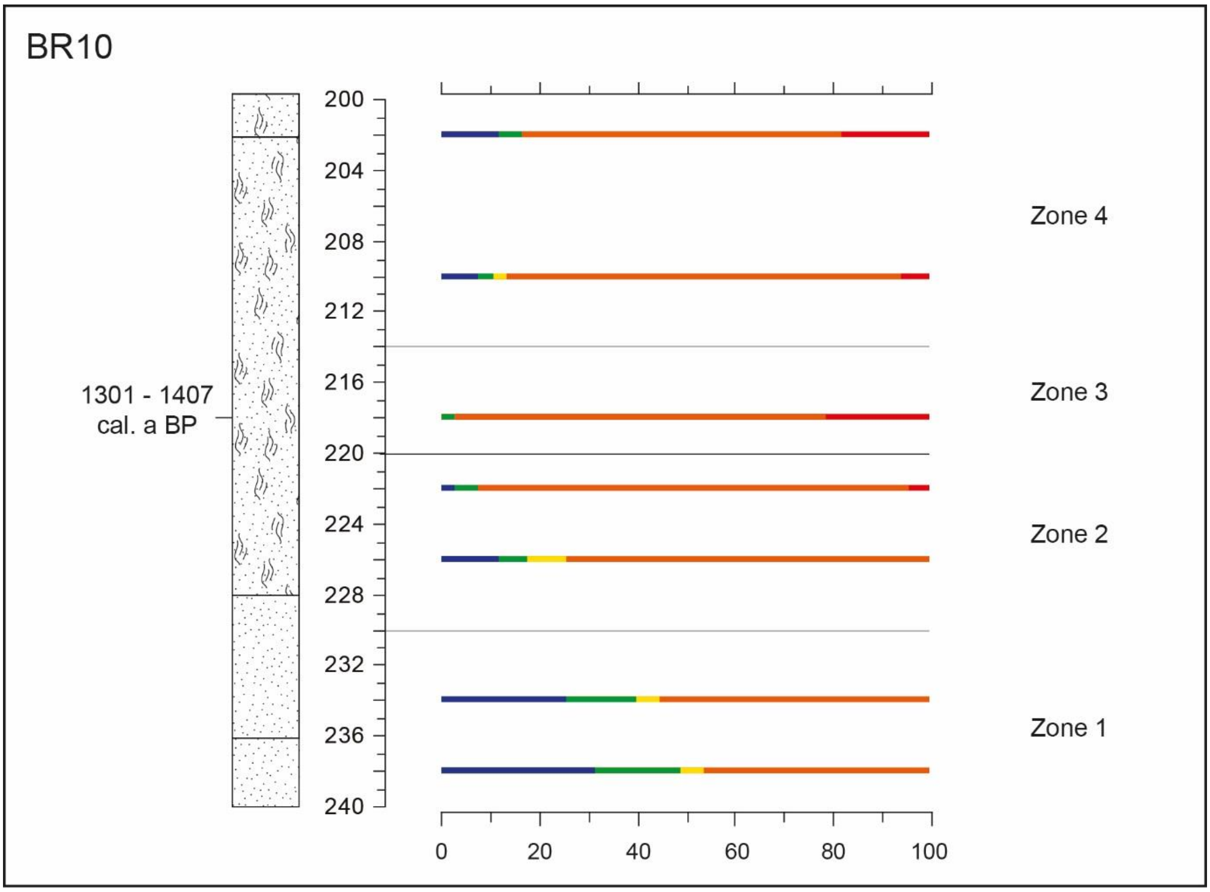

Figure 9: Summary diatom assemblages and stratigraphic profile for Breiðavík 10 in Breiðavík-Látrar, showing the key environmental changes recorded. For the key, refer to Fig. 4.

5.4.2 RSL record from Breiðavík-Látrar

One new SLIP has been generated for the region (see Table 1), which is supported by the local marine limit at ~85 m a.s.l. by Norðdahl and Pétursson (2005). Prominent shorelines have been identified at intermediate elevations (38 m and 79 m a.s.l. at Seljavík, southwest of BR10 (Pétursson, pers. comm, 2016). Additional sites with brackish diatoms were recorded at ~64 m, 67 m and 73 m a.s.l. (Fig. 9) but suffered from poor chronological control. It is likely that organic productivity was low immediately following deglaciation and as a result, limited organic material was available for dating within these sediment sequences. The ages generated are not consistent with the elevation of the samples and thus probable timing of isolation.

6. Discussion

6.1 RSL changes in northwest Iceland

Investigation of isolation basin, coastal lowland and geomorphological evidence has allowed the reconstruction of RSL changes at four locations in NW Iceland. The reconstructed patterns of RSL changes allow the testing of the contrasting uplift hypotheses, with the results having implications for GIA modelling, ice sheet configuration and deglacial pattern, as well as meltwater input into the North Atlantic.

6.1.1 Hlöðuvík and Rekavík bak Látrum

In Hlöðuvík and Rekavík bak Látrum, the new RSL data provide constraint on marine limit formation. The marine limit in Hlöðuvík is recorded at ~17.5 ± 1.0 m a.s.l. and is characterised by a basal till overlain by marine sediments and an upper till (15-26 m a.s.l., Hjort *et al*., 1985). Lake basin samples from close to the marine limit demonstrate entirely freshwater assemblages and therefore support the interpretation of this feature. The presence of the Saksunarvatn tephra in these lake basin sediments suggests that the lower part of the valley was ice free by 10.2 cal ka BP and provides a limiting (minimum) age for local marine limit formation. This interpretation is supported by Hjort *et al* (1985) who identified that the Saksunarvatn tephra was deposited close to sea-level, suggesting that RSL was below the elevation of the lake basin sites at 10.2 cal. a BP.

In Rekavík bak Látrum, following deglaciation RSL fell from the local marine limit at 15-25 m a.s.l. (Hjort et al., 1985). This RSL fall is constrained by the new RSL data to between 9.3 cal. ka BP and 10.2 cal. a BP, which acts as both the minimum age for marine limit formation and deglaciation. Additional sites explored in Rekavík bak Látrum demonstrate extensive gravel and sand deposits, limiting the potential for reconstructing environmental change for the westernmost section of the study area.

6.1.2 Reykjanes-Laugardalur

Following deglaciation, RSL fell from the local marine limit at ~30 m a.s.l. at ca. 10.6 cal ka BP until 9.3 cal. ka BP, after which RSL fell below present (Fig. 6). The RSL record generated in Reykjanes-Laugardalur therefore demonstrates that deglaciation may have occurred at a later date (10.6/11.9 cal. ka BP, GR1/VAT2) in Ísafjarðardjúp than north of Breiðafjörður (Lloyd *et al*., 2009 [ca. 14.1 cal. ka BP]) and on the north coast of Snæfellsnes (Brader *et al*., 2015 [ca. 12.7 cal. ka BP]). The fall of RSL below present during the early Holocene (9.3 cal. ka BP) in this area can be compared with dates for a similar fall below present elsewhere in NW Iceland of ca. 9.0 cal ka BP (estimated for Bjarkarlundur, Lloyd *et al.*, 2009); ca. 10.1 cal. ka BP (Snæfellsnes, Brader *et al.*, 2015); >10.2 cal ka BP (Skagi Peninsula, Rundgren *et al.*, 1997); and ca. >10.5 cal ka BP in southwest Iceland (Ingólfsson *et al*., 1995; Pétursson *et al*., 2015).

The new early Holocene RSL data from Reykjanes-Laugardalur can be compared to palaeoceanographic studies in Ísafjarðardjúp, which note a termination of glacio-marine conditions within the fjord by ca. 10.2 cal. ka BP and a lowered RSL between ca. 10.6 and 8.9 cal ka BP (Quillman *et al*., 2010). At Reykjanes-Laugardalur, our new sea-level data indicate glacier retreat by at least 10.6 cal ka BP (Fig. 6) leading to glacio-isostatic unloading and a subsequent fall in RSL, which can be compared with the results from Quillman *et al*. (2010) in inner Ísafjarðardjúp. The difference in deglacial age is possibly the consequence of later glacier retreat at the innermost part of the fjord system due to lesser ingress of the warm Irminger Current, which would have become fully established in NW Iceland by ca. 10.2 cal. ka BP (Ólafsdóttir *et al*., 2010).

Following the RSL fall below present sea level in the early Holocene (Fig. 6), a transgression must have occurred in the mid- to early Holocene, with the Reykjanes-Laugardalur RSL curve showing an associated regression from the proposed mid-Holocene highstand at ca 3.9 cal. ka BP (Fig. 6). The elevation and timing of this proposed highstand fit well with previous evidence from Ísafjarðardjúp, such as the raised beach surveyed by Principato (2008) at 5 m a.s.l. and dated to 3.5 cal. ka BP (3612 ± 40 ^{14}C a BP, marine shell). The SLIPs from Reykjanes-Laugardalur provide a minimum elevation of the proposed highstand which corresponds with both previous isolation basin records from NW Iceland (Lloyd *et al*., 2009) and the *Nucella* transgression (e.g. Símonarson and Leifsdóttir, 2002).

RSL appears to have fluctuated over the late Holocene in Reykjanes-Laugardalur, with RSL rise most recently, as shown by the radiocarbon ages from SHV1 (1.25 ± 0.30 m a.s.l.; 2.1 cal ka BP and 2.3 cal ka BP), the age of the proposed Little Ice Age shoreline in Ísafjarðardjúp (0.3-0.5 m a.s.l.; 162 [0-267] cal. a BP; Principato, 2008), and the age of the BB1 sample (-0.50 ± 0.25 m a.s.l.; 'modern'). Poor chronological control on the BB1 sample prevents a recent rate of RSL change being calculated, although RSL must have risen to present from this saltmarsh peat deposit, situated just below present sea-level.

6.1.3 Hrútafjörður-Heggstaðanes

The isolation basin records from Hrútafjörður-Heggstaðanes constrain the highest elevation reached by postglacial RSL in the region. Despite the lack of direct evidence for a raised shoreline, it is proposed that the marine limit lies between ~47 and 58 m a.s.l., with a minimum timing for deglaciation of 11.2 cal. ka BP (Fig. 6).

The highest recorded marine influence along Hrútafjörður (~58 m a.s.l.; MY1) is higher than the previously reported but undated marine limit in innermost Hrútafjörður at about 50 m a.s.l. (Ingólfsson, 1991). However, previous research in northern Iceland has noted a southerly decrease in marine limit elevations due to differences in deglacial timing (Norðdahl and Pétursson, 2005). In Hrútafjörður, it is likely that the marine limit formed during the Younger Dryas, based on the known extent of the ice sheet during this period (e.g. Pétursson *et al*., 2015). As a result, the marine limit features are assigned a tentative Younger Dryas age, given the lack of dateable material to confirm the age of this feature.

6.1.4 Breiðavík-Látrar

The new late Holocene data from Breiðavík-Látrar provides a valuable constraint on recent RSL changes in outermost Breiðafjörður, suggesting a rise in RSL since ca 1.4 cal ka BP. Investigation of higher elevation basins in the region provides evidence for marine influence up to 67 m a.s.l.; however, poor chronological control limits constraint of a regional RSL curve, likely as a consequence of low productivity immediately following deglaciation, leading to low organic content within dated bulk sediment samples. Investigation of the geomorphology of the area provides support for a marine limit ~85 m a.s.l. (Norðdahl and Pétursson, 2005; Fig. 6), with shorelines at ~38 and 79 m a.s.l.

6.2 Geomorphological evidence vs. hypothesised RSL patterns

The investigation of postglacial RSL change provides an opportunity to explore patterns of postglacial uplift across NW Iceland. As outlined in Fig. 3 and Fig. 6, contrasting patterns of RSL change would be expected in the four research locations studied under the two uplift scenarios. In particular, the elevation of the marine limit is an important factor in establishing the most likely ice loading/unloading scenario, which can be summarised as:

a) Central uplift scenario: there was a single uplift and therefore ice loading centre, with ice emanating from central Iceland and so the highest marine limits are expected in Hrútafjörður-Heggstaðanes and lower marine limits are proposed in Hlöðuvík and Rekavík bak Látrum (and Breiðavik-Látrar), or;

b) Local uplift scenario: there were multiple uplift centres (with localised glaciation in NW Iceland) and thus a concurrent, separate and independent ice cap was centred over Vestfirðir. As a result, if deglaciation was rapid, the highest marine limit would be found in Reykjanes-Laugardalur due to greater ice thickness resulting from the independent ice cap (Fig. 3) under the hypothesised scenario.

It is clear from the hypothesised RSL curves that the lowest marine limit elevation along the research transect is expected in Hlöðuvík and Rekavík bak Látrum (Fig. 3 and 6). In Reykjanes-Laugardalur, higher marine limit elevations would be anticipated under a local uplift centre due to the proximity to the proposed centre of secondary (local) ice loading in NW Iceland (Fig. 3 and 6). However, our new RSL data suggest that this region experienced later glacial retreat than elsewhere in NW Iceland, meaning that higher shorelines could not have formed due to the presence of ice cover. In Hrútafjörður-Heggstaðanes, the greatest contrast in marine limit elevation is anticipated by the hypothesised RSL scenarios (Fig. 3 and 6). Under the central Iceland uplift scenario, the marine limit would be highest due to increased proximity to the central Iceland ice loading centre (Fig. 3). In contrast, an intermediate elevation is expected under the local ice loading centre scenario due to its location between the two proposed ice loading centres (local and central).

Hlöðuvík and Rekavík bak Látrum are the northwesternmost terrestrial locations in this study and ice thicknesses were likely to be thinnest as they are furthest from the centres of uplift. This hypothesis is supported by the raised shoreline and lake basin evidence from the region estimating a marine limit of ~25 m, which is slightly lower than in Reykjanes-Laugardalur (~30 m a.s.l.) and considerably lower than in Hrútafjörður-Heggstaðanes (~58 m a.s.l.) (Fig. 6). Figure 6 demonstrates an increased marine limit elevation from Hlöðuvík and Rekavík bak Látrum to Reykjanes-Laugardalur and Hrútafjörður-Heggstaðanes (Fig. 6). We therefore associate lesser uplift with thinner ice loading as glacio-isostatic uplift occurred rapidly close to the retreating LGM IIS (Norðdahl and Ingólfsson, 2015).

Similar to Hlöðuvík and Rekavík bak Látrum, Breiðavík-Látrar, the westernmost location studied, is also situated at a location far from the proposed centre of uplift in central Iceland and thus the hypothesised RSL patterns are for an extreme terrestrial location from the uplift centre (Fig. 6). However, geomorphological evidence from Breiðavík-Látrar suggests greater uplift than in Hlöðuvík and Rekavík bak Látrum, with raised shorelines recorded at 85 m, 79 m, 64 m and 38 m a.s.l., exceeding those elevations recorded at Hlöðuvík and Rekavík bak Látrum (~ 25 m a.s.l.), Reykjanes-Laugardalur (~ 30 m a.s.l.), and Hrútafjörður-Heggstaðanes (~ 58 m a.s.l.) except for the 38 m a.s.l. shoreline. There are two possible explanations for this difference in marine limit elevation between Breiðavík-Látrar and Hlöðuvík and Rekavík bak Látrum:

a) Breiðavík-Látrar experienced early deglaciation and records uplift from multiple ice loading centres (localised glaciation and regional (central) glaciation), or;

b) Breiðavík-Látrar experienced earlier deglaciation and underwent greater uplift due to rapid retreat (of thicker ice) from Breiðafjörður, the site of a proposed major ice stream.

Breiðavík-Látrar and Hlöðuvík and Rekavík bak Látrum are not directly comparable due to the differences in potential ice accumulation within major fjord and smaller valley systems. The limited chronological control on the geomorphological features present in Breiðavík-Látrar means that it is not possible to differentiate between these two hypothesised explanations. Our preferred scenario is that of central uplift, as evidenced by the increased elevation of the marine limit with proximity to the ice loading centre in central Iceland. However, the geomorphological evidence in Breiðavík-Látrar may record uplift from multiple sources (i.e. a combination of central uplift and local uplift from Vestfirðir) and thus the local uplift scenario cannot be unequivocally rejected. Future glacio-isostatic adjustment modelling may be able to assist in differentiating between these two possible interpretations.

The RSL curves from Hrútafjörður-Heggstaðanes and Reykjanes-Laugardalur provide insights into rates of initial RSL changes following Lateglacial to early Holocene deglaciation, particularly when compared to previous records of RSL change in the region (Lloyd *et al*., 2009; Brader *et al*., 2015). In Hrútafjörður-Heggstaðanes, initial RSL fall occurred rapidly shown by the cluster of similar ages in basins of different elevation (Fig. 6). This rapid RSL fall corresponds with the results from Lloyd *et al.* (2009) and Brader *et al*. (2015), despite differences in deglacial timing, which both demonstrate rapid RSL fall in southern Vestfirðir and northern Snæfellsnes following deglaciation. It should however be noted that very high rates of RSL fall close to the margin of a glacier and at an earlier date have been recorded in western Iceland (Norðdahl and Ingólfsson, 2015). It is clear that proximity to the glacier edge of individual data points is therefore an important consideration when assessing regional signals.

In contrast, Reykjanes-Laugardalur demonstrates a lower rate of initial RSL fall, likely as a product of proximity to the local centre of uplift and the configuration of individual fjord systems. The complex geomorphology of Ísafjarðardjúp may have promoted a slower rate of ice retreat than seen in wider fjord systems and thus led to a reduction in the rate of initial RSL fall due to lower rates of uplift. Alternatively, rapid deglaciation of the fjord system and thus high rates of uplift may have led to equilibrium between eustatic sea-level rise and isostatic uplift within the region, leading to the slower rates of RSL fall (e.g. Norðdahl and Ingólfsson, 2015).

Late Holocene RSL records from NW Iceland suggest high spatial variability in recent RSL changes. In southern Snæfellsnes (Gehrels *et al*., 2006; Saher *et al*., 2015) and Reykjanes-Laugardalur (this study), low elevation coastal lowland and isolation basin sites provide evidence for recent RSL rise. In contrast, records from Hrútafjörður-Heggstaðanes (this study) suggest recent RSL fall, with assumed RSL fall to present also noted in southern Vestfirðir (Lloyd *et al*., 2009) and northern Snæfellsnes (Brader *et al*., 2015). Additional low elevation sites are required for locations throughout NW Iceland to further explore this variability.

The four new RSL records from NW Iceland allow the testing of two uplift (ice loading) scenarios. There is evidence to support the central uplift scenario along the research transect, based on the increased marine limit with proximity to the proposed ice loading centre (Fig. 6). There is however complexity within the uplift patterns presented, with the results from Breiðavík-Látrar suggesting that uplift from multiple ice loading centres cannot be excluded. Despite this complexity, our preferred scenario is that of central uplift with ice emanating from central Iceland.

6.3 Implications for Icelandic uplift (ice loading) scenarios

Offshore and onshore evidence suggests that substantial sectors of the LGM IIS were marine-based, extending to the shelf edge in a number of locations (Ólafsdóttir, 1975; Ingólfsson and Norðdahl, 2001; Norðdahl and Pétursson, 2005; Hubbard *et al*., 2006; Norðdahl and Ingólfsson, 2015). Marine-based sectors of ice sheets are particularly sensitive to changes in sea level (Hubbard, 2006) and ocean temperature (Schmidtko *et al*., 2014). Consequently, increases in the rate of eustatic sea-level rise associated with deglaciation of the major Northern Hemisphere ice sheets and correspondingly warmer surface waters would have had significant impacts on the IIS (Norðdahl and Ingólfsson, 2015). This would have led to a retreat of the grounding line, thinning of the ice sheet and increased rates of calving eventually leading to flotation and collapse of marine based sectors of the ice sheet, as posited elsewhere in western Iceland (Norðdahl and Ingólfsson, 2015). Some of the highest but as yet undated marine limits may originate from this period, such as those recorded in Breiðavík-Látrar (Norðdahl and Pétursson, 2005).

The new RSL curves from NW Iceland demonstrate an initial period of rapid early Holocene RSL fall, particularly in Hrútafjörður-Heggstaðanes (11.1-11.3 cal. ka BP) and in Reykjanes-Laugardalur (ca 10.2-10.6 cal. ka BP), indicating rapid glacio-isostatic uplift following deglaciation. Rapid rates of uplift support a moreorless instantaneous response of the Icelandic lithosphere to the removal of ice loading, likely as a consequence of rapid ice retreat (Norðdahl and Ingólfsson, 2015).

The new RSL data provide an insight into possible uplift scenarios in Iceland, with the preferred central uplift scenario being supported by evidence from the research transect. GIA modelling will allow the contrasting uplift scenarios to be further tested. The new RSL data generated will act as a valuable constraint for such models through the establishment of deglacial timing, age of marine limit formation, marine limit elevation, and subsequent Lateglacial to Holocene RSL changes. At present, there are few Lateglacial to Holocene RSL records for Iceland (Rundgren *et al*., 1997; Lloyd *et al*., 2009; Brader *et al*., 2015) and as such, these new data provide an opportunity to better constrain GIA model outputs than previously possible. As a result, the complexity of uplift in NW Iceland can also be tested to further explore the implications of the Breiðavík-Látrar record on GIA models.

6.4 Implications for thermohaline circulation

It is clear that the rapid deglaciation evident from the RSL records generated from NW Iceland suggest significant freshwater input to a sensitive region of the North Atlantic which would influence oceanic circulation in the region. Modelling studies have demonstrated the weakening of AMOC and cooling of the North Atlantic following freshwater input from non-Icelandic sources (Le Grande *et al*., 2006; Clarke *et al*., 2009), which has also been supported by proxy datasets (McManus *et al*., 2004; Thornalley *et al*., 2010). However, the influence of meltwater from the LGM IIS is less well explored. It is therefore important to better understand the LGM ice extent in Iceland and patterns of deglaciation, to provide constraints on models of the interactions between the IIS and surrounding ocean (Ingólfsson *et* al., 2010).

The new RSL data provide constraint on glacio-isostatic uplift in NW Iceland and whilst there is evidence to support the central uplift scenario, there is also evidence for regional complexity in deglaciation (and therefore uplift). The differences in rates of RSL change between study locations point towards a non-uniform pattern of deglaciation and thus suggest that freshwater input from different fjord systems may not have occurred at the same rate throughout NW Iceland. This has important implications for the timing and location of freshwater input into the North Atlantic and the new RSL data will therefore provide important constraint on models of ice sheet-ocean interaction.

7. Conclusions

Isolation basin and coastal lowland evidence from NW Iceland demonstrates spatial variability in RSL changes recorded in the region. These differences are shown through the elevation of the local marine limit in Hlöðuvík and Rekavík bak Látrum (NW), Reykjanes-Laugardalur (central) and Hrútafjörður-Heggstaðanes (SE), as well as the rates of subsequent RSL changes. There is also evidence for RSL fall below present sea level during the early Holocene. Currently, the minimum RSL position during this period is poorly constrained, but RSL likely fell no lower than 40 m below present in the early Holocene (Ingólfsson *et al*., 1995) but may have fallen about 85 m below present sea level in late Bølling and early Allerød times (Norðdahl and Ingólfsson, 2015). It is clear from the RSL histories generated in Reykjanes-Laugardalur (central) and Hrútafjörður-Heggstaðanes (SE) that RSL must have risen to a mid-Holocene highstand, which correlates well with geomorphological evidence from the region, as well as one previous isolation basin study (Lloyd *et al*., 2009).

Evidence from the research transect has allowed the testing of the different uplift scenarios. The increased elevation of the marine limit with proximity to the proposed uplift (and therefore ice loading) centre in central Iceland provides support for the central uplift hypothesis. This is further compounded by higher concurrent RSL throughout the Holocene in Hrútafjörður-Heggstaðanes (SE) compared to Reykjanes-Laugardalur (central) or Hlöðuvík and Rekavík bak Látrum (NW, see Fig. 3 and 6). The high elevation of the local marine limit in Breiðavik-Látrar (SW) highlights the complexity of uplift and deglaciation patterns in NW Iceland.

Future GIA modelling may help to further differentiate between the potential uplift scenarios through integration of the new RSL data on timing of deglaciation, marine limit age and elevation, and RSL changes. In addition, the new data are important constraints on ice sheet-ocean interaction models. In particular, the constraint of deglacial pattern and timing will assist in the modelling of freshwater input into sensitive areas of the North Atlantic.

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Table 1: New SLIPs and limiting ages from Hlöðuvík and Rekavík bak Látrum, Reykjanes-Laugardalur, Hrútafjörður and Heggstaðanes, and

Site Code	Lab Code	^{14}C age (1σ) BP	cal. age (2σ) BP	Uncorr. sill/ core elev. (m MHWST-sill)	Corr. sill/core elv. (m a.s.l.)	Core depth (cm)	Reference wtr. level	Indicative Meaning (m)	Relative sea level (m)
REK1	SUERC-54842	8275 ± 39	9130 – 9412	17.5 ± 0.15	18.63 ± 0.3	330	MHWST	1.1 ± 0.3	17.7 ± 0.6
HD3	Saksunarvatn	-	10175 – 10245	16.91 ± 0.15	18.01 ± 0.3	134	>HAT	N/A	Limiting
BB1	SUERC-47973	MODERN	N/A	-0.5 ± 0.15	-0.5 ± 0.25	16	N/A	N/A	N/A
SHV1	SUERC-47963	2123 ± 35	1996 – 2299	0.2 ± 0.15	1.25 ± 0.3	218	MHWST	1.05 ± 0.3	0.2 ± 0.6
SHV1	SUERC-47964	2269 ± 35	2158 – 2349	0.2 ± 0.15	1.25 ± 0.3	228	MHWST-MTL	0.65 ± 0.55	0.6 ± 0.85
VHF1	SUERC-47967	4886 ± 36	5584 - 5711	3.45 ± 0.15	4.5 ± 0.3	69	MHWST	1.05 ± 0.3	3.45 ± 0.6
RK3	SUERC-47965	3602 ± 37	3829 - 4071	5.15 ± 0.15	6.2 ± 0.3	147	MHWST	1.05 ± 0.3	5.15 ± 0.6
RK6	SUERC-47966	8299 ± 38	9139 - 9432	1.25 ± 0.15	2.3 ± 0.3	100	MHWST	1.05 ± 0.3	1.45 ± 0.6
RK10	SUERC-47970	8894 ± 41	9798 - 10190	15.45 ± 0.15	16.5 ± 0.3	238	MHWST	1.05 ± 0.3	15.45 ± 0.6
VAT1	SUERC-47971	8947 ± 39	9918 - 10216	21.15 ± 0.15	22.2 ± 0.3	204	MHWST	1.05 ± 0.3	21.15 ± 0.6
VAT2	SUERC-47972	10188 ± 42	11712 - 12067	28.45 ± 0.15	29.6 ± 0.3	428	>HAT	N/A	Limiting
GR1	SUERC-48877	9377 ± 47	10444 - 10724	27.45 ± 0.15	28.5 ± 0.3	212	MHWST	1.05 ± 0.3	27.55 ± 0.6
KB1	SUERC-54844	2332 ± 37	2185 - 2465	2.75 ± 0.15	3.45 ± 0.3	65	MHWST	0.7 ± 0.25	2.75 ± 0.55
KB2	SUERC-54845	338 ± 37	308 - 484	0.4 ± 0.15	1.09 ± 0.3	30	HAT	1.2 ± 0.25	-0.1 ± 0.55
KB4	SUERC-54846	2024 ± 37	1890 - 2107	1.55 ± 0.15	2.24 ± 0.3	100	MHWST	0.7 ± 0.25	1.55 ± 0.55
MY1	SUERC-54839	9831 ± 42	11191 - 11311	57.2 ± 0.15	57.9 ± 0.3	612	HAT	1.2 ± 0.25	56.7 ± 0.55
SN1	SUERC-47986	9689 ± 40	10814 - 11216	50.3 ± 0.15	51.02 ± 0.3	610	MHWST	0.7 ± 0.25	50.3 ± 0.55
SN2	SUERC-47987	9850 ± 41	11198 - 11327	45.8 ± 0.15	46.51 ± 0.3	610	MHWST	0.7 ± 0.25	45.8 ± 0.55
AH2	SUERC-47974	9751 ± 41	11109 - 11242	67.5 ± 0.15	68.22 ± 0.3	632	HAT	N/A	Limiting
AH1	SUERC-47985	9625 ± 40	10781 - 11174	69.9 ± 0.15	70.62 ± 0.3	613	>HAT	N/A	Limiting
BR10	SUERC-54849	1465 ± 35	1301 - 1407	2.9 ± 0.15	4.4 ± 0.3	218	MHWST	1.5 ± 0.3	2.9 ± 0.6

Breiðavík-Látrar, NW Iceland.