LATE- AND POSTGLACIAL SHORELINE DISPLACEMENT AND GLACIATION IN AND AROUND THE SKAGI PENINSULA, NORTHERN ICELAND

Hiroshi MORIWAKI*

Abstract In the present coastal area in and around the Skagi Peninsula, northern Iceland, two glacier readvances called Blönduős I and Blönduős II occurred. They are correlated with Older and Younger Dryas, respectively. The highest shoreline was formed in connection with the Younger Dryas glacier readvance. The height at 50-60 m a.s.l. everywhere indicates that no tilting uplift occurred in the Skagi Peninsula. The glacio-isostatic rebound uplift started immediately after the retreat of glacier, and probably ended about 7,000 or 8,000 years ago. The uplift rate between *ca.* 10,000 and 9,000 years ago had been 7 cm per year.

Key words: shoreline displacement, late-glacial, glaciation, Iceland.

1. Introduction

Purpose

Iceland was covered by an ice cap over nearly the whole island in the maximum stage of the Last Glacial. The glacier retreat after this stage greatly influenced the changes in the landforms of Iceland. In particular, glacio-isostatic rebound movement associated with the retreat of the glacier produced raised coastal features in and near the area of the present coast. In this paper I will deal with the problems concerning raised ancient coastal and glacial features in the present coastal area in the Skagi region of northern Iceland: (1) the highest late-glacial shoreline, (2) shoreline displacement due to glacio-isostatic rebound, (3) relation of the late-glacial glaciation to shoreline displacement.

The investigated area, the Skagi region of northern Iceland (Fig. 1) is most significant for studying these problems, because late-and postglacial glacial and coastal features are well developed, and glacio-isostatic rebound movement is easy to detect in this area distant from the median active zone which is tectonically active area. Furthermore, the most conspicuous character of this region is that the glacial and coastal features

*Faculty of Law and Letters, Kagoshima University

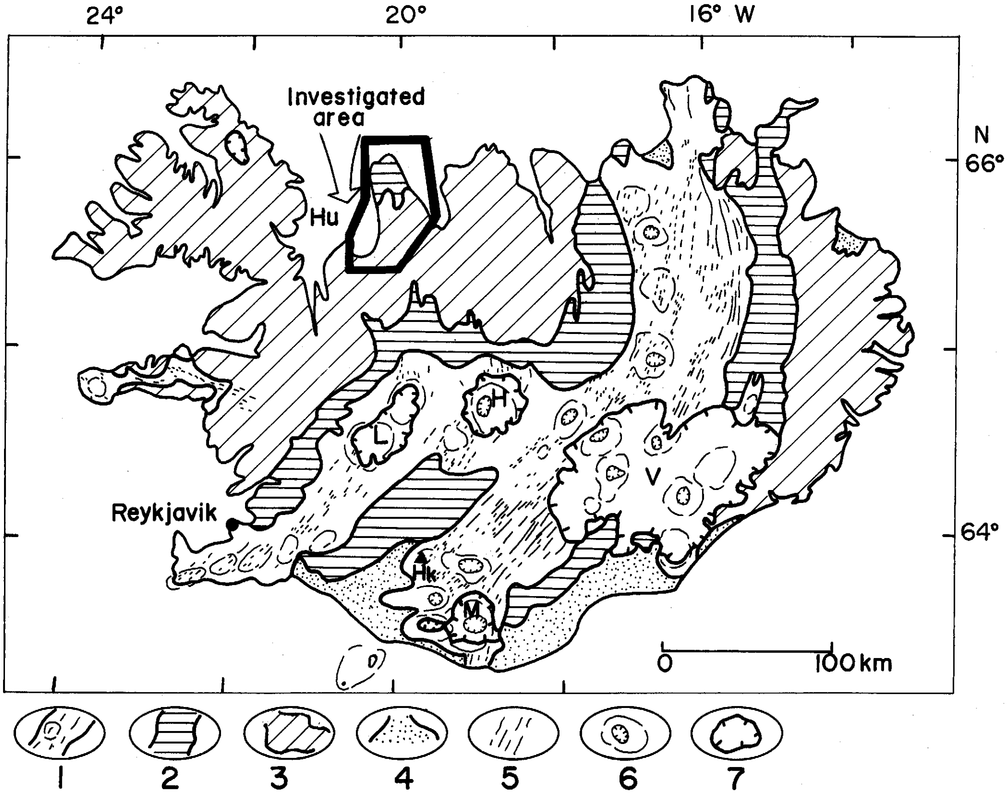

Fig. 1 Geology of Iceland (From Saemundsson, 1979)
1: Upper Pleistocene and postglacial series (<0.7 m.y.); 2: Plio-Pleistocene series (3.1-0.7 m.y.); 3: Tertiary series (>3.1 m.y.); 4: Outwash and lava apron; 5: Fissure trend; 6: Volcanic system and caldera; 7: Ice cap; V: Vatnajökull; H: Hofsjökull; L: Langjökull; M: Mýrdalsjökull; Hu: Húnafloi; Hk: Hekla volcano

probably formed at the end of the late-glacial, *i.e.*, Older and Younger Dryas, coexist in the coastal area. This coexistence makes it possible to directly understand the relation between the glaciation and the coastal development of these times. Precise analyses of this coastal area have scarcely been undertaken hitherto, although there are some reports and maps concerning these problems (Everts, 1974 ; Koefer, 1975).

In other present-day coastal regions of Iceland, recent studies in Borgarfjördur by Ingólfsson (1988) are very worthy of note, although precise studies on this type of theme are rare. In particular, Ingólfsson's view on the Older and Younger Dryas glaciation and coastal development is very interesting. The view that the Older and Younger Dryas glacier advances attained the present coast in Borgarfjördur, and that the shoreline at the time of the glacier advance is in agreement with the highest ancient one, is different from previous works (Einarsson, 1973). This view has provided a very stimulus for my study on Skagi area, as will be discussed below.

Method

First, geomorphological maps were made using air photographs (scale 1:36,000, taken by the U.S. Army in the 1960s) and topographic maps (scale 1:50,000, compiled by the U. S. Army). Then I reconfirmed the landforms and investitated their constituting sediments in the field. The age of landforms, in particular ancient shorelines, was estimated by ^{14}C dating of peat overlying the coastal gravels and tephra layers derived from Hekla volcano. Altitudes of ancient shorelines were measured using a barometric altimeter. The height was determined with an accuracy of the order of 0.5 meter.

Geology

Geologic and neotectonic background is fairly important to discuss the shoreline displacement resulted from glacio-isostatic rebound. Iceland consists of very young volcanic rocks, *i.e.*, Quaternary and Neogene basaltic rocks (Fig. 1). These rocks show zonal and synmetric distribution along the axis of a modern active zone trending in the N-S direction. The investigated area mainly consists of Tertiary or lower Quaternary basaltic rocks (Saemundsson, 1979). These features are quite different from those of other glaciated regions such as Scandinavia and Laurentide, which consist of considerably older rocks.

2. Glacial and Coastal Landforms and Deposits

The coastal area of this region is divided into two part in terms of late-and postglacial coastal and glacial geomorphology: the northern area and the southern area of the peninsula north of Skagaströnd. The former area generally consists of coastal landforms, and the latter area, of glacial as well as coastal ones.

Northern area of the Skagi Peninsula

Late- and postglacial landforms of this area mainly consist of coastal terraces and fossil beach ridges. Most coastal terraces are erosional ones, which have thin marine gravel beds. They are best developed in the northern tip of the peninsula (Photo 1). Six terrace surfaces, named terrace 1, 2, 3, 4, 5 and 6 from higher to lower, are recognized in this area (Fig. 2). The correlation of these terraces is difficult even in a very narrow area, because they lack continuity.

Fossil beach ridges are very effective for reconstructing past sea level changes, since they were formed at shore in a short time, Many fossil beach ridges are observed. They are distributed on bedrock slopes and terrace scarps as well as on terrace surfaces. However it is hard to correlate each of them over a wide area. Therefore, a detailed shoreline displacement history may be limited to a narrow area. Only the highest shoreline can be traced over a wide area. The shoreline presented by a beach ridge on Terrace 1 is 52.5 meters high (Fig. 2).

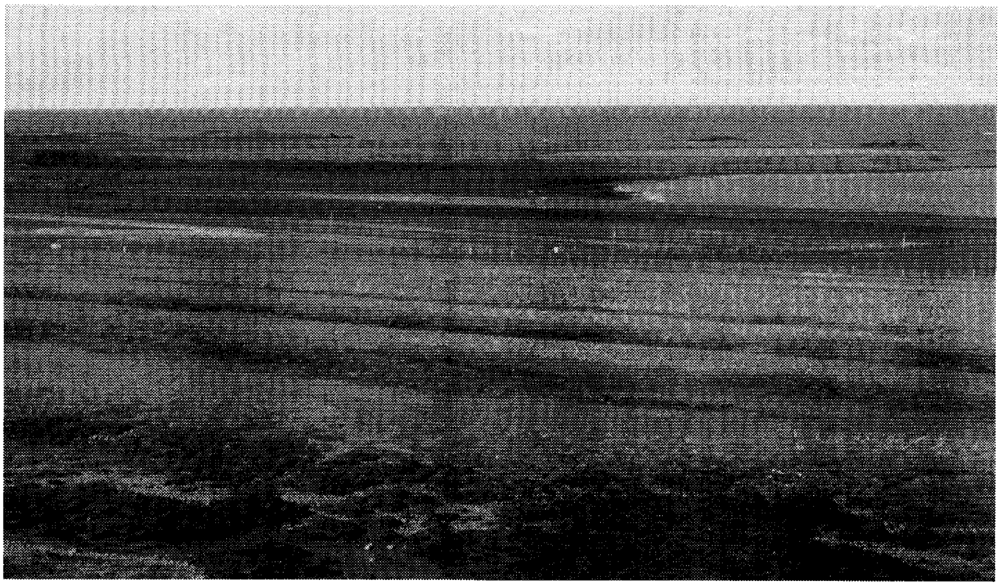

Photo 1 Raised fossil beach ridges in the northern tip of the Skagi Peninsula

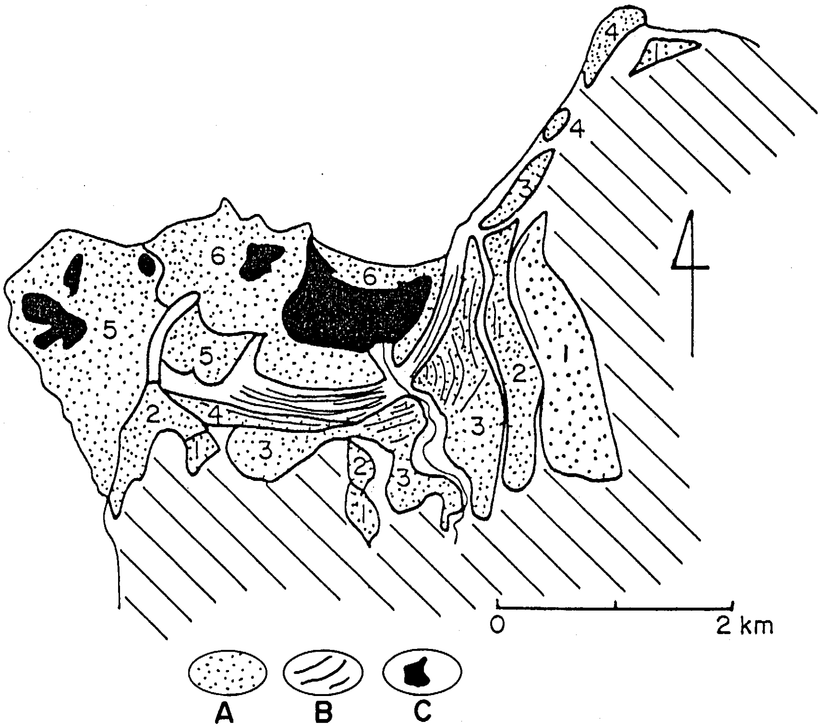

Fig. 2 Geomorphological map of the northwestern tip of the Skagi Peninsula, northern Iceland.
A: Coastal terrace; B: Fossil beach ridge; C: Lake. See Fig. 10 for position.

Southern area of the Skagi Peninsula

Five large valleys, Laxárdalur, Langidalur, Svinadalur, Vatnsdalur and Vididalur are distributed in this area. The last four lead to the central mountainous area. This makes it possible to investigate the change of the past main glacier in the present coast, in terms of late- and postglacial rebound movement. In fact, terminal moraines and raised outwash plains, probably formed by the main glacier in the late-glacial, are distributed in this coastal area, together with past coastal features, *i.e.*, fossil beach ridges, *etc.*

Area around the Laxá River

Almost all of this area consists of marine or fluvial terraces and there is no present alluvial lowland along the Laxá River. This suggests late-or postglacial rapid rise (Photo 2). These terraces are divided into eight surfaces; Terrace I, II, III, IV, V, VI, VII and VIII from higher to lower (Fig. 3).

The higher surfaces (I and II) are raised outwash plains, on which a large number of abandoned channels and kettle holes are observed. The two terraces lead to a terminal moraine. A fossil beach ridge, 60.5 meters high, extends along the margin of Terrace II surface. Therefore, the past glacier shown by the terminal moraine faced the former seashore. This fact indicates that the highest former shoreline coincides with the stage of glacier advance. This view is different from the former one (Einarsson, 1973) that the highest shoreline was formed in the Alleröd interstadial. The terraces lower than Terrace II are generally of marine origin, as indicated by the form of the terrace scarp and many beach ridges on the surfaces.

The deposits of these terraces are easily observed, because the Laxá River generally has cut into the bedrock (Fig. 4). The deposits are divided into three parts: lower thick clay, middle thick gravel and sand, and upper thin gravel. The lower clay deposits unconformably overlie baserock. Thin glacial till consisting of poorly sorted gravels

Photo 2 Marine and fluvial terraces of Laxá area

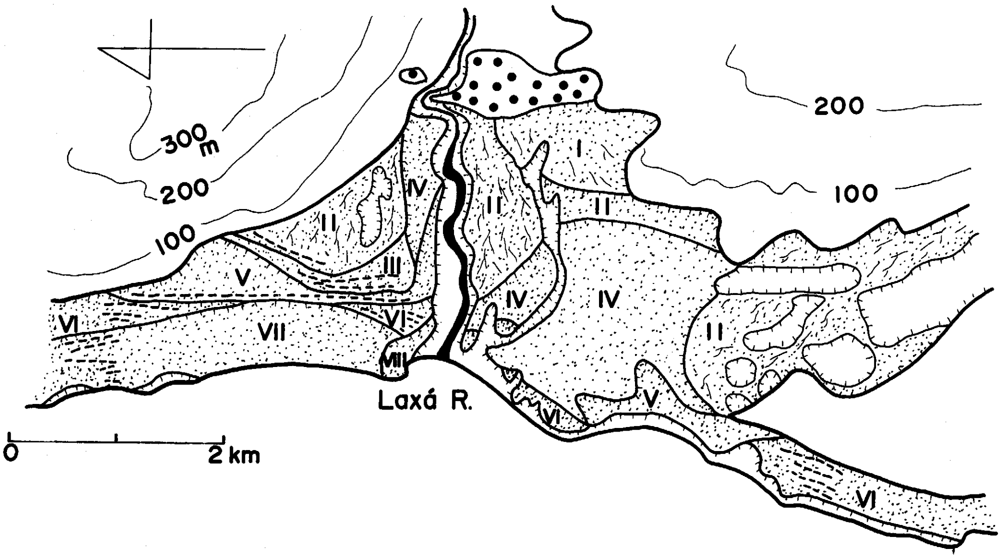

Fig. 3 Geomorphological map of the Laxá area
See Fig. 5 for legend and Fig. 10 for position.

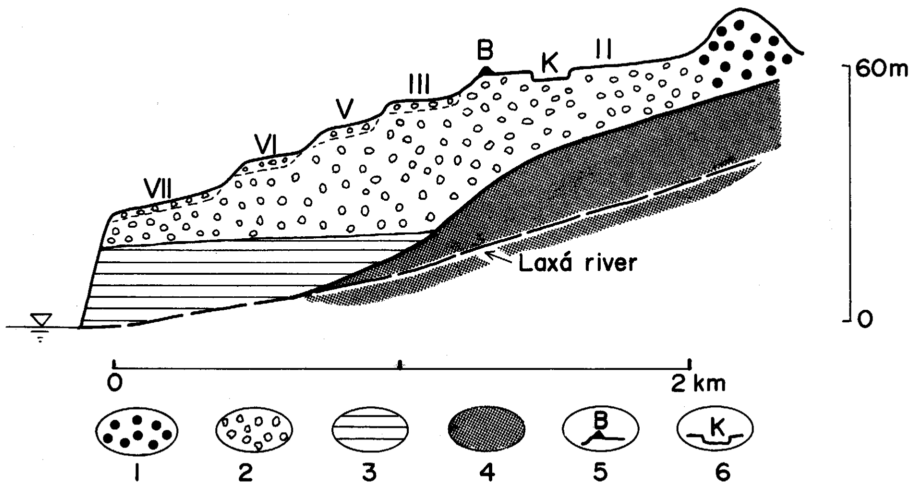

Fig. 4 Geologic section of Laxá area
1: Moraine; 2: Outwash gravel and sand; 3: Glacio-marine verved clay; 4: Bedrock; 5: Fossil beach ridge; 6: Kettle

occasionally underlie the clay. The grey clay in color is more than 20 meters thick. Many thin layered structure are observed in the deposits, indicating that these clay deposits correspond to those named "marine verved clay" (Gudmundsson and Kjartansson, 1984), which was derived from glacial sediments and deposited in slightly deeper sea water. They are quite homogeneous and include no fossil molluscan shells. A thin verved clay layer is a few centimeters thick or less. Middle sand and gravel deposits, more than 10 meters thick, conformably overlie the clay. The well-stratified sand and gravel beds are thought to be glacio-marine deposits. The top surface of the deposits is Terrace I. Terrace II was probably formed at nearly the same time, because it is associated with kettles and leads to the terminal moraine.

The upper thin gravel deposits consist of thin veneer constituting lower terraces, which are generally fill strath terraces. Because the gravel beds frequently overlie the middle thick gravel deposits, the unconformity is very ambiguous.

Gravels constituting the terminal moraine of this area are not so angular and not so poorly sorted.

Blönduős area

The area from the Blandá River to the Vatnsdalsá River is quite significant to discuss the relation between the late-glacial glaciation and isostatic rebound movement, because the following landforms are well developed: (1) late-glacial glacial landforms, indicating two readvances of glaciers, (2) many late-and postglacial shorelines, indicating past sea levels, and (3) Holocene alluvial lowlands or back swamps (Fig. 5).

Glacial landforms developed in this area are divided into two types on the basis of the age of the formation. The younger one consists of a terminal moraine and raised outwash plains. The terminal moraine is distributed in the east of Blönduős town (Photo 3). It closed the outlet of Langidalur valley. Well-developed raised outwash plains corresponding to this terminal moraine constitute the highest terraces, named Terrace I and I'. The terminal moraine and wide raised outwash plain of I' are associated with many abandoned river channels, kettles, and with fossil beach ridges, indicating that the terraces and the moraine are correlative to those of the Laxá area mentioned above. A raised outwash plain of Terrace I or I', with abandoned river channels, beach ridges and a kettle, is observed also in the east of Lake Húnavatn. The deposits constituting these outwash plains are quite similar to those of the Laxá area: they consist of thin basal till, lower thick clay, and upper thick gravel and sand (Photo 4).

An older glacial landform is the terminal moraine immediately east of Lake Húnavatn. The fact that this terminal moraine is situated seaward of the younger raised outwash plain indicates that glacier readvance occurred twice in the late-glacial (Fig. 6). This terminal moraine, occupied by many large and deep kettle holes, is associated with fossil beach ridges on its top (Photo 5), clearly indicating that the whole terminal moraine was once inundated into the sea after its formation. The top of the moraine, including a beach ridge, is 47 meters high. The highest shoreline (55.5 meters high) is situated on the younger raised outwash plain, indicating that this moraine clearly rose from the sea with relative sea level lowering after the sea level culmination of the stage of the younger raised outwash plain.

The stage of the highest shoreline is in accordance with that of the younger raised outwash plain, as mentioned above. The height is about 55 meters. Many shorelines of marine terraces and beach ridges are distributed in lower place than this highest terrace. Thick terrace deposits indicating conspicuous sea level fluctuation are not recognized in these lower coastal terraces, suggesting that relative sea level lowering, *i.e.*, isostatic rebound uplift, was not interrupted by conspicuous relative sea level rise.

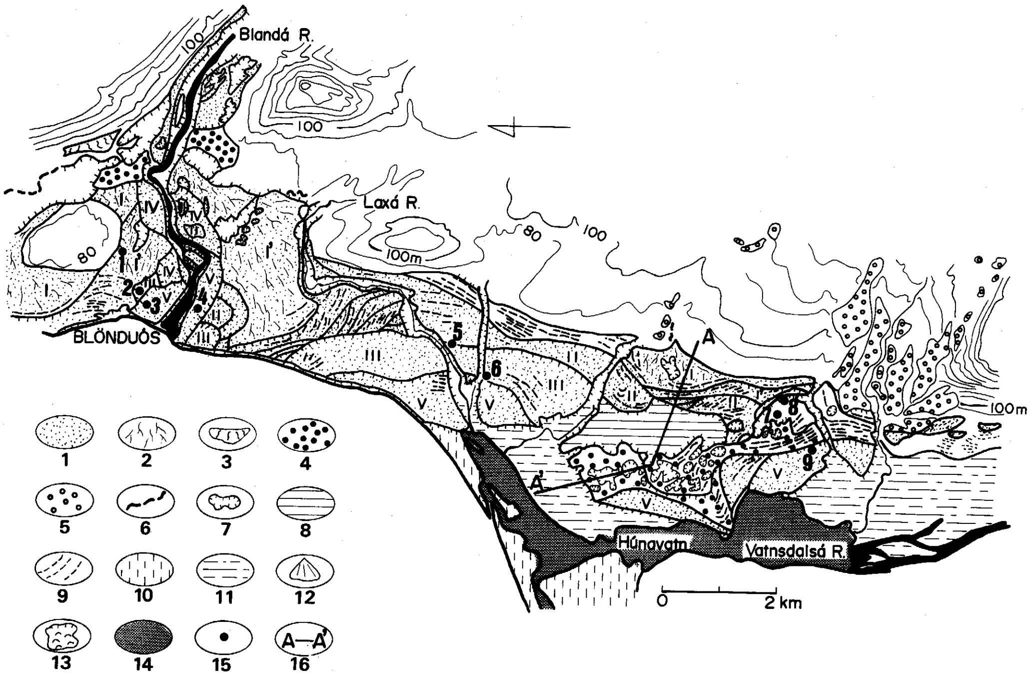

Fig. 5 Geomorphological map of Blönduős area
1: Coastal terrace; 2: Abandoned river channel; 3: Kame terrace; 4: Terminal moraine; 5: Ablation moraine; 6: Esker; 7: Kettle; 8: Abandoned lagoon; 9: Fossil beach ridge; 10: Barrier bar; 11: Alluvial lowland; 12: Alluvial fan; 13: Land slide landform; 14: Lake and lagoon; 15: Sampling site of peat layer for ^{14}C dating; 16: Position of geomorphic section of Fig. 6.
See Fig. 10 for position.

Photo 3 The younger terminal moraine in Blönduős area

Photo 4 Deposits constituting raised outwash plains in Blönduős

Photo 5 The older terminal moraine with kettles

Alluvial and coastal lowlands are developed along the Vatnsdalsá River and around Lake Húnavatn in this area. The formation age is estimated to be middle and late Holocene, as will be mentioned below.

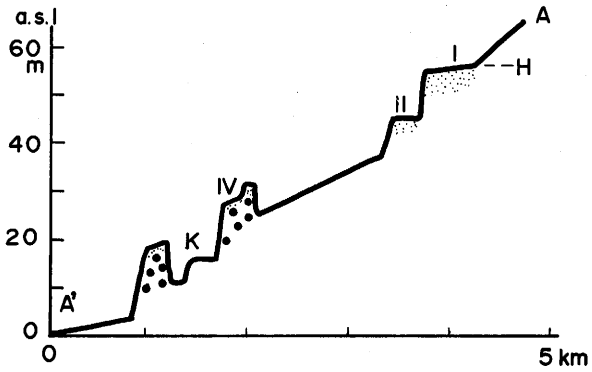

Fig. 6 Geomorphic section of Blönduős area
See Fig. 5 for position of A-A'.

Area around Lake Hőp

This area is characterized by the fact that there are no lower terraces, but the beach ridges on the bedrock slopes (Fig. 7). The coastal terraces are only raised outwash plains, which are not so well developed. They are distributed only in the area around the Gljűfurá River and northeast of Lake Vesturhőpsvatn, where terminal moraines with kettles are recognized. The highest shoreline lies on the raised outwash plains. There are older terminal moraines on the southeastern shore of Lake Hőp. They are situated seaward of the younger glacial landforms mentioned above, and their tops were sculpted by ancient shorelines. The following features are also recognized in this area: older and younger glacial depositional landforms exist, the older one was once drowned, and the highest shoreline coincides with the younger glacial readvance.

The development of the landforms of this area, however, is different from that of the Laxá and Blönduős areas mentioned above. The following characteristics of this area indicates poor sediment supply from past glaciation represented by the younger raised outwash plains and moraines: there are no lower coastal and river terraces, but many beach ridges on bedrock slopes, and raised outwash plains are very poor.

There are no coastal terraces or beach ridges in the Vatnsdalur Valley, though this valley is rather wide and deep. Beach ridges are arranged so as to close the outlet of the valley. These features suggest that the glacier attained the outlet of the valley in the age of the formation of the younger glacial landforms in this valley. In constrast, the glacier margin was situated a little landward in the Vididalur Valley.

In summarizing, glacial landforms indicating two glacier readvances are recogniged in and around the Skagi Peninsula (Fig. 8). These readvances are named Blönduős I (older) and Blönduős II (younger). The evidence of Blönduős I includes terminal moraines situated further seaward to those of Blönduős II at the eastern shore of Lake Hűnavatn and the southwestern shore of Lake Hőp. These moraines were once inundated by the sea. The evidence of Blönduős II consists of terminal moraines and raised outwash plains that formed the highest shoreline. The deposits of the outwash plains consist of thin glacial till, thick glacio-marine clay and thick glacio-marine gravel and sand deposits

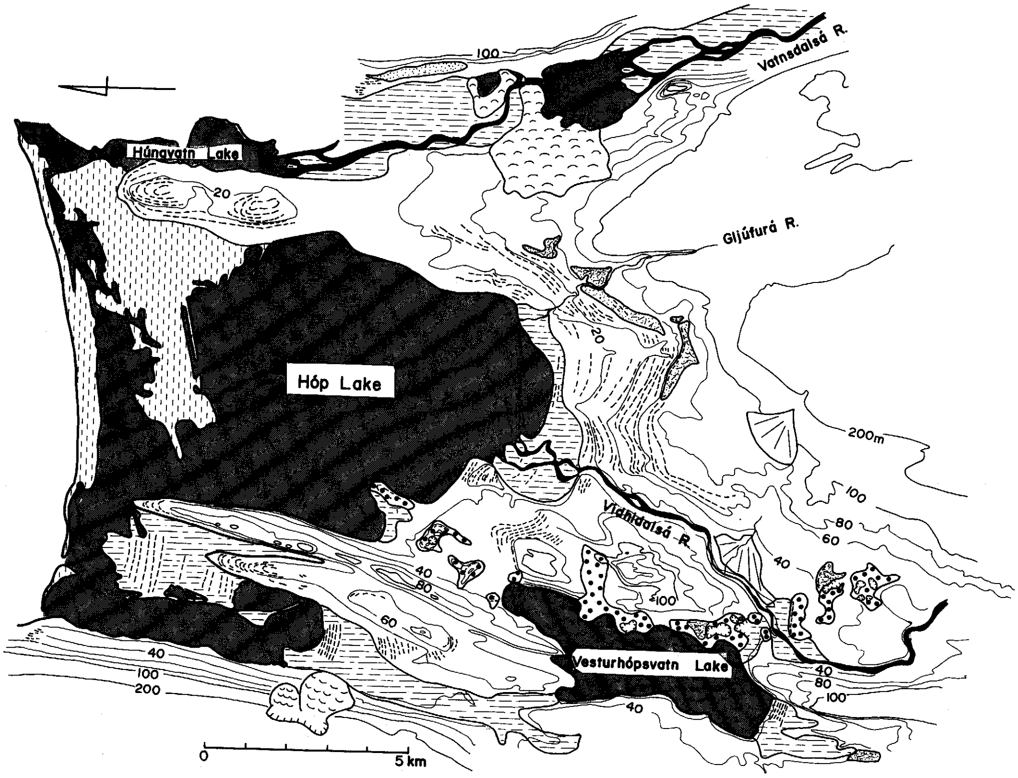

Fig. 7 Geomorphological map around Lake Hóp
See Fig. 5 for legend and Fig. 10 for position.

from lower to upper, indicating one cycle of submergence. There are many beach ridges and lower coastal terraces, whose deposits are very thin, indicating that isostatic rebound occurred continuously.

3. Chronology of Glacial and Coastal Features

The standard features in establishing landform chronology are the terminal moraines, the raised outwash plains, the glacio-marine deposits of Blönduős II and the lowest coastal terrace. Unfortunately, no data on age could be obtained from the thick glacio-marine deposists and the thin coastal deposits of the lower terraces, as they contain no fossil molluscan shells or organic matter. Though we cannot date the exact ages of the landforms, it is possible to indirectly estimate the age from ^{14}C dates of the basal peats overlying these past coastal deposits, tephras derived from Hekla volcano and comparing with other regions.

Fairly thick peat layers 1 to 2 meters thick generally overlie past coastal deposits. The ^{14}C dates of the basal peats immediately over the deposits of various terraces were used

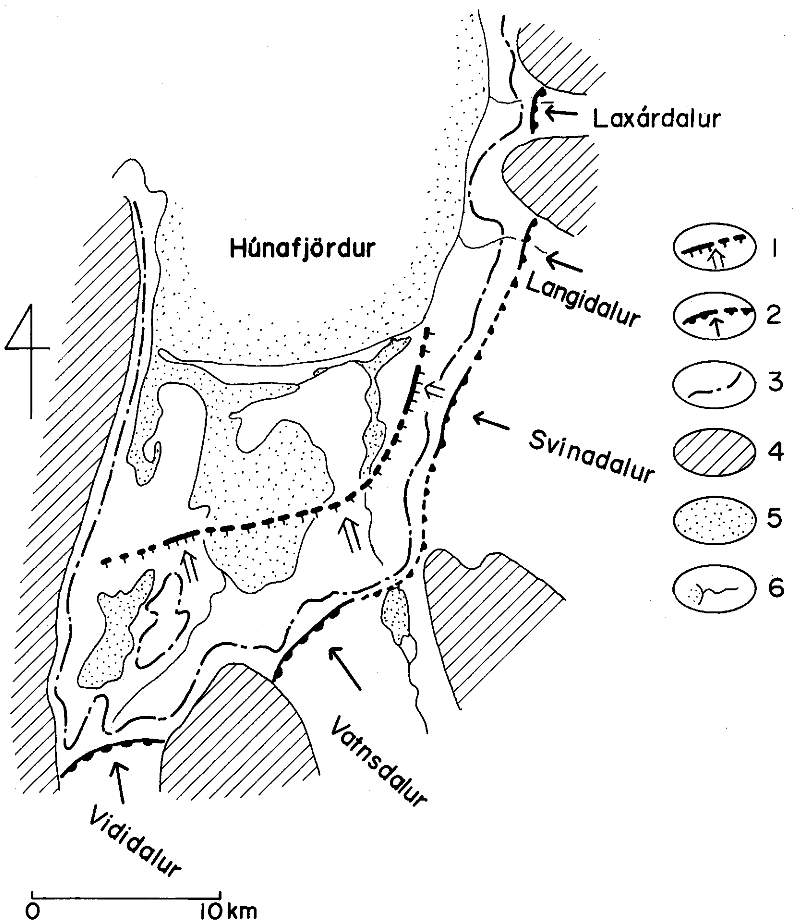

Fig. 8 Suggested positions of ice margins and the highest shoreline of Blönduős area
1: Blönduős I ice margin; 2: Blönduős II ice margin; 3: Highest shoreline; 4: Mountain; 5: Sea, Lagoon and Lake; 6: River

to estimate the ages of the past shorelines (Table 1). The dates are not so systematic. That is, some of the dates of higher terraces indicate younger ages than those of the lower ones, probably due to contamination with younger organic matter. The oldest age is 9,550±210 y.B.P. (Gak-12204) obtained from the lowest peat of Terrace III, 13.5 meters high. Though the highest terrace, about 60 meters high, with the terminal moraine seems to be considerably older, many ^{14}C dates do not indicate ages older than 10,000 y.B.P., suggesting that the highest terrace is not so old compared with the lower terraces.

This estimation is supported by the tephras and the thickness of peat layers. Four tephra layers, H_1, H_3, H_4 and H_5 pumice derived from Hekla volcano, whose ages are already known (Larsen and Thorarinsson, 1977), are distributed in this area. The lowest one, H_5 pumice of 6,200 y.B.P., is contained in the peat of the lowest terrace, 9 meters high (Fig. 9). Furthermore, the thickness of the peat layer from the H_5 pumice to the underlying terrace gravel is not so different between the lowest terrace (Fig. 9-3) and the highest terrace (-1). This fact indicates that there is not a great gap in age between the lowest and the highest terrace. Accordingly, the highest terrace, *i.e.*, the raised outwash plain and the terminal moraine of Blönduős II is probably correlative with the Búdi stage, *i.e.*, Younger Dryas (Einarsson, 1973). Since the highest shoreline on the terrace is correlative with Blönduős II, it may have been formed in Younger Dryas. Glacial readvance of Blönduős I seems to be correlative with the Alftanes stage (Einarsson, 1973), *i.e.*, Older Dryas.

The oldest age of the lowest Terrace V is 8,810±210 y.B.P. (Gak-12200), indicating that these coastal terraces were formed in the early Holocene.

Table 1 ^{14}C dates of basal peat overlying terrace gravel bed
See Fig. 5 for position.

Location no. (Fig.5)	Landform	Elevation (m)	Date (yBP)	Reference no.
1	Terrace I'	47.5	5,870±150	Gak-11891
2	Terrace III	17.5	6,850±170	Gak-12197
3	Terrace V	10.0	6,030±180	Gak-11890
4	Terrace V	7.5	7,280±170	Gak-12202
5	Terrace II	27.5	9,320±150	Gak-12198
6	Terrace III	13.5	9,550±210	Gak-12204
7	Terrace II'	31.7	5,130±170	Gak-12201
8	Terrace II'	31.5	7,080±140	Gak-12203
9	Terrace V	8.3	8,810±210	Gak-12200

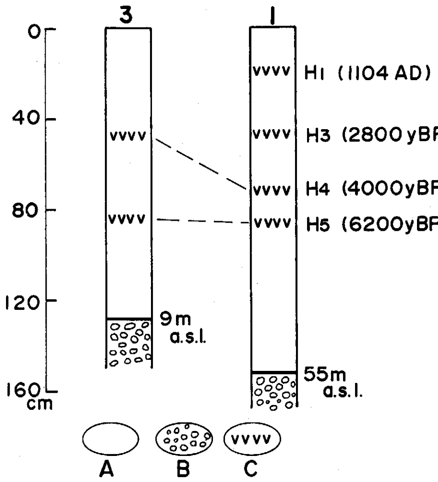

Fig. 9 Peat and tephra layers overlying the lowest (3) and the highest (1) terraces in Blönduős area
A: Peat layer; B: Terrace gravel; C: Tephra layer derived from Hekla volcano
See Fig. 5 for position.

4. Late- and Postglacial Shoreline Displacement

Late- glacial highest shoreline

As Fig. 10 shows, the altitudes of the highest shoreline do not vary a great deal in the Skagi Peninsula and around Lake Hóp : they are 50 to 60 meters high everywhere. This fact is different from the former view (Einarsson, 1963) that the altitude of the highest shoreline becomes lower seaward corresponding to the distribution of the former ice sheet. Such altitude distribution of the highest shoreline of this area suggests that another ice sheet center existed in the last glaciation in Iceland, or that tectonic movement was responsible. This will be discussed in detail in a separate paper.

Shoreline displacement history

Figure 11 shows the shoreline displacement curve obtained in this area, for which data on the age are not sufficient. Though detailed rebound movement cannot be analyzed, we can understand the essence of the shoreline displacement caused by isostatic rebound movement.

It was in Younger Dryas that isostatic uplift surpassed the eustatic sea level rise. Glacio-isostatic uplift was balanced by eustatic rise at this time, so that sea level was relatively stable over a rather long time. As a result, wide outwash plain and thick glacio-marine clay, sand and gravel deposits were formed in the coastal area.

It was 9,000 years ago that relative sea level attained the present sea level. The absolute (glacio-eustatic) sea level of 10,000 years ago is estimated to have been 40 m below the present sea level, and that of 9,000 years ago 30 m (Bloom, 1971). The shoreline of 10,000 years ago now lies at 60 m a.s.l. and that of 9,000 years ago at 0 m, respectively (Fig. 11). Therefore, the uplift amounting to 70 m (60 m+40 m−30 m) had occurred during the period from 10,000 years ago to 9,000 years ago. The rebound during the early Holocene is thus calculated to have been 7 cm per year. Probably the isostaic rebound movement ended about 7,000 or 8,000 years ago. The rebound rate was extremely high in the early Holocene. The high rebound rate and the early end of the rebound movement are different from those of Scandinavia (*e.g.* Mörner, 1969), where land has been gradually uplifting in the Holocene. These phenomena indicate that Iceland responded to the retreat of the glacier more sensitively than Scandinavia.

The relation of the late-glacial glaciation to shoreline displacement

As mentioned above, the age of the highest shoreline coincides with that of the glacier readvance of Younger Dryas. This means that the culmination of sea level change coincides with the glacial stadial. Such a case is already recognized in Borgarfjördur of Iceland (Ingólfsson, 1988). This is different from the case of other regions such as Japan where the culmination coincides with interstadial or interglacial periods.

This phemomenon is probably due to the fact that Iceland, as an island, sensitively responded to the retreat of the glacier, *i.e.*, as soon as the present coast was free from the glacier, rapid uplift occurred, as Fig. 11 shows. As a result, sea level rise could not

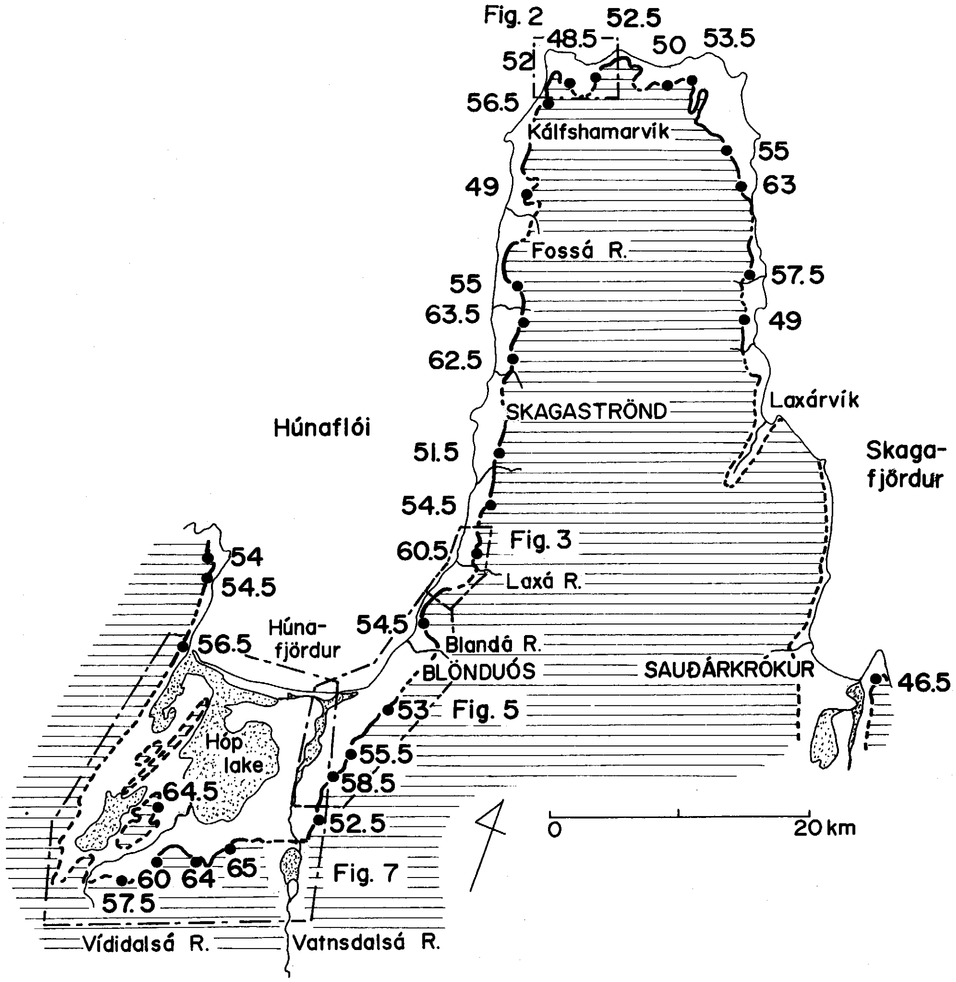

Fig. 10 Altitude of the highest shoreline of the Skagi Peninsula

surpass the rebound uplift. These phenomena are quite peculiar to the Icelandic coast, where there was a very short time lag between glacier retreat and isostatic rebound, as mentioned above.

5. Conclusions

The main results of this study are as follows:

(1) The two glacier readvances called Blönduős I and Blönduős II reached the present coastal area. They are probably correlated with Older and Younger Dryas, respectively.

(2) The highest shorelines probably formed in Younger Dryas are 50 to 60 meters high everywhere, and do not indicate tilting uplift in the Skagi Peninsula.

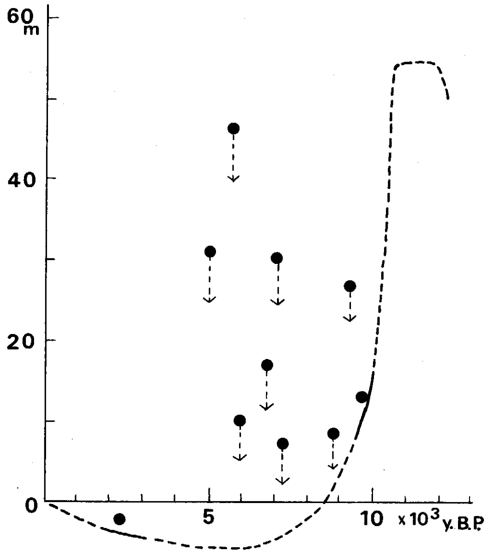

Fig. 11 Shoreline displacement curve estimated in Blönduós area
Arrows show direction of past see level position. See Table 1 for data.

(3) The rebound uplift probably ended about 7,000 to 8,000 years ago.
(4) The uplift rate during the period about 10,000 to 9,000 years ago was 7 cm per year, which was extremely high.
(5) There was very short time lag between glacio-isostatic rebound and retreat of the glacier.

Remaining problems regarding shoreline displacement are as follows: tracing the highest shoreline around the Skagi Peninsula and the whole Iceland coast, clarifying the relation of glacio-isostatic rebound to tectonic movement in the median active zone, and tracing the lower shorelines over a wide area.

Acknowledgements

I conducted this investigation as a member of the Iceland Research Project Team from Tokai University, Japan, in 1983 and 1984. This work was financially supported by Kyoikusha Co., Ltd. I should like to thank the staff of the project. I also acknowledge Dr. Tatsuro Asai, leader of the project and Prof. Kazuo Nakamura for their encouragement; Dr. Jón Eiriksson, my Icelandic collaborators; Dr. Hreggvidur Norddahl and Dr. Ólfar Ingólfsson for their helpful advice and discussion; and the National Research Council of Iceland for permission to work in Iceland.

I wish to dedicate this paper to Professor Sohei Kaizuka in commemoration of his retirement from Tokyo Metropolitan University.

References Cited

Bloom, A.L. (1971): Glacial eustatic and isostatic controls of sea level since the last glaciation. In Turekian, K.K. (ed.) "*Late Cenozoic Glacial Ages*", Yale Univ. Press, 355-379.

Einarsson, Th. (1961): Pollenanalytische Untersuchungen zur spät- und postglazialen Klimageschichte Islands. *Sonderveröff. Geol. Inst. Univ. Köln*, **6**, 1-52.

—— (1973): Geology of Iceland. *Arctic Geology, Memoir,* no. **19,** The Amer. Assoc. Petroleum Geologists, 171-175.

Everts, P. (1974): Die Geologie von Skagi und der Ost-Küste des Skagafjords (Nord-Island). *Sonderveröff. Geol. Inst. Univ. Köln,* **25,** 1-114.**

Gudmundsson, A. and Kjartansson, H. (1984): *Guide to the Geology of Iceland.* Bókaútgáfanörn og Örlygur hf, 88p.

Ingólfsson, Ó. (1988): Glacial history of the lower Borgarfjördur area, western Iceland. *Geologiska Föreningens i Stockholm Förhandlingar,* **110,** 293-309.

Koefer, L.E. (1975): Zur Geologie des Gebietes Hvammstangi - Bakkabrúnir - Blönduós (Nord-Island). *Sonderveröff. Geol. Inst. Univ. Köln,* **26,** 1-128.**

Larsen, G. and Thorarinsson, S. (1977): H_4 and other acid Hekla tephra layers. *Jökull,* **27,** 28-46.

Mörner, N.A. (1969): The late Quaternary history of the Kattegatt sea and the Swedish west coast. *Sveriges Geologiska Undersökning, Ser. C,* Nr. **640**, 487p.

Saemundsson, K. (1979): Outline of the geology of Iceland. *Jökull,* **29,** 7-28.

Thorarinsson, S. (1955): The Nucella shore line at Húnafloi in the light of tephrochronological and radiocarbon datings. *Náttúrufraedingurinn,* **25,** 172-186.*

(*: in Icelandic with English abstract, **: in German with English abstract)