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High Relative Sea Level during the Bølling Interstadial in Western Iceland: a Reflection of Ice-sheet Collapse and Extremely Rapid Glacial Unloading

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Abstract

New geologic data from western Iceland reveal raised marine terraces at elevations between 105 and 148 m a.s.l., 45–80 m above the late Younger Dryas (ca. 10.3 ka BP) raised beaches in the region. Radiocarbon dating assigns the high marine levels a Bølling Interstadial age of ca. 12.6 ± 0.1 ka BP. Inferred gradient for raised Bølling beaches in the lower Borgarfjördur area is close to 2.3 m km^{-1}. The marine terraces indicate a Bølling glacio-isostatic crustal depression of up to 250 ± 20 m, reflecting ice thickness of up to 840 ± 150 m. This is close to previously estimated Last Glacial Maximum (LGM) ice thickness. The Icelandic crust responds rapidly to changes in ice-load. Gradual thinning and retreat of the Icelandic ice sheet would have been concurrently compensated for by isostatic rebound, inhibiting formation of raised shorelines reflecting LGM isostatic crustal depression. The Bølling shorelines, together with recent marine and geophysical data, indicate a very rapid deglaciation of western Iceland shelf and coastal areas around ca. 12.6 ka BP. The rapid deglaciation coincides with a period of rapid eustatic sea-level rise, which destabilized the western part of the Icelandic ice sheet and caused it to collapse.

Introduction

Iceland was heavily glaciated at the Last Glacial Maximum (LGM, 20–18 ka BP), with coalescing outlet glaciers and ice streams extending from inland ice divides to positions beyond the present coastline around the island (Fig. 1) (Hoppe, 1982; Ingólfsson and Norddahl, 1994; Bourgeois et al., 1998; Andrews et al., 2000). It is assumed that the ice was partly grounded close to the shelf edge and partly was drained through troughs on the shelf (Norddahl, 1991a, 1991b; Ingólfsson et al., 1997; Syvitski et al., 1999). Geological mapping has revealed the existence of coastal nunataks at the LGM, but erosion prevailed in areas inside the present coast. Reviews by Ingólfsson and Norddahl (1994) and Ingólfsson et al. (1997) describe the initial deglaciation of the coastal areas to have occurred during the Bølling Interstadial, 13 to 12 ka BP, but little is known on how far inside the present coast glaciers retreated.

It has been known for a long time that raised marine sediments, containing fossil molluscs of Bølling Interstadial age, occur at a number of sites in southwestern and northeastern Iceland (Ashwell, 1967, 1975; Ingólfsson, 1988; Norddahl, 1991a, 1991b; Pétursson, 1991; Ingólfsson and Norddahl, 1994; Eiríksson et al., 1997; Ingólfsson et al., 1997). However, the altitude of relative sea level (RSL) at that time has been poorly documented. Ingólfsson (1988), Norddahl and Einarsson (1988), Pétursson (1991), Norddahl and Hjort (1993), and Rundgren et al. (1997) suggested that raised beaches of Bølling age may also occur at a number of sites in other parts of Iceland, mainly in the outer coastal areas beyond the assumed Younger Dryas glacial limit.

The purpose our study is to highlight Bølling sea levels in western Iceland for better understanding of the mode and dynamics of the deglaciation. The Icelandic crust is extremely sensitive to glacial loading and unloading (Norddahl, 1991a; Sigmundsson, 1991; Ingólfsson et al., 1995; Rundgren et al., 1997), which implies that gradual and slow changes in ice volumes are readily compensated for by glacio-isostatic adjustments. Consequently, studies of altitude and age of raised beaches in relation to eustatic sea level and deglaciation can give indications as to the dynamics of ice-volume changes.

Previous Research

Ingólfsson (1987, 1988) studied the glacial history of the lower Borgarfjördur region in western Iceland (Fig. 2) and presented lithostratigraphical evidence, supported by a number of radiocarbon dates of fossil marine molluscs, showing that by Bølling times (13–12 ka BP) glaciers in the Borgarfjördur region had retreated well inside the present coast. The Bølling-Allerød interstadial period was interrupted by a short-lived Older Dryas (12–11.8 ka BP) glacial advance (Ingólfsson, 1988). He suggested that high marine landforms in the Borgarfjördur area, such as marine abrasion cliffs and delta platforms on the outer coast, were formed in connection with this glacial advance. Abrupt cooling and renewed glacial advance, with glaciers extending beyond the present coastline in fjords and bays, occurred during the Younger Dryas stadial, between ca. 10.6 and 10.3 ka BP. Regionally extensive marine terraces at 60 to 70 m a.s.l. were formed subsequent to the Younger Dryas advance. *In situ* molluscs from marine sediments give 10.3 ka BP as a minimum date of deglaciation and age of the 60- to 70-m a.s.l. marine terraces.

During fieldwork in the Skorradalur valley (Fig. 3) in 1995–97, a number of sites with outcrops of shell-bearing sediments at altitudes above the 60- to 70-m Younger Dryas Shorelines were studied. These relate to a system of terraces situated along the southern slope of the Skorradalur valley. The most important of these sites is a large sedimentary exposure on the flank of a terrace called Stóri-Sandhóll. Its surface altitude is 148 m a.s.l.

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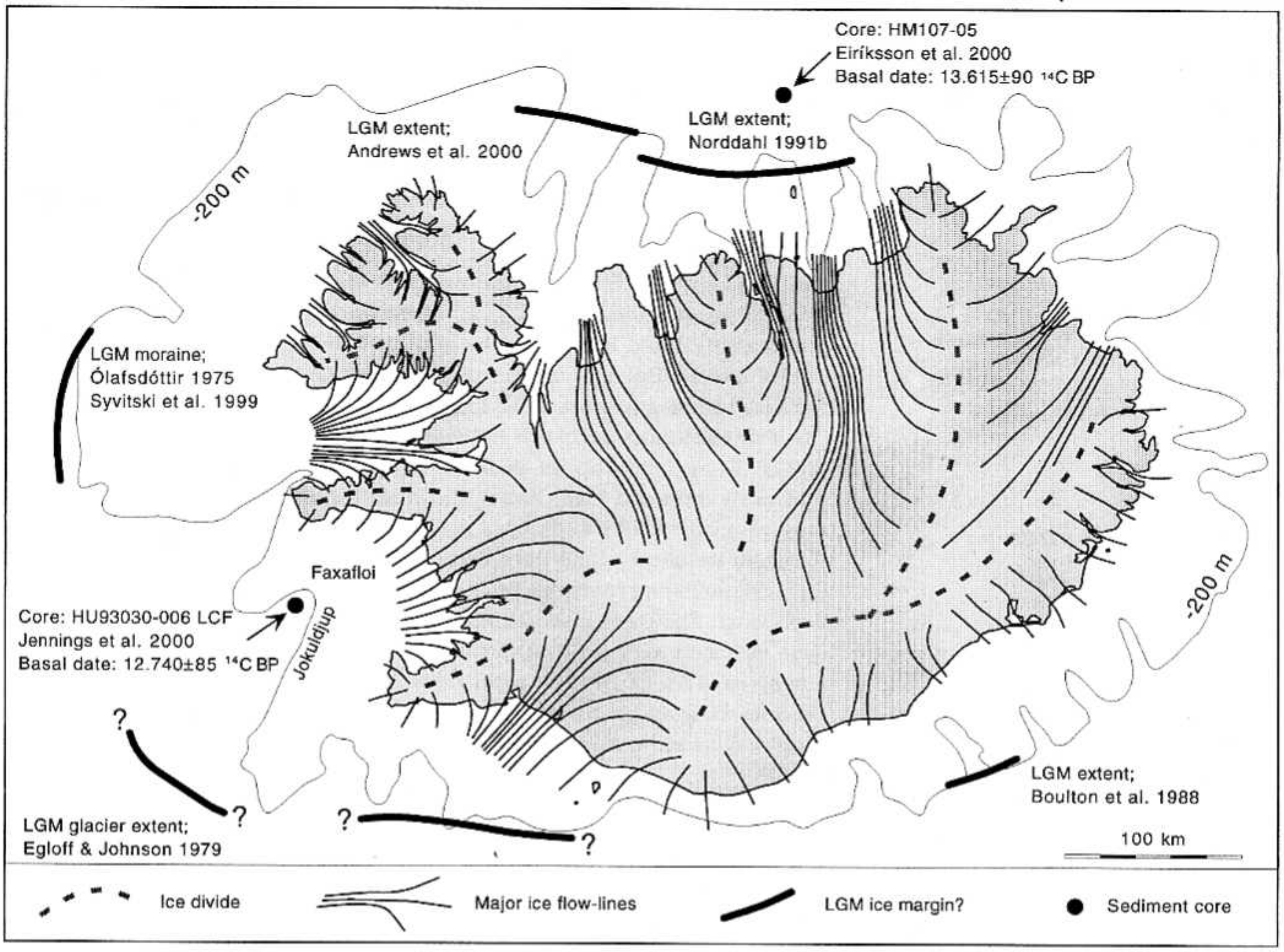

FIGURE 1. Iceland at the Last Glacial Maximum: possible ice extent, major ice-flow lines, and ice divides of the Icelandic inland ice sheet. Compilation based on Walker (1965), Ólafsdóttir (1975), Egloff and Johnson (1979), Boulton et al. (1988), Norddahl (1991a, 1991b), Einarsson, Th. (1994), Bourgeois et al. (1998), Eiríksson et al. (2000), and Andrews et al. (2000).

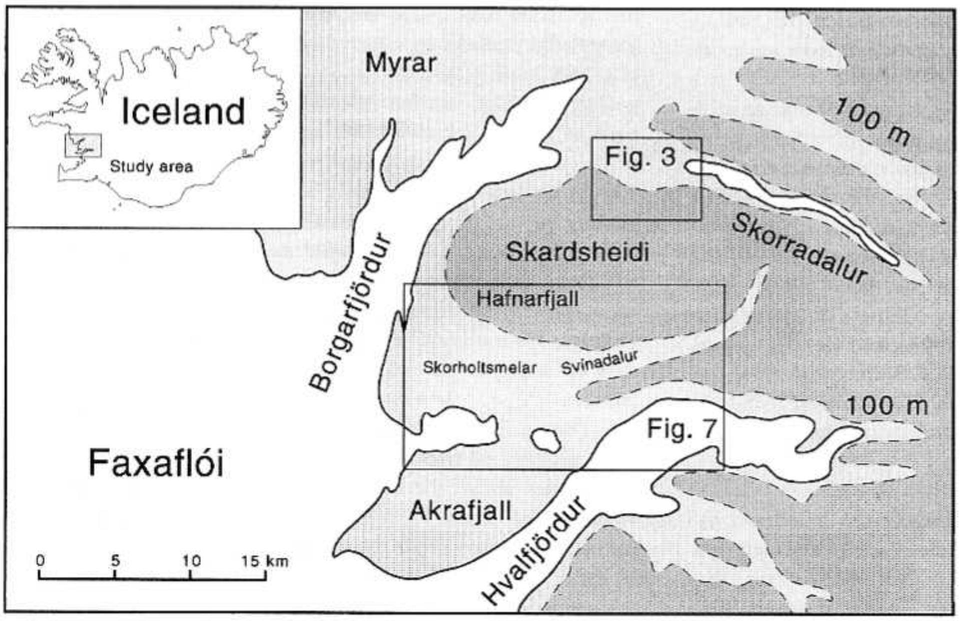

FIGURE 2. Location of the study areas in western Iceland.

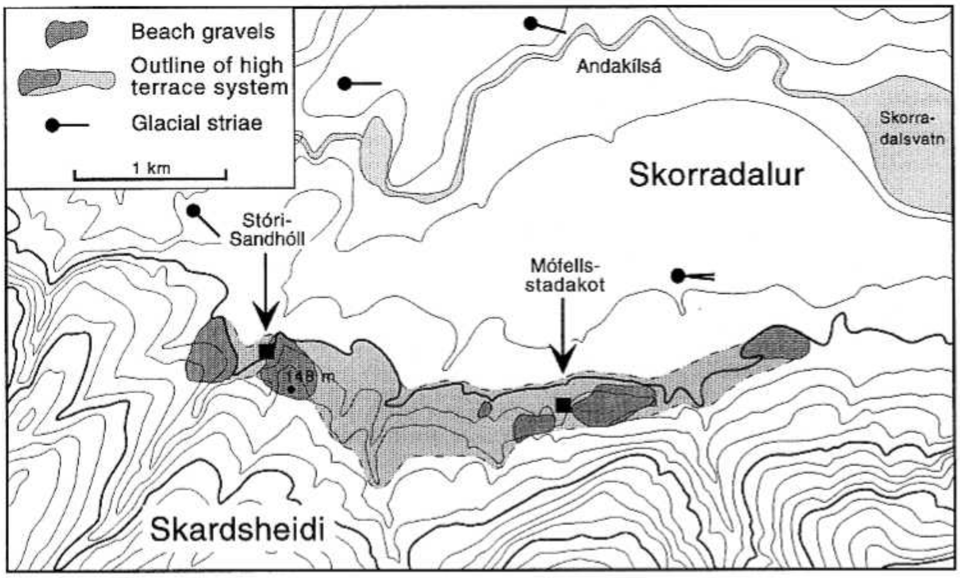

FIGURE 3. Skorradalur in western Iceland. Outline of the Bølling marine terrace system and location of the Stóri-Sandhóll and Mófellsstadakot sections.

The purpose of the study was to resolve if Stóri-Sandhóll and other terrace landforms were primary marine deposits or glacial landforms. Ashwell (1967, 1975) was first to study Stóri-Sandhóll. He interpreted it to represent a marine episode in connection with the deglaciation. Barnacles sampled from the Stóri-Sandhóll were radiocarbon dated to the Bølling Chronozone (12,270±150 BP; I-1824, Table 1). Einarsson, Th. (1968) presented an alternative explanation for the origin of Stóri-Sandhóll. He concluded that sea had transgressed a bedrock threshold at about 60 m a.s.l. during the Bølling Interstadial, but that Stóri-Sandhóll was a glacial deposit, pushed upslope from the valley floor during a post-Bølling glacial advance. Later, Ingólfsson (1988) adapted Einarsson's (1968) view.

Kjartansson (1955) suggested that during the last glaciation, the mountain Akrafjall (Fig. 2) divided a large outlet glacier coming from Hvalfjördur. He proposed that a zone of erratics at ca. 300 to 450 m a.s.l. marked the thickness of the passing glacier. Ingólfsson (1988) and Magnúsdóttir and Norddahl (2000) mapped glacial striae around Akrafjall, and found them to indicate coalescing outlet glaciers from Hvalfjördur and Borgarfjördur at LGM. The Skorholtsmelar ridges (Figs. 2, 7) define about 5-km-long and 2-km-wide area characterized by ridges and

TABLE 1

Radiocarbon dates of marine organisms of Bølling age (13 to 12 ka BP) from Western Iceland shelf and coastal areas

Laboratory Number	Sample description	Dated material	$\delta^{13}C$	Rad. carb. age (^{14}C yr BP)	Sea corr. age (^{14}C yr BP)	Altitude (m a.s.l.)	Reference
AA-12896	HU93030-006LCF	Foraminifera	n/a	13,105 ± 85	12,740 ± 85	−269	Manley and Jennings (1996)
AA-20735	HU93030-006LCF	Foraminifera	n/a	12,690 ± 195	12,325 ± 195	−269	Manley and Jennings (1996)
AA-20736	HU93030-006LCF	Foraminifera	n/a	12,810 ± 205	12,445 ± 205	−269	Manley and Jennings (1996)
AAR-0087	Ósmelur FR-3	Mollusc	1,60	12,600 ± 180	12,235 ± 180	8–14	Sveinbjörnsdóttir and Johnsen (1991)
AAR-3734	Stóra-Fellsöxl	Whalebone	−14,20	12,940 ± 80	**12,575 ± 80**	80	Magnúsdóttir and Norddahl (2000)
AAR-3654	Skorholtsmelar	Mollusc	1,90	12,370 ± 95	12,005 ± 95	40–45	Magnúsdóttir and Nordahl (2000)
I-1824*	Stóri Sandhóll	Mollusc	Not det.	12,270 ± 150		114–135	Ashwell (1975)
I-1825*	Andakílsárvirkjun	Mollusc	Not det.	12,240 ± 200		18–24	Ashwell (1975)
Lu-2055	Laxá	Mollusc	n/a	12,470 ± 110	12,105 ± 110	25	Ingólfsson (1988)
Lu-2192	Melaleiti	Mollusc	n/a	12,460 ± 120	12,095 ± 120	4	Ingólfsson (1988)
Lu-2193	Melaleiti	Mollusc	n/a	12,830 ± 110	12,465 ± 110	2	Ingólfsson (1988)
Lu-2194	Grjóteyri	Mollusc	n/a	12,830 ± 110	12,465 ± 110	19–20	Ingólfsson (1988)
Lu-2195	Ásbakkar 1	Mollusc	n/a	12,870 ± 110	12,505 ± 110	2–3	Ingólfsson (1988)
Lu-2339	Gröf	Mollusc	0,10	12,840 ± 110	12,475 ± 110	5–6	Ingólfsson (1988)
Lu-2371	Árdalsá 2	Mollusc	−0,20	12,510 ± 140	12,145 ± 140	47	Ingólfsson (1988)
Lu-2379	Ás	Mollusc	1,30	12,380 ± 110	12,015 ± 110	23–25	Ingólfsson (1988)
S-0289*	Hreppur	Mollusc	Not det.	12,100 ± 250		18–23	Ashwell (1975)
S-0290*	Árdalur 3	Mollusc	Not det.	12,100 ± 150		25–30	Ashwell (1975)
S-0291*	Grjóteyri	Mollusc	Not det.	12,800 ± 200		15–21	Ashwell (1975)
U-0641	Melar	Mollusc	n/a	12,270 ± 160	12,270 ± 160	5	Olsson et al. (1968)
U-2054	Melar	Mollusc	n/a	12,610 ± 200	12,245 ± 200	5	Olsson et al. (1968)
Ua-12021	Stóri-Sandhóll	Mollusc	n/a	12,880 ± 85	**12,515 ± 85**	112	This paper
Ua-11773	Stóri-Sandhóll	Mollusc	n/a	12,975 ± 105	**12,610 ± 105**	135	This paper

Samples marked * have been corrected for deviation from standard $^{13}C/^{12}C$ ratio and apparent age of living marine organisms. Other samples have been corrected for apparent age of 365 yr. Three datings of the ca. 12.6 ka BP Bølling raised beaches at 100 to 150 m a.s.l. are given in bold letters.

FIGURE 4. Stóri-Sandhóll. Notice the alpine scenery of the Skardsheidi massif in the background. (Photo: Ó. Ingólfsson 1996.)

channels that are mainly oriented from north-northeast towards south-southwest. The morphology of Skorholtsmelar indicates an interlobate origin between two glaciers retreating towards Borgarfjordur and Svinadalur/Hvalfjordur, respectively (Magnúsdóttir and Norddahl, 2000). Later, the morphology of Skorholtsmelar was modified by littoral abrasion. There are two sets of raised beaches flanking Skorholtsmelar: a higher set, up to 125 m a.s.l. (Magnúsdóttir and Norddahl, 2000), and a lower set, below 60 m a.s.l. Ingólfsson (1988) suggested the lower set was formed subsequent to the late Younger Dryas deglaciation, at ca. 10.3 ka BP. At Stóra-Fellsöxl, at the eastern flank of Akrafjall (Fig. 2), there is a large sediment terrace which Ingólfsson (1988) interpreted as a marginal delta formed when relative sea level was situated at 80 to 90 m a.s.l., and suggested that the northerly dipping foreset bed at this location showed that meltwater had been controlled by a glacier occupying the Hvalfjördur trough at the time of deposition. He suggested an Older Dryas age for the deposit. Finds of fossil whalebones in foreset gravels at the Stóra-Fellsöxl gravel pit at Akrafjall in 1997 (Magnúsdóttir and Norddahl, 2000) led to the re-examination of the deposits and gave the possibility for age determination of the higher set of raised beaches by ^{14}C.

Methods

Landforms and outcrops of sediments were mapped from aerial photos, and examined in the field during fieldwork in 1995, 1996, and 1997. Elevations (m a.s.l.) were recorded by repeated measurements by an AIR-HB-11 digital barometer/altimeter, with the Skorradalsvatn lake surface (57 m a.s.l.) and present mean sea level (± 0 m a.s.l) as calibration datum. The maximum inferred error in elevations is ± 2 m. The surface altitude of the Stóri-Sandhóll terrace at 148 m a.s.l. is given by a benchmark from the Geodetic Survey of Iceland. Stratigraphical work was carried out by excavation and logging. The AMS radiocarbon dating of fossil shells was carried out at the Ångström Laboratory of Uppsala University; the dating of the whalebone was carried out at the AMS ^{14}C Dating Laboratory Aarhus-Reykjavík.

Geomorphologic Setting

Topographically constrained glaciers have shaped the landscape of the lower Borgarfjördur area (Fig. 2). The large fjords/valleys of Borgarfjördur and Hvalfjördur are glacial troughs, eroded by large outlet glaciers that have drained the Icelandic inland ice sheet (Fig. 1). Skorradalur, a 25-km-long, glacially eroded valley, running approximately east-west, is partly occupied by a long (16 km) and narrow (1.5 km), 48-m-deep lake. The lake level is at 57 m a.s.l., dammed towards west by a bedrock threshold that reaches 60 m a.s.l. Upper reaches of the Skardsheidi massif, south of Skorradalur, were probably a nunatak during the LGM (Ingólfsson, 1988). Skardsheidi is characterised by glacial cirques, horns and arrêtes, created by interaction of glacial and periglacial activities. The Skardsheidi cirques have floors around 400 m a.s.l., and headwalls reaching 700–900 m. Most of the cirques lack a distinct basin threshold, which could indicate that the cirque glaciers fed and merged with outlet glaciers in the valleys during the glaciation. The LGM thickness of glaciers in coastal western Iceland has been estimated between 600 and 800 m (Ingólfsson, 1988; Rundgren and Ingólfsson, 1999).

Raised Bolling Shorelines in Skorradalur

Along the southern slope of Skorradalur, just before it opens into the main Borgarfjördur valley, there is a system of terraces, stretching for about 3 km at altitudes between 105 and 148 m a.s.l. (Fig. 3). This is considerably higher than the ca. 10.3 ka BP regional marine terrace system, which is marked by delta bodies and beach terraces at altitudes below 60–70 m a.s.l. along the eastern flank of the Borgarfjördur valley. The high terrace system in Skorradalur is dissected by postglacial fluvial erosion and in places partly covered by solifluction lobes. Surface materials on the terrace platforms are sorted and relatively well-rounded pebble gravels, with occasional boulders. The internal structure and stratigraphy of the terraces were studied at two sites: Stóri-Sandhóll, close to the mouth of the Skorradalur valley (Figs. 3, 4, 5), and above Mófellstadakot, about 1.5 km further in the valley (Figs. 3 and 6).

THE STÓRI-SANDHÓLL SECTION

The Stóri-Sandhóll section has the appearance of a hillock (Figs. 4, 5), defining a ca. 200-m-wide terrace below the slopes of Skardsheidi. The surface of the terrace slopes gently from the highest point at 148 m towards its intersection with the north-facing slope of Skardsheidi. The terrace sediments were studied in a 300-m-long and up to 30-m-high section of sediments. Two major lithofacies constitute the terrace sediments: a diamicton