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The Depositional History of the Younger Dryas–Preboreal Búdi Moraines in South-Central Iceland

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Abstract

Detailed sedimentological analysis of the Búdi morainal complex in south-central Iceland records a rapid accumulation within marine-, coastal, and glacial environments during a recessional phase of the glaciers within the Preboreal chronozone. Three principal outcrop areas are characterized by stratified diamictite, fine-grained silty-sandstone, and diamictite with dropstones; gravel-and sandfills of channels are also important. Elsewhere, the morainal complex is characterized by deltaic sedimentary structures that reflect an interweaving of marine and terrestrial processes. The Búdi morainal complex indicates a recession of the glacier margin, possibly since the Younger Dryas stadial. Sea-level changes, jökulhlaups, and glacier dynamics were responsible for fluctuation of the glacier margin and for the differential rate of calving during the accumulation of the morainal complex. Earlier conclusions on two separated glacier readvances are disputed.

Introduction

Recent literature on the climatic history of the northern hemisphere has emphasized the role of the marine environment, ocean currents, sea-ice cover, and the shifting position of the polar fronts in the North Atlantic region (Ruddiman and McIntyre, 1973; Broecker et al., 1985; Bond et al., 1992; Lehman and Keigwin, 1992; Koç et al., 1993; Koç and Jansen, 1994; Sarnthein et al., 1995; Oppo and Lehman, 1995). The location of Iceland (Fig. 1A) at important oceanographic boundaries in the North Atlantic allows for a study on the sensitivity of the terrestrial record to changes in the marine environment and delineation of these changes through time. To a considerable extent, the deglaciation history of Iceland has been based on geomorphological studies of moraines, raised deltas, and outwash deposits. The chronology is founded on relatively few radiocarbon dates, and in many cases, the stratigraphic and depositional significance remains equivocal. The Búdi morainal complex in south-central Iceland (Fig. 1B, 1C) is one of the most prominent morphological features related to the deglaciation of the island. It is located approximately 40 km inland from the current coastline and forms hills reaching 75 to 100 m a.s.l. The highest marine limit in the area is 110 m a.s.l. Up to now, little effort has been made to understand the association of sedimentary facies and depositional processes of this morainal complex and the surroundings. Its origin has been attributed to (1) a glacial readvance during the Younger Dryas chronozone (Kjartansson, 1943, 1958; Einarsson, 1964); and (2) a Preboreal ice advance in southern Iceland at 9800 BP (Hjartarson and Ingólfsson, 1988). Recent results from studies of sediments in southern and northern Iceland show that glacier oscillations due to temperature changes occurred during the transition from the Allerød interstadial to the Younger Dryas stadial (Ingólfsson, 1991; Norddahl, 1991; Sveinbjörnsdóttir et al., 1993; Geirsdóttir and Eiríksson, 1994; Rundgren, 1995). It has proved more difficult to relate the formation of the Búdi moraines with Preboreal temperature deterioration.

This study presents a new reconstruction of the paleoenvironment based on the sedimentological aspects of the Búdi morainal complex. The results deviate substantially from previous conclusions on the lithostratigraphy and formation of these sediments, particularly as to the number of sedimentary facies, glacial activity, and sea-level changes during the depositional history. Instead of a major glacier readvance during the Preboreal chronozone as proposed by recent investigators (Hjartarson and Ingólfsson, 1988), we suggest that the glacier margin was relatively stationary during the period of accumulation from the Younger Dryas stadial and into the Preboreal chronozone. A combination of sea-level fluctuations, topography, jökulhlaups, and glacier dynamics, rather than climatic deterioration, played a major role in the position of the glacier margin and the formation of the morainal complex.

Geographic Setting and Previous Research

The study area lies at the divide between the high interior and the southern lowlands of Iceland, at the head of Thjórsárdalur valley which drains parts of the central highlands (Fig. 1C, 1D). Active volcanoes, both within the valley and the bordering regions, contribute to the sediment input. The Búdi morainal complex forms a long string of broad, 10- to 20-m-high hills across the southern lowlands of Iceland (Fig. 1C). At several locations, major rivers cut through the complex affording up to 25-m-high sections through the deposits. Three such locations were selected for the present study (Fig. 1D): (1) the Búdafoss section, an approximately 1.2-km-long cliff exposure at ca. 65–75 m a.s.l., forms the northern banks of the river Thjórsá from the Búdi waterfall in the east; (2) the Thrándarholt section lies 2.5 km farther down the Thjórsá river by the farm Thrándarholt, where the 1.4-km-long exposure is at 65–75 m a.s.l.; and (3) the Hrepphólar section is located farther north below the farm Hrepphólar at 75 m a.s.l., where a 0.7-km-long section forms the northern banks of the river Stóra-Laxá.

The regional distribution of the Búdi morainal complex (Fig. 1C) is reasonably well documented from morphological studies (Keilhack, 1884; Thoroddsen, 1906; Kjartansson, 1939, 1943, 1958). Kjartansson (1939) correlated the morainal ridges with the Salpausselka end moraine complex in Finland and the

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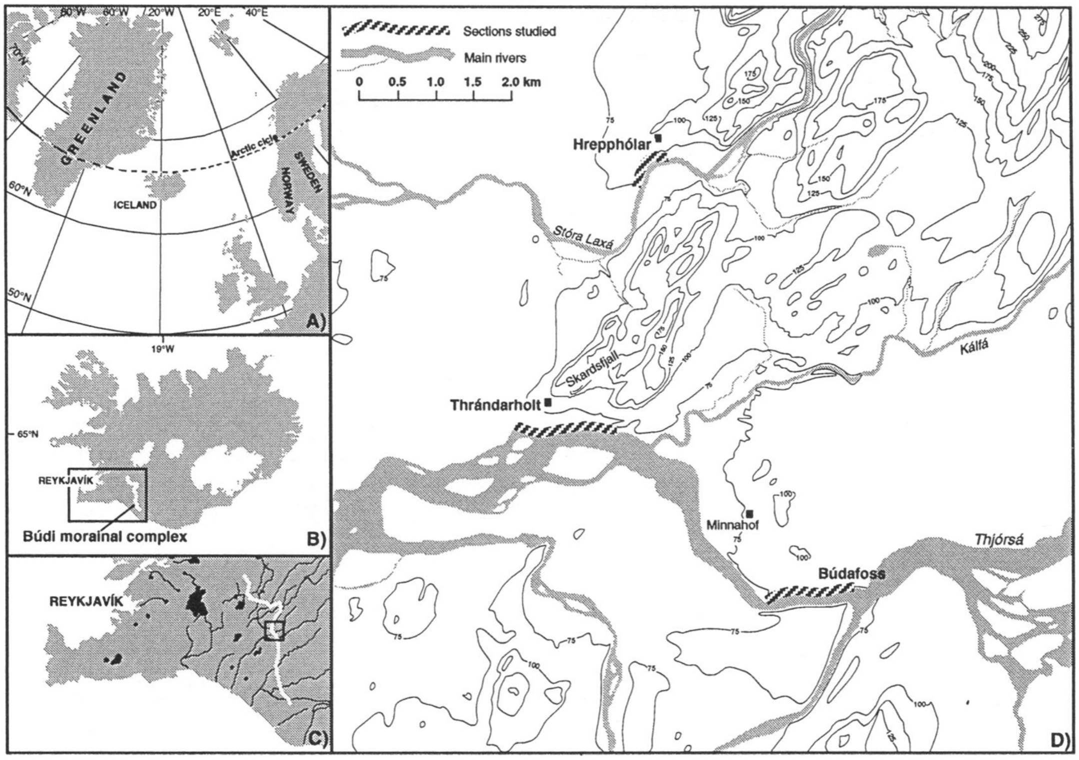

FIGURE 1. A. Location of Iceland in the North Atlantic. B. A map of Iceland showing the location of the Búdi morainal complex across the southern lowlands. C. The southern lowlands of Iceland. D. A topographic map of South-Central Iceland showing the location of the Búdafoss-, Thrándarholt, and the Hrepphólar sections.

Ra moraines in Norway, which had been related to a glacial advance during the Younger Dryas chronozone. Einarsson (1960a, 1960b, 1961, 1963) noted that the Búdi moraine is a complex of several ridges and concluded from palynological studies that the moraines were older than 14,000 yr BP. With the addition of new ^{14}C-dates from shell fragments found close to the morainal complex, he later agreed with Kjartansson's conclusions (Einarsson, 1964). A Younger Dryas age was suggested by Hjartarson (1985) on the basis of new ^{14}C-dates on shell fragments from the southern lowland. Hjartarson and Ingólfsson (1988) published some additional dates (Table 1), corrected for $^{13}C/^{12}C$ fractionation and the resevoir effect of sea-water, that suggested the morainal ridges were of Preboreal rather than Younger Dryas age.

Only sporadic descriptions have been available of the sediments that comprise the Búdi morainal complex. Áskelsson (1930) described the moraines as clay banks with some interfingering varves close to the Búdafoss waterfall. Kjartansson (1939) gave a more detailed description: striated lava flow underlying clast-loaded clay bed and sandy-clay, capped by conglomerate and eolian deposit. Hjartarson and Ingólfsson (1988) described the sediments at the Búdafoss location (Fig. 1D) as a stratified diamicton (basal tillite) on top of a striated pillow basalt, then a 25-m-thick silty diamicton bed (ice-proximal/near shore glaciomarine accumulation), overlain by a third diamicton (basal tillite). They concluded that an overriding glacier had tectonized and deformed the sediments up to this level and deposited the third diamicton. After the glaçier retreated, deposition of sand and gravel took over, forming the top of the section.

Sedimentary Facies and Environment

The principal outcrop areas of the Búdi morainal complex at Búdafoss, Thrándarholt, and Hrepphólar (Fig. 1D) have been reexamined in detail with the aim of identifying and mapping sedimentary lithofacies, and to reconstruct the environment through time. A cross section of the Búdafoss and the Hrepphólar sediments is presented in Figure 2, and a column of the major facies, facies assemblages (FA) and their depositional environment for each section, is presented in Figures 3, 5, and 6. A composite column with description of the depositional environment for all three sections is given in Figure 8.

THE BÚDAFOSS SECTION

The Búdafoss section (Fig. 2A) overlies a small outcrop of basaltic lava at the westernmost locality. The glassy and pillowy appearance of the basalt implies a formation within a wet environment, perhaps as a lava delta. Faint grooves or striations are detected at the lava surface. Lying directly upon the pillow lava is a chaotically stratified diamictite up to 2.4 m thick (Fig. 3; Facies Assemblage 1 [FA1]). The matrix is brownish-gray silty-sand. It contains a considerable amount of light colored and black tephra grains (up to 1 cm), some of them pumice-like. Well rounded and angular striated cobbles and boulders are also distributed throughout the diamictite. Clast fabric measurements show a girdle-like pattern, although a distinct vector with a direction of 105° is detected. Most of the clasts show an easterly long-axis dip direction (Fig. 3). The diamictite contains discrete mudstone, sandstone, and gravel lenses, which give it the chaotic appearance (Fig. 4A). Soft sediment deformation (loading) structures, mainly around clasts and boulders, are common. The bedding is most conspicuous in the uppermost part of the assemblage, where it also becomes more gravelly. Frequent *Balanus balanus* are found on the surface of the diamictite. The crude stratification of this facies assemblage and the girdle-like fabric of clasts, are consistent with an origin as a resedimented till or

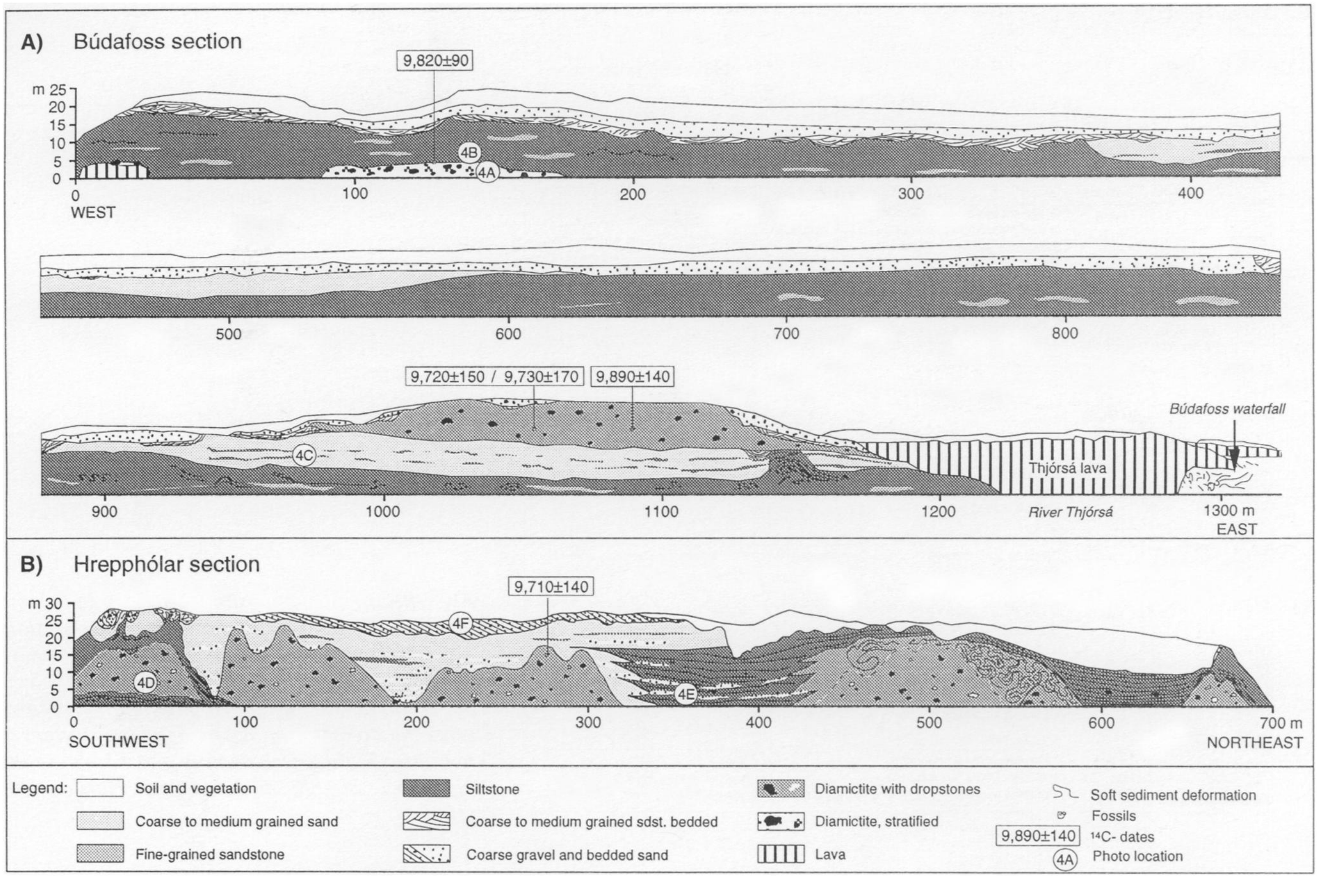

FIGURE 2. A. A cross section of the Búdafoss sediments, B. a cross section of the Hrepphólar sediments.

debris flow in front of a glacier margin. We depict a series of events which led to accumulation of diamict, gravel and sand, that was subsequently reworked by marine currents. During the diamictite formation, a contemporaneous calving ice-margin is envisaged, resulting in debris release from icebergs (Fig. 3; FA 1). This interpretation is compatible with results of Mackiewicz et al. (1984), Powell and Molnia (1989), and Eyles et al. (1991) from glaciomarine environments in Alaska. The age of this diamictite is not known, but the *Balanus balanus* found on the surface of the diamictite have been ^{14}C-dated at 9820 ± 90 BP (Hjartarson and Ingólfsson, 1988; Table 1, Lu-2404).

The diamictite is succeeded by an assemblage of alternating siltstone and sandstone beds (Fig. 3; FA 2, Fig. 4B). In some places sand and mud have been mixed together, elsewhere the brown sandstone beds show normal grading over to silt. The bedding becomes increasingly disturbed upwards, displaying numerous soft sediment deformations, such as load casts and flame structures. Black and light-colored pebbles of tephra are fairly common throughout the unit. Separate, 3-to 5-cm-thick lenses of coarser material, predominantly of tephra composition, are also present. The deformed unit is overlain by a thin (10 cm) horizontally laminated siltstone and a massive, pebbly siltstone to fine-grained sandstone (Fig. 3; FA 2). The sediments grade upwards into a unit of irregularly folded sandstone and siltstone layers alternating with thin massive siltstone beds and finally into a rhythmic succession of laminated siltstone and trough

TABLE 1

Radiocarbon dates used in this study

Sample number	Location	Uncorrected ^{14}C age[a]	Reservoir corrected ^{14}C age (400 yr)	Reference
AAR-1241	Búdafoss	10,290 ± 140	9,890 ± 140	This study
AAR-1242	Búdafoss	10,120 ± 150	9,720 ± 150	This study
AAR-1243	Búdafoss	10,130 ± 170	9,730 ± 170	This study
Lu-2404	Búdafoss	10,220 ± 90	9,820 ± 90	Hjartarson and Ingólfsson, 1988
Lu-2403	Thrándarholt	10,360 ± 90	9,960 ± 90	Hjartarson and Ingólfsson, 1988
Lu-2401	Hrepphólar	10,110 ± 140	9,710 ± 140	Hjartarson and Ingólfsson, 1988
Lu-2402	Hrepphólar	9,960 ± 160	9,560 ± 160	Hjartarson and Ingólfsson, 1988
W-482	Thjórsárbrú	8,065 ± 400	N/A	Kjartansson, 1964
W-913	Thjórsárbrú	8,170 ± 300	N/A	Kjartansson, 1966
Lu-2601	Búdafoss (peat)	7,800 ± 60	N/A	Hjartarson, 1988

[a] All uncorrected ^{14}C dates except samples W-482, W-913, Lu-2601 have been corrected for $\delta^{13}C/^{12}C$.

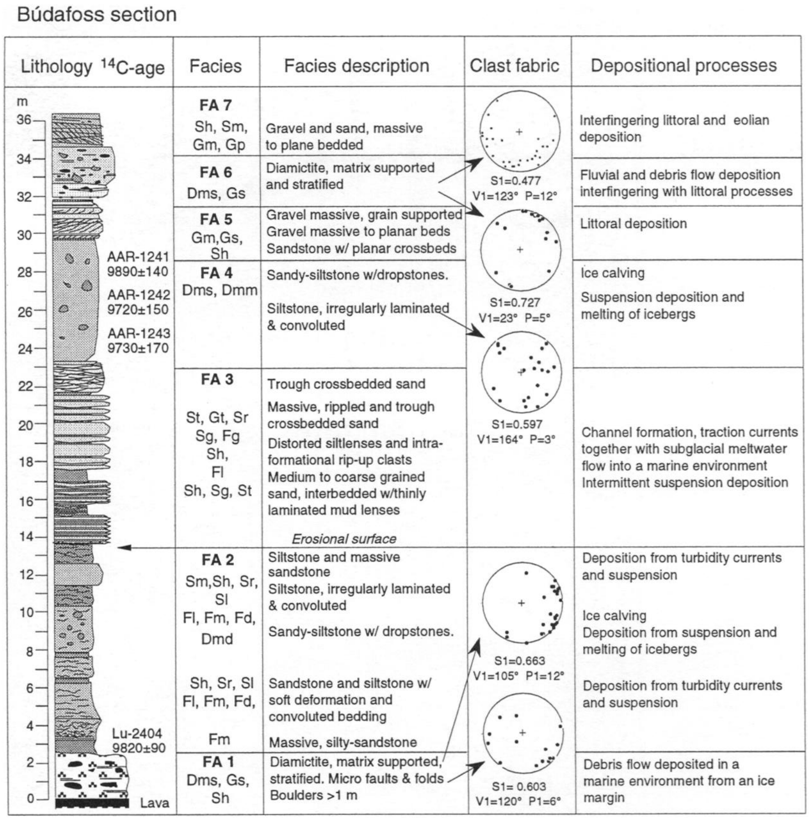

FIGURE 3. A composite stratigraphic column and clast fabric data from the Búdafoss section. Lithofacies codes based on Eyles et al. (1983). Number of clasts measured for each sample is 30, S1 indicates the fabric strength, V1 represents the direction of maximum concentration of long axes within each sample and P1 shows the dip of V1. Slightly modified from Hardardóttir (1993).

cross-bedded sandstone. The increasing deformation structures from bottom to top point to loading and syndepositional sliding processes, whereas flame structures probably indicate penecontemporaneous current activity or horizontal tension (Brodzikowski and Haluszczak, 1987). The loading structures imply a fairly high accumulation rate and a high energy depositional environment. Albeit, the overall appearance of these bedded, folded and convoluted facies suggests intermittent periods of sorting. Rhythmitic association of layered sandstone and siltstone indicates a deposition from turbidity currents and suspended material from over-interflow currents (Eyles and Lagoe, 1990). Some ice-rafting (icebergs and/or sea-ice) is denoted from abundant pebbles within the assemblage.

An erosional surface marks the beginning of the next assemblage. Channels, 50 to 200 m wide and 5 to 10 m deep, cut the underlying consolidated silty-sandstone assemblage (Fig. 2A). Medium to coarse grained sand interbedded with laminated mud fill the erosional channels (Figs. 3 [FA 3], Fig. 4C). The sand assemblage is both massive and bedded; planar and trough crossbedded. The silt-lenses are commonly distorted or form intraformational rip-up clasts within the sand beds. Small scale channels filled with planar and trough crossbedded sand become more frequent in the uppermost part of the assemblage (ca. 3 m), where troughs often start with a pebble layer. Formation of the erosional contact reflects a period of increased energy within the depositional environment (Fig. 3; FA 3). Pulses of subglacial meltwater (jökulhlaups) into the marine environment are thought to be the major cause for the formation of the channels and a subsequent deposition of the sand layers (e.g. Stewart, 1991). Silt lenses within the sandy channel fills are explained by a change in energy and reflect a deposition from over-interflow currents during calm periods. The intraformational rip-up clasts indicate current reworking of cohesive, muddy sediments during periods of increased flow that may be related to both tidal effect as well as increased runoff.

Overlying the channel deposit is a 5-to 15-m-thick diamictite (Fig. 3; FA 4). This diamictite can be traced approximately 300 m to the west from the Búdafoss waterfall (Fig. 2A). Its matrix is mostly silty-sand with irregular, fine-grained sandstone and conglomerate lenses. Distortion of laminae is obvious. Both light colored and black tephra is mixed within the matrix and sandstone lenses. Cobbles and boulders are randomly distributed within the matrix, the largest >25 cm in diameter. Fabric measurements made on cobbles show a widely distributed orientation and high dip angle (Fig. 3). Two fragments of *Balanus balanus* were found in this diamictite. They imply formation within a marine environment. Furthermore, numerous clasts within the unit and their fabric suggest ice rafting (Domack and Lawson, 1985; Fig. 3; FA 4). The diamictite suggests changing activity in iceberg accumulation. This could either be related to a minor readvance of the ice margin (Eyles and Lagoe, 1990) or increased calving due to the jökulhlaup event responsible for the underlying assemblage. A lack of an erosional contact between the two assemblages and signs of continuing sedimentation from suspension, supports the latter explanation. ^{14}C-dates on the two *Balanus balanus* fragments give ages of 9890 ± 140 BP, 9720 ± 150 BP, and 9730 ± 170 BP (Table 1, AAR-1241, AAR-1242, AAR-1243).

On top of the diamictite is a dark colored pebbly sand and gravel unit (Fig. 3; FA 5). It is semilithified with rounded pebbles and cobbles, which become smaller away from the Búdafoss waterfall. The lowest part of the assemblage is horizontally bedded, but crossbeds become more apparent towards the top. Bi-directional crossbeds are prominent at first, whereas uni-directional crossbeds become more common towards the top. The change from horizontally bedded strata towards bi-directional strata suggests a formation just below and then at the marine limit. This reflects a drop in sea level within the area.

A matrix supported boulder bed of variable thickness succeeds the sand and gravel unit (Fig. 3; FA 6). Clasts are mainly semirounded. Some stratification is apparent due to intervening lenses of coarse sand and pebbles and less common silt-lenses. Very fine laminations are also detected. Clast fabric measurements on pebbles show a southeasterly direction for the long axes (123°). The fabric pattern is rather scattered and shows high dips of the clasts' a-b plan (Fig. 3). This unit is interpreted as a remnant of a reworked flow unit that formed originally in front of a retreating glacier outlet. It marks the first major terrestrial sedimentation within the Búdafoss section. However, coastal processes may have reworked the assemblage.

Scattered outcrops of horizontal crossbedded sandstone are observed on top of and interweaving with the matrix supported boulder bed (Fig. 3; FA 7). The medium-grained sandstone shows a narrow grain distribution although scattered small pebbles and granules are present. Based on the narrow grain-size distribution, this assemblage is thought to be of an eolian origin.

THE THRÁNDARHOLT SECTION

The lowermost facies assemblage in the Thrándarholt section (Fig. 1D) comprises stratified diamictite, conglomerate, and sandstone, with occasional siltstone lenses. It is approximately 2 m thick and crops out in the westernmost part of the section (Fig. 5; FA 1). The matrix is mostly medium to coarse grained sand, gray-brownish colored. Pebbles, cobbles, and boulders form lenses within the otherwise chaotically stratified matrix. Numerous microfaults and folds are apparent. This unit resembles the lowermost stratified diamictite at the Búdafoss section (Figs. 3, 5; FA 1). Broad grain-size distribution, microfaults and folds indicate an accumulation at an ice-margin as a series of stacked debris flows.

An assemblage of sandy-siltstone facies lies on top of the diamictite (Fig. 5; FA 2). Stones are scattered within the matrix. The lower part of the assemblage is irregularly laminated with 1–3 mm thick laminae of siltstone and claystone and occasional cobbles. Its upper half grades into massive sandstone and siltstone accompanied with distinct change from brownish gray to silty gray color. Single sand lenses are found in the uppermost part of this assemblage. It is correlated with similar facies associations in the Búdafoss section (Figs. 3, 5; FA 2) and indicates accumulation from suspension and gravity currents at a higher sea level than today. The lower laminated part of the assemblage reflects a relatively slow accumulation rate whereas the massive part implies a higher accumulation rate with less current activity. Increasing number of dropstones towards the top of the facies assemblage indicates an increased rate of ice breakdown and melting.

A unit of pebbles and cobbles in a coarse-grained sand and

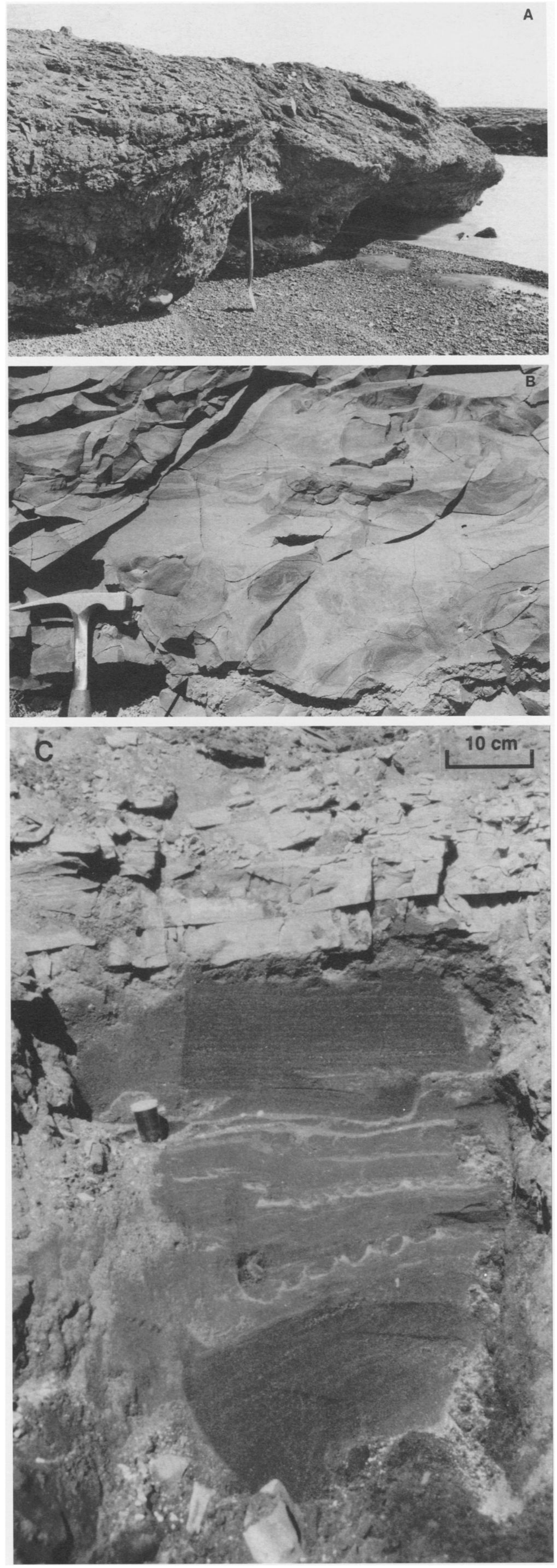

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FIGURE 4. Facies assemblages from the Búdafoss and Hrepphólar sections. A. Facies assemblage 1. Chaotically stratified diamictite in the westernmost part of the Búdafoss section. Approximate height of shovel is 1 m. B. Massive siltstone overlain by folded sandstone and siltstone in facies assemblage 2, Búdafoss. The contact is shown by the arrow. C. Facies assemblage 3. Stratified sand interbedded with laminated silt lenses in the Búdafoss section. Flame structures and minor faults are observed within the siltlayers.

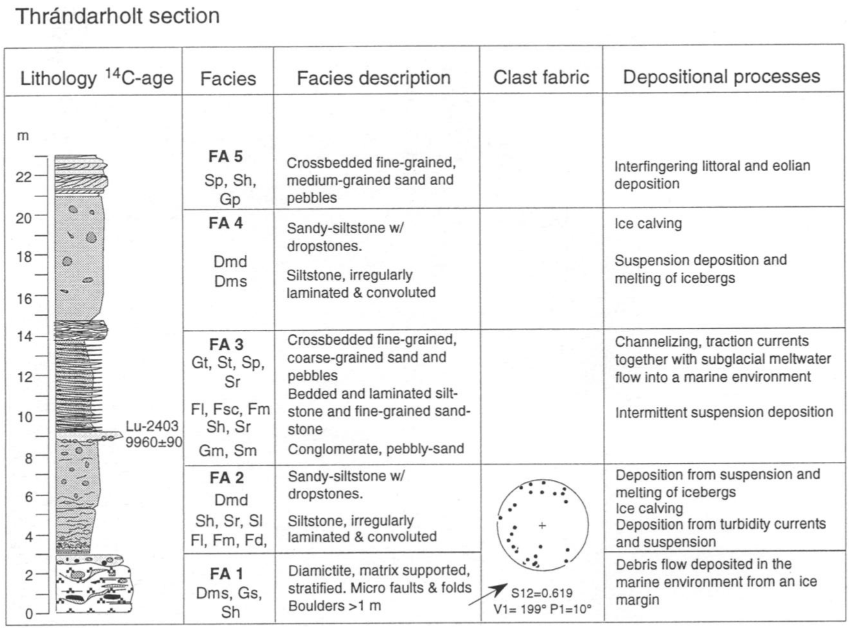

FIGURE 5. A composite stratigraphic column of the Thrándarholt section. Lithofacies codes based on Eyles et al. (1983).

gravelly matrix lies discordantly over the sandy-siltstone (Fig. 5; FA 3). This unit has variable thickness, forming a thin (50 cm) layer in one place, but filling up to 4-m-deep channels in other places. The channel-fills start with stratified successions of gravel and sand that grade into bedded and finely laminated sand and siltstone. Channel formation and subsequent deposition of gravel and sand is related to increased meltwater inflow and bottom current activity. This is correlated to facies assemblage 3 in the Búdafoss section (Figs. 3, 5; FA 3). The underlying sandy-siltstone penetrates the channels-fills in places, forming diapiric structures. It may be explained by a sudden reversal of the density gradient related to the deposition of the channel-fills.

Laminated siltstone overlies the channel-fill sediments. It grades upwards from convoluted siltstone to a faintly laminated to massive siltstone with randomly distributed clasts (Fig. 5; FA 4). The unit was formed within a similar environment as facies assemblage 4 in the Búdafoss section (Figs. 3, 5; FA 4), where numerous dropstones strongly suggest melting and glacier breakdown.

Crossbedded gravel and sand facies (Fig. 5; FA 5) discordantly overlie the siltstone. The sand shows a narrow grain-size distribution, although pebbles and cobbles can be found in lenses. Grain-size distribution and bedding indicate formation within concurrent fluvial and eolian environments.

THE HREPPHÓLAR SECTION

A 2-m-thick succession of laminated sandy-siltstone forms the base of the Hrepphólar section (Fig. 2B, 6; FA 1). The laminations become folded and distorted towards the top where numerous microfaults occur. This unit has comparable appearance to facies assemblage 2 at Búdafoss and Thrándarholt (Figs. 3, 5, 6; FA 2). It can be explained as a deposition from suspension and turbidity currents during higher sea level. Distortion and microfaults may be due to iceberg scouring (cf. Woodworth-Lynas and Guigné, 1990).

This facies assemblage grades into a diamictite with thin irregular laminae (Fig. 5; FA 2). Both pebbles and boulders are numerous and display diverse lithologies (Fig. 5A). Pumice grains (1–3 mm) are distributed throughout the matrix and shell fragments are also found. Configuration of this diamictite unit is very irregular. It forms an approximately 11-m-thick succession in the westernmost part of the section, but only 0 to 2 m thick unit farther east (Fig. 2B). The diamictite grades into a finely bedded to laminated fine- and coarse-grained sandstone (Fig. 6; FA 3). Towards the top the unit resembles the underlying diamictite again as both grain-size and laminations become finer and single clasts more common. The conformable basal contact indicates continuous accumulation from suspension, whereas the numerous clasts reflect deposition from melting icebergs. Shell fragments found in the diamictite have been ^{14}C-dated to 9710 ± 140 BP (Hjartarson and Ingólfsson, 1988; Table 1, Lu-2401).

A deformed erosional contact separates the diamictite and the overlying sedimentary unit (Fig. 6; FA 4). It starts with a pebbly layer, but is characterized by interbedded layers of conglomerate and pebbly bedded sandstone to laminated siltstone. Channels and trough crossbedding, along with small-scale normal faults and folds are conspicuous. A considerable difference is observed between the channel-fills from west to east along the Hrepphólar section. Erosional channels are filled with conglomerate, amalgamated and graded sandstone in the westernmost sections, but laminated siltstone layers with occasional sand and gravel lenses are more conspicuous in sections to the east (Fig. 7B). Flaser beds and localized folds and deformed laminae are common in these finer grained channel-fills. It is evident from erosional contacts and the coarser parts of this assemblage that higher energy and current activity prevailed during its formation (Stewart, 1991). The interfingering relationship between the coarse-and fine-grained channel-fills reflects contemporaneous coastal and glaciolacustrine processes. This marks a phase when equilibrium between the rate of eustatic sea level and isostatic rebound was reached.

A boulder bed, with boulders up to 1 m in diameter, overlies and interfingers with the pebbly layer (Fig. 6; FA 5). It becomes finer grained towards the top with some conglomerate and sandy matrix. Well-rounded and angular clasts are embedded in the coarse-grained matrix. The underlying sedimentary units form diapiric structures up through this bouldery conglomerate. Thrust faults are conspicuous and measurements of the bedding planes show a strike orientation of 150°, with dip towards 211°. The boulder bed is interpreted as a result of a catastrophic release of

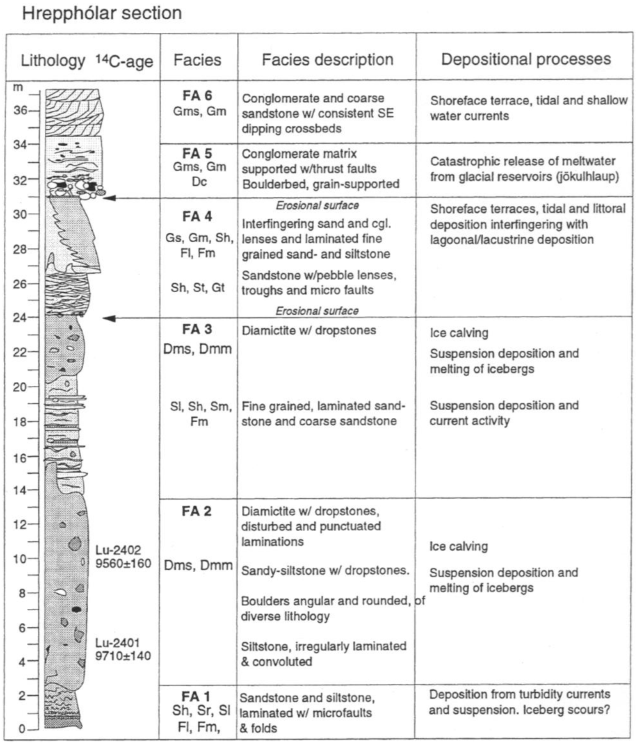

FIGURE 6. A composite stratigraphic column and clast fabric data from the Hrepphólar section. Lithofacies codes based on Eyles et al. (1983). Number of clasts measured for each sample is 30, S1 indicates the fabric strength, V1 represents the direction of maximum concentration of long axes within each sample and P1 shows the dip of V1.

meltwater from glacial and proglacial reservoirs (jökulhlaups). A large amount of sorted coarse-grained material and boulders accumulated in a very short time. The diapirs and the deformation structures in the underlying sediments were probably caused by this sudden impact. A release of numerous icebergs contemporaneous with the jökulhlaup event may also have contributed to the disturbance of primary structures and activated sediment flowage processes.

In the middle and easternmost part of the Hrepphólar section is a unit of crossbedded sand and gravel with a consistent dip towards northeast (strike 340°; dip 27°) (Fig. 6; FA 6, Fig. 7C). It is interpreted as a shoreface terrace that formed during a period of increased sediment supply and coastal activity subsequent to the retreat of the glacier margin.

Reconstruction of the Paleoenvironment on the Basis of the Búdi Morainal Complex

A COMPARISON OF THE SEDIMENT ACCUMULATION AT BÚDAFOSS, THRÁNDARHOLT AND HREPPHÓLAR

All three sections are characterized by an interfingering relationship between glaciomarine and terrestrial lithofacies. The facies assemblages consist of diamictite formed in front of a calving glacier, marine mud and glaciomarine mud with dropstones, shallow marine sandstone, sandy deltaic foresets and lacustrine sediment, fluvial sandstone, and conglomerate. Distinct channelizing is found in all sections. A composite section from Búdafoss, Thrándarholt, and Hrepphólar sediments is used to describe the general development in the glaciomarine environment during the build-up of the Búdi morainal complex (Fig. 8).

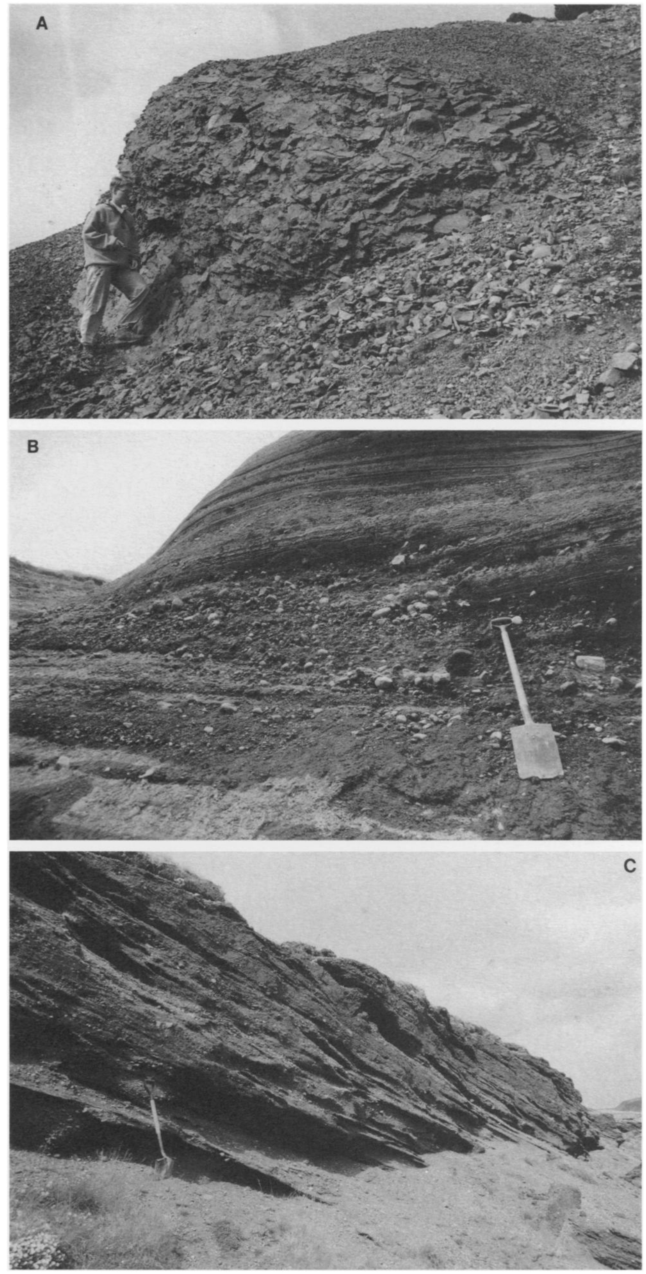

FIGURE 7. A. Facies assemblage 2 at Hrepphólar. Diamictite with dropstones of various sizes and lithologies. Dropstones are indicated by arrows. B. Facies assemblage 4 at Hrepphólar. Finely laminated silt with occasional gravel lenses. C. Facies assemblage 6 at Hrepphólar. Cross bedded sand and gravel.

However, it should be noted, that large part of the complex does not show such glaciomarine sediment, but is mainly characterized by deltaic sedimentary structures reflecting the interfingering of marine and terrestrial environments.

The Búdafoss and Thrándarholt sections display almost identical facies arrangement, although facies assemblages have variable significance in each succession (Figs. 3, 5, 6). Five of seven facies assemblages identified at the Búdafoss and Thrándarholt sections show a continuous marine setting for the successions. The pillow lava at the base of the section presumably flowed into an aqueous environment. Its age, however, is not known. The stratified diamictite on top of the pillow lava was deposited in the marine environment as debris flow deposit in front of an ice margin. ^{14}C dates of *Balanus balanus* found on

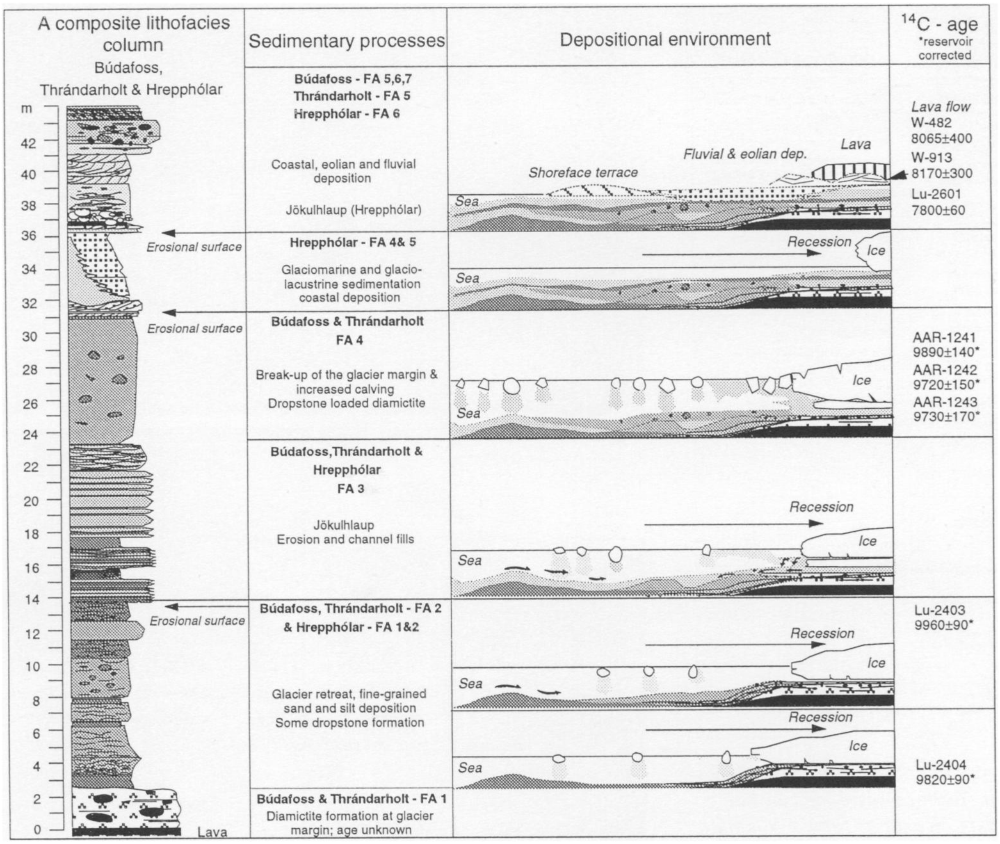

FIGURE 8. A composite column for the Búdafoss, Thrándarholt and Hrepphólar sections. Lithofacies codes based on Eyles et al. (1983). ^{14}C dates from peat and charcoal underneath the lava come from Kjartansson (1964, 1966) and Hjartarson (1988).

the surface of this diamictite give the minimum age of 9820 ± 90 BP (Hjartarson and Ingólfsson, 1988; Table 1) for this facies assemblage. Its formation could thus date back to the Younger Dryas stadial. Small pebbles found throughout the overlying silty material (FA 2) suggest some iceberg melting during the period of accumulation. Erosional channels within the silty-sandstone and filled with sand layers and siltstone lenses (FA 3), indicate a major change in the depositional environment. They are explained by increased subglacial meltwater inflow (jökulhlaup) into the marine environment. Dropstone loaded diamictite above the channel-fills indicate increased calving, probably caused by the break-up and melting of the glacier margin subsequent to the jökulhlaup event. ^{14}C dates of 9890 ± 140 BP, 9720 ± 150 BP, and 9730 ± 170 BP (Table 1) obtained from *Balanus balanus* found in the uppermost glaciomarine unit at Búdafoss give a similar age as the *Balanus balanus* obtained from the surface of the basal diamictite (Hjartarson and Ingólfsson, 1988; Table 1). The narrow ^{14}C range supports rapid deposition of the Búdi sediments above the basal diamictite, although the broken pieces and scarcity of epifauna in the upper diamictite indicate a reworking mechanism. An alternative is that the ^{14}C results may reflect anomalies in the late glacial CO_2 budget (Becker et al. 1991; Kromer and Becker, 1993). ^{14}C-dates made on peat samples underneath a lava flow capping the Búdafoss section (Fig. 8) suggest an ice-free and subareal environment before 8000 BP (Hjartarson, 1988).

The dropstone loaded glaciomarine diamictite in the Thrándarholt section is much more conspicuous than in the Búdafoss section (FA 2 and 4). A possible explanation for the difference is variable topography; whereas the Thrándarholt section is located at the base of Skardsfjall mountain, the Búdafoss section is situated in a broad and shallow valley (Fig. 1D). The Skardsfjall mountain may have built up a trap for icebergs where they accumulated and melted, resulting in a thicker succession of dropstone loaded diamictite at Thrándarholt.

The lower part of the Hrepphólar section displays a very similar depositional history as is observed at the other two locations. However, a diamictite bed at the base is missing and the interfingering relationship between terrestrial and coastal processes is more prominent. This is reflected in large-scale deformation structures and diapir formation that affect the whole succession at Hrepphólar. They indicate periods of rapid sedimentation probably caused by more frequent jökulhlaups at this site. During the retreat of the glaciers in Preboreal times, glacially dammed lakes drained into the proglacial marine environment and contributed to the sediment load (Kjartansson, 1943; Jóhannesson et al., 1995; Kaldal et al., 1995).

We envisage a thin glacier margin with separate lobes prograding into the marine embayment at several places. Islands may have controlled the extent of the glacier lobes and their possible halts during the recession of the glacier. However, our conclusion is, that the major factor affecting glacier dynamics and thus the extent of the glacier margin at this time, was increased subglacial meltwater pulses. The conspicuous amount of tephra grains found in lenses throughout the successions point to a very active volcanism that took place contemporaneously with the thinning and retreat of the inland ice sheet (Sejrup et al., 1989; Sigvaldason et al., 1992; Lacasse et al., 1995, Lacasse et al., 1996). This inferred volcanism may have triggered some of the jökulhlaups. The tephra grains are fresh with little or no sign of disintegration and the composition is basaltic, typical for the rift zone volcanism in Iceland (Grönvold, pers. comm., 1995). We depict a subglacial eruption with the formation of tephra that covered the ice surface. The scattered distibution of the tephra lenses within the sediments supports a rain-out from debris and tephra laden icebergs.

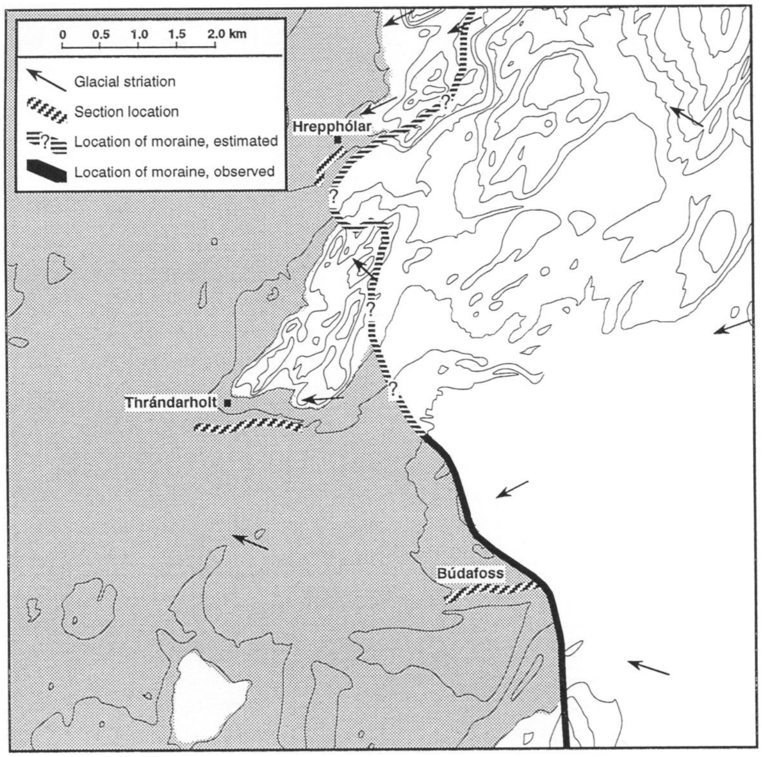

FIGURE 9. A tentative reconstruction of the depositional environment during the accumulation of the Búdi morainal complex. Shaded area indicates the marine environment.

Following the jökulhlaup event, the glacier retreated and the uppermost facies assemblages in all sections formed. Interweaving coastal, fluvial, and eolian deposition reflect the ensuing land emergence due to isostatic rebound.

IMPLICATION OF THE SEDIMENTARY STUDY FOR THE DEGLACIATION HISTORY OF THE SOUTHERN LOWLANDS

Previous research of the deglaciation history of southern Iceland propose an extensive Younger Dryas glacier reaching out onto the current Icelandic shelf. This extensive Younger Dryas glacier is based on the scarcity of shells found from the Allerød chronozone (Hjartarson and Ingólfsson, 1988; Hjartarson, 1991). Same research assigns the formation of the Búdi morainal complex to a glacier readvance during the Preboreal chronozone. Preboreal glacier sediments have been reported from northern Norway (Corner, 1980) and eastern Greenland (Funder, 1989; Landvik, 1994). Their formation has been explained by instability of the ice margin caused by increased atmospheric and sea surface temperature, resulting in greater evaporation. Our sedimentological study of the Búdi morainal complex does not indicate a glacier advance related to climatic deterioration during the Preboreal chronozone. Instead, it indicates a relatively stagnant glacier margin controlled by topography, sea level, and jökulhlaup processes. The morainal complex marks the approximate coastline during its formation at the divide between the current high interior and the southern lowlands of Iceland (Fig. 9). The lowlands have plausibly been submerged since the Younger Dryas and into the Preboral chronozone indicating high sea level throughout this period. This contradicts Ingólfsson et al. (1995) curve of relative sea-level displacement for the Reykjavík area in southwest Iceland (Fig. 1B). They suggest a sea-level change of 45 m over a period of 900 ^{14}C years–between 10,300 BP and 9400 BP (from 43 m to -2 m). However, it is well known that isostatic uplift rates are highly variable from one region to another reflecting not only different asthenosphere viscosities, but also proximity to regional centers of glaciation. The location of the Búdi morainal complex relatively close to the proposed inland ice sheet center may have favored a delayed isostatic uplift associated with the ice-sheet retreat within the area.

Conclusion

New insight into deglacial events in the southern lowlands of Iceland is provided by detailed sedimentological study of the Búdi morainal complex.

The lithofacies studies suggest a continuous accumulation within a marine, coastal, and glacial environment from the Younger Dryas stadial and during a recessional phase of the glacier in Preboreal time.

Topography, jökulhlaups, glacier dynamics, and sea level, rather than climatic deterioration, are responsible for the fluctuation at the glacier margin and differential rate of calving during the accumulation of the Búdi morainal complex

Slight changes of the partially marine-based ice margin occurred during Preboreal jökulhlaups, that resulted in break-up of the glacier margin and subsequent accumulation of dropstone-loaded diamictites.

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References Cited

Áskelsson, J., 1930: On two varve diagrams from southern Iceland. *Geologiska Föreningens i Stockholm Förhandlinger,* 52: 214–218.

Becker, B., Kromer, B., and Trimborn, P., 1991: A stable-isotope tree-ring timescale of the Late Glacial/Holocene boundary. *Nature,* 353: 647–649.

Bond, G., Heinrich, H., Broecker, W., Labeyrie, L., McManus, J., Andrews, J., Huon, S., Jantschik, R., Clasen, S., Simet, C., Tedesco, K., Klas, M., Bonani, G., and Ivy, S., 1992; Evidence for massive discharges of icebergs into the North Atlantic Ocean during the Last Glacial Period. *Nature,* 360: 245–249.

Brodzikowski, K. and Haluszczak, A., 1987: Flame structures and associated deformation in Quaternary glaciolacustrine and glacideltaic deposits: examples from central Poland. *In* Jones, M. E. and Preston, R. M. F. (eds.), *Deformation of Sediments and Sedimentary Rocks.* Geological Society of America Special Publication, 29: 279–286.

Broecker, W. S., Peteet, D. M., and Rind, D. 1985: Does the ocean-atmosphere system have more than one stable mode of operation? *Nature,* 315: 21–26.

Corner, G. D., 1980. Preboreal deglaciation chronology and marine limits of the Lyngen-Storfjord area, Troms, North Norway. *Boreas,* 9: 239–249.

Domack, E. W. and Lawson, D. E., 1985: Pebble fabric in an ice-rafted diamicton. *Journal of Geology,* 93: 577–591.

Einarsson, Th., 1960a: Thaettir ur jardfraedi Hellisheidar. *Náttúrufraedingurinn,* 30: 151–175.

Einarsson, Th., 1960b. *Geologie von Hellisheidi.* Sonderveröffentlichungen des Geologischen Institutes der Universität Köln 5. 55 pp.

Einarsson, Th., 1961: *Pollenanalytische Untersuchungen zur spät- und postglazialen Klimageschichte Islands.* Sonderveröffentlichungen des Geologischen Institutes der Universität Köln 6. 52 pp.

Einarsson, Th., 1963. Pollen analytical studies on the vegetation and climate history of Iceland in late and post-glacial times. *In* Löve, A. and Löve, D. (eds.), *North Atlantic Biota and Their History.* Oxford: Pergamon Press, 355–365.

Einarsson, Th., 1964. Aldursákvardanir á fornskeljum. *In* Kjartansson, G., Thórarinsson, S., and Einarsson, Th., C14-aldursákvardanir á sýnishornum vardandi íslenska kvarterjardfraedi. *Náttúrufraedingurinn,* 34: 127–134.

Eyles, N., Eyles, C., and Miall, A. D., 1983: Lithofacies types and vertical profile models: an alternative approach to the description and environmental interpretation of glacial diamict and diamictite sequences. *Sedimentology,* 30: 393–410.

Eyles, C. H. and Lagoe, M. B., 1990: Sedimentation patterns and facies geometries on a temperate glacially-influenced continental shelf: the Yakataga Formation, Middleton Island, Alaska. *In* Dowdeswell, J. A. and Scourse, J. D. (eds.), *Glaciomarine Environments: Processes and Sediments.* Geological Society Special Publication, 53. London: Geological Society, 363–386.

Eyles, C. H., Eyles, N., and Lagoe, M. B., 1991: The Yakataga Formation: A late Miocene to Pleistocene record of temperate glacial marine sedimentation in the Gulf of Alaska. *In* Anderson, J. B. and Ashley, G. M., (eds.), *Glacial Marine Sedimentation: Paleoclimatic Significance.* Geological Society of America Special Paper, 261: 159–180.

Funder, S., 1989. Quaternary geology of the ice free areas and adjacent shelves of Greenland. *In* Fulton, R. J. (ed.), *Quaternary Geology of Canada and Greenland.* Ottawa: Geological Survey of Canada, 743–763.

Geirsdóttir, Á. and Eiríksson, J., 1994; Sedimentary facies and environmental history of the late-glacial glaciomarine Fossvogur sediments in Reykjavík, Iceland. *Boreas,* 23: 164–176.

Grönvold, K., 1995: Personal communication. Nordic Volcanological Institute, Grensásvegi 50, 108 Reykjavik, Iceland.

Hardardóttir, J., 1993: Jardlög vid fossinn Búda. Lýsing og túlkun. BS ritgerd, Jard-og landfraediskor, Raunvísindadeild, Háskóli íslands. 91 pp.

Hjartarson, Á., 1985: Aldur Búdaradarinnar og kenningin sem féll. OS-85044/VOD-19B: 15 pp.

Hjartarson, Á., 1988: Thjórsárhraunid mikla—staersta nútímahraun jardar. *Náttúrufraedingurinn,* 58: 1–16.

Hjartarson, Á., 1991: A revised model of Weichselian deglaciation in south and southwest Iceland. *In* Maizels, J. K. Caseldine, C. (eds.), *Environmental Change in Iceland: Past and Present.* Dordrecht: Kluwer Academic Publishers, 67–78.

Hjartarson, Á. and Ingólfsson, Ó., 1988: Preboreal glaciation of Southern Iceland. *Jökull,* 38: 1–16.

Ingólfsson, Ó., 1991: A review of the late Weichselian and early Holocene glacial and environmental history of Iceland. *In* Maizels, J. K. and Caseldine, C. (eds.), *Environmental Change in Iceland: Past and Present.* Dordrecht: Kluwer Academic Publishers, 13–29.

Ingólfsson, Ó., Norddahl, H., and Haflidason, H., 1995: Rapid isostatic rebound in southwestern Iceland at the end of the last glaciation. *Boreas,* 24: 245–259.

Jóhannesson, H., Geirsdóttir, Á., Einarsson, P., and Grönvold, K., 1995: Vitnisburdur um jardskjálfta fra sídjökultíma í setlögum í grennd Heklu. Jardfraedafelag Íslands. Vorrádstefna 1995, ágrip erinda og veggspjalda, Reykjavík. p. 12. (Abstract volume, Geological Society of Iceland.)

Kaldal, I., Vilmundardóttir, E., and Larsen, G., 1995: Súr gjóska í vatnaseti ad Fjallabaki. Jardfraedafélag Íslands. Vorrádstefna 1995, ágrip erinda og veggspjalda, Reykjavík. p. 39. (Abstract volume, Geological Society of Iceland.)

Keilhack, K., 1884: Über postglaciale Meeresablagerungen in Island. *Zeitschrift der Deutschen Geologischen Gesellschaft,* 376–449.

Kjartansson, G., 1939. Stadier i isens tilbagerykning fra det sydvestislandske lavland. *Meddelelser fra Dansk Geologisk Forening,* 9: 426–458.

Kjartansson, G., 1943: *Árnesinga saga. Náttúrulýsing Árnessýslu, fyrri hluti. Yfirlit og jardsaga.* Reykjavík: *Árnesingafélagid.* 250 pp.

Kjartansson, G., 1958: Jarðmyndanir í Holtum og nágrenni. Rit landbúnadardeildar, B-flokkur nr. 11. Atvinnudeild Háskólans, Reykjavík. 22 pp.

Kjartansson, G., 1966: Nokkrar nýjar C-14 aldursákvardanir. *Náttúrufraedingurinn,* 36: 126–141.

Kjartansson, G., Thorarinsson, S., and Einarsson, Th., 1964: C-14 aldursákvardanir á sýnishornum vardandi íslenska kvarterjardfraedi. *Náttúrufraedingurinn,* 34: 97–145

Koç, N, Jansen, E., and Haflidason, H., 1993: Paleoceanographic reconstructions of surface ocean conditions in the Greenland, Iceland and Norwegian seas through the last 14 ka based on diatoms. *Quaternary Science Reviews,* 12: 115–140.

Koç, N. and Jansen, E., 1994: Response of the high-latitude Northern Hemisphere to orbital climate forcing: Evidence from the Nordic Seas. *Geology,* 22: 523–526.

Kromer, B. and Becker, B., 1993: German oak and pine ^{14}C calibration, 7200 BC to 9400 BC. *Radiocarbon,* 35: 125–135.

Lacasse, C., Sigurdsson, H., Jóhannesson, H., Paterne, M., and Carey, S., 1995: Source of Ash Zone 1 in the North Atlantic. *Bulletin of Volcanology,* 57: 18–32.

Lacasse, C., Sigurdsson, H., Carey, S., Paterne, M., and Guichard, F., 1996: North Atlantic deep-sea sedimentation of Late Quaternary tephra from the Iceland hotspot. *Marine Geology,* 129: 207–235.

Landvik, J. Y., 1994: The last glaciation of Germania Land and adjacent areas, northeast Greenland. *Journal of Quaternary Science,* 9: 81–92.

Lehman, S. J. and Keigwin, L. D., 1992: Sudden changes in North Atlantic circulation during the last deglaciation. *Nature,* 356: 757–762.

Mackiewicz, N. E., Powell, R. D., Carlson, P. R., and Molnia,

B. F., 1984: Interlaminated ice-proximal glacial-marine sediments in Muir Inlet, Alaska. *Marine Geology,* 57: 113–147.

Norddahl, H., 1991: Late Weichselian and early Holocene deglaciation history of Iceland. *Jökull,* 40: 27–50.

Oppo, D. W. and Lehman, S. J., 1995: Suborbital timescale variability of North Atlantic Deep Water during the past 200,000 years. *Paleooceanography,* 10: 901–910.

Powell, R. D. and Molnia, B. F., 1989: Glacimarine sedimentary processes, facies and morphology of the south-southeast Alaska shelf and fjords. *Marine Geology,* 85: 359–390.

Ruddiman, W. F. and McIntyre, A., 1973: Time-transgressive deglacial retreat of polar waters from the North Atlantic. *Quaternary Research,* 3: 117–130.

Rundgren, M., 1995: Biostratigraphic evidence of the Allerød-Younger Dryas-Preboreal oscillation in Northern Iceland. *Quaternary Research,* 44: 405–416.

Sarnthein, M., Jansen, E., Weinelt, M., Arnold, M., Duplessy, J.-C., Erlenkeuser, H., Flatøy, A., Johannessen, G., Johannessen, T., Jung, S., Koç., N., Labeyrie, L., Maslin, M., Pflaumann, U., and Schulz, H., 1995: Variations in Atlantic surface ocean paleoceanography, 50°–80°N: a time-slice record of the last 30,000 years. *Paleoceanography,* 10: 1063–1094.

Sejrup, H.P., Sjøholm, J., Furnes, H., Beyer, I., Eide, L., Jansen, E., and Mangerud, J., 1989: Quaternary tephrachronology on the Iceland Plateau, north of Iceland. *Journal of Quaternary Science,* 4: 109–114.

Sigvaldason, G. E., Annertz, K., and Nilsson, M., 1992: Effect of glacier loading/deloading on volcanism: postglacial volcanic production rate of the Dyngjufjoll area, central Iceland. *Bulletin of Volcanology,* 54: 385–392.

Stewart, T. G., 1991: Glacial marine sedimentation from tidewater glaciers in the Canadian High Arctic. *In* Anderson, J. B. and Ashley, G. M. (eds.), *Glacial Marine sedimentation: Paleoclimatic Significance.* Geological Society of America Special Paper, 261: 95–105.

Sveinbjörnsdóttir, Á. E., Eiríksson, J., Geirsdóttir, Á., Heinemeier, J., and Rud, N., 1993: The Fossvogur marine sediments in SW Iceland—confined to the Allerød/Younger Dryas transition by AMS ^{14}C dating. *Boreas,* 22: 147–157.

Thoroddsen, Th., 1906: *Island. Grundriss der Geographie und Geologie.* Petermanns Mitteilungen. Ergänzungsheft n. 153. Gotha: Justus Perthes. 358 pp.

Woodworth-Lynas, C. M. T. and Guigné, J. Y., 1990: Iceberg scours in the geological record: examples from glacial Lake Agassiz. *In* Dowdeswell, J. A. and Scourse, J. D. (eds.) *Glacimarine Environments: Processes and Sediments.* Geological Society Special Publication, 53. London: Geological Society, 217–223.

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