Late Weichselian and Early Holocene deglaciation history of Iceland

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ABSTRACT

During approximately 100 years of deglaciation studies in Iceland Late Weichselian deglaciation models have developed from the earliest models of uninterrupted continuous deglaciation to single advance deglaciation (SAD) and double advance deglaciation (DAD) models, and finally towards the present multi advance deglaciation (MAD) model.

The MAD-model contains two widely recognized advances of the Icelandic inland ice sheet in Late Weichselian and Early Holocene times, which culminated at about 9,700 and 10,600 B.P., i.e. during the Preboreal and Younger Dryas Chronozones. The MAD-model also comprises two advances of the inland ice sheet that have only been recognized at one locality each, where the younger advance culminated at about 11,800 B.P. in West Iceland and the older one at about 12,700 B.P. in Northeast Iceland, i.e. during the Older Dryas and Bølling Chronozones, respectively.

The MAD-model also accounts for markedly greater extent of the Icelandic inland ice sheet during the Preboreal and the Younger Dryas advances than was proposed by the preceding SAD and DAD-models. The extent of the inland ice sheet during the Older Dryas and the Bølling advances is as yet unknown.

INTRODUCTION

Tahe main purpose of this paper is to describe our present state of knowledge concerning the Late Weichselian deglaciation history of Iceland and to outline the models of deglaciation, which have been developed during the last 100 years of deglaciation research in Iceland. This development has been from a simple model of continuous deglaciation towards a more complicated model of repeated stadials and interstadials. End-moraines and end-moraine complexes formed by advancing glaciers during the Late Weichselian deglaciation of Iceland are the main subject of this paper. On land, these features are found below the 100 m contour line, in a zone which is fairly broad in South and West Iceland but relatively narrow in other parts of the country. The review of the Late Weichselian deglaciation history of Iceland given here is not a comprehensive bibliographical review of the research history as it only accounts for selected references concerning the most important contributions to Late Weichselian studies in Iceland.

End-moraines and end-moraine complexes in the zone between present sea-level and the 100 m level were formed by glaciers, that advanced in response to Late Weichselian and early Holocene climatic deteriorations. During the deglaciation of the interior parts of Iceland (above the 100 m level), topography and glacier surges are thought to have played a greater role in stagnation and readvances of glaciers than climatological factors such as temperature and precipitation (Kaldal and Víkingsson, 1991). Changes in the position of relative sea-level have been coupled with changes in the extent of the inland ice sheet. Glacier readvance was usually accompanied by a transgression up to a maximum level, that was reached concurrently with the culmination of the glacier extent (Kjartansson, 1958; Th. Einarsson 1985; Norðdahl and Einarsson, 1988). This pattern of sea-level changes, i.e. the intimate relationship between glacial isostatic movements and glacier extent in Iceland is explained by comparatively low viscosity of the asthenosphere underneath Iceland and great deformability of a relatively thin ocean-crust, which almost instantly reacts upon even minor changes in the overburden load (Tr. Einarsson, 1966; Tryggvason, 1973, 1974; Norðdahl, 1983 and Sigmundsson, 1990).

This paper follows the chronostratigraphical terminology for Norden as proposed by Mangerud *et al.* (1974). If not otherwise stated all ^{14}C ages of marine organisms mentioned in this paper (Table I) have been corrected with respect to the $^{13}C/^{12}C$ ratio and in accordance with the apparent sea-water correction of 365 ± 20 ^{14}C years for living marine organisms around Iceland as determined by Hakansson (1983). The ^{14}C dates given by the Trondheim ^{14}C laboratory (samples T-4467, 4468, 4470) were originally corrected for sea-water influence of some 440 ^{14}C years. In this paper, however, the Trondheim laboratory ages have been adjusted to Hakansson's 365 ^{14}C years sea-water correction for Icelandic waters. In the early days of ^{14}C dating in Iceland, geologists were unaware of the influence of the apparent age of living marine organisms and the effect of sea-water correction. Those ^{14}C dates marked with [1)] in this paper have been corrected with respect to their respective $^{13}C/^{12}C$ ratios, but they were not corrected for sea-water influence when originally i published. Samples showing dates marked with [2)], have not had their $^{13}C/^{12}C$ ratios determined. Consequently the apparent age of living marine organisms cannot be subtracted from the obtained ^{14}C values (Table I).

MODE OF DEGLACIATION

At the time of maximum extent of the Icelandic inland ice sheet, the whole of Iceland with the exception of mountainous coastal areas was ice-covered (Thoroddsen, 1905–06). Glacial striae were found at sea-level on all major peninsulas around Iceland to support this observation. The orientation of glacial striae indicates, that the major part of Iceland was covered by a single continuous ice sheet with ice-streams and outlet glaciers flowing radially away from ice-divides that more or less coincided with the present water-divides in Central Iceland. At the same time Northwest Iceland was apparently covered by an independent ice cap with ice-streams and outlet glaciers flowing away from an ice-divide above the central parts of the Vestfirðir peninsula. Although a monoglacialist, Thoroddsen (1905–06) mentioned several end-moraines, which he found during his research expeditions through Iceland at the end of the 19th century, and he was of the opinion that these moraines had been formed at stationary ice margins during a continuous deglaciation. On the other hand, it is not clear whether he associated the formation of these moraines with climatic deterioration or considered them to be a product of topographical influence during the continuous deglaciation. Thoroddsen (1905–06) did not mention that end-moraines in different parts of the country might be formed by a simultaneous standstill or readvance of the glaciers.

The first among Icelandic geologists to realize that the deglaciation was not only interrupted by arbitrary standstills of the glacier margins, but in fact by readvances of the glaciers, was Pjeturss (1910). He suggested that the end-moraines in southwestern Langanes and south of Þistilfjörður in Northeast Iceland were not formed during the maximum extent of the glaciation but during a later advance, which he named "Das Langanesstadium". He correlated this advance in Northeast Iceland with an advance and formation of moraines on the Skagi peninsula in North Iceland, and also with an advance and formation of a conspicuous end-moraine in South Iceland (Pjeturss 1910).

A little later, Bárðarson (1921, 1923) demonstrated that end-moraines in the inner parts of the Breiðafjörður area and in the Borgarfjörður area in West Iceland were formed when the deglaciation was interrupted by standstills of the glacier margins. Subsequently, and further inland in these areas, less impressive end-moraines were formed during a temporary stagnation of the retreating glaciers. Bárðarson also suggested that contemporaneous end-moraines were to be found elsewhere in Iceland. According to the

Table I: Radiocarbon dates mentioned in the text. — *Skrá yfir ^{14}C aldursákvarðanir sem getið er um í texta greinarinnar.*

Sample name	Lab. no.	Original ^{14}C dates	Estimated ^{14}C dates	References
Nauthólsvík	AAR-2C	11,800 ± 150	11,435 ± 150	Hjartarson 1989
Austurströnd	AAR-3B	10,180 ± 150	9,815 ± 150	Hjartarson 1989
Skerjafjörður	AAR-8	11,130 ± 120	10,765 ± 120	Hjartarson 1989
Stóri-Sandhóll 2)	I-1824	12,270 ± 150		Ashwell 1967, 1975
Flateyjardalur	Lu-1433	9,650 ± 120		Norðdahl 1979
Súluá	Lu-2056	11,350 ± 100	10,965 ± 100	Ingólfsson 1988
Ásbakkar 1	Lu-2195	12,870 ± 110	12,505 ± 110	Ingólfsson 1988
Ásbakkar - Ásgil	Lu-2372	12,080 ± 120	11,715 ± 120	Ingólfsson 1988
Skipanes 2	Lu-2374	12,250 ± 100	11,885 ± 100	Ingólfsson 1988
Skipanes 3	Lu-2378	10,520 ± 150	10,155 ± 150	Ingólfsson 1988
Hrepphólar (Unit A)	Lu-2401	10,110 ± 140	9,745 ± 140	Hjartarson and Ingólfsson 1988
Hrepphólar (Unit C)	Lu-2402	9,960 ± 160	9,595 ± 160	Hjartarson and Ingólfsson 1988
Þrándarholt - Miðhús	Lu-2403	10,360 ± 90	9,995 ± 90	Hjartarson and Ingólfsson 1988
Þjórsá at Minnahof	Lu-2404	10,220 ± 90	9,855 ± 90	Hjartarson and Ingólfsson 1988
Ytri-Rangá at Bjarg	Lu-2406	10,380 ± 90	10,015 ± 90	Hjartarson and Ingólfsson 1988
Syðri-Rauðalækur	Lu-2598	9,870 ± 90	9,505 ± 90	Hjartarson and Ingólfsson 1988
Nauthólsvík	Lu-2599	11,530 ± 100	11,165 ± 100	Hjartarson 1987
Fell 2	Lu-2673	9,980 ± 70	9,615 ± 70	Norðdahl and Hjort 1987
Fell 3a	Lu-2674	10,230 ± 90	9,865 ± 90	Norðdahl and Hjort 1987
Skógaeyri 1	Lu-2675	10,050 ± 90	9,685 ± 90	Norðdahl and Hjort 1987
Grjóteyri 2)	S-291	12,800 ± 220		Ashwell 1975
Brúará 1)	T-362	9,930 ± 190	9,565 ± 190	Th. Einarsson 1964
Kópasker	T-4467	10,570 ± 80	10,205 ± 80	Pétursson 1986
Hvalvík	T-4468	13,020 ± 90	12,655 ± 90	Pétursson 1986
Hvalvík	T-4470	12,500 ± 150	12,135 ± 150	Pétursson 1986
Reykjavíkurflugvöllur 1)	U-413	9,940 ± 260	9,575 ± 260	Th. Einarsson 1964
Reykjavíkurflugvöllur 1)	U-414	10,450 ± 160	10,085 ± 160	Th. Einarsson 1964
Hellisholtalækur 1)	U-417	9,800 ± 150	9,435 ± 150	Th. Einarsson 1964
Melar 1)	U-641	12,290 ± 160	11,925 ± 160	Olsson *et al.* 1969
Ekruhorn 1)	U-2019	11,620 ± 240	11,255 ± 240	Kjartansson 1966
Kópasker 1)	U-2225	12,830 ± 170	12,465 ± 170	Olsson *et al.* 1972
Kaldá	U-2227	11,630 ± 160	11,265 ± 160	Th. Einarsson pers. comm.
Félagsstofnun	U-2596	11,620 ± 255	11,255 ± 255	Th. Einarsson pers. comm.
Varmá	U-2817	10,180 ± 150	9,815 ± 150	H. Torfason pers. comm.
Varmá	U-2898	10,780 ± 110	10,415 ± 110	H. Torfason pers. comm.
Þjórsárbrú	W-482	8,065 ± 400		Kjartansson 1964
Þjórsárbrú	W-913	8,170 ± 300		Kjartansson 1964

^{14}C dates marked with 1) in this paper have been corrected with respect to their respective $^{13}C/^{12}C$ ratios, but they were not corrected for sea-water influence (365 ± 20 ^{14}C years for the waters around Iceland) when originally published. Samples showing dates marked with 2), have not had their $^{13}C/^{12}C$ ratios determined. Consequently the apparent age of living marine organisms cannot be subtracted from the obtained ^{14}C values. — *Aldursákvarðanir sem eru merktar með 1) hafa verið leiðréttar samkvæmt $^{13}C/^{12}C$ hlutfalli, en sýndaraldur sjávar við Ísland (365 ± 20 ^{14}C ár) var ekki dreginn frá ^{14}C gildunum, þegar aldursákvarðanirnar voru fyrst birtar. Aldursákvarðanir sem eru merktar með 2) hafa ekki verið leiðréttar samkvæmt $^{13}C/^{12}C$ hlutfalli og því er ekki hægt að draga sýndaraldur sjávar frá ^{14}C gildunum.*

early students of deglaciation in Iceland, the recession of the inland ice sheet occurred in the form of a frontally retreating glacier, a conclusion which still is considered valid, at least for the deglaciation of the area below the 100 m level.

Both Thoroddsen (1891, 1905–06) and Bárðarson (1921, 1923) were of the opinion, that two stages could be recognized in the evolution of sea-level changes. First, recently deglaciated areas in West and Northwest Iceland were successively flooded by a rising sea-level, which reached its highest relative position (70–80 m a.s.l.) concurrently with the formation of end-moraines. Secondly, further development of sea-level changes was mainly characterized by a continuous regression of relative sea-level, which finally fell below present sea-level. Furthermore, Bárðarson (1923) implied a possible transgression of relative sea-level up to an intermediate position (40–50 m a.s.l.) in the Borgarfjörður area.

Having studied the faunal assemblages collected from raised marine sediments in the Breiðafjörður area, Bárðarson (1921) concluded that high Arctic conditions must have prevailed in the sea at the beginning of the deglaciation period. Consequently the marine environmental conditions shifted from Arctic towards increased Boreal.

SINGLE ADVANCE DEGLACIATION (SAD) MODEL

The next phase in the development of deglaciation models in Iceland was the appearance of a model which contained one widespread glacier advance that interrupted the otherwise continuous deglaciation of Iceland. The first geologist to be mentioned in this context is Guðmundur Kjartansson. His studies in South Iceland enabled him to map an apparently continuous end-moraine complex, the Búði moraine (Fig. 1) from Vatnsdalsfjall in the southeastern part of the area and across the South Icelandic lowlands to Efstadalsfjall (Kjartansson, 1943; 1958). Consequently the advance leading to the Búði moraine was termed the Búði advance. Later, Kjartansson (1964a) argued that the Búði moraine could be traced from Efstadalsfjall to Kjölur in the central highlands, thus indicating an ice-flow from an easterly direction in that area.

According to Kjartansson (1943) the Búði moraine was formed in subaquatic position during a readvance of the inland ice sheet and a concurrent transgression of relative sea level, which ultimately reached about 110 m a.s.l. Near the end of the Búði stage relative sea level had retreated to 90–100 m a.s.l. and at about 8,100 B.P. (8,065 ± 400 , W-482; 8,170 ± 300 , W-913) it had fallen below present sea-level (Kjartansson, 1958; 1964b).

On the basis of his studies of glacial striae, Kjartansson (1955) modified Thoroddsen's (1905–06) pattern of ice-flow and located the main ice-divide in the area south of the present water-divide in Central Iceland. The orientation of glacial striae in this area shows, that during the retreat of the ice sheet ice-flow became more and more influenced by the local topography, and that the direction of ice-flow and, thus, the position of the ice-divide, had successively been shifted towards the south. Furthermore, the directions of glacial striae on Melrakkaslétta in Northeast Iceland strongly indicate the existence of a former north - south orientated ice-divide above the peninsula (Kjartansson, 1955).

A comparable glacier readvance was demonstrated in North Iceland when Thorarinsson (1951) interpreted the huge sediment formations on the northern side of Mývatn — the Reykjahlíð moraine as "a complex of terminal moraines and ice-marginal fluvioglacial deposits", which he correlated with "terminal moraines and kames" at Breiðamýri and Laugar in Reykjadalur west of Mývatn and with "terminal moraines of heavy boulders (Hauksstaðahólar)" in Jökuldalur in East Iceland (Fig. 1). Thorarinsson was of the opinion that these moraines were formed during the Hólkot stage. Gravel terraces at the mouth of Laxárgljúfur, about 27 km north-northwest of Mývatn, were formed when relative sea-level stood about 50 m a.s.l. This transgression of relative sea-level coincided with the advance of the inland ice sheet during the Hólkot stage (Thorarinsson, 1951).

Kjartansson (1940) and Thorarinsson (1951) were both of the opinion that the Búði and Hólkot moraines had been formed by a climatically induced glacier readvance. They individually suggested that this advance and the coinciding transgression of relative sea-level up to the marine limit in South and North Iceland probably was equivalent with the Salpausselkä - Ra stage of Fennoscandia.

A correlation between Kjartansson's (1964a) Búði moraine in Kjölur and Thorarinsson's (1951) Hólkot moraine was first proposed by Th. Einarsson (1960, 1964) when he showed a hypothetical position of an ice sheet margin across the area between Kjölur in

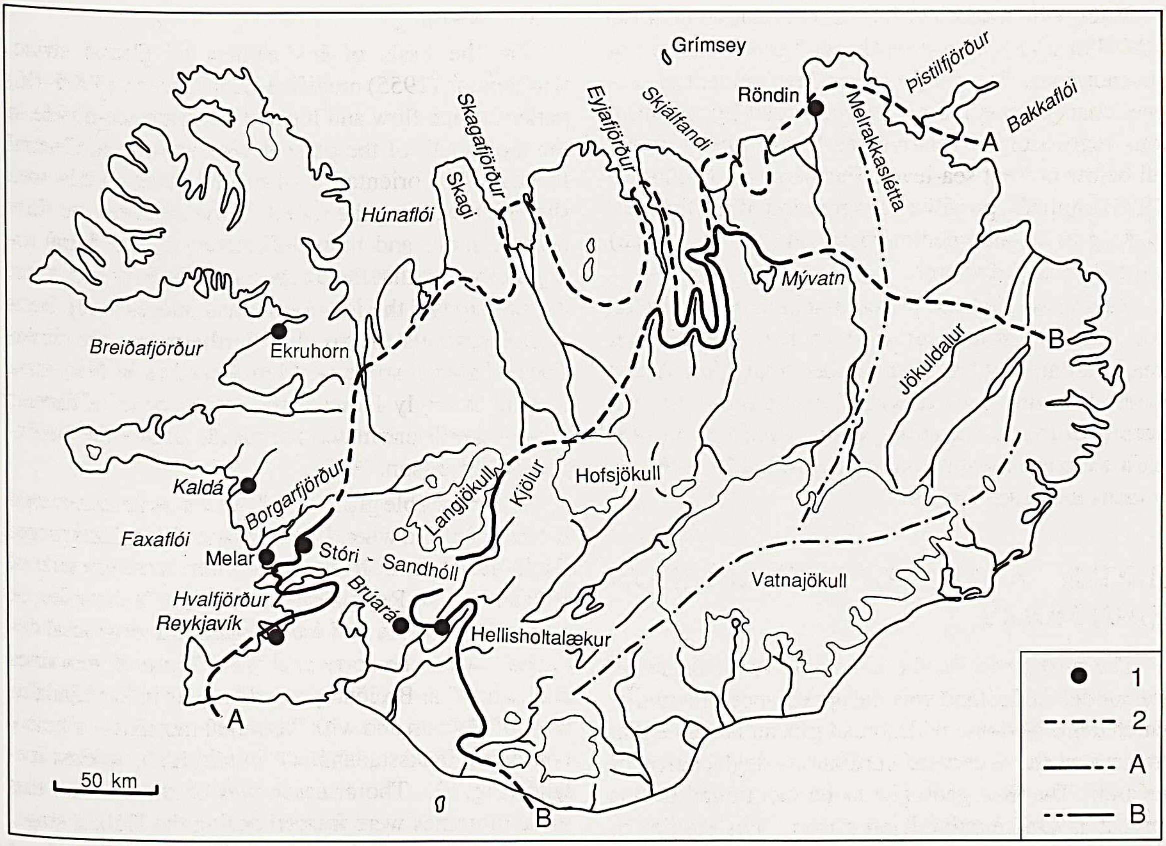

Figure 1. The maximum extent of the inland ice sheet and its major ice-divides during the Búði advance (Younger Dryas) and the Álftanes advance (Older Dryas) as first presented by the single advance deglaciation (SAD) model and later by the double advance deglaciation (DAD) model. Legend: 1) ^{14}C dates. 2) Main ice-divides. A) Margin of the "Álftanes ice-sheet". B) Margin of the "Búði ice-sheet" (Redrawn and modified from Th. Einarsson and Albertsson, 1988). —*Hámarksstærð íslenska meginjökulsins og lega meginísaskila hans á Búðaskeiði og Álftanesskeiði samkvæmt fyrri hugmyndum um tímasetningu og útbreiðslu þessara tveggja framrásarstiga. Tákn: 1) Geislakolsaldursákvarðanir. 2) Meginísaskil. A) Jaðar Álftanesjökuls. B) Jaðar Búðajökuls (Th. Einarsson and Albertsson, 1988, breytt og endurteiknað).*

the central highlands and Vestmannsvatn at the mouth of Reykjadalur in North Iceland (Fig. 1). This continuous inland ice sheet has been referred to as the "Búði ice-sheet" (Th. Einarsson, 1967). Two ^{14}C dates of subfossil molluscs collected from marine sediments at Hellisholtalækur and Brúará in South Iceland have yielded ages of 9,435 ± 150 B.P. [1)] (U-417) and 9,565 ± 190 B.P. [1)] (T-362), respectively (Fig. 1) (Th. Einarsson, 1964). Four ^{14}C dates of marine molluscs from sand sediments at Reykjavíkurflugvöllur in Reykjavík, have yielded ages ranging between 10,085 ± 160 B.P.[1)] (U-414) and 9,575 ± 260 B.P. [1)] (U-413) (Fig. 1). Not considering the effect of apparent age of living marine organisms, Th. Einarsson (1964) concluded, that the shells at Hellisholtalækur dated an early Preboreal retreat from the Búði moraine, and that the moraine was formed during a Younger Dryas advance of the "Búði ice-sheet", and that the shells at Reykjavíkurflugvöllur postdated the marine limit in Reykjavík.

DOUBLE ADVANCE DEGLACIATION (DAD) MODEL

The SAD-model remained unchanged only for a relatively short while, or until Th. Einarsson (1960) correlated the formation of two moraines; one on Álftanes in the vicinity of Reykjavík (Tryggvason and Jónsson, 1958) and another in the outer parts of Hvalfjörður (Bárðarson, 1923), with a glacier readvance preceding the Búði-Hólkot stage (Fig. 1). He referred to this older advance of the inland ice sheet as the Álftanes advance and compared it with Pjeturss' (1910) "Langanesstadium" (Th. Einarsson, 1961). Later Th. Einarsson (1967, 1968) correlated these moraines with terminal moraines in the upper Borgarfjörður, Húnaflói, and Eyjafjörður areas (Fig. 1). Furthermore, the margin of the "Álftanes ice-sheet" between Álftanes in Southwest Iceland and Langanes in Northeast Iceland was reconstructed on basis of morphological correlations (Th. Einarsson, 1971). Chronostratigraphically the Álftanes advance occurred during the Álftanes stage which was presumed to be of an Older Dryas age (Th. Einarsson, 1967).

^{14}C dates of subfossil molluscs from Stóri-Sandhóll and Melar in West Iceland (Fig. 1) yielded apparent ages of 12,270 ± 150 B.P. [2)] (I-1824) (Ashwell 1967, 1975) and 11,925 ± 160 B.P. [1)] (U-641) (Olsson *et al.*, 1969), respectively. Still unaware of the effect of sea-water correction, Th. Einarsson (1968) concluded that the apparent late Bølling age of the Melar sample (U-641) predated the Álftanes advance, which according to Th. Einarsson (1967, 1968) terminated at the mouth of upper Borgarfjörður tributary valleys.

This new concept of the mode of deglaciation, the double advance deglaciation (DAD) model displaying two Late Weichselian readvances of the inland ice sheet, also accounted for the areal extent of the "Álftanes and Búði ice-sheets" (Fig. 1). According to Th. Einarsson (1968, 1985) the main ice-divide of these two glaciers was extended in a northeastward direction from the Tungnaáröræfi area in South Iceland to East Iceland, and towards the north from the Kverkfjöll area to Melrakkaslétta in Northeast Iceland (Fig. 1). Furthermore, the maximum extent of the Weichselian glaciation in Iceland, was most likely reached concurrently with the European Weichselian maximum glaciation at about 18,000 B.P. This timing of the maximum glaciation was first proposed by Kjartansson (1962). An approximately 100 km long and 20-30 m high ridge of probable glacial origin occurs at a depth between 200 and 250 m below sea-level and close to the edge of the shelf about 130 km west of Breiðafjörður. This ridge has been interpreted as a marginal moraine representing the Weichselian maximum glacier extent in Northwest Iceland at about 18,000 B.P. (Ólafsdóttir, 1975).

Gravel terraces at 70–90 m a.s.l. in the upper Borgarfjörður area in West Iceland were formed when relative sea-level reached approximately that height (Bárðarson, 1923). Th. Einarsson (1961) determined a regional marine limit in this area at about 70 m a.s.l. According to Th. Einarsson (1968) this height of relative sea-level was reached at about 11,000 B.P. Generally speaking, the DAD-model implies that the marine limit in Iceland was normally reached at the beginning of the Búði advance at about 11,000 B.P.

Sediments of an apparent Allerød age were first described when Kjartansson (1966) reported a date of 11,255 ± 240 B.P.[1)] (U-2019) for subfossil molluscs at Ekruhorn in Saurbær in Northwest Iceland (Fig. 1). Additional ^{14}C dates yielding Allerød ages were later obtained for marine molluscs at Kaldá in West Iceland and at Félagsstofnun in the University area in Reykjavík (Fig. 1). The Kaldá sample yielded an age of 11,265 ± 160 B.P. (U-2227) and the Félagsstofnun sample an age of 11,255 ± 255 B.P. (U-2596) (Thorleifur Einarsson; personal communication 1991). Sediments of apparent Bølling age were first described when Th. Einarsson (1971) reported a date of 12,465 ± 170 B.P.[1)] (U-2225) (Olsson *et al.*, 1972) for subfossil molluscs collected from the Röndin sediments at Kópasker in Northeast Iceland (Fig. 1). According to Th. Einarsson (1971), the Röndin sediments were overridden during a subsequent glacier advance, which he correlated with the

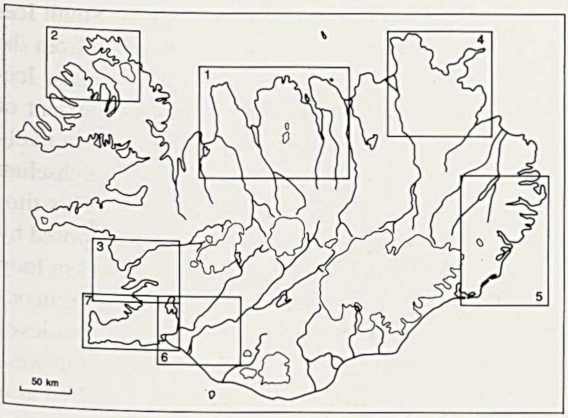

Figure 2. An index map with the individual research areas (1-7) indicated: 1) North Iceland. 2) Northwest Iceland. 3) West Iceland. 4) Northeast Iceland. 5) East Iceland. 6) South Iceland and 7) Southwest Iceland. — *Lega þeirra landsvæða (1-7), sem þessi grein fjallar um: 1) Norðurland. 2) Norðvesturland. 3) Vesturland. 4) Norðausturland. 5) Austurland. 6) Suðurland og 7) Suðvesturland.*

Álftanes advance in Southwest Iceland. The Kópasker and Ekruhorn localities were later proposed as "type sites" for the Kópasker stage and the Saurbær stage in an Icelandic chronostratigraphical arrangement, which comprised two stadials; the Álftanes and Búði stages corresponding to the Older and Younger Dryas stadials in Northwest Europe, and two interstadials; the Kópasker and Saurbær stages corresponding to the Bølling and Allerød interstadials in Northwest Europe (Th. Einarsson, 1979).

RECENT STUDIES OF THE DEGLACIATION

During the last 10–15 years several geologists have been studying different aspects of Late Weichselian deglaciation and sea-level changes in different parts of Iceland. This account reviews the main results and conclusions from studies in North, Northeast, East, South, Southwest, West and Northwest Iceland (Fig. 2). Although the aims and methods of these studies are somewhat different, their results throw some new light upon and enable conclusions to be drawn concerning the deglaciation history of Iceland at the end of the Weichselian glaciation and the beginning of the Holocene.

NORTH ICELAND

In his study of Late Weichselian deglaciation history of the Skagafjörður district in the western part of North Iceland, Víkingsson (1976, 1980) concluded that the deglaciation of the area was accelerated by calving and that it proceeded without any regional interruptions. Furthermore, he inferred that end-moraines found within the study area only reflected local readvance or standstill of the glacier margin. Víkingsson (1980) described three major deltas in Skagafjörður; at Sauðárkrókur, Reynistaður and Vindheimamelar, which were all formed when relative sea-level stood about 45 m a.s.l. (Fig. 3). The deltas are not synchronous formations and they indicate that glacial isostatic recovery of the land kept pace with eustatic rise of sea-level along with a southward recession of an ice margin in Skagafjörður. Absolute dates are as yet not available concerning the deglaciation history of Skagafjörður, but Víkingsson (1980) proposed an Allerød age for the deglaciation of the area and for the formation of the marine limit at about 45 m a.s.l. Morivaki (1990) determined the height of the marine limit on the Skagi peninsula west of Skagafjörður and in the Húnaflói area west thereof to 50-60 m a.s.l. and suggested that the marine limit was reached concurrently with a glacier advance in Younger Dryas time (Fig. 3).

Comprehensive geomorphological, sedimentological and lithostratigraphical studies of sediments within the Fnjóskadalur drainage basin in central North Iceland (Fig. 3) have elucidated the Weichselian glacial history of the area (Norðdahl 1981, 1983). The main features of the stratigraphical arrangement in Fnjóskadalur are several different and repeated depositional environmental phases that have been assigned to nine stages of glacier readvance (stadials) and seven stages of glacier retreat (interstadials), which together comprise the Fnjóskadalur Sequence. The Fnjóskadalur Sequence and thus the glacial history have been divided into three main phases (Norðdahl 1983).

The maximum phase includes the culmination of

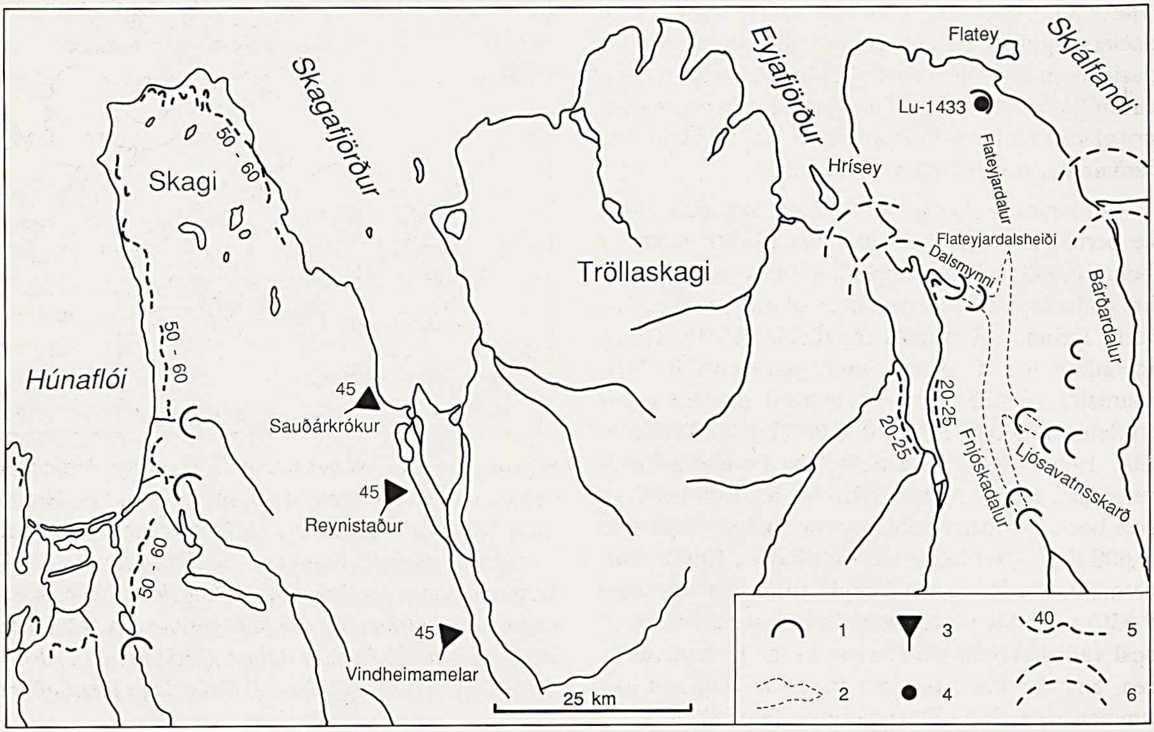

Figure 3. Late Weichselian and early Holocene end-moraines, marine-limit features and ice-dammed lakes in North Iceland. Legend: 1) End-moraines. 2) Ice-dammed lake. 3) Raised deltas. 4) ^{14}C dates. 5) Raised beaches. 6) Terminal zones. —*Jökulgarðar, sjávarborðsmenjar og jökulstífluð lón frá síðjökultíma og upphafi nútíma á Norðurlandi. Tákn: 1) Jökulgarður. 2) Jökullón. 3) Fornar óseyrar. 4) Geislakols aldursákvarðanir. 5) Forn fjörumörk. 6) Óviss lega jökuljaðars.*

the Weichselian glaciation when Grímsey, about 40 km off the present coast (Fig. 1), was overridden by glaciers from the mainland. *An intermediate phase* was apparently characterized by climatologically controlled variations in the extent of the main outlet glaciers in North Iceland. A consequence of variable glacier extent was, that Dalsmynni and Ljósavatnsskarð were repeatedly and simultaneously blocked by glacier tongues from the outlet glaciers in Eyjafjörður and Bárðardalur. At the same time the northern part of Fnjóskadalur remained ice-free and at least eight successive ice-dammed lakes, with their outlets over the Flateyjardalsheiði threshold (Fig. 3), were formed in the valley (Norðdahl 1983). Of these eight ice-dammed lakes the youngest four have left prominent strandlines along both sides of Fnjóskadalur. A survey of these strandlines has led to a fairly accurate reconstruction of the extent of the two youngest ice-dammed lakes, the Austari-Krókar and Fnjóskadalur ice-dammed lakes (Fig. 3), which were formed during the Fornhólar and the Belgsá readvances (Norðdahl, 1983). In both instances the outlet glacier in Eyjafjörður terminated in a zone south of Hrísey, and the outlet glacier in Bárðardalur terminated in a zone close to the present coastline of Skjálfandi (Fig. 3) (Norðdahl, 1982; 1991). In Fnjóskadalur the outlet glacier terminated in the southernmost part of the valley (Norðdahl, 1983). A *third phase* includes a readvance of local valley and cirque glaciers especially in the outer parts of the elevated peninsulas Tröllaskagi and Flateyjarskagi. Concurrently with the advance of the local glaciers a glacier tongue from the Bárðardalur outlet glacier terminated just west of Ljósavatn in the eastern part of Ljósavatnsskarð. The position of a contemporary glacier terminus in Eyjafjörður, Fnjóskadalur and Bárðardalur is still unknown (Fig. 3).

Chronologically the Fnjóskadalur Sequence spans the period between the maximum glacier extent at about 18,000 and the concluding phase of deglaciation including the final departure of glaciers from the North Icelandic lowlands (Norðdahl, 1990; 1991). According to ^{14}C dated limnic sediments in Flateyjardalur (Fig. 3), this withdrawal did not occur any later than 9,650 ± 120 B.P. (Lu-1433) (Norðdahl, 1979; 1991). Recently, the Fornhólar readvance and, thus, the Austari-Krókar ice-dammed lake have been indirectly dated by the Skógar Tephra to 10,600 B.P. (Norðdahl and Hafliðason, 1990). Furthermore, the ^{14}C dated sample from Flateyjardalur (9,650) probably postdates a Preboreal readvance of local valley and cirque glaciers in the Flateyjardalur area, and the water outflow from the youngest ice-dammed lake along Flateyjardalur (Fig. 3) in North Iceland (Norðdahl, 1979; 1991). This means, that the Fornhólar, Belgsá, and Ljósavatn/Langhóll advances, and the formation of the Austari-Krókar and Fnjóskadalur ice-dammed lakes all occurred later than 10,600 B.P. but before the beginning of limnic sedimentation in Flateyjardalur, 9,650 B.P. (Norðdahl, 1990).

Among many important results that have emerged from the above cited studies of the sediments in Fnjóskadalur, is the initiation of a complex multi advance deglaciation (MAD) model for North Iceland (Norðdahl 1979, 1983). Another major conclusion is, that the glaciers in North Iceland were more extensive in Younger Dryas time than the foregoing DAD-model suggested (Norðdahl and Hafliðason 1990, Norðdahl 1990). Numerous marginal deltas and raised marine terraces found at 20–25 m a.s.l. between Hörgá and Akureyri in Eyjafjörður (Fig. 3) are heterochronous features formed along with southward retreat of the outlet glacier in Eyjafjörður. Consequently, the marine limit in Eyjafjörður is younger than the Belgsá readvance (Younger Dryas) and it probably reached its most elevated position in the southern parts of Eyjafjörður in Preboreal time (Norðdahl, 1991).

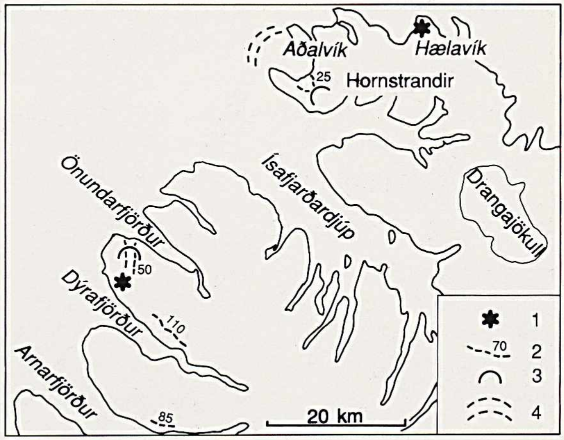

Figure 4. Late Weichselian and early Holocene end-moraines and marine-limit features in Northwest Iceland. Legend: 1) Occurrence of tephra layers. 2) Raised beaches. 3) End-moraines. 4) Terminal zones. —*Jökulgarðar og sjávarborðsmenjar frá síðjökultíma og upphafi nútíma á Norðvesturlandi. Tákn: 1) Fundarstaður gjóskulaga. 2) Forn fjörumörk. 3) Jökulgarðar. 4) Óviss lega jökuljaðars.*

The four ice-dammed lake strandlines in Fnjóskadalur have distinct positive gradients of 2.22; 2.00; 2.65 and 1.59 m/km towards the south (Norðdahl, 1983). The different gradients indicate variable depression of the land, due to glacier overburden load. They are also diagnostic of different uplift durations and clearly indicate that the four strandlines were formed by four successive ice-dammed lakes; the Ytri-Hóll, Grímsgerði, Austari-Krókar and Fnjóskadalur ice-dammed lakes (Norðdahl 1981, 1983).

NORTHWEST ICELAND

During the Weichselian maximum glaciation the Vestfirðir peninsula was most likely covered by an ice cap, that was dynamically independent of the main inland ice sheet. The peripheral plateaux in Hornstrandir (Fig. 4) — at about 400 m a.s.l. — were not covered by active glaciers as no signs of glacial erosion or deposition have been found there (Hjort *et al.*, 1985). Earlier a similar conclusion, concerning the

700-800 m high peninsula between Dýrafjörður and Önundarfjörður (Fig. 4) was reached by Sigurvinsson (1982, 1983).

The approximately 100 km long and 20–30 m high submarine ridge at the edge of the shelf 130 km west of Breiðafjörður may represent the Weichselian maximum glacier extent about 18,000 B.P. (Ólafsdóttir, 1975). Sigurvinsson (1982) pointed out that a 750 m thick glacier at the mouth of Dýrafjörður and Önundarfjörður with a parabolic surface profile, would have terminated only 25–30 km offshore, i.e. 70–80 km inside the edge of the shelf. It has, furthermore, been suggested by Hjort *et al.* (1985) that during the Weichselian maximum glaciation the glaciers on Hornstrandir could not have extended more than 6-10 km beyond the present coastline. At the entrance to Aðalvík a concentric zone of shallow banks running southwestwards from Straumnes to a position about 4 km northwest of Ritur (Fig. 4) may represent the true Weichselian maximum position of the glacier margin outside Aðalvík (Hjort *et al.*, 1985).

During the deglaciation of Hornstrandir, relative sea-level stood at the marine limit at about 25 m a.s.l. when the general retreat of the glaciers was interrupted by a readvance. A Younger Dryas age has been inferred for the advance and thus for the marine limit on Hornstrandir (Hjort *et al.*, 1985). In the area south of Ísafjarðardjúp the marine limit is found at somewhat different altitudes. It lies at 40-50 m a.s.l. at Ingjaldssandur in Önundarfjörður (Sigurvinsson, 1982), and according to Lárusson (1977) it reaches as high as 110 m a.s.l. in Dýrafjörður and 85 m a.s.l. in Arnarfjörður (Fig. 4). Kjartansson (1968) shows the marine limit at 80 m a.s.l. near Gilsfjörður on the south coast of the Vestfirðir peninsula, and at 70 m a.s.l. on Gjögur on the east coast of the peninsula. The age of the marine limits is still unknown.

Two redeposited tephra layers have been found in Northwest Iceland (Fig. 4), the rhyolitic Skagafjall Tephra in glaciolacustrine sediments in Dýrafjörður (Sigurvinsson, 1983) and the basaltic Hælavík Tephra in glaciomarine sediments on Hornstrandir (Hjort *et al.*, 1985). The Hælavík Tephra has been correlated with the Saksunarvatn Ash in the Faroe Islands (Kvamme, 1988), which in turn has been ^{14}C dated to 9,000–9,100 B.P. (Mangerud *et al.*, 1986). This date postdates both the glacier readvance and the marine limit on Hornstrandir.

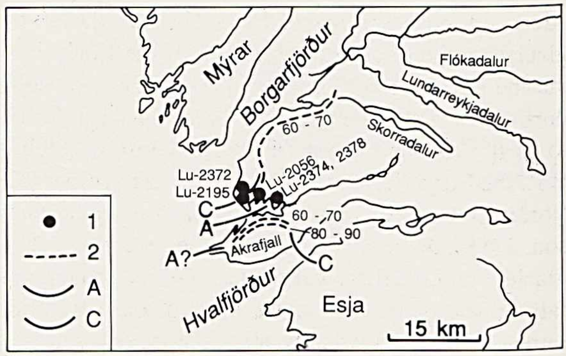

Figure 5. Late Weichselian and early Holocene end-moraines and marine-limit features in West Iceland. Legend: 1) ^{14}C dates. 2) Raised beaches. A) End-moraines from the Skipanes event. C) End-moraines from the Skorholtsmelar event. — *Jökulgarðar og sjávarborðsmenjar frá síðjökultíma og upphafi nútíma á Vesturlandi. Tákn: 1) Geislakolsaldursákvarðanir. 2) Forn fjörumörk. A) Jökulgarðar Skipanessstigs. C) Jökulgarðar Skorholtsmelastigs.*

WEST ICELAND

Ingólfsson (1984, 1985, 1987, 1988) studied the glacial development of the lower Borgarfjörður region in West Iceland (Fig. 5) with regard to morphology, lithostratigraphy and chronology of glacial events. The chronological studies were supported with a total of about 25 ^{14}C dates.

In Bølling time the lower Borgarfjörður area was ice-free but submerged as relative sea-level stood above the 60 m level at about 12,300 B.P. in the northernmost part of the investigation area. This is referred to as the Ásbakkar event, which has been ^{14}C dated between 12,505 ± 110 B.P (Lu-2195) and 11,885 ± 100 B.P. (Lu-2374) (Ingólfsson, 1988). Around 12,000 B.P. a glacier from Borgarfjörður advanced and reached Skipanes in the southern part of the investigation area. At the same time a glacier from Hvalfjörður advanced and was probably divided by Akrafjall as the glacier reached out into the mouth of the fjord. The marine limit at 80–90 m a.s.l. was probably reached during this readvance of the glaciers, which is referred to as the Skipanes event (Fig. 5). Close to 11,700 B.P., the Borgarfjörður glacier and the glacier in Hvalfjörður both retreated to an unknown position (Ingólfsson, 1988). Simultaneously with the recession of the glaciers relative sea-level was lowered, although not falling below the 35 m level. This episode of glacier retreat and regression of relative sea-level is referred to as the Látrar event and has been ^{14}C dated between 11,715 ± 120 B.P. (Lu-2372) and 10,965 ± 80 B.P. (Lu-2056) (Ingólfsson, 1988). Some time around 11,000 B.P. the glacier in Borgarfjörður advanced and reached a position similar to the one reached during the Skipanes event, and formed the conspicuous Skorholtsmelar moraine (Fig. 5). This episode of glacier advance has been named the Skorholtsmelar event and it was terminated close to 10,155 ± 150 B.P. (Lu-2378). About 10,300 B.P. the glacier retreated from the Skorholtsmelar moraine when relative sea-level was 60–70 m a.s.l. (Fig. 5). Subsequently relative sea-level fell towards present sea-level. This event has been named the Melabakkar event (Ingólfsson, 1988). Additionally, Ingólfsson (1988) assumed that an intermittent 40–50 m raised shorelevel could be of Preboreal age and possibly have been formed concurrently with a glacial episode in the upper Borgarfjörður tributary valleys.

The most important result from these studies in the lower Borgarfjörður region is the occurrence of two Late Weichselian glacier advances and retreats (stadials and interstadials). The stadials, the Skipanes and Skorholtsmelar events culminated about 11,800 and 10,600 B.P. respectively, closely correspond to the Older Dryas and the Younger Dryas stadials, and the Ásbakkar and Látrar events consequently correspond to the Bølling and the Allerød interstadials in Northwest Europe. The Melabakkar event covers the latest part of the Younger Dryas Chronozone and the beginning of the Holocene (Ingólfsson, 1988). Another and equally interesting conclusion is that the Icelandic inland ice sheet and its outlet glaciers were much more extensive in Younger Dryas time than the previous DAD-model had suggested, and that the glaciers attained approximately the same extent during the Younger Dryas as they did in Older Dryas time (Ingólfsson, 1988).

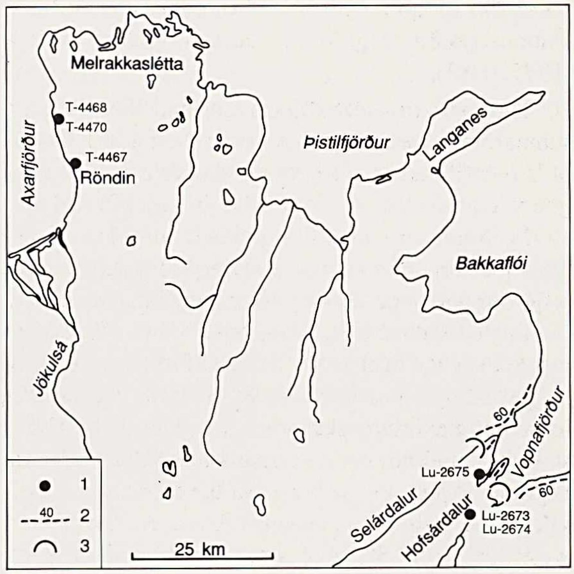

Figure 6. Late Weichselian and early Holocene end-moraines and marine-limit features in Northeast Iceland. Legend: 1) ^{14}C dates. 2) Raised beaches. 3) End-moraines. —*Jökulgarðar og sjávarborðsmenjar frá síðjökultíma og upphafi nútíma á Norðausturlandi. Tákn: 1) Geislakolsaldursákvarðanir. 2) Forn fjörumörk. 3) Jökulgarðar.*

NORTHEAST ICELAND

In his studies of Weichselian sediments in the western part of the Melrakkaslétta peninsula in Northeast Iceland (Fig. 6), Pétursson (1986; 1991) reached a conclusion, which in important aspects differs from the DAD-model concerning the chronological position of the glacier readvance that overrode the Röndin sediments at Kópasker and the deglaciation history of the area. The sediments in western Melrakkaslétta were overridden by a glacier that flowed towards the west away from a north-south orientated ice-divide above the central parts of the peninsula and across the present coastline (Fig. 6) (Pétursson, 1986). The age of this glacier advance has now been determined between 10,205 ± 80 B.P. (T-4467) and 12,135 ± 150 B.P. (T-4470), a period that covers the Younger Dryas, Allerød and Older Dryas Chronozones (Pétursson, 1986; 1991). Hence, instead of an Older Dryas age, Pétursson year has on lithostratigraphical and chronological grounds inferred a Younger Dryas age for this glacier advance. These results imply that during the Younger Dryas the glaciers in the Melrakkaslétta area were much more extensive than previously suggested. Furthermore, data from Hvalvík in western Melrakkaslétta (Pétursson, 1986; 1991) may indicate that a marine transgression up to 40–60 m a.s.l. and a contemporaneous glacier advance occurred at 12,655 ± 90 B.P. (T-4468) in these parts of Northeast Iceland (Fig. 6).

Hjartarson *et al.* (1981) have described terraces at about 90 m a.s.l. in the innermost parts of the Vopnafjörður area, presumably formed when relative sea-level reached 80-90 m a.s.l. and glaciers advanced down into the southern part of the area. Later, Norðdahl and Hjort, (1987), not recognizing the 90 m marine level, concluded that raised marine features at about 60 m a.s.l. in the outer parts of the Vopnafjörður area were formed in close relation to glaciers that terminated at the mouth of Hofsárdalur and Selárdalur (Fig. 6). Furthermore, standstills or glacier readvances have been recognized farther south in Hofsárdalur and Vesturárdalur.

Fossiliferous marine sediments in these valleys postdate a glacier retreat from the outermost parts of the valleys, and probably date relative sea-level at about 35 m a.s.l. and a glacier readvance in Hofsárdalur and Vesturárdalur. Two samples of subfossil molluscs collected from the marine silt in Hofsárdalur have yielded ages of 9,615 ± 70 B.P. (Lu-2673) and 9,865 ± 90 B.P. (Lu-2674), and one sample collected from the sediments in Vesturárdalur has yielded an age of 9,685 ± 90 B.P. (Lu-2675) (Norðdahl and Hjort 1987). The results from the Vopnafjörður area indicate that the glaciers in this part of Northeast Iceland were much more extensive in early Preboreal time and possibly in late Younger Dryas time too, than was previously indicated by the DAD-model.

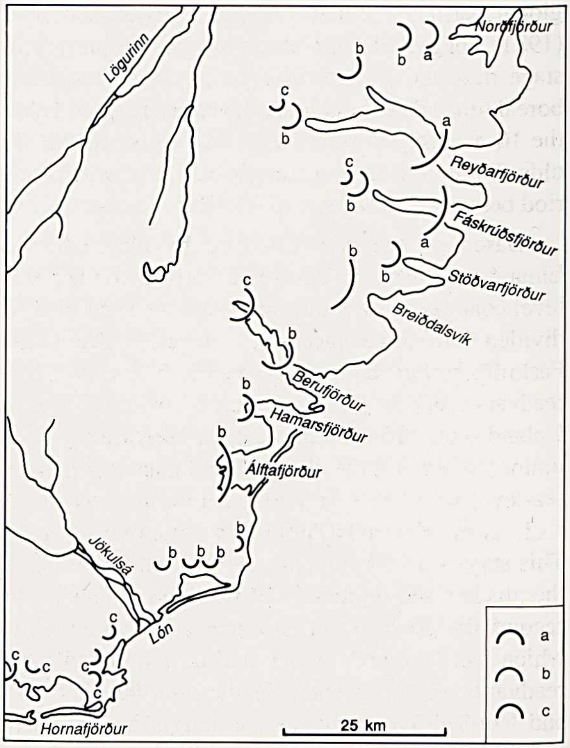

Figure 7. Late Weichselian and early Holocene end-moraines and marine-limit features in East Iceland. Legend: a) Fáskrúðsfjörður stage moraines. b) Breiðdalsvík stage moraines. c) Berufjörður stage moraines. — *Jökulgarðar og sjávarborðsmenjar frá síðjökultíma og upphafi nútíma á Austurlandi. Tákn: a) Jökulgarðar Fáskrúðsfjarðarstigs. b) Jökulgarðar Breiðdalsvíkurstigs. c) Jökulgarðar Berufjarðarstigs.*

EAST ICELAND

Surveys of moraines and marine limits in East Iceland (Fig. 7) by Hjartarson *et al.* (1981) and by Norðdahl and Einarsson (1988), have clarified the course of Late Weichselian deglaciation and sea-level changes in this part of the country.

Hjartarson *et al.* (1981) divided the deglaciation history of East Iceland into two stages; an older stage of readvance called the Valley-glacier stage and a younger Cirque-glacier stage. Subsequent to the Valley-glacier stage relative sea-level reached the regional marine limit at 30–40 m a.s.l. Hjartarson *et al.* (1981) suggested, that the younger Cirque-glacier stage occurred in late Younger Dryas or early Preboreal time when relative sea-level had receded below the 10 m level. Furthermore, they proposed that the older Valley-glacier stage might correlate with the period between 12,000 and 10,000 B.P.

Based on the data collected by Norðdahl and Einarsson (1988), the course of deglaciation and sea-level changes in East and Southeast Iceland has been divided into three successive stages. The oldest Fáskrúðsfjörður stage represents the first standstill or readvance of the glaciers recorded on land in East Iceland since their retreat from the Weichselian maximum position on the shelf. Simultaneously relative sea-level rose to its highest position at about 50 m a.s.l. at the Fáskrúðsfjörður stage moraines (Fig. 7). This stage was subsequently terminated by retreat of the glaciers and regression of relative sea-level. The second Breiðdalur stage is represented by moraines which were formed, either during a standstill or a readvance of the glaciers in the area between Lón and Norðfjörður, when the ice margin had retreated to within the present coastline (Fig. 7). Simultaneously sea-level rose to a new elevated position at the Breiðdalsvík stage moraines. Finally the Berufjörður stage comprises the third and youngest set of moraines and raised beaches at the Berufjörður stage moraines (Fig. 7) (Norðdahl and Einarsson, 1988).

Comparison with the results of Hjartarson *et al.* (1981) shows, that the Berufjörður stage correlates with the Cirque-glacier stage, the Breiðdalur stage with the Valley-glacier stage, and consequently that the Fáskrúðsfjörður stage predates the Valley-glacier stage. The stratigraphical position of the Fáskrúðsfjörður, Breiðdalur and Berufjörður stage moraines and their related marine limits is uncertain so far, as radiometric dates are still lacking. On basis of parallelism between the above described course of deglaciation and sea-level changes in East Iceland and the one described by Ingólfsson (1988) in West Iceland the Fáskrúðsfjörður stage may correspond to the Skipanes event (Older Dryas) and the Breiðdalur stage to the Skorholtsmelar event (Younger Dryas) (Norðdahl and Einarsson, 1988).

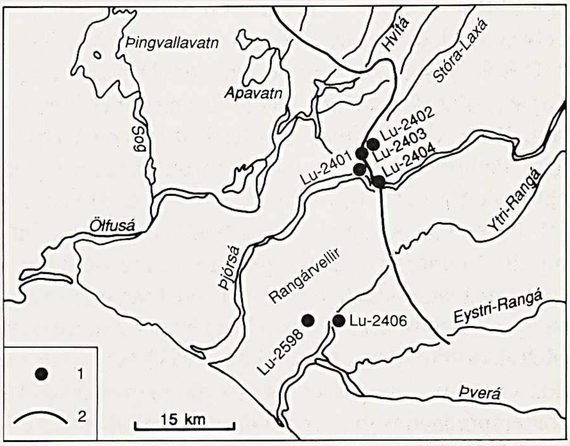

Figure 8. Early Holocene end-moraines and marine-limit features in South Iceland. Legend: 1) ^{14}C dates. 2) The Búði moraine. —*Jökulgarðar og sjávarborðsmenjar frá upphafi nútíma á Suðurlandi. Tákn: 1) Geislakolsaldursákvarðanir. 2) Búðaröðin.*

SOUTH ICELAND

Since the identification of the Búði stage (Kjartansson, 1943; 1958; Th. Einarssoni, 1964), the Búði moraine itself has been subjected to very limited research efforts. Kjartansson (1958) described the Búði moraine (Fig. 8) as "a belt of terminal moraine ridges" and later Th. Einarsson (1960) pointed out that the moraine is a complex of several ridges. In a seismic study of the Markarfljót sandur area in central South Iceland an extension of the Búði moraine was detected 25-50 m below the sandur surface (Haraldsson 1981). Jóhannesson (1985) emphasized that the Búði moraine is a complex of up to seven more or less parallel moraine ridges and speculated that the outermost ridges of the Búði moraine were at least of an Older Dryas age (about 12,000 B.P.) and that the innermost ridges were at least of a Younger Dryas age (about 10,000 B.P.).

Recently, Hjartarson and Ingólfsson (1988) have, on basis of substantial stratigraphical and chronological evidence, drawn quite different conclusions concerning the age of the complex Búði moraine. Out of twelve ^{14}C dated samples of marine molluscs gathered from raised marine sediments in the South Icelandic lowlands, four samples were collected from sediments in close relation to the Búði moraine in the area between Þjórsá and Stóra-Laxá in Hreppar (Fig. 8). Two samples from a position below the moraine yielded ages of 9,995 ± 90 B.P. (Lu-2403) and 9,855 ± 90 B.P.(Lu-2404), a sample from within the moraine itself provided an age of 9,745 ± 140 B.P. (Lu-2401) and a sample taken above the moraine showed an age of 9,595 ± 160 B.P. (Lu-2402) (Hjartarson and Ingólfsson, 1988). The stratigraphical and chronological evidence suggests that at least this part of the Búði moraine was formed at about 9,670 B.P. (between 9,745 ± 140 B.P. and 9,595 ± 160 B.P.), i.e. in Preboreal time. Furthermore, three ^{14}C dated samples from the western, formerly submarine part of the huge raised Rangárvellir sandur area, formed proximally to the southeastern part of the Búði moraine, indicate that it was formed between 10,015 ± 90 B.P. (Lu-2406) and 9,505 ± 90 B.P. (Lu-2598), i.e. also in Preboreal time (Hjartarson and Ingólfsson, 1988).

An important result of the studies by Hjartarson and Ingólfsson is, that South Iceland was subjected to a much heavier Younger Dryas glaciation than was formerly suggested by the DAD-model. According to Hjartarson and Ingólfsson (1988) relative sea-level was above the 60–75 m level both prior and subsequent to the glacier advance which formed the Búði moraine between Þjórsá and Stóra-Laxá. Kjartansson (1943) concluded that the advance coincided with formation of the marine limit at 110 m a.s.l., which consequently should date from the Preboreal Chronozone.

SOUTHWEST ICELAND

The Fossvogur beds in Reykjavík (Fig. 9) are generally considered to have been deposited during the last (Eemian) interglacial (Th. Einarsson, 1968). The sequence begins with a lodgement tillite on top of striated bedrock surface. Erosional unconformities and fluvial, marine and debris-flow sediments above the tillite indicate phases of sea-level changes which may have been accompanied by renewed glaciation of the area. Finally a lodgement till was deposited indicating the last glacial episode in Reykjavík, which was followed by deposition of sand and gravel from the final deglaciation of the area (Geirsdóttir and Eiríksson, 1990). Measurements of aminoacid racemization in the lowest facies sequence of the Fossvogur beds have yielded aIle/Ile ratios ranging from 0.16 to 0.58, indicating Eemian or pre-Eemian age (Eiríksson *et al.*, 1990).

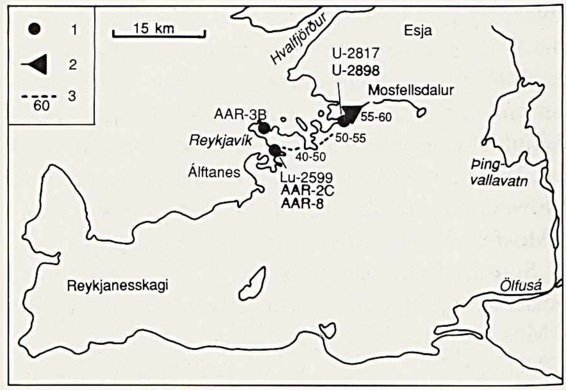

Figure 9. Late Weichselian and early Holocene end-moraines and marine-limit features in Southwest Iceland. Legend: 1) ^{14}C dates. 2) Raised marginal delta. 3) Raised beaches. — *Jökulgarðar og sjávarborðsmenjar frá síðjökultíma og upphafi nútíma á Suðvesturlandi. Tákn: 1) Geislakolsaldursákvarðanir. 2) Forn jaðaróseyri. 3) Forn fjörumörk.*

A conventional ^{14}C date from the Fossvogur beds in Nauthólsvík yielded an Allerød age of 11,165 ± 100 B.P. (Lu-2599) (Hjartarson, 1987). A series of AMS ^{14}C dates from Nauthólsvík have produced ages ranging between 11,435 ± 150 B.P. (AAR-2C) and 10,765 ± 120 B.P. (AAR-8) (Andersen *et al.*, 1989). According to Hjartarson (1989), the marine sediments in Fossvogur are overlain by a tillite, which he correlated with a Younger Dryas glacier advance. This indicates, that the Reykjavík area was covered by glaciers in Younger Dryas time. Hjartarson (1989) suggested that the area was finally deglaciated close to 9,815 ± 150 B.P. (AAR-3B) and that relative sea-level reached the marine limit in Reykjavík at 40–45 m a.s.l. at the same time, i.e. in early Preboreal times (Fig. 9).

At the time of maximum elevation of relative sea-level in the Reykjavík area, a large ice-contact delta was formed close to the 55–60 m level at the mouth of Mosfellsdalur northeast of Reykjavík when a readvancing glacier terminated there (Fig. 9). The marine limit at 55–60 m a.s.l., the 50–55 m shore level on Höfði and Borgarholt near Keldnaholt (Tryggvason and Jónsson, 1958), and the 40–45 m level on Öskjuhlíð in Reykjavík (Thorkelsson, 1935; Hjartarson, 1989) are probably synchronous features (Fig. 9). A lower set of beach-ridges and a raised delta is found at Mosfellsdalur and close to the 40 m level.

Subfossil marine molluscs, collected from the bottomset units of the ice-contact delta at Varmá just south of Mosfellsdalur, have been ^{14}C dated to 9,815 ± 150 B.P. (U-2817). A ^{14}C date of another sample composed of shells that have apparently been weathered out of the sediments, has yielded an age of 10,415 ± 110 B.P. (U-2898) (Halldór Torfason; personal communication 1991). It is not possible at this moment to decide whether this date is less reliable or if it actually dates an older phase of sea-level changes in Southwest Iceland. The formation of the ice-contact delta, and the termination of a glacier in the mouth of Mosfellsdalur occurred most likely in early Preboreal time. This again indicates that the glaciers in Southwest Iceland may have been much more extensive in early Preboreal and Younger Dryas times, than was previously indicated by the DAD-model.

DISCUSSION AND CONCLUSIONS

Our ideas concerning the mode of deglaciation in Iceland have developed from the earliest model of apparently continuous deglaciation that was randomly interrupted by standstills, towards a single advance deglaciation (SAD) model and later a double advance deglaciation (DAD) model (Fig. 1). The most important features of the DAD-model were, firstly, that it accounted for two regional and simultaneous readvances of the Icelandic inland ice sheet, and secondly, that concurrently with the glacier advances the land subsided due to increased glacier overburden load, and relative sea-level transgressed and reached a temporary maximum elevation. With regard to the number of Weichselian glacier readvances, the DAD-model remained mostly unchanged until Norðdahl (1981, 1983) put forward a multi advance deglaciation (MAD) model for North Iceland, a model that contained at least nine advances (stadials) in the period between the Weichselian maximum glaciation and the beginning of the Holocene, i.e. between 18,000 B.P. and 9,650 B.P. (Norðdahl, 1990).

The simultaneous changes in the extent of the inland ice sheet and in the elevation of relative sea-level indicate that these changes had a common cause in climatological variations and in altered mass-balance of the ice sheet, but were not caused by inconsistently dispersed factors such as local topography or glacier surges. Correlations between glacier readvances and marine transgressions in different parts of the country - based on morphology and deglaciation pattern only - have never been but presumptive and reliable correlations must be based on stratigraphical correlations and absolute dates such as ^{14}C dates.

Until the early 1980's approximately 16 ^{14}C dates concerning the history of deglaciation and sea-level changes in Iceland had been published. Their number has quadrupled in the last 10 years, and today between 50 and 60 such stratigraphically controlled ^{14}C dates covering the time span between the Bølling and Preboreal Chronozones (Table I and Fig. 10), have been published. The increased number of ^{14}C dates has enabled both correlation and separation of events in the deglaciation history of Iceland.

An early Preboreal glacier readvance has now been dated at four different localities in Iceland (Fig. 10). In North Iceland local cirque and valley glaciers probably advanced and extended out of their confining valleys shortly before 9,650 B.P. (Norðdahl, 1979), and in the Vopnafjörður district in Northeast Iceland, the glaciers probably advanced just before 9,700 B.P. (Norðdahl and Hjort, 1987). In South Iceland the Búði moraine was formed during a glacier advance that reached into the sea at 9,670 B.P. (Hjartarson and Ingólfsson, 1988). Approximately at the same time (9,815 B.P.), a glacier advance was terminated in the mouth of Mosfellsdalur northeast of Reykjavík (Fig. 10).

A number of ^{14}C dates in West Iceland bracket a Younger Dryas glacier advance, the Skorholtsmelar event which culminated at about 10,600 B.P. (Fig. 10) (Ingólfsson, 1988). In North Iceland a glacier advance, the Fornhólar stage of the Fnjóskadalur Sequence, has indirectly been dated to 10,600 B.P. (Norðdahl, 1990; Norðdahl and Hafliðason, 1990). A

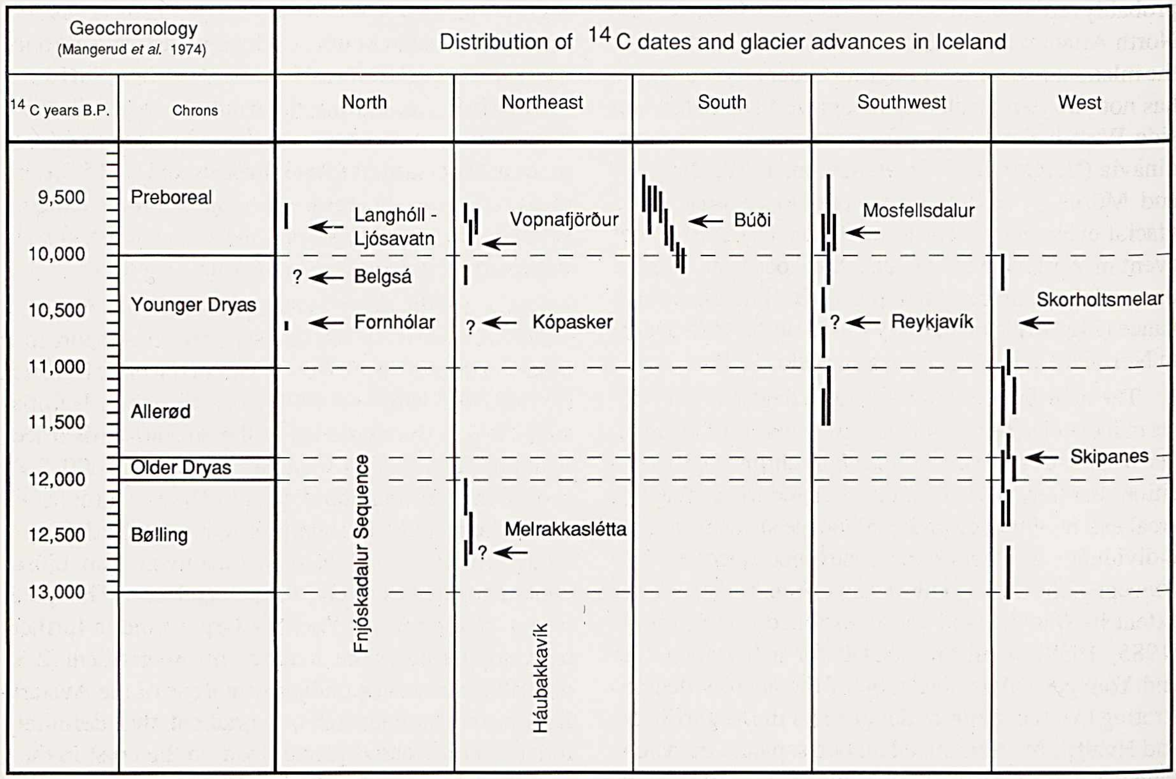

Figure 10. Distribution of ^{14}C dates (thick lines) and glacier advances (arrows) dealt with in this paper. The ^{14}C dates are shown with ± one standard deviation, and glacier advances of uncertain age are marked with ? — *Dreifing ^{14}C aldursákvarðana (þykkar línur) og framrásir jökla (örvar) í ýmsum landshlutum. Aldursákvarðanir eru sýndar með ± einu staðalfráviki og jökulframrásir af óvissum aldri eru auðkenndar með ?*

Younger Dryas age has also been assigned to a glacier readvance on western Melrakkaslétta in Northeast Iceland (Pétursson, 1986; 1991) and in the Reykjavík area in Southwest Iceland (Fig. 10) (Hjartarson, 1989).

The Skipanes event in West Iceland is as yet the only glacier readvance that has been directly dated to the Older Dryas (Fig. 10). According to the ^{14}C dates this advance culminated at about 11,800 B.P. (Ingólfsson, 1988). A ^{14}C dated marine transgression on western Melrakkaslétta in Northeast Iceland was seemingly accompanied by a glacier advance in Bølling time (12,655 B.P.) (Fig. 10), and the Háubakkavík profile displays a number of glacial events that are older than the assumed Bølling advance (Pétursson, 1986; 1991). In North Iceland the Fnjóskadalur Sequence displays a number of glacier readvances prior to the Younger Dryas Fornhólar readvance (Fig. 10) (Norðdahl, 1990).

On basis of the data presented above it may be concluded that changes in the extent of the Icelandic inland ice sheet and in its major outlet glaciers occurred simultaneously on at least two separate occasions, i.e. around 10,600 and 9,700 B.P. (Fig. 10). Comparable Younger Dryas and Preboreal readvances are relatively well documented in Scandinavia (Berglund, 1979; Sørensen 1979; Andersen 1980; Corner 1980) and in East Greenland (Hjort, 1979). These concurrent changes in the extent of the Icelandic inland ice sheet probably reflect regional climatological changes in the North Atlantic region and an altered mass-balance of the inland ice sheet. Although an Older Dryas advance has not yet been positively recognized and dated outside West Iceland (Fig. 10), comparison with Scandinavia (Berglund, 1979; Mangerud, 1980; Berglund and Mörner, 1984) lends support to an idea that a glacial event equivalent to the Older Dryas Skipanes event in West Iceland may also have occurred in other parts of the country. An apparent Bølling glacier advance (Fig. 10) is as yet only found on Melrakkaslétta in Northeast Iceland (Pétursson, 1986; 1991).

The increased research efforts in deglaciation studies in Iceland have not only led to a revision of the number of glacier readvances and their chronological position, but have also radically changed the concept of areal extent of the Icelandic inland ice sheet during the individual Late Weichselian readvance episodes. The concept of the DAD-model of Late Weichselian glacier extent in West Iceland was questioned by Ingólfsson (1985, 1988) when he pleaded for a heavier Older and Younger Dryas glaciation of the area by demonstrating that the major outlet glaciers in Borgarfjörður and Hvalfjörður terminated on two separate occasions (about 11,800 and 10,600 B.P.) in the vicinity of Akrafjall in the outer parts of the West Icelandic lowlands (Figs. 5 and 11).

The DAD-model's concept of glacier extent was also disputed in Northeast Iceland, when Pétursson (1986; 1991) presented a Younger Dryas glacier advance that reached at least as far north as the Röndin sediments at Kópasker on western Melrakkaslétta (Figs. 6 and 11), about 75 km north of the previously defined Younger Dryas glacier margin. A comparable conclusion was reached when Norðdahl and Hjort (1987) described a probable Preboreal glacier advance in the inner parts of Hofsárdalur and Vesturárdalur in Vopnafjörður in Northeast Iceland (Figs. 6 and 11).

New stratigraphical and chronological evidence places the Búði moraine in South Iceland within the Preboreal Chronozone (Figs. 8 and 11). Furthermore, a lack of sediments of Allerød age in the area beyond the Búði moraine (Fig. 10) is believed to indicate that the South Icelandic lowlands were ice-covered during the Younger Dryas glaciation (Hjartarson and Ingólfsson, 1988). According to Hjartarson (1989) the Reykjavík area in Southwest Iceland was at least once overridden by glaciers in the period between 9,815 and 11,000 B.P., i.e. during the Younger Dryas Chronozone. Furthermore, a termination of a glacier advance in the area northeast of Reykjavík around 9,815 B.P. indicates that the glaciers may possibly have been more extensive in early Preboreal time, than was previously indicated by the DAD- model (Figs. 9 and 11).

New results from investigations in the Fnjóskadalur area in North Iceland also render support to a modification of the DAD-model's concept of glacier extent (Norðdahl, 1990; 1991 Norðdahl and Hafliðason, 1990). The existence of the Austari-Krókar ice-dammed lake in Fnjóskadalur at about 10,600 B.P., shows that during the Younger Dryas Chronozone the outlet glaciers in Eyjafjörður and Bárðardalur extended at least north beyond Dalsmynni and Ljósavatnsskarð, respectively (Figs. 3 and 11). This great extent of glaciers in Younger Dryas time is furthermore supported by the great southward gradient (2.65 m/km) of the corresponding strandline of the Austari-Krókar ice-dammed lake, a gradient that definitely reflects an increased glacier load on the crust in the i Fnjóskadalur area (Norðdahl, 1983).

This review of the Late Weichselian deglaciation history of Iceland, leads to the conclusion that the above outlined MAD-model now contains four plausible glacier readvances in the period between 12,655 and 9,650 B.P. Two of these advances, the early Preboreal and Younger Dryas advances, which have been ^{14}C dated in a few localities in Iceland, probably occurred simultaneously throughout the country. On the other hand, the Older Dryas advance has as yet only been securely dated in West Iceland, and the presumed Bølling readvance has only been dated in Northeast Iceland. The previous DAD-model contained two widespread glacier readvances, while the present MAD-model additionally includes two locally identified readvances. In early Preboreal time considerable portion of present day land area, although at that time submerged in the sea, may have protruded beyond the margin of the inland ice sheet in South, Northeast, North and West Iceland. In Younger Dryas time a continuous inland ice sheet probably reached beyond

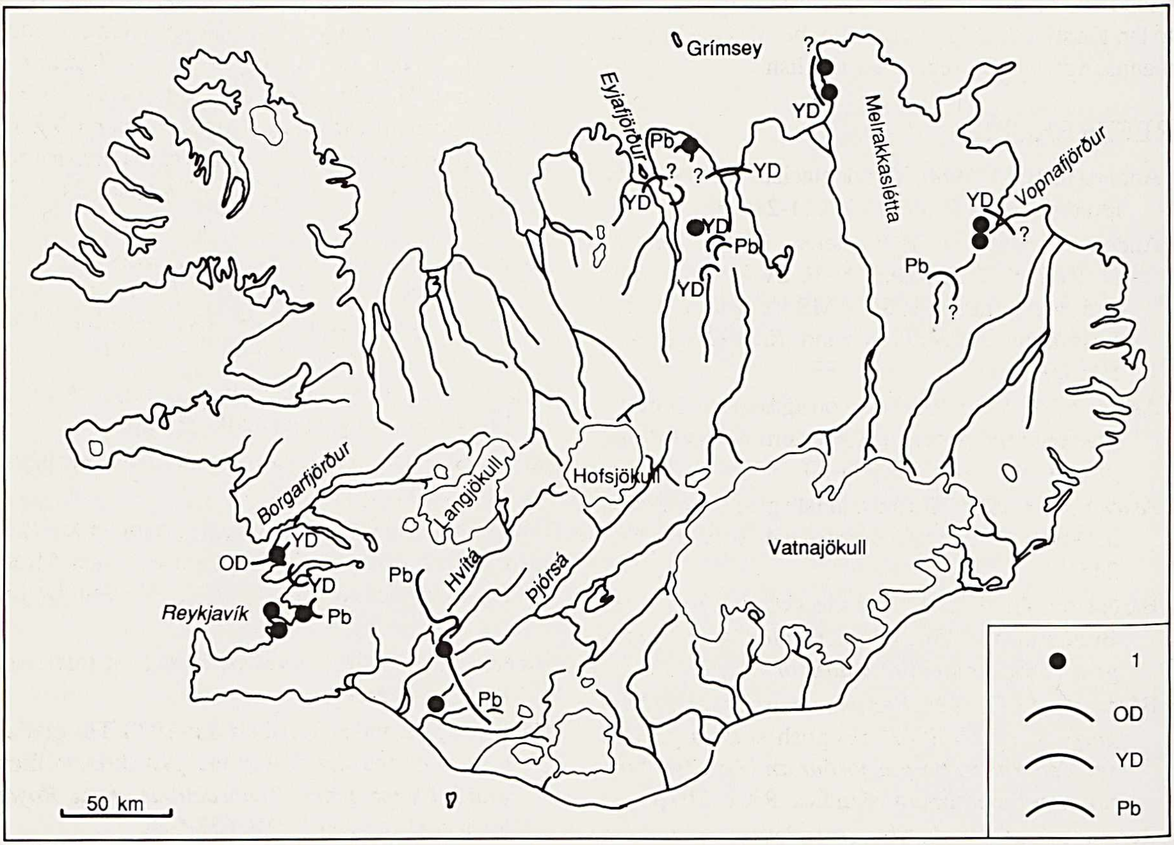

Figure 11. The present concept of Late Weichselian and early Holocene multi advance deglaciation (MAD) model with important ^{14}C dated localities and end-moraines in Iceland. Legend: 1) ^{14}C dates. OD) Older Dryas position of glacier margin. YD) Younger Dryas position of glacier margin. Pb) Preboreal position of glacier margin. —*Núverandi hugmynd varðandi aldur og legu jökulgarða sem mynduðust við framrás íslenska meginjökulsins á síðjökultíma og í upphafi nútíma. Tákn: 1) Geislakolsaldursákvarðanir. OD) Jökuljaðar frá "eldri Dryas" tíma. YD) Jökuljaðar frá "yngri Dryas" tíma. Pb) Jökuljaðar frá upphafi nútíma.*

the present coastline and covered all of Iceland except some of its most peripheral parts in West, North and Northeast Iceland. Thus, the MAD-model recognizes markedly greater extent of the Icelandic inland ice sheet in early Preboreal and Younger Dryas times than previously was indicated by the DAD-model. The extent of the inland ice sheet during the Older Dryas and Bølling advances in West and Northeast Iceland respectively, is as yet unknown.

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ÁGRIP

YFIRLIT UM SÖGU JÖKULHÖRFUNAR Á ÍSLANDI Á SÍÐJÖKULTÍMA

Í þessari grein er lauslega lýst þeirri þróun sem hefur orðið síðustu 100 árin á hugmyndum okkar varðandi hörfun íslenska meginjökulsins í lok síðasta jökulskeiðs. Við upphaf rannsókna á hörfun jökulsins átti sú hugmynd mestu fylgi að fagna, að jökulbrúnin hafi færst jafnt og þétt inn yfir strönd landsins og inn til miðhálendisins. Þorvaldur Thoroddsen getur þess á mörgum stöðum í ritum sínum að víða á Íslandi séu jökulgarðar, sem hafa myndast við tímabundna kyrrstöðu jökulbrúnarinnar. Þess sér aftur á móti ekki stað, að myndun garðanna hafi verið talin tengjast víðtækum breytingum á loftslagi, né heldur að þessir garðar hafi myndast við samtíma framrásir eða kyrrstöðu jökulbrúnarinnar. Helgi Pjeturss varð fyrstur til að setja fram þá kenningu, að myndun jökulgarða á Langanesi og sunnan Þistilfjarðar og framrás jökla og myndun jökulgarða á Skaga tengdist framrás íslenska meginjökulsins á því tímabili sem hann nefndi Langanesskeið. Hann var einnig þeirrar skoðunar, að sunnanlands hafi á sama tíma myndast miklir jökulgarðar. Vera má að hér hafi Helgi haft í huga myndun þeirra jökulgarða, sem síðar voru kenndir við fossinn Búða í Þjórsá. Guðmundur G. Bárðarson veitti athygli jökulgörðum sem hann taldi myndaða við kyrrstæða jökulbrún við innanverðan Breiðafjörð (í Dölum) og í Borgarfirði. Samkvæmt athugunum Þorvalds Thoroddsen og Guðmundar G. Bárðarsonar fylgdi tímabili sjávarborðshækkunar í kjölfar þess að jökulbrúnin hörfaði frá þessum jökulgörðum. Hæst varð afstaða láðs og lagar þegar jökulbrúnin hörfaði inn fyrir núverandi strönd landsins og inn til dala. Eftir það fór sjávarborð stöðugt lækkandi í átt til þeirrar afstöðu sem nú er á milli láðs og lagar.

Þessi meginhugmynd um eina samfellda hörfun meginjökulsins hélst sem næst óbreytt þar til Guðmundur Kjartansson lýsti myndun Búðaraðarinnar á Suðurlandi og Sigurður Þórarinsson myndun Hólkotsraðar á Norður- og Norðausturlandi, en þeir töldu að aðeins ein víðtæk framrás hefði rofið hörfun meginjökulsins. Í yngri ritsmíð sýndi Guðmundur Kjartansson fram á að rekja mætti jökulgarða Búðaraðarinnar úr Laugardal og inn á Kjöl. Síðar setti Þorleifur Einarsson fram tilgátu þess efnis, að á myndunartíma jökulgarða Búða- og Hólkotsraðar hafi brún meginjökulsins legið frá Kili um Eyjafjörð og Bárðardal til Vestmannsvatns í mynni Reykjadals. Jökulgarðar beggja raðanna voru taldir myndaðir við framrás meginjökulsins, sem varð vegna kólnandi loftslags á svonefndu Búðaskeiði. Búðaskeið var talið hafa staðið yfir frá því fyrir um 11.000 árum og þar til fyrir um 10.000 árum. Hugmyndin um að lok síðasta jökulskeiðs hafi orðið með einni framrás meginjökulsins breyttist þegar Þorleifur Einarsson tengdi myndun jökulgarða á Álftanesi og við utanverðan Hvalfjörð við aðra og eldri framrás íslenska meginjökulsins. Síðar voru jökulgarðar í mynni Borgarfjarðardala, á Norðurlandi og á Langanesi einnig taldir myndaðir við þessa framrás jökulsins, sem varð vegna tímabundinnar loftslagskólnunar á svonefndu Álftanesskeiði fyrir um 12.000 árum. Samfara þessum stærðarbreytingum íslenska meginjökulsins á Álftanes- og Búðaskeiði breyttist afstaða láðs og lagar á þann veg, að sjór gekk á land við upphaf beggja framrásanna. Hæst varð afstæð afstaða láðs og lagar í upphafi Búðaskeiðs fyrir um 11.000 árum , en þá var talið að efstu fjörumörk hafi myndast í um 110 m h.y.s. á Suðurlandi, í um 70 m h.y.s. á Vesturlandi en í um 50 m h.y.s. annars staðar á landinu. Með skýrgreiningu Álftanesskeiðs var talið að íslenski meginjökullinn hefði hörfað af landinu í tveimur aðgreinanlegum áföngum. Sjávarsetlög í Saurbæ í Dalasýslu, við Kaldá í Hnappadalssýslu og í grunni Félagsstofnunar stúdenta í Reykjavík eru þau fyrstu frá tímabilinu milli Álftanes- og Búðaskeiðs sem voru aldursákvörðuð. Sjávarsetlög frá Röndinni við Kópasker, en þau eru eldri en Álftanesskeið, voru aldursákvörðuð skömmu síðar.

Þessi hugmynd um tvö tímabil jökulframrása vegna loftslagskólnunar á Álftanes- og Búðaskeiði, og tvö tímabil jökulhörfunar vegna loftslagshlýnunar á Kópaskers- og Saurbæjar- skeiði, var að mestu óbreytt þar til fyrir nokkrum árum, að fram komu nýjar hugmyndir um aldur Búðaraðarinnar á Suðurlandi og Hólkotsraðarinnar á Norðurlandi svo og varðandi aldur jökulframrása á Vestur-, Norður- og Norðausturlandi. Einnig hafa á síðustu árum komið fram nýjar hugmyndir um að framrásir meginjökulsins hafi verið mun fleiri á tímabilinu frá því fyrir um 18.000 árum og til upphafs nútíma fyrir um 10.000 árum. Í upphafi áttunda áratugar þessar aldar voru ^{14}C aldursákvarðanir varðandi íslenska kvarterjarðfræði tæpir tveir tugir, en nú um tuttugu árum síðar hafa 50-60 slíkar aldursákvarðanir verið birtar. Hinn aukni fjöldi aldursákvarðana hefur einkum auðveldað tengingar og samanburð jarðfræðilegra atburða á milli landsvæða og landshluta.

Rannsóknir allmargra jarðfræðinga á hörfunarsögu íslenska meginjökulsins á síðustu 10-15 árum hafa m.a. leitt í ljós, að jökullinn stækkaði og brún hans færðist fram snemma á nútíma. Aldur þessa atburðar hefur verið ákvarðaður á fjórum stöðum á landinu: Nýlegar rannsóknir á Suðurlandi hafa leitt í ljós, að Búðaröðin myndaðist við framrás meginjökulsins fyrir um 9.700 árum samtímis því að efstu fjörumörk á Suðurlandi urðu til í um 110 m h.y.s. Við tímabundna loftslagskólnun stækkuðu staðbundnir dal- og skálarjöklar á utanverðu Norðurlandi og náðu jöklarnir víða út úr dölum sínum og mynduðu jökulgarða niður undir núverandi sjávarmál. Samkvæmt aldursákvörðun í Flateyjardal hörfuðu jöklarnir frá þessum jökulgörðum ekki síðar en fyrir um 9.650 árum. Í Hofsárdal og Vesturárdal í Vopnafirði á Norðausturlandi steig sjávarborð og náði 35 m h.y.s. fyrir um 9.700 árum. Myndun þessara fjörumarka tengist framrás og síðar kyrrstöðu jökulbrúnar innarlega í Vopnafjarðardölum. Fjörumörk í um 60 m h.y.s. og nokkru utar með firðinum eru eldri og frá þeim tíma þegar jökulbrúnin lá um þveran botn Vopnafjarðar, líklega í lok "yngri Dryas". Nærri mynni Mosfellsdals á Suðvesturlandi myndaðist óseyri í 55-60 m h.y.s. fyrir framan jökul sem þá náði út í mynni dalsins. Aldursákvörðun á fornskeljum, sem teknar voru úr setlögum þessarar fornu óseyrar, bendir til þess að hún hafi myndast fyrir um 9.800 árum. Aldursákvörðun á skeljum sem höfðu veðrast út úr setlögunum gaf nokkru hærri aldur eða um 10.400 ár. Að sinni verður ekki úr því skorið hvort þessi aldursákvörðun sé ekki eins áreiðanleg og sú fyrrnefnda, eða hvort hún aldursákvarðar annað og eldra skeið sjávarstöðu- breytinga á Suðvesturlandi.

Á tímabilinu "yngra Dryas", sem stóð yfir frá 11.000 árum og þar til fyrir 10.000 árum, varð önnur og eldri framrás íslenska meginjökulsins. Framrás af þeim aldri hefur nú verið aldursákvörðuð á fjórum stöðum á landinu: Vestanlands gengu skriðjöklar til suðurs út Borgarfjörð og allt til Skorholtsmela og á sama tíma náði skriðjökull í Hvalfirði út undir mynni fjarðarins. Hámark þessarar framrásar varð samkvæmt aldursákvörðunum fyrir um 10.600

árum. Um svipað leyti myndaðist víðáttumikið jökullón í Fnjóskadal á Norðurlandi, þegar skriðjöklar í Eyjafirði og í Bárðardal náðu norður undir Hrísey og norður fyrir Ljósavatnsskarð. Aldur jökullónsins og framrásarinnar er jafn aldri Skógagjóskunnar, en hún barst út í jökullónið fyrir um 10.600 árum. Á Norðausturlandi náði jökull út fyrir strönd Melrakkasléttu fyrir um 10.200 árum og í Reykjavík er talið að jökull hafi náð út yfir núverandi strönd fyrir um 11.000 árum. Nokkru fyrr, eða fyrir um 11.800 árum, stækkuðu jöklar á Vesturlandi og náði skriðjökull úr Borgarfirði suður fyrir Skorholtsmela á sama tíma og skriðjökull í Hvalfirði náði út í eða jafnvel út úr mynni fjarðarins. Á Melrakkasléttu er vísbending um að jöklar á Norðausturlandi hafi stækkað og gengið fram fyrir um 12.700 árum. Þessar tvær síðast töldu framrásir íslenska meginjökulsins eru enn sem komið er aðeins þekktar á þessum tveimur stöðum á landinu.

Helstu niðurstöður framangreindrar umfjöllunar eru þær, að íslenski meginjökullinn hefur að minnsta kosti tvisvar sinnum stækkað og gengið fram á tímabilinu frá því fyrir um 12.700 árum og þar til fyrir um 9.700 árum. Hámark þessara framrása varð annars vegar í upphafi nútíma fyrir um 9.700 árum og hins vegar á "yngri Dryas" tíma fyrir um 10.600 árum. Auk þessara tveggja útbreiddu framrása íslenska meginjökulsins þá stækkuðu jöklar á Vesturlandi og náðu hámarki fyrir um 11.800 árum og á Norðausturlandi fyrir um 12.700 árum. Ummerki enn eldri framrása eru þekkt í lausum jarðlögum í Fnjóskadal á Norðurlandi og á Melrakkasléttu á Norðausturlandi. Hvað varðar stærð íslenska meginjökulsins á tímabilinu frá 12.700 til 9.700 árum fyrir okkar daga er ljóst, að hann var til muna stærri í upphafi nútíma og á "yngra Dryas" en gert hafði verið ráð fyrir í eldri hugmyndum um stærð og hörfunarsögu jökulsins í lok síðasta jökulskeiðs ísaldar og upphafi í nútíma.

Esjufjallaskáli hinn síðari, nýfrágenginn á páskadag, 10. apríl 1977. Á myndinni eru, talið frá vinstri: Rúnar Nordquist, Gunnar Guðmundsson, Ólafur Nilsson, Stefán Bjarnason, Kristbjörn Egilsson, Gylfi Gunnarsson, Helga Árnadóttir, Ástvaldur Guðmundsson, Jórunn Garðarsdóttir, Guðjón Halldórsson, Óli R. Gunnarsson, Valur Jóhannesson, Jóhannes Ellert Guðlaugsson og Vilhelm Andersen. Ljósm. Jón E. Ísdal.
The Esjufjöll hut, April 10, 1977. Photo. Jón E. Ísdal.