Aspects of the glacial geomorphology of the Vestfirdir Peninsula of northwest Iceland with particular reference to the Vestur-Isafjarsarsysla area

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ASPECTS OF THE GLACIAL GEOMORPHOLOGY OF THE VESTFIRÐIR PENINSULA OF NORTHWEST ICELAND WITH PARTICULAR REFERENCE TO THE VESTUR-ÍSAFJARÐARSÝSLA AREA

By

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ABSTRACT

The evolution of the landscape of Vestfirðir, made almost entirely of volcanic rocks, is traced from the Miocene, when the oldest rocks formed, through the Pliocene and Pleistocene. Volcanic activity ceased first in the northwestern part leaving a basalt plateau with occasional large volcanoes protruding. Fluvial erosion, guided by a westerly dip of the plateau and tectonic lineaments, left a well developed drainage pattern there by the time volcanic activity ceased in the southeast. The snowline fluctuated widely during the Plio-Pleistocene. Cirque and valley glaciations were very effective in sculpturing the landscape where the preglacial relief was greatest, in the northwest. Ice sheet glaciations affected the whole peninsula and offshore areas with linear erosion dominant in the northwest and areal scouring elsewhere.

The glacial geomorphology of Dýrafjörður and northern Arnarfjörður is mapped. The highest marine limit is in the Núpur area, about 110 m, and shorelines and marine limits higher than 70 m are at 7 other localities at least. At least two stages of glacial readvances are recognized: The Tjaldanes stage occurred when sea level was between 11 and 22 m and is probably of "Younger Dryas" age; later a readvance occurred in the cirques in the area.

On the basis of evidence on cirque distribution, cirque elevation, zeolite zonation, distribution of glacial erosional landscapes, glacial history, marine limits, ice cap profiles and shelf moraine a model of maximum glaciations of Vestfirðir is proposed: The whole of Vestfirðir and the surrounding shelf areas was completely ice covered with no ice free areas. Such a stage of glaciation, the Látragrunn stage, probably prevailed in the Vestfirðir area during the last glaciation.

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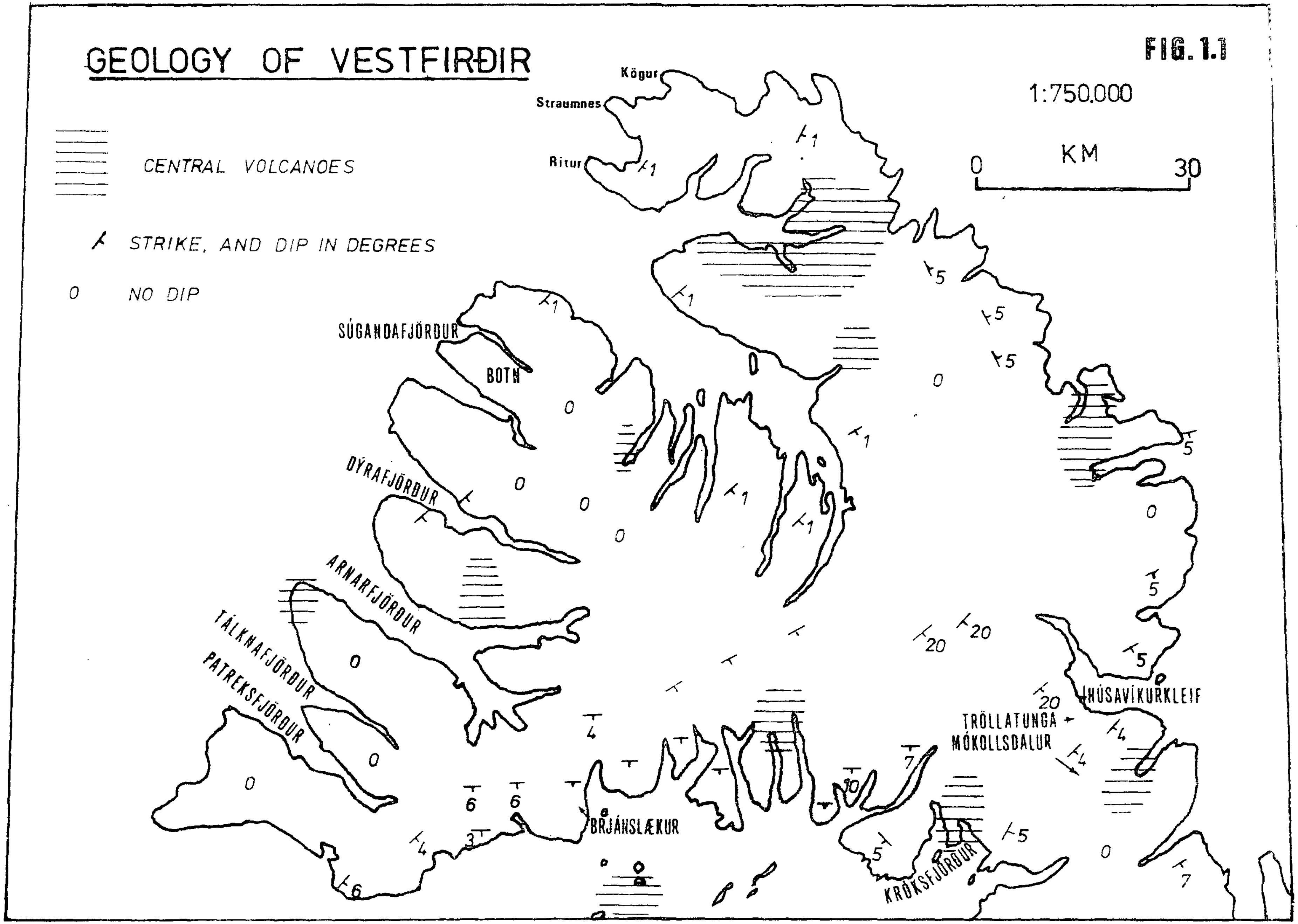
CHAPTER 1. TERTIARY LANDSCAPE EVOLUTION.

1.1. GEOLOGICAL HISTORY.

The Vestfirðir peninsula is the westernmost and oldest part of the Icelandic Tertiary Plateau Basalt (TPB) formation. The formation consists almost entirely of volcanics interbedded with thin sediments. The dips of the formation in Vestfirðir are mostly gentle, 1-5°, predominantly to the south-east or south (fig.1.1).

1.1.1. Age. The earliest attempt to date the sequence was made by Heer (1868). He made a comprehensive study of the macroscopic plant remains collected by Winkler (1863) and suggested Miocene age for them. Later studies of the macroscopic plant remains (e.g. Áskelsson 1961) and pollen (Pflug 1959) suggested that they were much older, mainly Eocene and similar in age to the rest of the North-Atlantic Tertiary Basalt Province. Recently, however, radiometric dating has confirmed a Miocene and Pliocene age for the TPB of Vestfirðir (fig.1.2). Moorbath et al. (1968) dated three samples from the altitudes of 538 m, 558m and 603 m from Breiðadalsheiði. A mean of the samples gave the age 16.0 ± 0.3 million years. The samples contained no secondary minerals or alteration products so the dates are highly reliable. This is the greatest age yet measured by the K/Ar method in Iceland. Rocks further down the sequence are, however, still older, and considering the dip (fig. 1.1), rocks to the north and north-west are also older. In fact, the oldest rocks are to be found in the extreme north-west of the peninsula of Vestfirðir.


GEOLOGY OF VESTFIRÐIR
FIG. 1.1
1:750,000
0 KM 30
CENTRAL VOLCANOES
STRIKE, AND DIP IN DEGREES
0 NO DIP
Kögur
Straumnes
Ritur
SÚGANDAFJÖRÐUR
BOTN
DÝRAFJÖRÐUR
ARNARFJÖRÐUR
TÁLKNAFJÖRÐUR
PATREKSFJÖRÐUR
BRJÁNSLÆKUR
KRÓKSFJÖRÐUR
HÚSAVÍKURKLEIF
TRÖLLATUNGA
MÓKOLLSDALUR

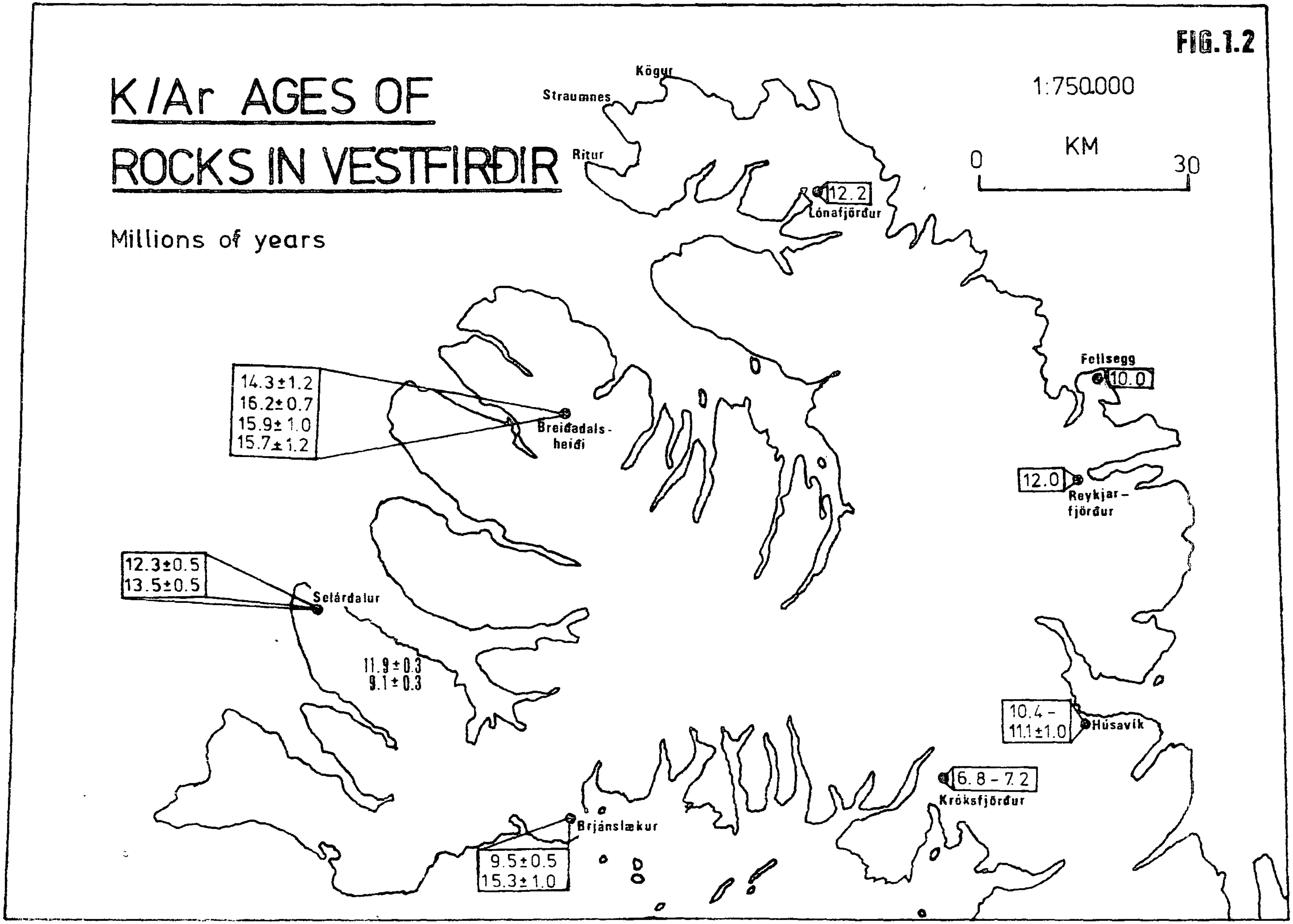


FIG.1.2
K/Ar AGES OF
ROCKS IN VESTFIRÐIR
Millions of years
1:750.000
KM
0
30
Kögur
Straumnes
Ritur
12.2
Lónafjörður
Fellsegg
10.0
12.0
Reykjar-
fjörður
14.3±1.2
16.2±0.7
15.9±1.0
15.7±1.2
Breiðadals-
heiði
12.3±0.5
13.5±0.5
Selárdalur
11.9±0.3
9.1±0.3
10.4 -
11.1±1.0
Húsavík
6.8 - 7.2
Króksfjörður
Brjánslækur
9.5±0.5
15.3±1.0

in Ritur, Straumnes and Kögur (Þ. Einarsson 1968). Jakobsson (quoted in Pálmason and Sæmundsson 1974) has obtained two dates from Selárdalur in Arnarfjörður, 12.3 ± 0.5 and 13.5 ± 0.5 million years. No details on the conditions of the samples have been published. Kristjánsson et al. (1975) obtained two dates from the peninsula between Arnarfjörður and Tálknafjörður, 11.9 ± 0.3 and 9.1 ± 0.3 million years. The samples were taken very close to each other stratigraphically so the big difference in age between them is surprising. The dates of these three localities are broadly consistent with the dip and strike and render the possibility of a repetition of the sequence through large faults unlikely.

1.1.2. Stratigraphy. Apart from the numerous studies which have been made on the plant beds, the bedrock geology of Vestfirðir has received little attention. Winkler (1863) and especially Thoroddsen (e.g. 1888) travelled widely and confirmed its structure as a TPB. Very little else was done until Kjartansson´s (1969) geological map (1:250 000) was published. Detailed mapping of the lava pile has only just started.

Friedrich (1966) mapped a small area around Brjánslækur in conjunction with his studies of the plant beds there. Hald et al. (1971) mapped the central volcanic complex near Króksfjörður in the south-east of Vestfirðir. Kristjánsson et al. (1975) mapped the lava pile in the southern Arnarfjörður-Patreksfjörður region. Sigurðsson (1967) made an air-photo interpretation of the orientation of tectonic lineations, mainly dykes and faults, in some selected parts of Vestfirðir. In 1975 Orkustofnun (the National Energy Authority) launched a major project of detailed geological mapping which will eventually cover the whole peninsula. The results have not yet been published.

The volcanics are considered to have originated in three types of volcanoes:

(1) The bulk of the basaltic lavas, the flood basalts, were produced by volcanic fissures. Only rarely are craters from these eruption found in the succession. Numerous dykes cut the succession. They are considered to be the feeders of the flood basalts, one dyke corresponding to one lava flow. In places they can make up to 15% of the rocks (Þ. Einarsson 1968). Their density decreases with altitude in the lava pile.

(2) Shields volcanoes or "lava shields" (Walker 1971) are occasionally observed in the TPB. One eruption then forms a thick succession of thin (0.2 - 2 m) flow units. In consequence, they display at present precipitous cliffs in contrast with the terraced cliffs of the flood basalts (e.g. Núpur mountain, fig. 3.17).

(3) Central volcanoes are also rather rare. So far about ten central volcanic complexes have been found in Vestfirðir (Jóhannesson 1975). These are shown in fig. 1.1. Only the one in Króksfjörður has been mapped in detail (Hald et al. 1971). Though sparse, the central volcanoes are very important stratigrapically. They cover large areas and a great variety of rocks is associated with them. Intermediate to acid rocks like andesites and rhyolites

are common and intrusive rocks like gabbros and granophyres sometimes occur. Rocks of little resistance to erosion like tephras are interbedded with the lavas. This makes the complex subject to rapid breakdown due to weathering and erosion. Mountains near the cores of central volcanoes are, therefore, often covered with talus to the top and also have a more jagged appearance.

1.1.3. The Tertiary vegetation and climate.

Sedimentary horizons with well preserved plant remains are relatively common in Vestfirðir: about 70 localities are known there (Friðriksdóttir 1978) The principal localities are Botn in Súgandafjörður (Áskelsson 1942), Brjánslækur (Áskelsson 1954, Friedrich 1966), Selárdalur in Arnarfjörður (Áskelsson 1946, 1957), Tröllatunga (Pflug (1956) and Húsavíkurkleif (Pflug 1959, Schwarzbach 1955) and Mókollsdalur (Friedrich et al. 1972).

Þ. Einarsson (1968) has summarized the evidence. The plant remains, most of them of trees, are found as pollen, spores, traces of leaves and pseudomorphs of tree trunks. About 50 genera have been found. They indicate that coniferous forests were most common, but there were also large areas of deciduous forests. On the whole, the flora is most related to the present day flora of the eastern United States, south of New York State to the Gulf of Mexico.

Heer (1868) concluded that the annual mean temperature was close to 9°C, and later studies have confirmed this Schwarzbach 1955). The temperature of the coldest month was above 0°C, and the mean air temperature of the warmest month was 15-20°C. Annual precipitation was of the order of 1000 mm. A distinct climatic cooling took place during the Pliocene, as shown by the disappearance of the deciduous forests and the appearance of glaciers in middle western Iceland as early as 4.4 million years ago (Jóhannesson 1975).

1.1.4. The Tertiary relief and hydrography. From considerations of evidence present in the lava pile and analogues with the present day active volcanic regions of Iceland, it is possible to get a fair idea of the Tertiary relief and hydrographical conditions. The land was a rather featureless lava plain with numerous, up to at least 25 km long, rows of low tephra cones rising above the lava plain, and occasional lava shields and central volcanoes.

The biggest lava shields stood 600-700 m above the surrounding lava plain. They had gentle slopes, usually less than 8°. They were mostly formed during single eruptions. At least two lava shields have been discovered so far in Vestfirðir, one in southern Dýrafjörður (Þ.Einarsson 1968) and the other in southern Arnarfjörður (Kristjánsson et al. 1975). Many more are bound to exist.

Central volcanoes have been mapped in detail in eastern Iceland by Walker (1963), Gibson (1963) and Carmicheal (1964), and in western Iceland by Sigurðsson (1970), Friðleifsson (1974), Sæmundsson and Noll (1974), Jóhannesson (1975) and Fransson (1978). In Vestfirðir only the badly exposed Króksfjörður central volcano has been mapped (Hald et al. 1971). Commonly the life span of a central volcano was of the order of 0.5-1 million years, their height 2-3 km and their diameter 25-30 km. Effusion rates in the central volcano were much greater than the rates of flood basalt effusion, so they commonly stood about 300-600 m above the surrounding lava plain. After becoming extinct each central volcano was gradually buried by flood basalts.

Thus, the general picture as indicated by the volcanic geology, is one of a lava plain with an occasional lava shield or a central volcano standing above it. In the TPB there is also evidence of depressions, probably tectonic grabens, often the sites of lakes. This is shown by the hyaloclastic deposits and pillow lavas which mark the sites where lava flows entered ponds or lakes. Lake sediments are also found, e.g. in southern Arnarfjörður (Kristjánsson et al. 1975). Evidence for streams occurs sparsely, mainly as conglomerates, interpreted as river gravels. Although precipitation was quite high, direct runoff rivers must have been limited since fresh lavas are extremely porous and permeable. Most of the rain infiltrated the rocks and only reappeared in lows and grabens as springs. The only rivers then were spring-fed, where the discharge throughout the year is extremely even, which means that they had very little erosional capacity. This is precisely what is observed in the present day active volcanic regions of Iceland, e.g. Ódáðahraun and Reykjanesskagi (Kjartansson 1965 where the drainage density is extremely low. Gradually, through the deposition of secondary minerals, the Tertiary bedrock has become almost completely impermeable, except near the top where some rain infiltrates but reappears only short way down as springs.

It is not known when the bedrock became impermeable.

It is reasonable, however, to infer that 1-3 million years after the cessation of volcanic activity, direct runoff rivers had become rather common, and river erosion started to make its mark on the landscape. Time is here the crucial factor: the oldest parts of the TPB were longest exposed to fluvial erosion and there the pre-glacial relief should have been strongest.

1.1.5. Synthesis and conclusion. The Tertiary Plateau Basalt formation of Vestfirðir is Miocene in age. Both the dip and K/Ar dating indicate that the oldest rocks are in the north-west part of the peninsula becoming progressively younger to the south and south-east. The Tertiary climate was humid and temperate. The dominant vegetation was coniferous forest with large areas of deciduous forest. After cessation of volcanic activity the dominant feature of the landscape was a lava plain with occasional lava shields and central volcanoes standing above it. Occasional depressions were filled with lakes or ponds. The rivers were spring-fed and had little erosional capacity. About 1-3 million years after cessation of volcanic activity direct runoff rivers, with greater erosional capacities, had become common. Fluvial erosion must have been more effective in the older parts, longer time was available for erosion there.

In light of all this it is concluded that by the time the first glaciation occurred in Vestfirðir fluvial valleys had been formed in the north-western part of the area, at least. Their dimensions, however, are not known.

1.2. TECTONIC LINEATIONS AND THE TERTIARY DRAINAGE PATTERN.

1.2.1. Introduction. Tectonic lineations in volcanic areas are faults, dykes and fissures. As these are lines of weakness in the bedrock it is highly likely that they were important in guiding rivers on their course, and the consequent fluvial valleys in turn guided ice streams on their course. To throw some light on the Tertiary drainage pattern the fjords and larger valleys were mapped and the orientation of these was compared to the orientation of tectonic lineations. From this an attempt has been made to reconstruct, with data examined in section 1.2., the Tertiary drainage pattern.

1.2.2. Previous work. There is at present little dispute about the glacial origin of fjords and U-shaped valleys in glaciated areas (e.g. Embleton and King 1975). But so far little detailed work has been devoted to the question if, and to what extent, rock structure in general and tectonic lineations in particular have exerted their influence on fjord and valley direction.

Koch (1929) mapped structural elements in parts of East-Greenland. He stressed the occurrence of fjord-valleys along fault planes and believed the erosion was subsequent to the faulting, the valleys not being fault valleys per se.

Gregory (1913, 1927) had taken the opposite view that fjords were largely of tectonic origin, only slightly modified by erosion. He based his view on detailed work in The Hebrides and other areas of Scotland. Randall (1961), working in a small area in northern Norway, was able to demonstrate a very close relationship between the orientation of fractures and fjord-valleys, and believed this supported Gregory´s contention. Winkler´s (1938) work in Vestfirðir (see later) also seemed to strengthen Gregory´s hypothesis.

Nicholson (1963), working in a small area in northern Norway, found that fractures were absent. But he was also able to demonstrate a distinct correlation between fjord-valley orientation and rock strike. This correlation was not a very close one because of the cross-cutting habit of the fjord-valleys. He concluded that fractures were not a prerequisite to fjords, contrary to Gregory´s claim.

Embleton and King (1975) and Holtedahl (1967) extended Nicholson´s conclusions, they stressed the importance of all elements of rock structure in affecting fjord-valley direction, and agreed that erosion merely selects the most important weakness in any region.

Winslow (1966) discussed the problems encountered by the glacial hypothesis, among these the existence of large fjords in locations where ice accumulation must have been limited. To account for these he suggested that fjords represent glacially modified submarine canyons, eroded initially by submarine processes before uplift and glaciation. Soons (1968) applied this hypothesis to fjords in New-Zealand and concluded that it created more problems than it solved.

Recently Bostrom (1970) has given added support to Gregory´s tectonic hypothesis of fjord-valley origin by applying the theory of sea-floor spreading to explain the origin of fjords in Chile and British Columbia. He suggested that along the continental margins, which had been rifted apart by sea-floor spreading in the Pacific, relaxational extension had occurred resulting in the collapse of the continental margin and oceanward movement of the broken fragments. Accompanying glaciation concentrated along the fracture zones, and resulted in a landscape with strongly marked linear elements. Bostrom further suggested that the Norwegian and Greenland fjord systems had originated in a similar way.

In summary, three main hypotheses seem to prevail:

(1) Gregory´s hypothesis that fjords are tectonic in origin.

(2) Bostrom´s hypothesis that in some areas fjords are fractures which resulted from the collapse of the continental margins as a consequence of sea-floor spreading.

(3) The generally accepted theory that fjords are mainly glacially eroded former fluvial valleys, their direction affected by all elements of rock structure.

1.2.3. The fracture pattern in Vestfirðir.

1.2.3.1. Introduction. The peninsula of Vestfirðir in Iceland is an ideal area for testing the relationship between fractures and fjord directions. The area is well defined and is dissected by a number of fjords and valleys. It has an area of 8590 km^2 (author´s measurement) or about 8% of the area of Iceland, while a third of the 6000 km of Icelandic coastline is found there. The largest fjords open out to the west coast with a few large fjords on the north and east coast. The largest fjord, the 77 km long Ísafjarðardjúp/Ísafjörður carries an intricate system of tributary fjords, draining a large area, and displaying a variety of fjord directions.

1.2.3.2. Previous work. The splendid fjords of the Vestfirðir peninsula have attracted the attention of a number of workers, who have attempted to explain their origin. The first was Thoroddsen (1901, 1902). His conclusion was that the fjords are fluvial valleys, slightly modified by glacial erosion. As was the fashion in his time, stemming from the work of Nansen, he believed the largest fjords were sites of former fault planes and went on to reconstruct a pattern of curved faults from the direction of the fjords (fig.1.3). In order to test this hypothesis, Winkler (1938) investigated the submarine morphology of Skálmarfjörður on the south coast of Vestfirðir. He was able to demonstrate the presence of a "rift" running parallel to the outlines of the fjord in N-S direction. Near the mouth of the fjord this "rift" turns abruptly and continues for a while in a NE-SW direction and then turns abruptly to a NW-SE direction before going back to a N-S direction. Because of the presence of this zig-zag moving "rift" he concluded that the fjord could not have originated from glacier erosion or any other erosion agent, and explained it instead as a tectonic feature, possibly widened by erosion. He then turned to the rest of Vestfirðir and concluded that a system of NW-SE and NE-SW fissures dominates the orientation of fjords, with a secondary system of N-S, E-W fissures. His overall conclusion was that all Icelandic fjords are tectonic in

Fig. 1.3. Thoroddsen´s inferred fracture pattern

origin.

Tr. Einarsson (1963, 1967) was of the same opinion as Thoroddsen regarding the tectonic origin, but he reconstructed a system of north-west - south-east and north-east - south-west fractures and then went on to apply them for the whole of Iceland.

Sigurðsson (1967) mapped tectonic lineations from air-photos and compared their orientations with those of fjords and valleys. He presented his results in two series of rose diagrams. One is map showing rose diagrams of fracture orientations at 10° intervals for each group of air-photos, the other for 52 fjords and valleys, mainly from Vestfirðir. His main conclusions are as follows: "In the northern and north-eastern part of the region a northerly trend is dominant, but gradually decreasing in magnitude southward being replaced by a set of northeast and northwest fractures and dykes, which dominate in Barðaströnd" (Sigurðsson 1967, p. 164-165). He thought that these fracture systems were significant in shaping the morphology of the Vestfirðir peninsula, especially the north-south, west-north-west - east-south-east and the north-east - south-west systems, but could find little correspondance in the trend of fjords and valleys with the east-north-east - west-south-west system.

As can be seen from this review of the literature, there exists a distinct controversy as to the origin of fjords in general, and in Vestfirðir in particular.

<u>1.2.3.3. The mapping procedure.</u> The plateau of the Vestfirðir peninsula is practically devoid of vegetation,

and over large areas the regolith is thin or absent, exposing the bedrock. This makes it very easy to spot tectonic lineations on air-photos. The tectonic lineations are practically all fault lines and dykes. It is not possible to distinguish these from each other on the air-photos. A very large majority of the fractures were seen to be straight lines, indicating that the faults and dykes are vertical. In some areas, indicated on fig.1.4., hardly any fractures were observed on the air-photos. However, during fieldwork in Dýrafjörður, the author observed 10 dykes along a 2 km stretch of coastline (in Mýrarfell), although none of them could be detected on the air-photos. The reason why fractures fail to show up on air-photos in these areas must be due to the fact that in these areas bedrock is generally only exposed in cliffs, the valleys being covered with glacial drift, talus and alluvium, and the plateau remnants covered with other superficial deposits. In other words, this study made it possbile to approximately delimit the areas where bedrock is exposed, a very important clue for reconstructing former ice bodies in Vestfirðir (see sections 2.5 and 5.5).

The air-photos used for this study are of the scale 1:30 000 and 1:36 000 (approx.), taken in 1959 and 1960. The base maps used were excellent 1:50 000 photogrammetricall compiled U.S. Army Map Service maps which made it possible in most cases to locate the fractures with great accuracy. The fractures so mapped were then transferred onto a map with a scale of 1:250 000, admittedly with some loss of precision in location; however, great care was taken in ensuring that their orientation was correctly transferred.

This survey of fractures in Vestfirðir is not exhaustive. Many more fractrues are bound to exist, to be revealed only by fieldwork. It is believed, however, that in most places all fractures of importance have been spotted in the mapped areas, and it is assumed that this sample represents the whole spectrum of orientations.

The mapped areas are shown in fig. 1.5. The Vestfirðir peninsula has been divided into several subareas on the basis of their pattern of fracture orientations. For comparison the pattern of fjords and valleys is shown in fig. 1.6. These are lines drawn along the midaxis of all valleys and fjords 2 km long and longer. Discrete cirques are not considered in this study.

1.2.3.4. Results.

Area A. In area A two directions of fractures are dominant. These are approximately north-east - south-west and north-west - south east. Some fractrues with north-south and east-west directions also occur, but very sparsely. This pattern is clearcut and simple and therefore offers a good opportunity for meaningful comparison with the fjord-valley pattern. The three largest fjords in area A (Arnarfjörður, Tálknafjörður and Patreksfjörður) all have approximately the same orientation, north-west - south-east. Three short and broad valleys south of Patreksfjörður also have this same orientation. As can be seen from the fracture map, this is the second most frequent fracture orientation. Most of the valleys, especially in the western part of the area, are orientated towards the north-east - south-west, which is by far the most common fracture orientation. In

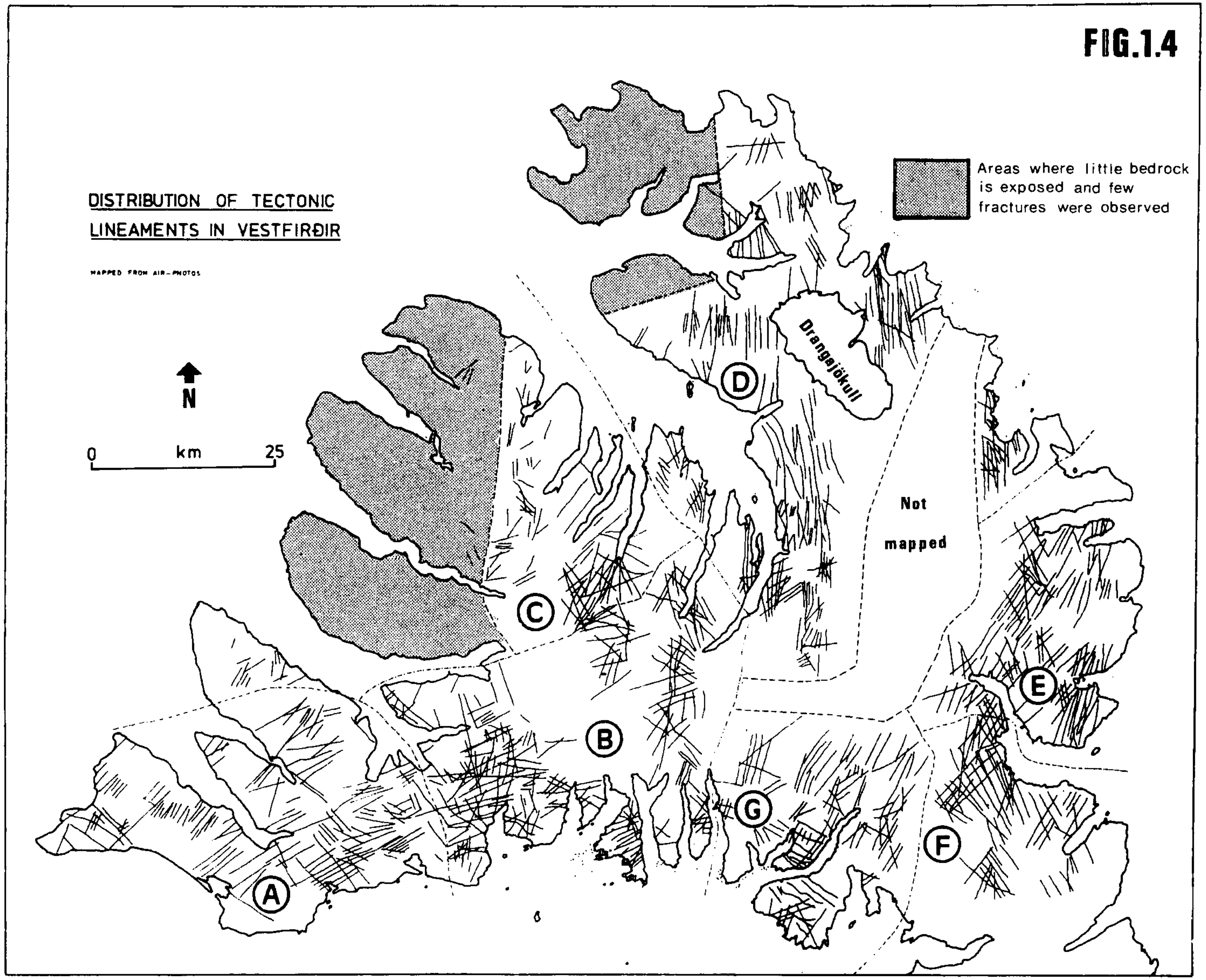
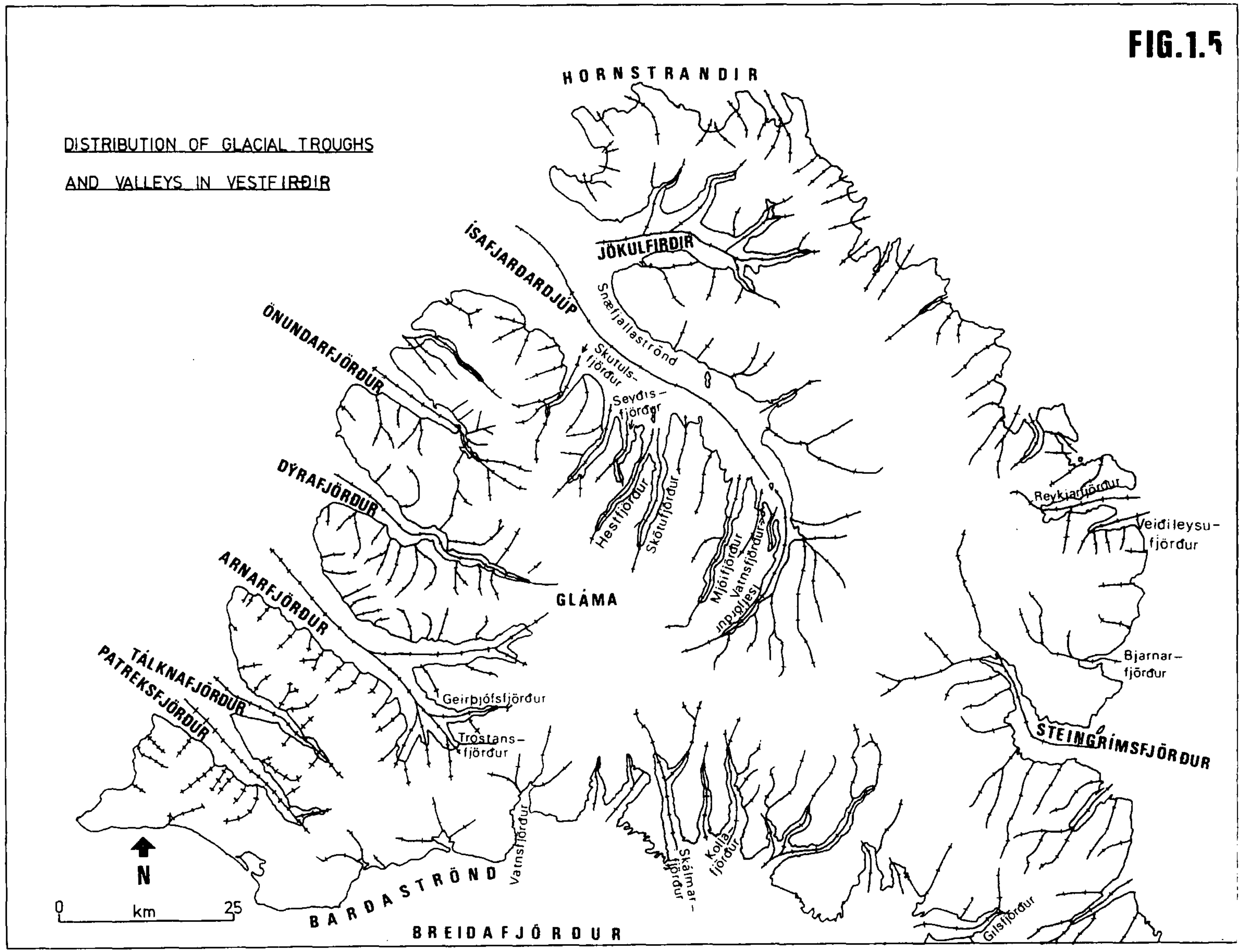


FIG.1.4
DISTRIBUTION OF TECTONIC
LINEAMENTS IN VESTFIRÐIR
N
0 km 25
Areas where little bedrock is exposed and few fractures were observed
Drangajökull
Not mapped
A
B
C
D
E
F
G

FIG.1.5

DISTRIBUTION OF GLACIAL TROUGHS AND VALLEYS IN VESTFIRÐIR



the eastern part of area A are fewer valleys but greater range in their orientations. Their orientations there show little relation to the orientation of fractures.

It is concluded that on the whole there is a close correlation between the pattern of fjord-valleys and fractures.

Area B. In this area the pattern of fracture orientations is more complicated than in area A. In addition to north-west - south-east and north-east - south-west directions, which are well represented, there is a much stronger trend towards north-south, north-north-west - south-south-east, east - west and east-north-east - west-south-west orientations as well as west-north-west - east-south-east. Because of this large range of orientations, it is likely that a close correlation exists with the pattern of fjord-valley orientation, even if it was random. Some significant inferences can be made, however. Near the heads of Geirþjófsfjörður, Trostansfjörður and Skálmarfjörður there are fractures running parallel to the orientation of the fjord. This same relationship is found among some of the valleys like the ones at the head of Mjóifjörður and Vatnsfjörður.

It is concluded that because of the great spectrum of orientations, without a much more detailed study little significant correlation can be found between the orientations of fractures and fjord-valleys. However, in the case of some of the fjords and valleys, a significant relationship seems to be present, which is likely to be causative.

Area C. This area is also characterized by a chaotic pattern of fracture orientations. The two most common orientations are NNE-SSW and NNW-SSE. Again this chaotic pattern makes it difficult to reliably correlate it with the pattern of fjord-valley orientation. At the head of Skutulsfjörður, however, there are fractures running parallel to the main axis of the fjord, and further, close to Hestfjörður and Seyðisfjörður the only observed fractures have the same orientations as the fjords, though Seyðisfjörður changes course abruptly. Relatively few fractures have been observed in this area because bedrock is well exposed only in the eastern part of it.

It is concluded that because the observed fractures are few, and their pattern and orientation chaotic, no relationship could be detected between fracture orientation and the direction of fjord-valleys, except possibly, in two or three areas.

Area D. Fractures orientated N-S dominate in this area. NW-SE and NE-SW orientated fractures are common in some places, with an occasional fracture orientated WSW-ENE or WNW-ESE. No fractures were observed on air-photos in the NW-part of this area, probably due to lack of extensive exposures of bedrock. A large piece of plateau in the eastern part of this area was not mapped, air-photos not being available. In spite of this, a reasonably good cover is available to compare orientation of fractures to fjord-valley orientation. Between Skötufjörður and Ísafjörður correlation is found between fracture orientation and the N-S trend of the fjords and valleys, except Ísafjörður´s southernmost part. On Snæfjallaströnd two valleys have the same orientation as the fractures, and the same goes for the southern part of Jökulfirðir.

It is concluded, that because of the relatvely simple pattern of fracture orientations, it is easily possible to compare them with orientation of fjord-valleys. On the whole it can be said that this area fails to show good correlation between fractures and fjord-valleys. There are few exceptions, however, but these are not convincing as they are in favourable situations in as much as they are the routes of outlet glaciers draining large plateau areas and that the location of fractures would have had little influence on this drainage pattern.

Area E. The fracture pattern is again relatively simple in this area, and the area is therefore favourable for comparing it with the pattern of fjord-valley orientation. Dominating are fractures with a NE-SW and NNE-SSW orientation. Apart from this, only the NW-SE direction occurs. The orientation of fjords bears no relation to the orientation of fractures in this area. Only the valleys at the head of Bjarnarfjörður and the valleys to the south of Reykjafjörður and Veiðileysufjörður bear some relation to the fracture pattern.

It is concluded that in spite of favourable conditions, this area fails to show significant correlation between orientations of fractures and fjord-valleys. Out of 26 valleys, only about 8 have orientations parallel to fracture directions.

Area F. This is another area with a simple fracture pattern, practically all the fractures are orientated either NE-SW or NW-SE. A few fractures are orientated N-S. This gives another opportunity for meaningful correlation with the fjord-valley pattern. Practically all the valleys have a NE-SW orientation, and the same applies to Kollafjörður, Bitrufjörður and the inner part of Gilsfjörður.

It is concluded that in Area F there is such a close relationship between the orientation of fractures and fjord-valleys, that this relationship is almost certainly causative rather than coincidental.

Area G. In this area a fairly simple pattern emerges. Most frequent are NNE-SSW fractures with WNW-ESE fractures also being common. There are also N-S, NE-SW and NW-SE fractures, which makes it more difficult to establish a meaningful relationship with the pattern of fjords and valleys. By far the most common fjord-valley orientation is NE-SW, which corresponds well with the fractures.

The conclusion is that in Area G there exists a close relationship between the orientations of fractures and fjord-valleys, a relationship which is believed to be causative.

1.2.3.5. Discussion. Embleton and King (1975) emphasized that all elements of rock structure may affect fjord direction and that erosion merely selects the most important weakness in any region. The present survey of the orientation of fractures and fjord-valleys in Vestfirðir shows that in some areas there exists such a distinct relationship between the two that it must be causative.

Having established that in some areas in Vestfirðir there is present a relationship between rock structure, in this case the orientation of fractures, and fjord-valley orientation, the question arises which, if any, elements of rock structure have influenced the pattern of pre-glacial drainage in Vestfirðir. Fortunately, since the Vestfirðir peninsula is very young, geologically speaking, the pre-glacial drainage pattern is much the same as the initial drainage pattern, albeit much better developed. Kristjánsson et al. (1975) observed at two feeder-dykes in the Arnarfjörður - Patreksfjörður area that their corresponding lava flows petered out east of the dykes, with the bulk of the lava flowing to the west of the dykes. This strongly indicates a westerly tilt of the plateau at the time of eruption. In light of the fact the the largest fjords drain towards the NW or WNW, this observation becomes very important. As was shown for area A, the orientation of Patreksfjörður, Tálknafjörður and Arnarfjörður corresponds to the second most important fracture orientation. By far the most common fracture orientation in area A is NE-SW. This raises the question why the more common NE-SW fractures were not important in guiding the drainage. The reason must be that after the cessation of volcanic activity, when direct run-off streams were gradually increasing in size and numbers as the bedrock became less porous and permeable, the dip of the plateau was important in steering the drainage and the fractures only played a secondary role. Once the main streams had taken a westerly course, however, they exploited the NW directed fractures. The tributary streams then conveniently exploited the NE-SW fractures. The conclusio drawn from this is that the original dip of the plateau was, in this area at least, of primary importance in guiding the streams on their course, the fracture pattern being only of secondary importance. Unfortunately, since the geology of Vestfirðir is so imperfectly known, no other stratigraphic evidence is known as yet for the original dip of the plateau.

It seems, however, reasonable to assume that this westerly dip prevailed over most of the western part of the Vestfirðir peninsula, because at present dips are very gentle in this area, or there are no dips at all, and all the drainage is westerly orientated. However, to reconstruct the direction of the original tilt of the plateau on the basis of the amount and direction of drainage is dangerous, and would, in fact involve making a circular argument.

Thoroddsen´s (1901, 1902) hypothesis of curved fault lines controlling the orientation of the largest fjords in Vestfirðir can now be safely rejected on the grounds that no such faults exist in the area.

Tr. Einarsson´s (1963, 1967) hypothesis of large NW-SE faults being primarily responsible for the orientation of the largest fjords, Ísafjarðardjúp-Ísafjörður and Arnarfjörður, is also suspect.

Winkler´s (1938) hypothesis of the fjords largely being tectonic fissures has not, admittently, been tested, as this would involve a lot of field mapping of tectonic phenomena and soundings in the fjords. It can be pointed out, however, that his conclusions from the soundings in Skálmarfjörður are premature, because he ignored the possibility of sediments being on the bottom of the fjord. There are certainly sediments there, but to what exent these sediments control the configuration of the fjord bottom remains to be seen. The following alternative hypothesis is put forward here: The main part of the "fissure", the N-S part, is a normal fjord basin. The zig-zag part owes its existence to peculiar sediment morphology. This hypothesis ca be tested by measuring the thickness of the bottom sediments.

western, while in other areas no meaningful relationship could be found between the orientation of fractures and the orientation of fjords and valleys.

The original dip of the plateau was of primary importance in controlling the Tertiary drainage in one area at least, south-western part of Vestfirðir.

At present, the largest fjords and glacial troughs, Patreksfjörður-Tálknafjörður, Arnarfjörður, Dýrafjörður, Önundarfjörður, Ísafjarðardjúp-Ísafjörður and Jökulfirðir are located in the western and northwestern part of Vestfirðir.

1.3. SYNTHESIS AND CONCLUSION: TERTIARY LANDSCAPE EVOLUTION.

In light of all this it is concluded that by the end of the Tertiary, prior to the onset of glaciations, the landscape was as follows:

The Vestfirðir peninsula was a plateau. Above the plateau occasional lava shields and central volcanoes protruded. The highest central volcanoes may have carried small glaciers. Sizable fluvial valleys had developed in the oldest part, in the west and north-west, where the largest fjords and troughs are located at present. The largest valley formed in the oldest part where the Ísafjarðardjúp fjord system is at present. By the end of the Tertiary it had grown to such proportions that it was dominating the drainage of a large part of the area. South of the Ísafjarðardjúp fjord system the drainage was guided north-west by tectonic fractures and a dip of the plateau in that direction. There, also, were sizable fluvial valleys. In the south-east part of Vestfirðir, although this is the youngest part, fluvial valleys must also have formed because tectonic fractures appear to guide the drainage there.

CHAPTER 2. PLEISTOCENE LANDSCAPE EVOLUTION.

2.1. THE PLEISTOCENE OF ICELAND.

In high latitude areas of Pleistocene volcanism there exist very favourable conditions for the preservation of deposits of glacial origin. This is because they have a good chance of being protected from erosion by subsequent glaciations by lava flows covering them. This however, necessitates high effusion rates. Areas where Pleistocene vulcanism and glaciations coincided, and from which early glaciations have been described, include the following: Iceland, Antarctica (e.g. LeMasurier 1972, Nichols 1971) Patagonia Mercer et al. 1975, Mercer 1975)Alaska (Denton and Armstrong 1974). Other areas containing evidence for early glaciations include the Arctic Ocean (Herman 1974), the Barents Sea (Kvasov and Blazhcishin 1978), the Labrador Sea (Berggren 1972), Sierra Nevada (Curry 1966) and Antarctic Ocean areas Mercer (1973). On land the evidence for glaciations in these areas is in the form of tillites and in ocean areas ice rafted detritus. In volcanic areas on land hyaloclastites provide another clue to the glacial history. They form when magma comes in contact with water, and form in three different environments, subglacial, subaquatic and submarine. Hyaloclastites have been used in research on glacial history in Antarctica and Iceland. Since they can form in these three environments, great care must be taken in using them in the interpretation of glacial histories. By detailed studies of the local geology it is sometimes possible to distinguish hyaloclastites formed under ice and in lakes. Submarine environments are distinguished from the others by considering distance from the shore and height above sea level.

An additional advantage to delimiting glacial histories in volcanic areas is provided by the fact that volcanic rocks are usually easily subjected to accurate dating by the K/Ar method and paleomagnetism.

The first to describe interbedded tillites from Iceland was Pjeturss (1900). This was revolutionary at the time. He identified tillites in many parts of the country and claimed that they were found in rocks of Pleistocene age. This view was opposed by many (e.g. Thoroddsen 1906, Hawkins 1938, Tr. Einarsson 1946). A final proof of Pjeturss´ hypothesis came with the dates of lava flows in sequences containing tillites. Vilmundardóttir (1972) described two tillites in eastern Iceland supposed to be younger than 3.1 million years (m.y.) from paleomagnetic dating. Later McDougall et al. (1976) K/Ar dated the same sequence and found that the two lowest tillites were 6.3 - 6.6 m.y. and 4.8 m.y. old. McDougall et al however, disputed the glacial origin of these diamictons. Jóhannesson (1975) described what seems to be a typical tillite in middle western Iceland. K/Ar dating of the sequence gave the age 4.3 - 4.4 m.y. (McDougall et al. 1977). This is the oldest tillite of undisputed origin so far found in Iceland.

In Tjörnes, north-eastern Iceland, there is a unique assemblage of fossiliferous deposits and tillites. Þ. Einarsson et al. (1967) and Þ. Einarsson (1968) attempted paleomagnetic dating of the sequence. The fossiliferous deposits are mainly shell beds. The species assemblage of these shell beds shows a sudden and drastic switch to species tolerant of cooler climatic conditions close to 3-3.32 m.y. ago. On the basis of this evidence Þ. Einarsson (1968) places the Pliocene/Pleistocene boundary at 3 or 3.32 m.y. ago for Iceland. This date is significant in other respects, because after it tillites become abundant in many areas in Iceland. In Tjörnes there is evidence for at least 10 glaciations during the Icelandic Pleistocene (Þ. Einarsson 1968).

Sæmundsson and Noll (1974) present a most convincing sequence from Húsafell in middle western Iceland. The section, controlled by many K/Ar dates, contains evidence for 11 glaciations ranging in time from the Mammoth magnetic event, close to 3.1 m.y. ago to about 1.5 m.y. ago. The lower part of the section is unbroken and contains 8 glacial horizons in a period of about 0.7 m.y. The first three appear to have occurred at intervals of 120 000 years while the latter five every 90 000 years. These glacial periods seem to have been of short duration only, perhaps of the order of 5000-10 000 yrs.

Kristjánsson et al. (1980) presented evidence for at least 11 glaciation and possibly 16 glaciations in the Esja - Akrafjall area in south-western Iceland in the time span from the Mammoth event. 3.1 m.y. ago, to about 1.8 m.y. ago. They were able to correlate their profile with the Húsafell profile some 60 km further NE and on the basis of this they concluded that "at least 13 glaciations occurred in Western and Southwestern Iceland between 3.1 and 1.8 m.y. ago" (Kristjánsson et al. 1980, p. 41).

McDougall and Wensink (1966) K/Ar dated rocks from a sequence in eastern Iceland containing 7 tillites in the age range 3.1 - 1.6 m.y. ago. By taking hyaloclastites into account, this sequence possibly contains evidence for as many as 9 glaciations.

In Reykjavík there is evidence for two glaciations prior to the last main glaciation (Þ. Einarsson 1968).

The evidence from these 5 areas is summarized in fig. 2.1. The summary gives the impression that glaciations were much more common before the Gilsá event. This, however, is most likely due to the fact that in many areas the section ends at the Gilsá event and, therefore, pre-Gilsá rocks are much more common.

No tillites have been discovered in Vestfirðir, the rocks, of Miocene age, being too old.

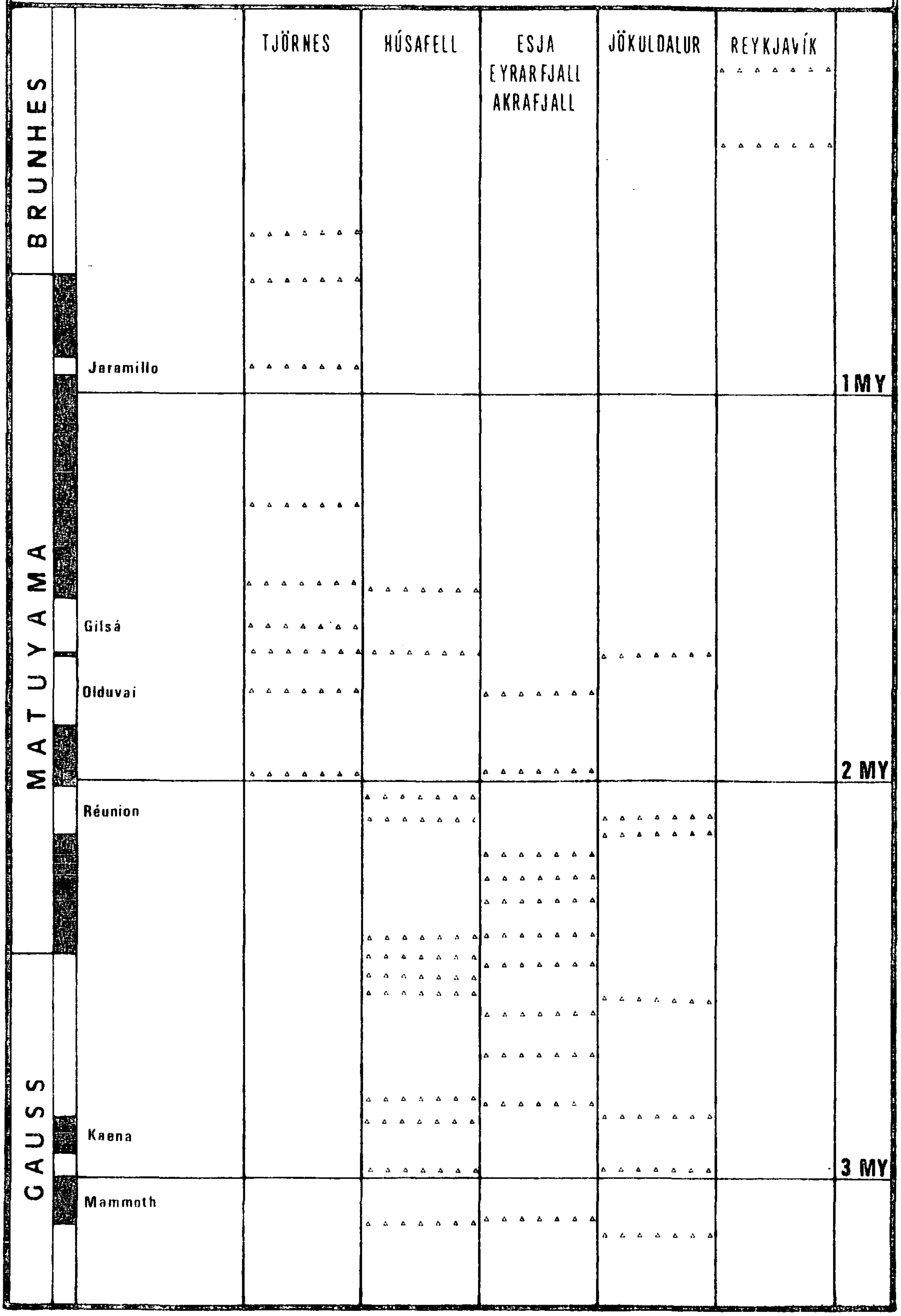
Sæmundsson (pers. comm. 1976) has suggested that glaciations in Iceland occurred approximately every 100 000 years. This makes about 30 in all in the last c. 3 m.y. He stresses, however, that at least some of these glaciations did not cover the whole country, with peripheral areas less affected than other parts. This is in good agreement with Kukla´s (1977) results who concluded that in Europe at least 17 glacials and 17 interglacials occurred there over the last 1.7 m.y. Kukla (1977) came to this conclusion after reinterpreting the existing evidence for glacial and interglacials.

2.1.1. Discussion. There is abundant evidence in Iceland for glaciations during the last c. 3 m.y. In the time span 3.1 - 1.6 m.y. the evidence is particularly abundant and signs of glaciations have been found in all rock sequences of this age. Most of the research has been concentrated in western

FIG. 2.1

PLIO-PLEISTOCENE GLACIATIONS IN ICELAND

(Partly after Albertsson 1976)



and south-western Iceland and this area is therefore best known. At least 13 glaciations have been found there in the time span 3.1-1.6 MY, indicating that on the average the glaciations took place every 100 000 years. Although there are less data available for the period after about 1.6 MY there is no reason to believe that glaciations were less frequent after that date. Assuming that on the average glaciations occurred in Iceland approximately every 100 000 years, which is reasonable in light of the available data, then about 30 glaciations took place in the last c. 3 MY. The extent of these glaciations, however, is unknown.

In Vestfirðir no evidence has been found for glaciations earlier than the last glacial. In light of the fact, however, that at present the glaciation limit in Iceland is lowest in Vestfirðir (Ahlmann 1937) there is no reason to believe that glaciations have been less frequent in Vestfirðir than elsewhere.

2.2. RATES OF PLEISTOCENE VALLEY EROSION IN ICELAND.

At the time when Pjeturss (1900) first discovered tillites in Iceland, the prevailing opinion was that the topography of Iceland was almost entirely of Tertiary age (e.g. Thoroddsen 1901, 1906, Hawkes 1938). But the hypothesis that these tillite bearing sequences were Pleistocene in age meant that "it is certain that even the principal features of the surface relief of Iceland are younger than the first glaciation" (Pjeturss 1939, p.235). This implied that glacial erosion during the Pleistocene had been more rapid than many workers (e.g. Hawkes 1938) could accept.

With the advent of K/Ar dating it was confirmed that these tillite-bearing rock sequences are in fact young and that very rapid erosion had taken place in, say, the last 3 m.y. Þ. Einarsson (1968) cites the example of Grundarfjörður in Snæfellsnes in western Iceland. There the fjord and the valley at the head of it are cut to a depth of 600-700 m in rocks younger than 1 m.y. This means that a 600-700 m deep valley has been eroded there during the last 0.7 - 1 m.y.

Another area where very rapid erosion has taken place is the Hvalfjörður area in south-western Iceland. On the south side of the fjord the youngest rocks on the mountain tops date from the Gilsá event, between 1.6 and 1.8 m.y. ago (Kristjánsson et al. 1980, Arason et al. 1973).

The valleys were eroded subsequently to a depth of 400-500 m.

The examples cited show that 600-700 m deep valleys have been excavated in less than 1 m.y. This goes to show that when glaciers are present, the erosion of valleys can be very rapid. It is suggested here that the processes of glacial erosion, abrasion and plucking, need not have been the only processes responsible for the excavation. This hypothesis is elaborated below. It is maintained that other processes, especially mass-wasting, could well have been significant together with the glacial processes in excavating valleys. This is based on the following considerations:

Landsliding, in some cases on a massive scale, has taken place in many valleys in Vestfirðir (see Chapter 3, Rafferty 1974) in Post-Glacial times. It is considered that in many cases these slope failures were due to oversteepening of the flanks of glacial troughs, the oversteepening being due to glacial erosion. Mass-wasting processes, mainly scree formation and landsliding, would, during interglacials, supply new glaciers with tools to abrade. In this way there is a positive feedback between mass-wasting and glacial erosion: Increased glacial erosion will intensify mass-wasting during interglacials which in turn supplies consecutive glaciers with tools to make their work more effective. Considering that glaciers can only abrade when there is debris at the glacier sole, it may be that intermittent deglaciations of troughs, with subsequent mass-wasting of the trough slope, had the effect, in the long run, of enhancing glacial erosion.

2.2.1. Conclusion. During the last 1.6 MY at least, valley erosion has been very rapid, with examples of 600-700 m deep valleys being excavated entirely in less than 1 MY. It is suggested that glacial processes of erosion were not entirely responsible for this very rapid valley erosion, mass-wasting, mainly landsliding and scree formation, were important during interglacials in denuding the valley sides and providing glaciers of consecutive glacials with tools to abrade, thereby forming a positive feedback with the glaciers.

2.3. GEOLOGICAL METHODS OF ESTIMATING THE AMOUNT OF EROSION.

The examples in the foregoing section involve minimum values of erosion as the height of the original surface of the lava pile has to be taken into account. Volcanic geology possesses at least three methods of estimating the original surface of the pile, all being first developed and applied by Walker (1960, 1974) in eastern Iceland.

The first of Walker´s methods is to extrapolate upwards in the pile the density of dykes, since if they are all feeder-dykes, they should approach zero density at the original surface. This method requires very detailed mapping of geology and dykes. With the lack of such detailed maps of local geology this method is of little use in Vestfirðir at present. The second method is based on the mapping of zeolite zones and has proved particularly useful (Sæmundsson 1967, 1970, Arason et al. 1973, Aronson and Sæmundsson 1975). Zeolites and other amygdale minerals formed at depth some considerable time after the eruption and the cooling down of the individual lavas. The depth at which they start to form is about 200 m. This would normally be well below the water table where the slaggy and vesicular flows are saturated with water, and where due to the steady rise of the geoisotherms, the appropiate temperatures are attained, making it possible for the heated ground water to react with the basalts to produce zeolites and other secondary minerals. Different zeolites form at different depths and at different temperatures, forming a distinct zonation sequence. By knowing the vertical distribution of the zeolite zones and the depth at which they form, it is possible to estimate with reasonable accuracy the original top of the lava pile. Walker´s conclusions for eastern Iceland are that in general 500-1000 m of rock have been removed from the top of the lava pile, with extreme values of about 2000 m for SE-Iceland. Valleys and fjords have since been eroded below this surface. Similar results are obtained by the third method, the dip method, developed only recently (Walker 1974). This method uses the vertical distribution of dips of the lava pile. Over most of eastern Iceland it is an observed fact that dips decrease with height in the lava pile. By extrapolating upwards to a zero dip it is assumed that this represents the original surface of the lava pile. This method assumes zero dip or close to zero dip of the original surface.

Applying these methods to Vestfirðir is difficult at present since the geology is little known. There is no data on the vertical distribution of dykes but some data is available on the zeolite zonation and dips.

Moorbath et al. (1968) note that the tholeiitic rocks from Breiðadalsheiði selected for dating were totally free of any secondary minerals. Their lowest sample was from a height of 538 m. Kristjánsson et al. (1975) give little information on zeolites from their area between Patreksfjörður and Arnarfjörður. They mention, however, that generally zeolites are present, and that the most common ones are chapazite and thomsonite. These are typical of Walker´s uppermost zone, which forms at depths greater than 200 m.

Hald et al. (1971) found a variety of zeolites, but these are close to the Króksfjörður central volcano, with its presumed much higher than average geothermal gradient, that they have to be treated with great caution.

In 1975 officers of Orkustofnun (The National Energy Authority) started detailed mapping of the geology of Vestfirðir. Some preliminary results on zeolite distribution have been made available to the author (Sæmundsson pers. comm. 1976). Generally the zeolite zones get higher above sea level towards the south-east of Vestfirðir. At the mouth of Ísafjarðardjúp (the area close to Breiðadalsheiði) the analcim zone is at sea level, but near Hagavaðall on the south coast of Vestfirðir, the mesolite-scolecite zone is at sea level.

Though meagre, these data give important clues as to the original top of the lava pile. The analcim zone of Walker is some 150 m thick, and starts at depths of 600 m below the original surface. The highest mountain tops around the outer reaches of southern Ísafjarðardjúp are 700-800 m. But the plateau there is mostly 500-600 m. The fact that the analcim zone is here at sea level strongly suggests that very little, if anything, has been removed from the plateau.

The mesolite-scolecite zone of Walker´s has a thickness of about 750 m, and starts to form at depths of about 750 m below the surface. Its top is at present near sea level at Hagavaðall. The highest mountain tops there just reach 600 m. Most of the territory is at heights below 500 m. This strongly suggests that a minimum of about 200 m and in general about 300-400 m of rock have been removed by erosion in this part of Vestfirðir. Of course, valleys have been cut deeper than this level. Areal scouring has been significantly greater here than around Ísafjarðardjúp. In this context it may be significant that many more fracture lines were observed around Hagavaðall than around the mouth of Ísafjarðardjúp. Also, dips are much greater in the south and the south-east of Vestfirðir than around the Skutulsfjörður area. As most of these dip measurements refer to the mountain tops this is highly suggestive that more erosion has been accomplished in the south and the south-east than in the north-west. The pattern of depth of erosion indicated by the dip method is almost identical with the pattern indicated by the zeolite method.

2.3.1. Discussion. The evidence of the zeolite zonation and the present landscape indicates that in the south and south-east of Vestfirðir areal scouring has been dominant, up to 400 m of rock may have been removed from the area. In the north-western part, however, very little areal scouring has taken place. Instead the erosion has been largely selective and has concentrated on enlarging the troughs, the former Tertiary fluvial valleys. This areal variation in the nature and effectiveness of glacial erosion is, it is suggested, due to two factors:

(1) The preglacial landscape had a profound effect. Where the preglacial relief was greatest, in the oldest, north-western part, the glacial erosion selected the well developed fluvial valleys and exploited them. In the younger, south-eastern part, where the preglacail relief was much less, the dominant ice movement was sheetflow and areal scouring resulted.

(2) The south-eastern part is closer to the main Icelandic ice sheet and ice thicknesses were probably, at least in some of the glaciations, greater there, and the ice was therefore less likely to have been constrained by the topography. Also, since temperature in ice sheets increases with depth, it is likely that the thinner ice in the north-western part was cold-based along the interfluves and frozen to the bottom there. This would have greatly reduced erosional capacity on the interfluves.

2.3.2. Conclusion. The evidence of the zeolite zonation indicates that large scale areal scouring has taken place in the south and south-east of Vestfirðir, with 300-400 m of rock at least having been removed from the top of the mountains and then valleys being excavated below that. In the north-western part of Vestfirðir the zeolite zonation indicates that areal scouring has been much more limited, the erosion having been largely selective. The variation of the glacial shaping of the landscape is suggested to be due to two factors, the preglacial relief and the thickness of ice.

2.4. MODELS OF GLACIATION OF VESTFIRÐIR AND THE SPATIAL DISTRIBUTION OF CIRQUES.

It has become apparent in the foregoing sections that glacial erosion on a large scale has been chiefly responsible for sculpturing the present landscape of the Vestfirðir peninsula. In some areas the pattern of orientation of tectonic lineations has determined the orientation of the glacial troughs, but much of the actual excavation of the troughs has, most likely, been the work of glaciers and ice streams. Similarly, very strong evidence exists to indicate the absolute amount of erosion since the building up of the basalt pile, and also spatial differences in the amount of rock removed. It was shown (section 2.3) that very little had been eroded from the plateau remnants around Skutulsfjörður, while hundreds of metres of rock had been removed from the southern and south-eastern part of Vestfirðir. From fig. 1.6 it also became apparent that the spatial distribution of glacial troughs in Vestfirðir is very uneven. They are generally large and numerous along the west coast, smaller along the south coast, while along the east coast they are relatively sparse. It is also apparent from fig 1.4. that the pattern of exposed bedrock is clear-cut: bedrock is covered with regolith in the extreme north and west, north of Arnarfjörður, but largely free of a superficial cover further south.

The distribution of erosional features mentioned above demands an explanation. This might possibly be sought by inferring different glacier types and their different flow patterns and basal ice temperatures, as these are of obvious importance in determining the amount and pattern of glacial erosion.

2.4.1. Previous work. Thoroddsen (1906), the first to work on the glacial geomorphology of Vestfirðir, concluded on the basis of his observations of striae that Vestfirðir had been a local centre of glaciation and that ice thicknesses had hardly exceeded 400-500 m.

Thorarinsson (1937) was the first to propose a model of glaciation of Vestfirðir. On the basis of Thoroddsen´s work, Keilhack´s (1933) work of mapping 111 cirques in the area between Patreksfjörður and Álftafjörður, and his own observations on the Danish 1:100 000 maps, he proposed the following model of glaciation: "While the last glaciation was at its maximum the district was then very similar to what the southeastern part of Vatnajökull is at the present time. Small glaciers covered the plateaux between the fjords, while the whole of the central area was covered by a large continuous glacier cap, from which valley glaciers flowed through all the fjords, sloping towards their mouth, thus gradually leaving more space for local glaciers on the sides" (p. 171-172). This model rests on the assumption that "most likely the cirques were formed while the last glaciation was at its maximum"(p. 171). Þ. Einarsson (1961) and Steindórsson (1962) adopted Thorarinsson´s model to show that there had been ice free plant refugia in Vestfirðir during at least part of the Pleistocene. However, since his discovery of the evidence for the glaciation of Grímsey, Þ. Einarsson (1968) has proposed an alternative model implying a more extensive ice cover: "On the Vestfirðir peninsula there was a separate ice cap. From this ice centre outlet glaciers flowed through valleys and fjords and joined the main ice streams in Húnaflói and Breiðafjörður" (1968, p. 275, the author´s translation). Although this model is not very precisely stated, it is evident that it allows for ice free upper slopes of the large western troughs where, presumably, cirque glaciations prevailed.

A third model can be said to come from Sugden and John (1976, p.207) who suggested that in the cirque areas of Vestfirðir nunataks abounded, implying a similar degree of ice cover as Þ. Einarsson did.

All these models depend to a large degree on the assumption that the cirques were formed during maximum glaciation. Also, those who proposed these models seem to have taken the very presence of the cirques as a proof that a main ice cap did not cover them. It is worth pointing out here, therefore, that recent depth soundings of the Antarctic ice sheet have revealed "alpine" landscapes buried beneath hundreds of metres of ice (e.g. Drewry 1972).

Indeed, the very presence of these "alpine" landscapes has been used to argue that they represent earlier stages of less extensive glaciations, possibly as old as the Eocene (e.g. Drewry 1972, Mercer 1972). In any case, the presence of cirques or "alpine" landscapes cannot be used anymore to prove that a main ice cap or ice sheet did not cover the area in question.

2.4.2. The spatial distribution of cirques in Vestfirðir. The models related above are dependant on assumptions about the age and the distribution of cirques. However, very little is known about either. Previous work includes Keilhack´s (1933) mapping of cirques in the area between Patreksfjörður and Álftafjörður. He visited the area by boat in 1924 and made most of his observations from sea, or from maps. His results are as follows: In total 111 cirques were observed. The majority of cirques had floors at heights between 200 and 400 m, with some as low as 200-300 m. As Keilhack admitted, this survey of the cirques in Vestfirðir is obviously very incomplete. Despite the incomplete nature of this work some very interesting results emerged. Using this as a basis it was decided to attempt to map the whole cirque population in Vestfirðir, and measure the height of the cirque lip and headwall aspect.

2.4.2.1. Methods. It was decided to use the operational definition of cirques agreed upon by the meeting of the BGRG Small Research Group on Geomorphometry in Durham in November 1973 (Evans and Cox 1974). It is stressed that this definition includes "valley head" cirques.

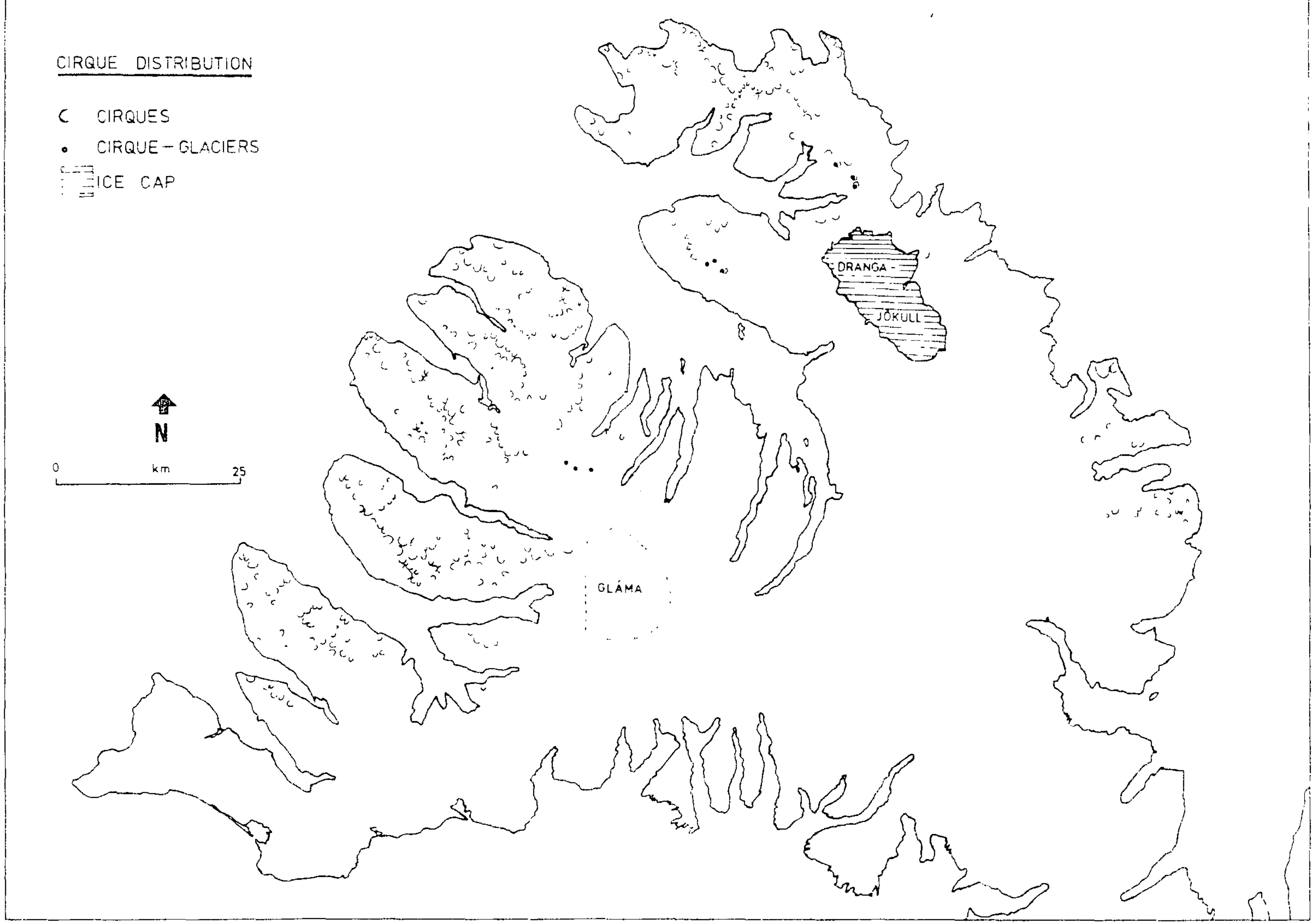
The U.S. Army Map Service photogrammetric maps with the scale of 1:50 000 and a contour interval of 20 m were used as base maps in the mapping procedure. Almost all the cirques were identified through air-photo interpretation, the photos being taken in 1956, 1959 and 1960 by the USAF, with the scale of approximately 1:30 000. Besides, many of the cirques in the area between Arnarfjörður and Skutulsfjörður were visited in the field, and this proved to be invaluable help in the air-photo interpretation.

It must be emphasized here that because of obvious subjectivity which must be present when cirques are identified in this way, other workers would have come up with different results. However, since the large majority of the features are well defined and obvious cirques, it is maintained that mistaken interpretation of marginal features will not have a large bearing on the final outcome.

The height of the cirque lip was read from the map to the nearest contour. It was found that in a large majority of cases it was easy to define a change in slope between the cirque floor and the subsequent slope downstream, and the "cirque lip" was defined where this occurred. In a few cases, however, mainly in valley head cirques, no such break could be detected, but since in these cases the slope was quite gentle anyway, there is not a large error involved.

2.4.2.2. Results. Fig. 2.2 shows the distribution of cirques in Vestfirðir. In total 300 cirques were identified, the distribution of which shows a high degree of clustering. Three clusters can be identified: The western fjords, comprising the area between Patreksfjörður and Álftafjörður

FIG. 2.2


CIRQUE DISTRIBUTION
CIRQUES
CIRQUE - GLACIERS
ICE CAP
N
0
km
25
DRANGA -
JÖKULL
GLÁMA

with the largest number of cirques, 217. The second area, the Hornstrandir-Jökulfirðir area, north of Ísafjarðardjúp, contains 73 cirques. The third area is around Reykjarfjörður on the east coast and contains 20 cirques. Outside these areas no cirques were observed; even valley heads showed no resemblance in form to the valley heads which were identified as cirques in the cirque areas.

Fig. 2.3 shows the frequency distribution of cirque lip altitudes in Vestfirðir. Table 2 . 1 shows some statistics of the distribution of cirque lip altitudes.

Table 2 . 1.

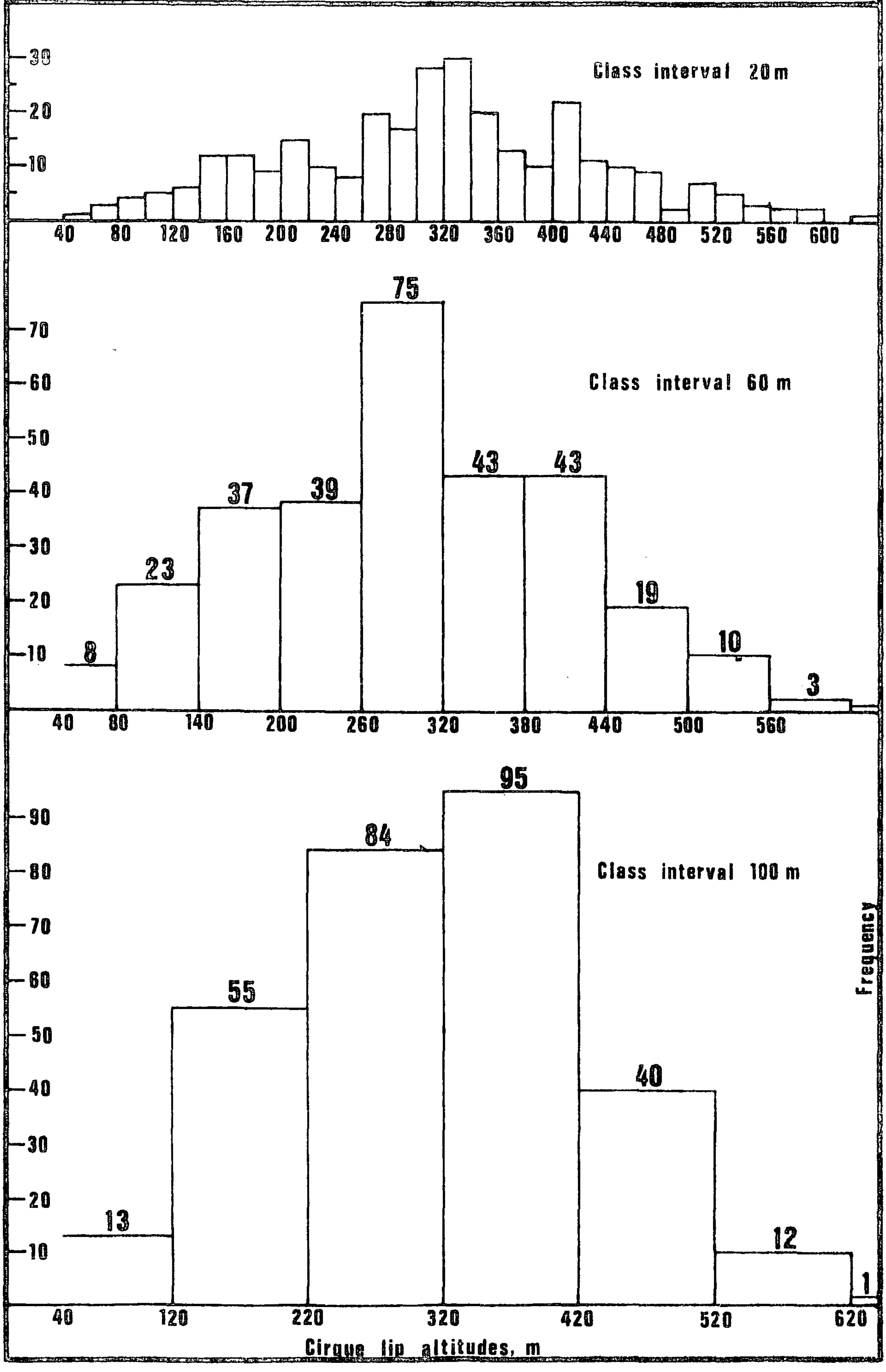
Range	40-620 m
Mean	306 m
Mode	320 m
Median	301 m
Skewness	-0.122
Standard Deviation	±114.8
95% Confid. limits	12.99

The distribution is very little skewed and quite close to being normal. The range of altitudes, 40-620 m is very high and so is the Standard Deviation; this is of great importance in relation to the cirque distribution.

2.4.2.3. Discussion. The distribution of cirques in Vestfirðir is highly clustered, with three clusters readily recognizable. The largest number of cirques is in the area between Patreksfjörður and Álftafjörður where 217 cirques have been identified. Keilhack (1933), however, only

FIG.2.3

FREQUENCY DISTRIBUTION OF CIRQUE LIP ALTITUDES IN VESTFIRDIR



identified 111 cirques in the area. This difference is not surprising considering Keilhack´s methods of observatio and the fact that Keilhack seems to have ignored valley head cirques.

It is suggested here that the distribution of cirques in Vestfirðir can be explained by reference to three main factors:

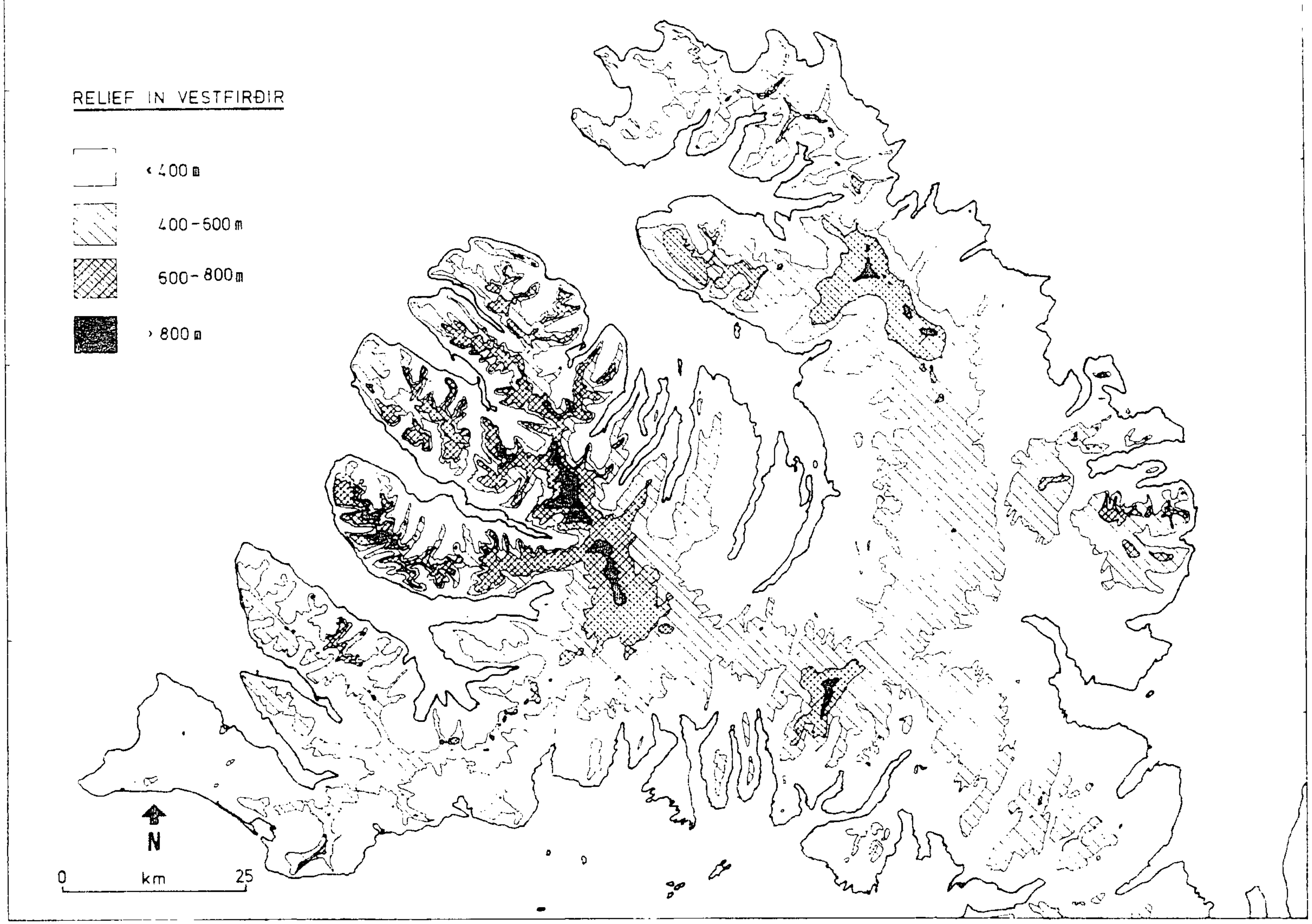
(1) Distance from the outer coast, defined as the distance from the mouth of the fjords, including Breiðafjörður and Húnaflói. This is a climatic factor, controlled by increase in summer temperatures and decrease in precipitation as one moves inland, which has the effect of lifting the snowline. All the cirques in Vestfirðir are within 32 km of the outer coast.

(2) Areas of high altitudes. This factor is also related to the snowline height. As can be seen by comparing the map of the cirques to the relief map (fig. 2 . 4 .), all the cirque areas coincide with areas of high ground, although altitudes in the Hornstrandir-Jökulfirðir area are generally lower than in the other areàs. Some areas of high ground are devoid of cirques, however, notably the Reiphólsfjöll area, the Gláma-Hornatær massif and the Drangajökull area.

(3) Areas of high relief. This factor is purely topographic; there must be sites suitable for the cirques to form. All the ciique areas are also areas of high relief But again there are areas of high relief supporting no cirques, e.g. the Barðaströnd area.

These three factors seem to be sufficient to explain the distribution. Where one of these factors is not present

FIG.2.4



in an area no cirques occur. The southern limit of the cirques is on the peninsula north of Patreksfjörður, the inhibiting factor there presumably being lack of high ground. Also, the Drangajökull area possesses both high ground and proximity to the outer coast, but there is little relief. Moreover, the south-east of Vestfirðir possesses both reasonably high ground and reasonable relief, but is remote from the outer coast.

It is significant to note that the cirque areas coincide with the areas where the bedrock is oldest, because this can be related to the erosional history. The extreme north and west of Vestfirðir have had a longer history of erosion than, say, the south-eastern part. Therefore, it can be argued that, at the onset of the Pleistocene glaciations, valleys were much better developed there than in the south-east, and hence cirques were more likely to form in these locations. Also, the evidence provided by the vertical distribution of the zeolite zones strongly suggests that hundreds of metres of rock have been removed from the mountain tops and plateaux by erosion in the south and south-east of Vestfirðir. This erosion was almost certainly accomplished by glacial erosion during the last 3 million years or so. Therefore, prior to glaciation, these parts possessed much higher altitudes than at present but still failed to nourish any cirques, probably because of low relief and little dissection by fluvial erosion, a topography favouring the formation of ice caps rather than valley- and cirque glaciers. Thus the preglacial relief would appear to an important factor in explaining the present distribution of cirques in Vestfirðir.

However, it should be stressed that many of the cirques are old, some perhaps as old as 3 million years.

The distribution of cirques in Vestfirðir coincides with the distribution of regolith covered bedrock, bare bedrock occurring everywhere else. Also, the area where very little rock removal has taken place from the mountain tops and plateaux also coincides with the main cirque area. It is suggested here that the remarkable coincidence of these phenomena can be related to ice conditions during maximum glaciation, and is discussed in section 5.5.

The frequency distribution of cirque lip altitudes is shown in Table 2.1. Here it is important to note the large range of cirque lip altitudes, 580 m, and the high Standard Deviation. Cirque floor levels have been used by various workers to reconstruct hypothetical former "composite" snowlines (Flint 1957, Linton 1959, Porter 1964, Flint and Fidalgo 1964). More recent attempts at snowline reconstruction involve the fitting of polynomial trend surfaces to the cirque floors (Paterson and Robinson 1969, Andrews et al. 1970, Unwin 1973). These methods are, however, riddled with difficulties. Flint (1971) notes that "the cirque floor measurement is only valid where former glaciers never grew beyond the cirque-glacier condition" (p. 68). This condition is certainly not met in Vestfirðir. Furthermore, Evans (1974), who has studied the problem in detail, stated that "unless isolated cirques which never contributed to valley glaciers are carefully selected, cirque floor altitude trend surfaces will tell us no more about former snowlines than they do about regional topography" (p. 133). Also, the identification of isolated cirques depends upon paleogeographic reconstruction of glacier distribution. It is therefore concluded that in the case of Vestfirðir it is not possible, at the present state of knowledge, to reconstruct former composite snowlines. This is further emphasized by the large range in cirque lip altitudes and the high Standard Deviation. Also, as was shown in section 2.1., the Vestfirðir peninsula may have had as many as 30 glaciations, some of them with extensive ice cover while others have been more marginal. To meaningfully reconstruct a composite snowline repersenting all these varying degrees of ice cover is out of the question.

The large range of cirque lip altitudes and the high Standard Deviation have important implications for former ice extent, because all the cirques could not have been occupied by cirque glaciers at the same time. When the highest cirques (lip altitudes greater than 500 m) had cirque glaciers, the lowest cirques (lip altitudes lower than c. 100 m) must have been ice free. During such a stage the snowline would not have to be much lower than at present. Such conditions probably prevailed during the Little Ice Age (c. A.D. 1600-1900) when an active ice cap was actually centred on the Gláma plateau (Thorarinsson 1943). Equally, when the lowest cirques were occupied by cirque glaciers, the snowline must have been so low that ice cap glaciation prevailed on higher ground, with the higher cirques over-ridden by external ice and, in turn, supplying valley glaciers

It is concluded, therefore, that the large range of cirque lip altitudes and the high Standard Deviation can be taken as strong evidence for a widely fluctuating snowline in Vestfirðir, which from time to time has been stable enough at certain altitudes to allow cirque glaciers to build up and erode and enlarge the cirques.

2.4.2.4. Conclusion. The 300 cirques of Vestfirðir, believed to be the whole population, are found in three clusters. The distribution of cirques is suggested to be related to three factors, distance from the outer coast, areas of high ground and areas of high relief. Where one of these factors is missing, no cirques occur.

The three cirque areas coincide with the areas where the oldest bedrock outcrops. It is suggested that this is to be expected because in these areas the preglacial amplitude of relief was greatest. This hypothesis assumes a considrerable age for many of the cirques.

The large range of altitudes of the cirque lips and the high Standard Deviation indicate that the snowline in Vestfirðir has fluctuated widely in the past.

2.5. THE CLASSIFICATION OF LANDSCAPES OF GLACIAL EROSION IN VESTFIRDIR.

2.5.1. Introduction and previous work. Remarkably few attempts have been made to classify landscapes of glacial erosion. The earliest effort was by Clayton and Linton (1964), who suggested five "Zones of Glacial Erosion". This classification scheme was later developed more fully by Clayton (1974). The five zones, as defined by Clayton (1974) are supposed to represent a "sequence of landscapes showing progressive modification by ice" (p.166). Recently

Sugden (1974) has introduced a classification of landscapes of glacial erosion in Greenland "based on their form. The forms are then viewed as elements of glacial systems and are related at the outset to two main types of glacier systems: ice sheets and mountain valley glaciers" (p. 177). Later, Sugden (1977) has further tested, with apparent success the applicability of the clasification scheme to the area of the former Laurentide ice sheet.

The advantages of the Sugden scheme of classification of glacial erosional landscapes are considered to be the following: The classes are in most cases quite distinct and rarely transitional. The landscape types can be related to types of ice masses forming them, and the dynamics of these ice masses. There are similarities between the Clayton and the Sugden scheme, e.g. both identify a class or zone of no glacial erosion. Clayton,however, does not attempt to make his system a "regionalization of ice sheet dynamics" (p. 174) as does Sugden, a factor considered by the author to be the greatest merit of the Sugden scheme. The author therefore decided to attempt to apply the Sugden classification to Vestfirðir, hoping that by this means it would be possible to throw some light on the past ice masses of the area and their dynamics.

Only John (1976) has previously attempted to classify the landscapes of glacial erosion in Vestfirðir. He identified three types of landscapes of glacial erosion as most distinctive: (1) Alpine landscapes. These coincide with the areas where the present author has identified cirques (fig. 2.2). (2) Amphitheatre landscapes. These occur mainly in the Skutulsfjörður-Önundarfjörður area and the Hornstrandir area. (3) Fjord landscapes. These comprise most of the larger fjords. He also identified a "heavily denuded landscape of areal scouring in the extreme south-west" (p. 29) while "selective linear erosion has affected most other parts of the peninsula" (p.30).

2.5.2. Results. Sugden´s types of landscapes of glacial erosion are as follows (Sugden and John 1976, table 10.1.):

Glacier system	Landscape type
Ice sheets and ice caps (unconstrained by topography)	Landscapes of little or no erosion Landscapes of areal scouring Landscapes of selective linear erosio
Glaciers constrained by topography	Alpine landscapes Cirque landscapes

Landscapes of areal scouring were clearly described by Linton (1963) who used the term "knock and lochan" topo graphy. The main characteristics are irregular, glacially eroded rock surfaces abounding with rock knobs and lakes in the intervening depressions. The relief is mainly low.

Landscapes of selective linear erosion describe situations where ice erosion has been concentrated in a trough or a series of troughs and has left the intervening plateaux unmodified. The intervening plateau areas may be regolith covered and devoid of glacial erosional forms.

Landscapes of both areal scouring and selective linear erosion exist in some places (Sugden and John, p. 197). Such landscapes possess the main characteristics of both types: There are distinctive troughs, but the intervening interfluves are affected by typical areal scouring. The cliff top of the trough is often rounded.

Alpine landscapes are characterized by a network of troughs with steep, often precipitous slopes. Where the relief is well developed the upper slopes may abound in aretes and horns.

Cirque landscapes "include cases where essentially discrete cirques are set into a hill massif" (Sugden and John 1976, p. 197).

The fifth type, landscapes with little or no signs of erosion are known from other evidence to have been covered by ice sheets or ice caps, but bear no obvious signs of it.

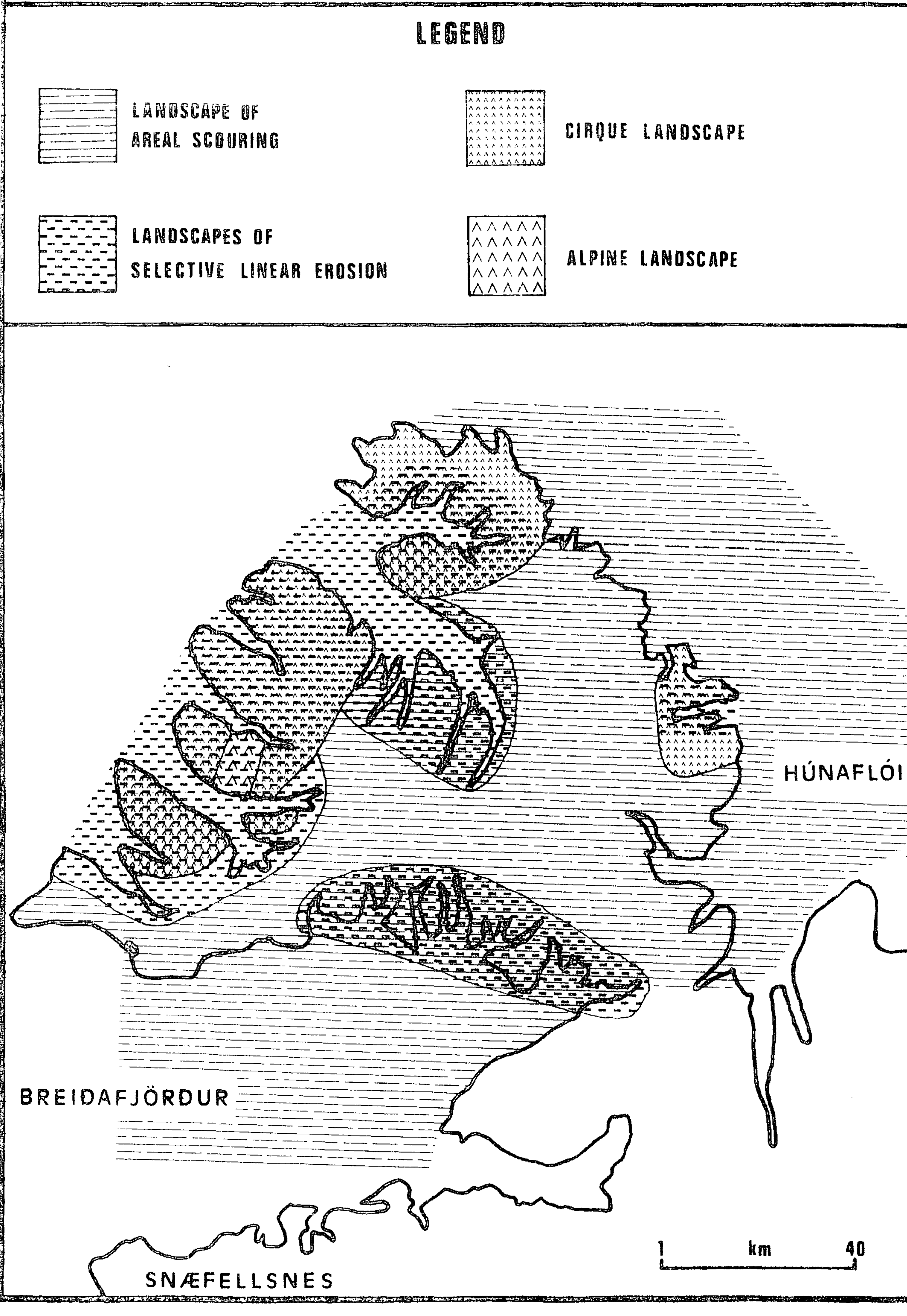
Fig. 2.5 is a map showing the landscapes of glacial erosion in Vestfirðir, using Sugden´s scheme of classification Together landscapes of areal scouring and selective linear erosion, the typical landscapes associated with ice sheets, affect the whole peninsula.

The landscape type of areal scouring dominates the east and the central plateau of Vestfirðir. Here valleys are relatively few, and most of them are shallow. This applies especially to the fjords which are in areas of low ground. This implies that powerful ice streams within the ice sheet must have been minimal. Most of the area has obviously been heavily denuded by ice action: it is a plateau, with little relief, and strewn with innumerable lakes occupying the depressions between the bare rock knobs. This is typical for landscapes of areal scouring.

Outside areas of areal scouring, landscapes of

FIG.2.5

LANDSCAPES OF GLACIAL EROSION IN VESTFIRÐIR



selective linear erosion are found everywhere, coinciding either with areas of areal scouring, as in the south and the south-west and southern Ísafjarðardjúp, or with cirque landscapes in the west and outer Ísafjarðardjúp, and the Reykjafjörður area in the east.

Landscapes of areal scouring and linear erosion constitute a prominent landscape type in Vestfirðir. Typically, the troughs are long and narrow, with the upper edges of the troughs rounded, and the intervening interfluves clearly affected by glacial erosion. This description especially applies to the troughs draining the Gláma plateau to the north and south. In the south-west of Vestfirðir linear erosion becomes less important, but there are still significant troughs. Indeed, the small catchment areas of the large troughs of Patreksfjörður and Tálknafjörður indicate that they must have served mainly as channels of ice streams in an ice sheet, at least during the latest part of the Pleistocene. Initially they probably drained a bigger land area than now, which, if true, indicates the amount of erosion, marine and glacial, which has taken place.

Cirque landscapes are not very well defined by Sugden. Here they are taken to mean landscapes where cirques are cut into plateau remnants and include almost all the areas where cirques have been mapped (see fig. 2.2.). Since these areas are traversed by large troughs, they have also been classified as landscapes of selective linear erosion. Therefore, this landscape type, which is not included in Sugden´s scheme, has been designated landscapes of cirques and selective linear erosion. It includes the landscape type called amphitheatre landscapes (John 1976). Landscapes of cirques and selective linear erosion are characterized by a large number of cirques, cut into plateau remnants divided by valleys. Large fjords drain the whole area. The crucial question in identifying this landscape type, which joins up the two Sugden landscape types of cirque landscapes and landscapes of selective erosion, is whether a significant proportion of the fjords can be attributed to erosion under an ice sheet. This question is difficult to answer, but it is maintained that at least in the case of the largest fjords with their tributary fjord systems, Arnarfjörður, Ísafjarðardjúp and Jökulfirðir, a significant part of their erosion can be attributed to ice streams within ice sheets during maximum glaciations, as the size of these troughs is out of proportion with their catchment area. During maximum glaciation the plateau remnants and the cirques must have been largely protected from erosion by cold ice, ice below the pressure melting point, which would have made possible basal slip in the fjords and therefore made erosion possible. Anyway, the essential morphological features of both landscape types are present. The fjords have been affected by selective linear erosion of an ice cap, while the peninsulas contain landforms characteristic of more marginal glaciations.

Alpine landscapes as defined by Sugden comprise massifs shaped essentially by local valley glaciers. The trough pattern is coarsely dendritic and horns and arêtes are characteristic. This landscape type only occurs on the middle of Kaldbaksnes between Dýrafjörður and Arnarfjörður. This area is characterized by long, narrow troughs, valley head cirques and horns. Aretes occur everywhere. No plateau remnants are left in the area, and amphitheatres as described by John (1976) do not occur. This area coincides exactly with the Hrafnseyri central volcano, with its easily eroded rock succession. Therefore, the alpine characteristics of the scenery here are ascribed to lithologic factors, as there is no reason to believe that the climatic régime in this area has been drastically different from the neighbouring areas.

It was also attempted to include the neighbouring shelf areas in the landscape classification. This, however, is hampered by the lack of accurate bathymetric charts. Reasonably accurate bathymetric information exists for areas where depths are less than 100 m. Here 50 m contours are shown and, in some cases, even 10 m contours. Areas where this information is available include Breiðafjörður, and the area east of Vestfirðir.

Breiðafjörður is for the most part very shallow. Numerous small islands are scattered in the fjord. The maximum amplitude of relief is 50-100 m. Glacial striae have been found on three of the islands (Kjartansson 1955, 1969). Depressions (closed contours) are very common in this shallow fjord. This type of submarine topography has been identified by Sugden and Clapperton (1977) as a landscape of areal scouring, and most of Breiðafjörður can be classified with certainty as a landscape of areal scouring.

The other area where the bathymetry is presented with reasonable accuracy is the area east and north-east of Vestfirðir. The north-east area,off Drangajökull, is mostly shallower than 150 m. Close to the shore small islands, skerries, submarine reefs and depressions are common. Relief is irregular, but mostly less than 50 m. On the whole, the submarine topography is typical of glacial erosion. Further to the south-east the submarine topography becomes more rugged and complicated. Small islands, skerries and reefs are still common, but some of the depressions are of great amplitude and dimensions, especially off Steingrímsfjörður.

It is concluded, however, that here also the submarine topography indicates areal scouring. The complications were probably caused by locally strong ice streams from Hrútafjörður and Steingrímsfjörður.

2.5.3. Discussion. The two landscape types formed under ice sheets, landscapes of areal scouring and selective linear erosion, are well defined and easily recognized. The same, however, does not apply to the landscape types formed by glaciers constrained by topography, cirque landscape and alpine landscapes. This is because in both landscape types valley glaciation can be prominent. The discriminating factor mainly used in this study is the presence or absence of plateau remnants. The presence of these plateau remnants is of crucial importance because they can, locally at least, give rise to small ice caps or ice fields, which in turn would give rise to a totally different pattern of glacier erosion, distinctly different from areas of alpine landscapes, where plateau remnants are not found. Another discriminating factor, at least in Vestfirðir, are horns and aretes. They abound in areas of alpine landscapes while they are rarely met in areas of cirque landscapes.

The main modification of the Sugden scheme has been the introduction of "landscapes of cirques and selective linear erosion". This type of landscape is not really allowed for in the Sugden scheme as it breaches the boundary between glaciers constrained and glaciers unconstrained by topography. However, the justification for its use is that both glacier systems have left their clear marks on the landscape.

In spite of these difficulties, it can be stated that, with modifications, the Sugden scheme of classification of landscapes of glacial erosion has been successfully applied to Vestfirðir. This conclusion is in itself of great importance as the scheme has not before been applied to an area of such a small size, and suggests its possible universal applicability.

The landscape types of ice caps and ice sheets are found everywhere on the Vestfirðir peninsula, and also in submarine areas in Breiðafjörður and to the east of Vestfirðir. Areal scouring, with or without selective linear erosion, is found everywhere except where cirques are found. It was shown earlier that the cirque areas in the west and north coincide with areas where the evidence of zeolite zones suggests that very little, if any, rock removal from the mountain tops had taken place. Equally, the areas where the typical ice cap landscapes of areal scouring with or without selective linear erosion are found, the zeolite zone evidence indicates large scale rock removal from mountain tops. Areas of bare rock (fig. 1.4.) almost exactly coincide with the areas where areal scouring, with or without selective linear erosion, has taken place. This suggests the possibility that where extensive areas of bare bedrock in glaciated lands occur, these could be used as an objective measurable variable to define areas where scouring has taken place. It is very important to correctly identify the landscape type of areal scouring if conclusions are to be drawn about the thermal régime at the base of an ice cap.

2.6. SYNTHESIS AND CONCLUSIONS: LANDSCAPE EVOLUTION.

During the Tertiary the landscape evolved thus: When volcanic activity ceased the Vestfirðir peninsula was a basalt plateau. Above it occasional lava shields and central volcanoes protruded. The bedrock was porous and the only rivers were spring-fed and had little erosional capacity. Gradually the bedrock became less porous and direct-runoff rivers started to make themselves felt. This took probably about 1-3 million years. Fluvial erosion then led to the formation of fluvial valleys. These had formed in the oldest part, the north-western part, before volcanic activity ceased in the south-eastern part. One river valley, approximately where Ísafjarðardjúp is now, soon dominated the drainage pattern. Sizable fluvial valleys soon formed in the area south-west of Ísafjarðardjúp. Fluvial erosion there was guided by the original dip of the plateau to the west and by tectonic lineations. By the time volcanic activity ceased in the south-eastern part there was already a well developed drainage pattern in the north-western part. The drainage pattern in the south-east is to a large extent controlled by tectonic lineations which means that by the end of the Tertiary fluvial valleys had formed there also.

This was the scene when the Pleistocene glaciations started in Iceland about 3 million years ago. During the Pleistocene the landscape evolved thus: In the north-western part, where the preglacial relief was greatest, cirques formed and valleys glaciers and ice streams were dominant in sculpturing the landscape. In the south-eastern part, where the preglacial relief was much more limited, cirques did not form and linear erosion played a small part. Instead, the glacial sculpturing of this part was dominated by areal scouring. Landscapes typical of ice sheets, landscapes of selective linear erosion and areal scouring have affected the whole of Vestfirðir and also offshore areas, at least in Breiðafjörður and to the east of Vestfirðir. This indicates a large ice extent where the ice margin must have stood far off the present shore. The large range in the altitudes of the cirques, however, indicates that the snowline in the area has fluctuated widely during the Pleistocene, and that many types of glaciations have taken place ranging from cirque glaciations through valley glaciations and ice cap glaciations probably to ice sheet glaciations.

CHAPTER 3. FIELD EVIDENCE OF GLACIAL VARIATIONS AND SHORELINE DISPLACEMENTS.

3.1. INTRODUCTION. The field area lies wholly within Vestur-Ísafjarðarssýsla. It comprises the southern part of the peninsula between Önundarfjörður and Dýrafjörður, here called the Skagi peninsula, and the whole of the peninsula between Arnarfjörður and Dýrafjörður, here called the Kaldbaksnes peninsula

Previous studies by Thoroddsen (1892) and Kjartansson (1969) on shoreline displacements and glacial history in Vestfirðir consist of a series of scattered observations over the whole peninsula. During reconnaissance work in 1973 and 1974 it became evident that their studies were superficial in the sense that they reported and mapped only a small proportion of the shorelines and end moraines which are actually present. This approach of scattered observations is akin to taking a biased sample from a population and can lead to grave errors in interpretation. It is believed that only detailed mapping and studying of shoreline landforms, glacial landforms and stratigraphy can elucidate the sequence of events which led to the present landforms. For this purpose a suitable field area had to be selected which displayed a sufficient abundance of mappable features and sections. The reconnaissance in 1973 and 1974 showed that glacial landforms and shorelines are relatively abundant in Dýrafjörður and, consequently, this area was chosen for detailed mapping and field investigations. Besides, the area is easily accessible, with roads along most of the coast. In Dýrafjörður there are school houses in two places, Núpur and Þingeyri; both are centrally located and served excellently as bases during fieldwork.

The initial research goal was to determine the maximum extent of ice during the last glaciation, and the stages of glacial retreat and associated shoreline displacements. Systematic fieldwork started in 1975 from the bases in Núpur and Þingeyri. Early on it became apparent that there was little direct evidence for glacial retreat. On the other hand, a relative abundance of shoreline landforms and end moraines was discovered. Soon it also became apparent that it would be possible to link up end moraines, which were found at valley mouths, with shorelines, indicating a relative age of the end moraines. Consequently, the research theme had to be changed somewhat, and it was decided to map all the end moraines and associated landforms and try to link these up with heights of sea level at the time they were formed. In 1975 most of Dýrafjörður was mapped in this way. In 1976 the field season was spent completing the mapping and checking some observations in Dýrafjörður and then moving on to northern Arnarfjörður pursuing the same theme in the area between Hafnardalur and Hrafnseyrardalur. The results of this fieldwork are the contents of this chapter.

The chosen field area is dissected by numerous valleys. It is considered that this fact must have affected the course of deglaciation of the area. The way it did so and supporting arguments are as follows:

As the ice cap which covered Vestfirðir during the last glaciation receded and got thinner, it must have reached a stage where the landscape influenced its shape and movements.

It is likely then, that the central plateau of Vestfirðir was covered by an ice cap that drained via peripheral topographic lows. Hence outlet glaciers would be produced in the fjords. On the peninsulas, topographic highs dissected by numerous valleys and cirques, valley and cirque glaicers would have developed. This is significant from the climatic point of view since it is well established that valley and cirque glaciers respond faster to climatic input than do ice caps (e.g. Nye 1960). Small climatic fluctuations are, therefore, likely to be better registered in the stratigraphic and landform record of valley and cirque glaciers than that of ice caps. The study of these features hence facilitates the reconstruction of climatic environments and definition of the different climatic input variables which gave rise to the variations of the glaciers. This has been demonstrated by Sissons (1972a, 1977) and Sissons and Sutherland (1976).

3.2. METHODS. Before the main field season, in 1975, thorough air-photo interpretation was undertaken and base maps were constructed from the air-photos. Fieldwork consisted of

(1) mapping glacial landforms,

(2) mapping shorelines and measuring their altitudes,

(3) examining sections and exposures for the purpose of establishing stratigraphy.

Where possible exposures were excavated in marine deposits in search of molluscs and other organic materials. This work met with very little success, however, and no material suitable for radiometric dating was discovered.

The approach taken to the research is essentially one of fieldwork. This is considered necessary for elucidating the glacial chronology in an area where very little was known about glacier variations and shoreline dispacements. A few sediment samples were taken for particle size analysis. The methods for this and the results are discussed in Appendix A.

Altitudes of shorelines and other significant features were determined by three methods:

(1) Measuring with a KERN level. This method gives great accuracy, and was used to measure some high features relatively far from the shore. Its main disadvantages are that it is time-consuming and requires two persons to carry out the measurements.

(2) Measurement with a surveying aneroid barometer. This is scaled to read to the nearest 0.6 m. The instrument is read at sea level and the time is noted. It is then carried to the feature to be measured, read and time taken again. It is then taken back to sea level and read again and the time taken. This procedure is then repeated as often as is thought neccessary for reliable results. Sudden changes of barometric pressure result in spurious readings. If two readings at sea level and the feature gave similar results, stable conditions are indicated. In slightly unstable conditions the procedure was repeated up to five times. Most of the measured features are close to the present shore and the time which passed between readings was typically 5-10 minutes.

The shoreline altitudes were calculated thus: All readings at sea level and the measured features were plotted against time and line drawn joining all these sea level points. The vertical distance between this line and a measured feature point gave the altitude of the feature and the mean of all these was used. This was then converted to the nearest 0.5 m.

(3) Altitudes were estimated from the contour map on features which, for various reasons, were not measured in the field. The contour map was then compared with the air-photos. The contours are at 20 m intervals and where they are not too closely spaced it is possible to read the altitude of well defined features to the nearest contour interval, or to an accuracy of ± 10 m. In some cases, where the contours are widely spaced, it is possible to read altitude from the map with an accuracy of ± 5 m.

"Sea level", relative to which all the measurements are reported, is mean sea level, estimated from the morphology of the beach. It is approximately 1,5 m below high tide level. Only sandy beaches were used and rocky areas avoided.

Sources of error in determining the altitude of shoreline landforms by these methods are many and are listed below:

(1) Error in determining the base level is estimated to be of the order of ± 0.3 m.

(2) Error in determining former sea level at the morphological feature measured. This varies from one feature to another. Terraces, however, with a distinct break of slope at the back-end were measured wherever possible and this break of slope was taken to represent the former sea level. Estimated error in this case is ± 0.3 m.

(3) Error in the measuring procedure. The aneroid is read off to the nearest 0.6 m (2 feet), an error of ± 0.3 m. It is estimated that the instrument error of the aneroid is 1.5 m or less. In some cases the error was found to be greater. The error in the measuring procedure with the level is

negligible.

Altitude figures in the text include the total estimated error margin.

2.7. TERMINOLOGY. The following definitions of some important concepts are used:

End moraine. Flint´s (1971) definition is used: "a ridgelike accumulation of drift built long any part of the margin of an active glacier" (p.200). It is, therefore, a collective term and includes both terminal moraines and lateral moraines. Flint (1971, p.200) defines terminal moraine as "an end moraine built along the downstream or terminal margin of a glacier lobe occupying a valley" and lateral moraine as "an end moraine built along the lateral margin of any glacier lobe occupying a valley". Ideally, therefore, a lateral moraine grades into a terminal moraine". This use of these terms was found to be very useful and convenient.

Marine limit. Andrews´(1970) definition is used: "the maximum elevation at which the late- and post-glacial sea reached at a coastal site" (p.7).

Marine terrace. Most of the features interpreted to be marine shorelines in the area are marine terraces. These are relatively flat, elongate platforms bound by a steeper ascending slope(here termed backslope, representing the former sea-cliff) on one side and a steep descending slope on the other, which sometimes is the backslope of another lower terrace. The platform, or the former beach, is usually covered with gravels, sands and other shallow-water deposits. When the beach material is lacking and the platform is made of bedrock the feature is termed abrasion terrace. Synonyms for marine terraces include raised beaches, wave-cut benches, wave-cut terraces, raised shorelines. The marine terraces in the area are distinct features and their location and setting are such that the only processes which could account for their formation are marine. In fig. 3.31 is shown a typical marine terrace with a well developed backslope.

Ice streams. They are "narrow zones within an ice sheet along which flow is much faster than in adjacent, broader zones, in many cases because buried valleys are present at depth" (Flint 1971, p.30).

Protalus ramparts. These are ridges, typically 1 to 6 m high, below firn banks, formed by coarse fragments sliding down the firn bank and accumulating at its toe.

Tabular planar cross-bedding. Bedding inclined to the principal surface of accumulation with relatively planar surfaces bounding the unit.

3.4. PRESENTATION OF RESULTS. In presenting the results the field area is divided into several subareas, each usually comprising one valley. The morphology of each subarea is briefly described, and then observations on glacial geomorphology and shorelines are presented and interpreted. This is followed by a discussion where chronology is elucidated and then conclusions follow. A geomorphological map follows each section. Legend to the maps is in a pocket on the inside cover.

The treatise starts in the west on northern Dýrafjörður moving east and from there west along southern Dýrafjörður and east along northern Arnarfjörður.

In fig. 4.10 is a location map for Dýrafjörður and Arnarfjörður.

3.5. GERÐHAMRADALUR.

General morphology. Gerðhamradalur is relatively short and wide, about 4 km long and 2 km wide, and is cut north-east into the plateau (see fig. 3.1.). Two cirques open into it from the north-east and south-east, they are respectively Arnarneshvilft and Gerðhamrahvilft.

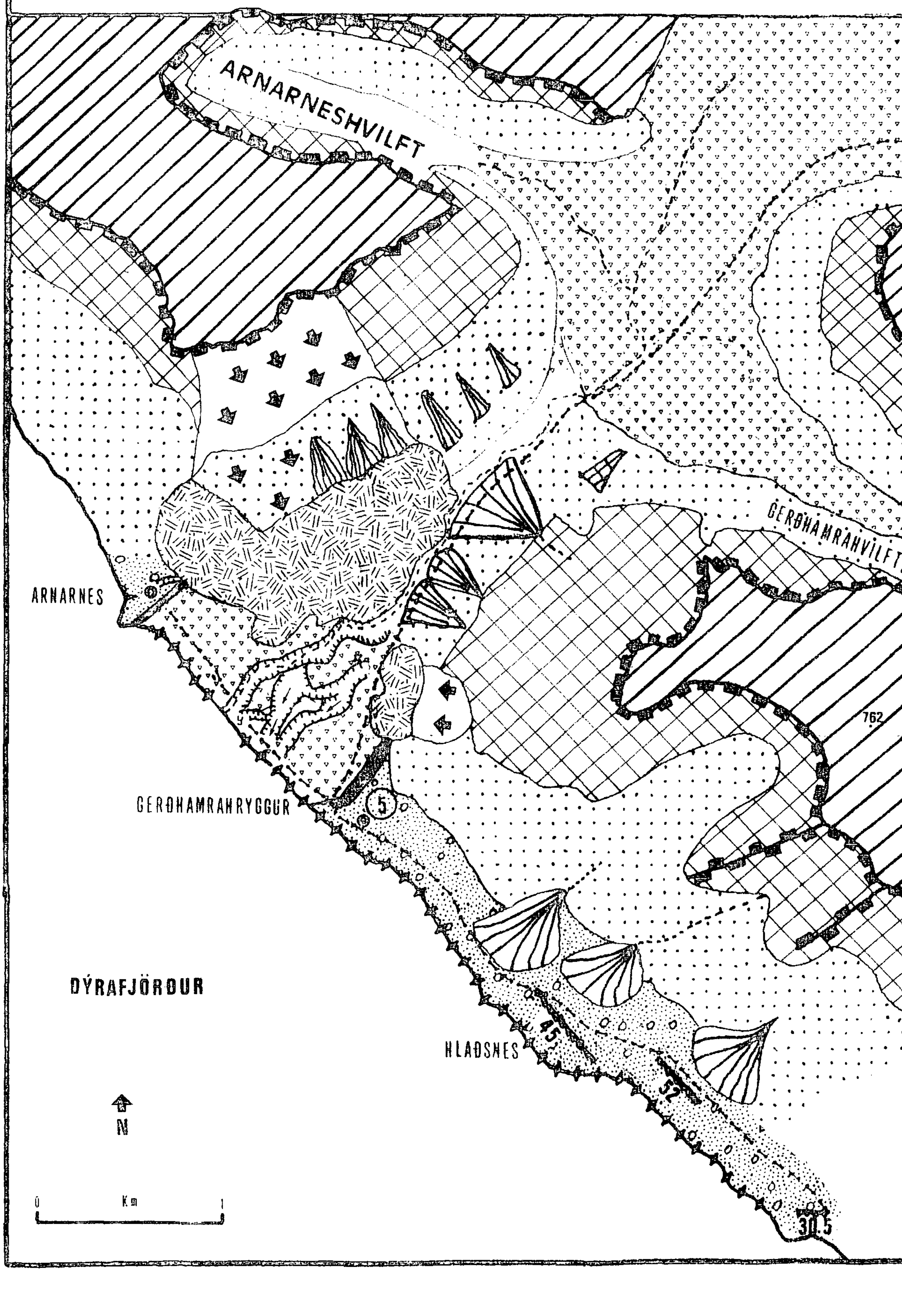
Glacial geomorphology. The glacial geomorphology of Gerðhamradalur is shown in fig 3.1. Most of the valley bottom is covered with glacial deposits, mostly till. These are, however, covered with landslide debris near the valley mouth where on both sides of the valley there are large landslides which overlie and hence post-date the glacial deposits. The landslides are particularly large on the north-western side where many have occurred and the debris has almost crossed the valley. On the south-east side there are two smaller landslides.

The glacial deposits extend right down to the shore where they end in 20-40 m high cliffs. No exposures were found in the well vegetated banks. Outside the valley mouth on the eastern side is a very prominent ridge, called Gerðhamrahryggur. (fig. 3.2.) It is almost straight and in places reaches a relative height of over 20 m. The ridge is asymmetrical in profile, the proximal side having gentler slopes. Its upper end disappears below landslide debris. A sample for particle size analysis was taken from the crest of the ridge (S-5 on map). The results are tabulated in Appendix A. (Sample 5), and discussed there with reference to other samples. It is noted here, though, that fines (defined here as sizes smaller than 4.0 phi, 0.063 mm) constitute 9,74% of the sample. A less conspicuous ridge (relative height 5-6 m)

GERÐHAMRADALUR AND HLAÐSNES AREA

FIG. 3.1.

Glacial Landforms and Shorelines



ig. 3.2. The Gerðhamrahryggur lateral moraine. Across the fjord can be seen the mouth of Keldudalur and Helgafell.

Fig. 3.3. The lateral moraine near Arnarnes fa 1 in the background.

occurs in a similar position on the north-west side of the valley. (fig. 3.3). The form and relationship of these ridges to the other landforms in the vicinity strongly suggest that they are lateral moraine ridges.

Within these lateral moraines (see fig. 3.4) the glacial deposits have an uneven surface, taking the form of innumerable irregularly spaced hummocks and short ridges interspersed with occasional hollows interpreted as kettle-holes. The overall amplitude of relief of this area is less than about 5 m except where dry channels cut through them. South-east of the river this area of hummocky ground is cut by a series of deep (up to 8 m), sinuous, dry channels. The channels range in width from 50 to 150 m. Because of their form, size and relationship to other glacial landforms these dry channels are interpreted as being abandoned melt water channels.

In close proximity to the largest channel two areas of rounded gravels were found, one just east of the river mouth (y on map) the other on the steep bank of a channel (x on map). At the first locality (Y) the pebbles occur on the surface of a small flat area near the edge of the river bank and the coastal cliffs. A branch of the largest dry channel opens into this flat area. The rounded pebbles are in obvious contrast to the angular glacial deposits surrounding the area. No rounded pebbles were found in the dry channel. The gravels at the second locality (x) were exposed in a section showing 2 m of well rounded pebbles and cobbles overlain by about 4 m of till. As the exposure was poor it was not possible to ascertain wether the rounded deposits are bedded. The height of the contact between gravels and till was 50 m ± 10 m (contour map). The rounded gravels were sampled for particle size analysis. The results are tabulated in the Appendix A (Sample 15). It is noted here that fines constitute 3.21% of the sample.

Outside the lateral moraine ridges the landforms are much smoother, to the east of Gerðhamrahryggur shoreline landforms dominate and are discussed in the next section on Hlaðsnes. To the north of the smaller ridge on the north-western side of valley a dry channel issues close to where the moraine is buried by landslide debris and this channel continues down the hayfields of Arnarnes farm gradually merging with them. It could not be ascertained if the Arnarnes hayfields are in marine deposits, no sections in the deposits or shorelines were observed.

Discussion. The lowest altitude at which glacial deposits were observed in Gerðhamradalur is about 20 m near the top of the coastal cliffs where these are lowest. The marine limit in the area, however, is much higher up, as is shown in later section, e.g. in the Núpur area. This shows that a glacial readvance has taken place in the valley. The position of the lateral moraines on either side of the valley, and the absence of a terminal moraine, also shows that the time of the readvance the glacier was well advanced into the fjord.

The gravels under the till are argued to be deposited in a high energy environment on the basis of their coarseness, the high degree of rounding and the low precentage of fines (this last point is further discussed in the Appendix A with reference to other samples from the area). Most likely this high energy environment was marine. Alternatives like fluvioglacial activity are unlikely because of the small size of the valley, resulting in short transportation distances. This

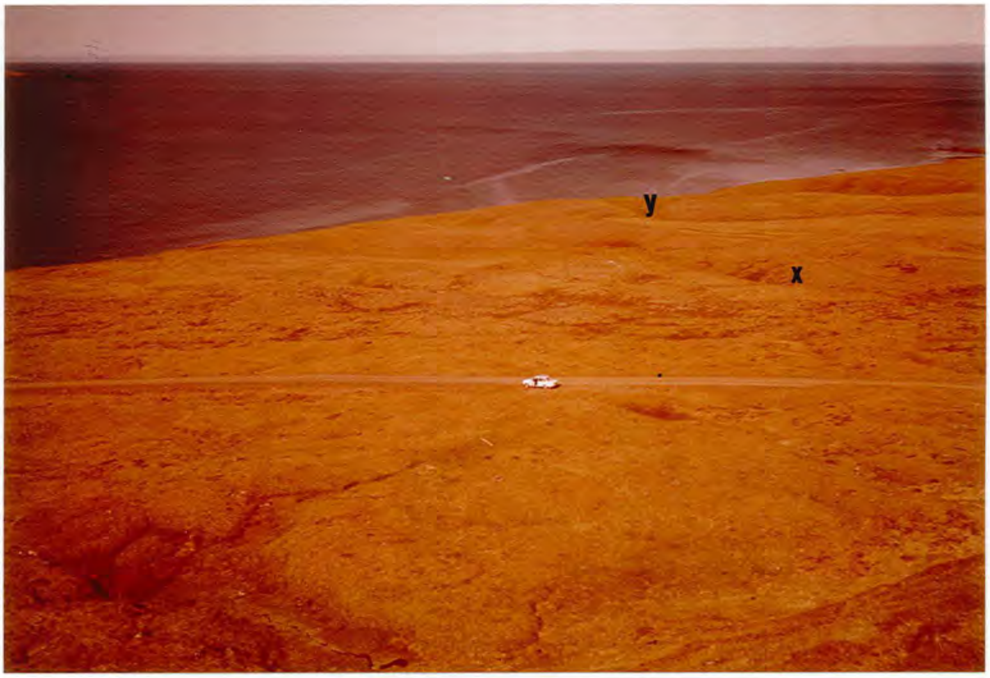


Fig. 3.4. View due west from the upper end of Gerðhamrahryggur to the glacial landforms in front of Gerðhamradalur. At x and y are shown the locations of rounded pebbles, see text. Note the dry channels.

stratigraphy, marine deposits overlain by till, also suggests that a glacial readvance took place in the valley.

It was not possible to exactly determine the height of sea level during the readvance in the valley, since no shorelines were observed associated with the glacial deposits. However, it is possible to say that the readvance must have taken place when sea level was lower than the edge of the coastal cliffs where these are lowest. This altitude, about 20 m (contour map, aneroid) is the lowest at which the glacial deposits were observed.

<u>Conclusion.</u> A glacial readvance took place in Gerðhamradalur when sea level was lower than about 20 m.

3.6. THE HLAÐSNES AREA.

General morphology. Between Gerðhamradalur and Litlidalur there extends a broad platform, mostly about 0.5 km in width (see fig. 3.1.). It is covered with well rounded deposits except in the vicinity of Gerðhamrar farm. The height of the platform varies but in most places the back of the platform is at 90 m ± 10 m (contour map).

Shoreline landforms. Some very fine terraces occur on this platform. The highest is at an altitude of 52 m ± 2.5 m (aneroid) and is located just east of Hlaðsnes (fig. 3.5.). Another terrace is directly above the jetty below Alviðra farm, at an altitude of 30.5 m ± 4 m (aneroid) (fig. 3.6.). One more terrace is at Hlaðsnes. (fig. 3.7.) Its height was not measured in the field but it is estimated to be 45 m ± 5 m (contour map).

Near the eastern end of the air-strip is a small gravel quarry exposing 1 m of bedded sands and gravels, all very well rounded. Near the western end of the air-strip, right next to the 52 m terrace, is a small gully. The exposure is not good, but shows sand and gravels grading upwards into coarse gravel and cobbles, all very well rounded. About 10 m below this section silts are exposed at an altitude of 40 m ± 5 m (aneroid). The silts are mostly unbedded, with pebbles and stones in many places. Near the top of the silt section distinct beds of alternating fine and coarse silts occur.

Fig. 3.5. The backend of the terrace at 52 m just east of Hlaðsnes.

Fig. 3.7. The terrace at 45 m in Hlaðsnes. Gerðhamrar farm, dykes and the lateral moraine Gerðhamrahryggur in the background.

Fig. 3.6. The terrace at 30.5 m near Alviðra farm.

These silts are overlain by bedded fine sands and very well rounded gravels. Near the western edge of the Hlaðsnes terrace is a 5 m section showing bedded coarse sands and gravels.

All unvegetated patches on the platform show very well rounded pebbles. This was especially noticable along the road which displayed small sections along its entire length.

Above Gerðhamrar farm the bedrock is mostly bare. There spectacular dykes protrude vertically into the air. (figs. 3.8. and 3.9.). The upper limit of the exposed dykes is at an altitude of 90 m ± 10 m (contour map).

Discussion. The platform has been strongly affected by wave action. The deposits are everywhere very well rounded and there are three distinct shorelines. The upper limit of wave action was not located in the field. Its minimum height is 90 m ± 10 m (contour map) which is the altitude of the back-end of the platform and the upper limit of exposed dykes.

A marine origin of this platform is concluded because the coarseness of the deposits and their high degree of rounding indicate a high energy environment. Further evidence for a high energy environment are the exposed dykes above Gerðahamrar farm. Exposing the dykes must have required strong wave action. An alternative source of wave action is a lacustrine environment, involving an ice-dammed lake. Such a lake, however, would have been a low energy environment, its dimensions must have been small. Furthermore, it is not at all clear how ice could have dammed up a lake at this locality.

Conclusion. Along the coast between Gerðhamradalur and Litlidalur is a wave-cut platform covered in most places with marine deposits. Three distinct shorelines occur on this platform, at 30.5 m $\pm$ 4 m, 45 m $\pm$ 5 m and 52 m $\pm$ 2.5 m. A minimum height of the marine limit is 90 m $\pm$ 10 m.

3.7. THE NÚPUR AREA.

General morphology. The area discussed in this section is shown in fig. 3.10., fig 3.11., fig 3.22., and fig 3.23. and fig. 3.24. It includes the valley Núpsdalur with its cirques, the cirque Litlidalur just west of Núpsdalur, the cirques Garðshvilftir and Vatnadalur just east of Núpsdalur and the low mountain Mýrarfell SE of Núpsdalur.

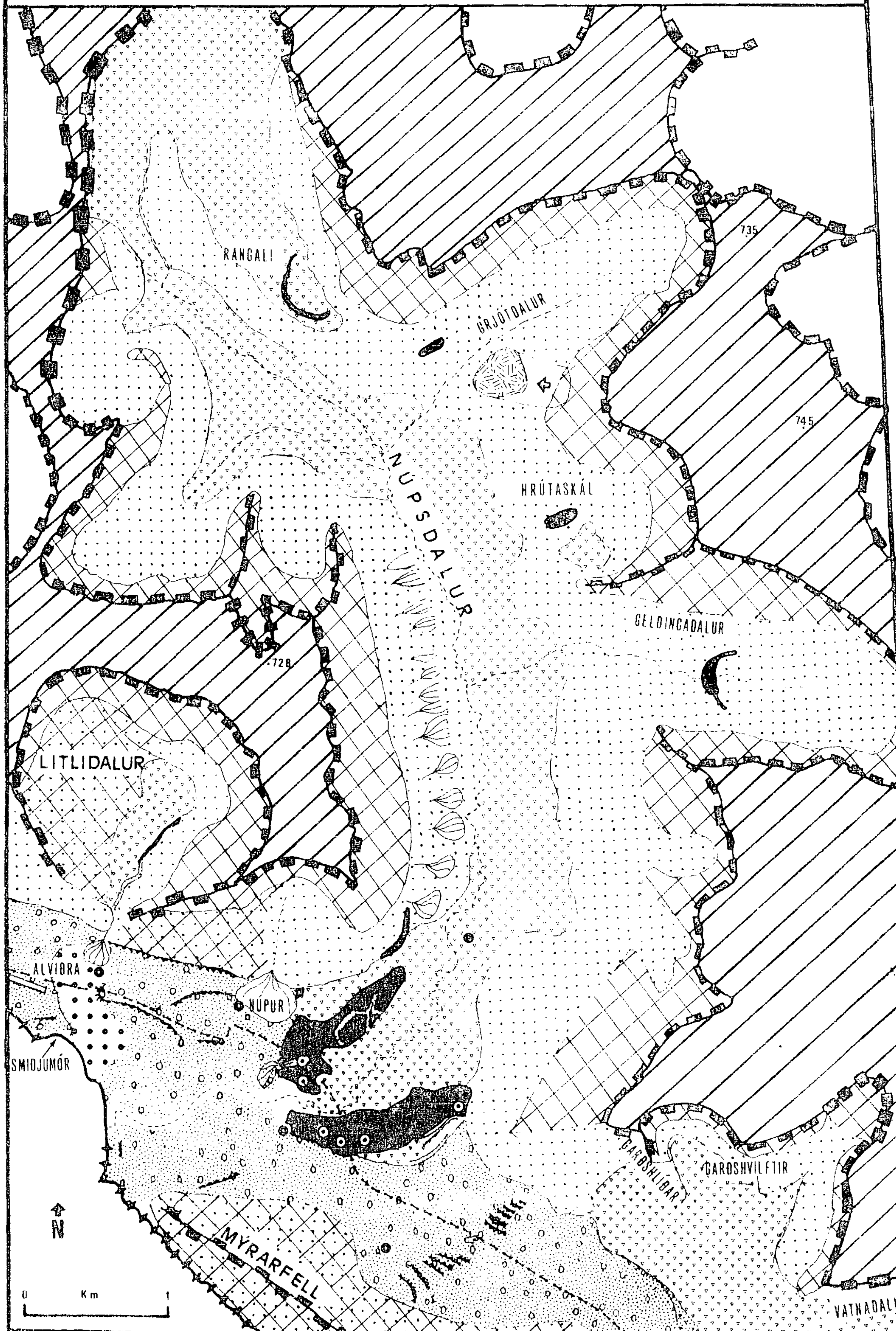
Litlidalur is a south-west facing cirque located about 2 km west of Núpsdalur. It is rather large, about 1.5 km long and 1.5 km wide.

Núpsdalur is one of the largest valleys on the northern side of Dýrafjörður, about 7 km long and mostly about 1.5 km - 2 km wide. It curves around from SSW direction at its mouth to a NW direction at its head. It is surrounded by plateau remnants mostly about 700 m high. Nine cirques open into the valley. At the

THE NÚPUR AREA

FIG. 3.10.

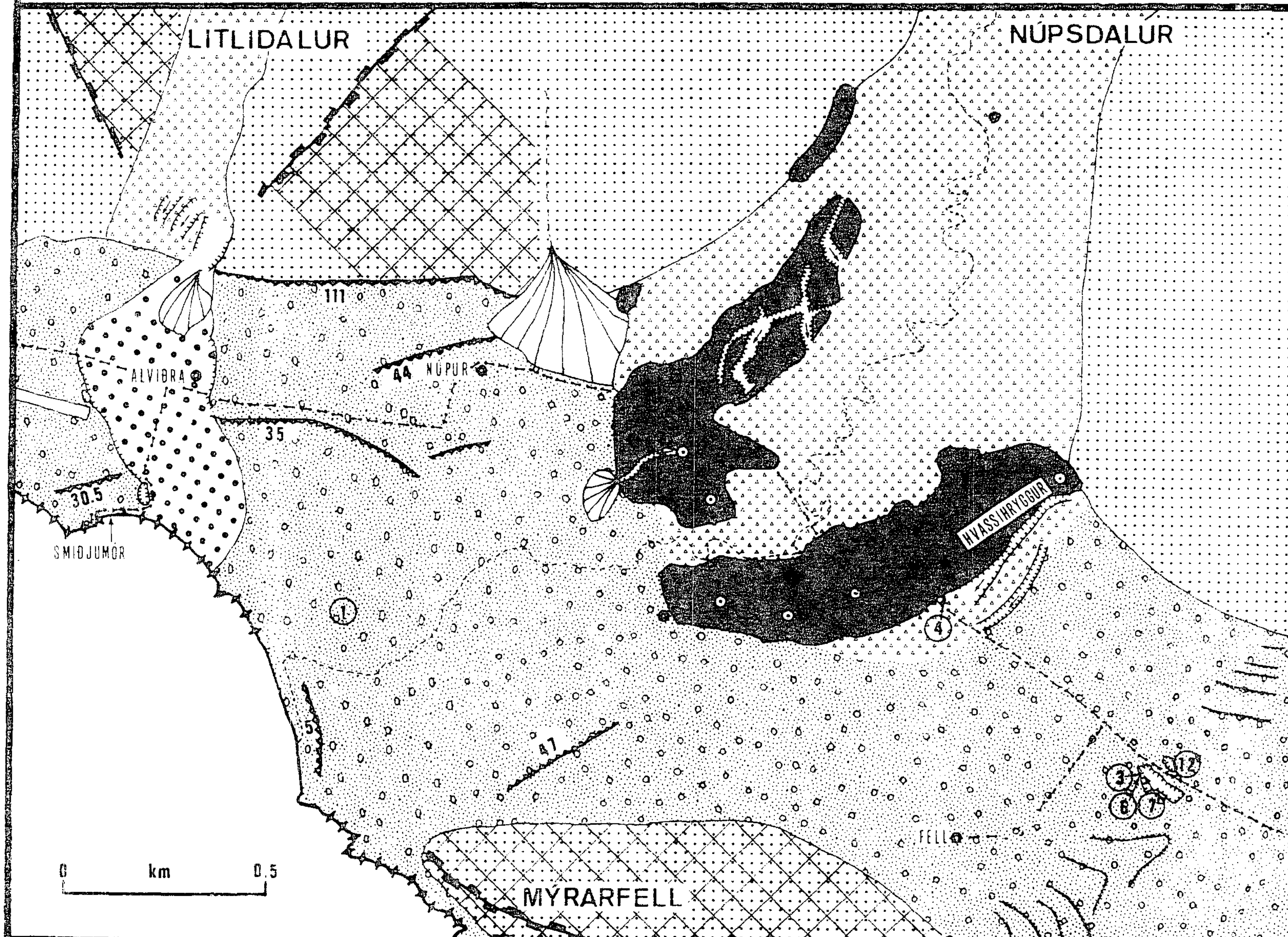
Glacial Geomorphology and Shorelines



NÚPSDALUR — LITLIDALUR

FIG. 3.11.

Glacial geomorphology and shorelines



mouth of Núpsdalur, and on either side of the valley, is one of the largest lowland areas in Dýrafjörður, about 4 km^2 in area.

Just east of Núpsdalur are the two Garðshvilftir cirques, there called Garðshvilftir east and west respectively.
East of Garðshvilftir is a short and shallow valley, Vatnadalur (fig. 3.24.).
South of Garðshvilftir is the low, ridgelike mountain Mýrarfell, 312 m where highest.

Glacial geomorphology. The Núpur area is characterized by extensive lowlands. Such widespread lowlands are rare in Vestfirðir. In mountainous terrain shoreline landforms have little chance of surviving, the slopes being too steep. These lowlands, therefore, offer good prospects for preservation of shoreline landforms. This is seen to be the case. Glacial landforms are also abundant so this area offers good prospects for establishing a relative chronology based on shoreline dispacements.

In presenting the data, the description and interpretation of the landforms and their often complicated associations, the Núpur area is divided into three subareas, the Litlidalur - Alviðra area, the Núpsdalur area and the Garðshlíðar - Mýrarfell area.

The Litlidalur - Alviðra area. The floor of Litlidalur is covered with thick drift, with an uneven surface with a relative relief up to 5 m. This is interpreted to be ground moraine. Along the eastern side of the cirque there runs a narrow terrace, with an uneven surface, just above the valley floor. This feature is interpreted as having formed along the margin of a glacier, being either a lateral moraine or a kame terrace. Near the head of the cirque the terrace is overridden by a complex of ridges. Inside this complex the cirque floor is smooth and flat. The complex of ridges is interpreted as being formed at an ice margin.

At its mouth Litlidalur gets rather narrow and there are three dry channels (figs. 3.11. and 3.12.). Two of these channels are very short, while the one to the east is quite long and starts where the lateral moraine terminates. At present there is no surface drainage from Litlidalur. There is, however, an alluvial fan immediately in front of it extending down to Alviðra farm. West of the mouth of Litlidalur are the shoreline landforms and marine deposits which were dealt with in the previous section on the Hlaðsnes area. East of the mouth of Litlidalur the mountain slope is almost completely covered by a thin veneer of scree debris. (fig.3.13.) Only small patches of bedrock outcrop. Near the lower end of this slope is a terrace cut in the bedrock. It stretches all the way between Litlidalur and the gully just east of Núpur farm. This terrace is about 5 m in width and slopes towards the fjord. The altitude of the backend of the terrace is 148.4 $\pm$ 1 m (level). Three possibilities for the mode of origin of this terrace are:

(1) It marks the site of an easily eroded basalt - layer, which has suffered more weathering than other layers in the lava sequence. In this case a hypothesis accounting for the removal of the weathering products is required because this terrace slopes much more gently than the scree slope above and below and at present traps the debris descending on to it from above. This mode of origin seems to the author to be unlikely.

Fig. 3.12. View from the terrace at 30.5 m towards Litlidalur and Alviðra. Arrows point to two short dry channels at the mouth of Litlidalur and to the terrace at 111 m.

Fig. 3.13. View from the terrace at 44 m to the convex slopes above. Entrance to Litlidalur in the background. Arrow points to terrace at 111 m.

(2) The feature is the result of erosion by glacier melt water streams running at the margin of the fjord glacier. If this was the case the feature should have a longitudinal slope. No such slope could be detected by eye, but levelling across the terrace was not attempted. This mode of origin is also considered unlikely.

(3) The feature is a wave-cut abrasion terrace. In this case it would mark a shoreline, either of an ice-dammed lake, or of marine origin. The possibility that the terrace is an ice-dammed lake shoreline is remote because it is not at all clear how ice could have dammed up a lake at this locality. The main objection to the possibility that the terrace is a marine shoreline is the fact that its height would make it the highest marine limit in the whole of Iceland. Because of this it is concluded, until further evidence is forthcoming, that the origin of this terrace remains unknown.

Below the terrace at 148.4 m the mountain slope is convex until it ends on an almost horizontal terrace which is 2-3 m in width. This terrace, although in many places covered with mass movement debris and solifluction lobes, is built up of loose deposits as is shown by shallow cuttings in the terrace made by small seasonal streams. The convex, lower end of the scree slope shows that it has been undercut, since scree slopes are normally straight and usually concave near the base (e.g. Kirkby and Statham 1975). It is concluded, therefore, that the terrace is wave-cut. Its altitude is 111.0 m $\pm$ 1 m (level).

Below this terrace is a well vegetated, concave slope. In many places, however, there are unvegetated patches where the deposits could be observed, these were everywhere found to be well rounded sands and gravels. Further evidence for wave action on this concave slope comes from above Alviðra farm where there are many large boulders, 0.5 - 1 m in diameter, all very well rounded, in obvious contrast to the angular boulders which are found on the 111 m terrace and have rolled down the mountain side above. The altitude of the highest boulders is 75 m ± 1 m (level). Just below these boulders is a break of slope, the slopes are more or less convex below it. All these observations of alternating convex and concave slopes, rounded boulders and pebbles and the terrace at 111 m strongly indicate a marine environment, the only likely high energy environment at the locality.

The convex slopes below the 111 m terrace, which in the Alviðra area are at altitudes below 70 m (level), terminate in steep slopes which form backends of two terraces. One is near Alviðra where the convex slopes terminate in a high and steep bank (fig. 3.14) which forms the backend of a rather extensive terrace, interpreted as a distinct shoreline; the altitude of this shoreline is 35 m ± 3 m (aneroid). The other terrace is just near Núpur where the convex slopes terminate in a rather steep bank (fig. 3.13) at the foot of which is the backend of the terrace on which Núpur farm stands. Its altitude is 44 m ± 3 m (aneroid).

Below these terraces there are gentle slopes and smooth landforms. A sample of the deposits there (see fig. 3. 11 for location) was analysed for particle size. The results of the analysis are discussed in Appendix A but it can be mentioned here that fines constituted 6.42% of the sample (sample 1).

Fig. 3.14. The backend of the terrace at 35 m below Alviðra. Height of person is about 130 cm.

Fig. 3.15. The Smiðjumór site. Arrow 1 points to where the unbedded silts, Layer E, is exposed and arrow 2 to where Layer A is exposed around the corner.

Below the alluvial fan in front of Litlidalur, and west of the shoreline landforms discussed above, is a wide dry channel which is cut right through the deposits on either side, most notably the platform west of this channel. The material making up the floor of the channel is exposed in many places in drainage ditches and was found to be coarse, consisting mainly of pebbles and cobbles. The grain shape was found to be distinctly angular. Both the size and shape of these grains is different from the rounded sands and gravels of the marine deposits on either side of this channel. The lower end of the channel ends at an altitude of 15 m $\pm$ 1 m (level). It was not possible to observe the deposits underlying the angular channel deposits.

Just west of the lower end of this channel is the terrace at 30.5 m discussed in the section on the Hlaðsnes area. At its lower end, where this terrace ends in a steep coastal cliff (fig. 3.15), is a very good exposure over 10 m in height (fig. 3.16 and fig. 3. 15). The locality is called Smiðjumór and its location is shown in fig. 3.11).

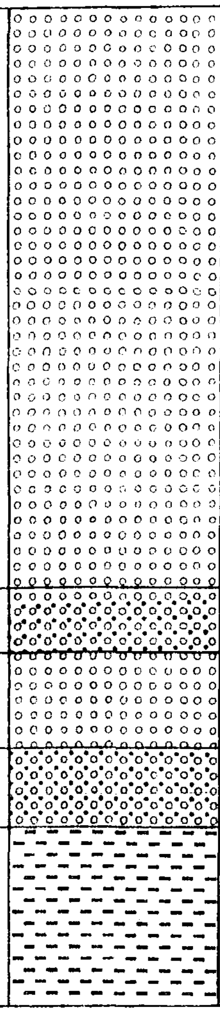
Layer A is exposed in a small quarry which is situated about 30 m to the east of the rest of the section and its location is shown in fig 3.15.

The Smiðjumór section can be divided into two parts on the basis of the dip of the layers. Layer D dips at an angle of less than 5° away from the sea while in the overlying layers the dip is towards the sea.

The dip of layer D is in the opposite direction to the ones above, indicating that it is significantly older than the upper layers, being separated from them by an unconformity.

Fig. 3.16.

The Smiðjumór section



A	10 m	Well bedded gravels (tabular planar cross bedding). The beds are inclined at an angle of about 20° towards the sea. Occasional sand beds 5-10 cm in thickness. For the most part, however, alternating beds of coarse and fine gravels.
B	0.4 m	Fine sand with gravel and stones
C	0.2 m	Gravel
D	2 m	Bedded sand and pebbles. Many 0.5 cm silt beds. Little rounding.
E	5 m	Top of bed at 14.4 m (level). Unbedded silts. Sand grains 1-3 cm scattered throughout the bed. Also pebbles 1-5 cm and an occasional cobble

In Layer E there were observed two pseudomorphs of unidentified molluscs. This, and the fact that the silts are unbedded, shows that Layer E displays marine facies of intermediate depth. The occasional pebbles and stones in the silt matrix can be interpreted as drop stones from calving ice of a nearby glacier.

Layer D is coarser than E and is bedded which, together with the fact that the grains are rather angular, is taken to indicate that it was deposited at shallower depths than Layer E, when the fjord had become ice free at the locality, and that a stream was involved.

The upper part of the section, Layers C, B and A, are separated from the lower part by an unconformity which indicates a time lag. Shallower depths are also indicated because the upper part is coarser. Layers C and B could be different facies of the same unit, oscillations of the stream which was involved with the deposition. Alternatively, since Layer C is coarser than B it was possibly deposited at depths shallower than Layer B. This would imply oscillating sea level.

Layer A is interpreted as being a delta deposit. This is supported by the coarseness of the layer, its well rounded pebbles and the relatively steep angle of its sedimentation units (c. 30°).

The possibility that Layer A was formed by reworking of older deposits during lowering of sea level is untenable since the marine deposits higher up are more finely grained than Layer A, which shows they must have originated further away.

The top of Layer A is formed by a terrace which is interpreted as being a marine shoreline and was discussed in the previous section on the Hlaðsnes area. The height of this terrace is 30.5 m $\pm$ 4 m (aneroid). Although the uppermost part of the section was so poor that it was not possible to see if the sedimentation units are crossbedded or horizontal, topset beds or foreset beds, it is argued that sea level must have been at the 30.5 m terrace at the time of formation of the delta.

At the time of formation of Layer A and, very likely, Layers B and C, an active stream existed here although at present there are no streams. The source of this stream must have been Litlidalur, and it must have been the same stream which eroded the large channel below Alviðra. To account for the presence of an active stream issuing from Litlidalur at this time it is necessary to hypothesize that it contained a glacier at this time. This glacier must have been active from the time when sea level was at the terrace at 30.5 m until sea level fell to 15 m, which is the height of the lower end of the channel. Apparently, the glacier was there continuously throughout this period, at least there is no evidence to suggest otherwise.

<u>The Núpsdalur area.</u> The northern part of Rangali (fig.3.10.) has an uneven surface, small hummocks with intervening depressions. This is interpreted as being the surface of glacial deposits. In the southern part of Rangali, however, there is a curved ridge. The ridge is narrow, about 3 - 5 m high and is seen on the northern side to override a hummock which is about 30 m high. The ridge encircles an area with a pitted surface, characterized by innumerable small hummocks with some of the intervening depressions being distinct kettle-holes. This area inside the ridge is interpreted as being dead-ice

topography while the ridge encircling it is interpreted as being a terminal moraine. The hummock, which the ridge overrides, appears to be made wholly of glacial deposits. It has almost totally escaped modification by the glacier which deposited the moraine.

On the north side of Grjótdalur there is a short ridge some way up the slope and ending abruptly at the cirque mouth. This is also interpreted as being a lateral moraine. On the south side of the cirque there is landslide debris.

In Hrútaskál there is a short terrace feature on the north side (fig. 3.17.), ending abruptly at the slopes in front of the cirque. This terrace is interpreted as being a lateral moraine. It is located on scree slopes and no other mode of origin is evident. On the south side are hummocks with kettle-holes in between, typical dead-ice topography.

In Geldingadalur there is a ridge about 3 - 4 m high on the valley floor but narrow ridges ascend the slopes on either side. This ridge, which is made of till, is interpreted as being a terminal moraine ascending the valley sides.

The western side of Núpsdalur, which forms the concave side of the curve of the valley, is almost totally devoid of glacial deposits. The valley slopes are here covered with scree and numerous *debris cones.* The eastern side, in contrast, is covered by till, especially upvalley from Geldingadalur. This till is in many places 5 - 10 m thick. The valley floor above Grjótdalur is covered with till in places exceeding 10 m in thickness, indicated in stream cut channels.

At the mouth of Núpsdalur there is a large assemblage of ridges and hummocks. The main body of it lies east of the river. It ranges in width from 100 to 300 m and rises 5 - 10 m above the ground. The surface of this assemblage is characterized by innumerable small hummocks with intervening depressions, some of which are circular. Along the NE margin of this assemblage is a ridge, called Hvassihryggur (for location see fig. 3.11.) (fig. 3.17). Outside Hvassihryggur are two dry channels (fig. 3.18.). One is immediately outside it and the other is some 100 m further east. Between the channels are deposits with an uneven surface in contrast to the very smooth landforms further east (fig. 3.18.).

A sample of the deposits just south-east of Hvassihryggur was taken for particle-size analysis (see fig. 3.11. for location). The results are discussed in Appendix A, but it is mentioned here that fines constitute 6.72% of the sample (No 4).

The river Núpsá runs through a gap in the assemblage. This gap is just over 100 m wide but Núpsá is much narrower. This, and the fact that Núpsá meanders through the gap, shows that the stream is misfit. It is suggested, therefore, that the gap in the assemblage was eroded by glacial melt water streams.

West of Núpsá the hummocks and depressions are much less conspicuous. They resemble their counterparts east of the stream only just west of the stream where circular depressions abound on the hummocky surface. One of the circular depressions contains a lake about 50-60 m across. Out of this runs a dry channel terminating in a small alluvial fan just outside the assemblage.

North of the road, west of Núpsá, the surface of

Fig. 3.17. View from Mýrarfell to Núpsdalur. Note the assemblage of hummocks and depressions. The arrows point, from left to right, to terrace feature, lateral moraine in Hrútaskál, Hvassihryggur and the two channels east of it.

Fig. 3.18. Hvassihryggur and the two dry channels east of it. Arrows point to Hvassihryggur and the dry channel immediately east of it. Note the uneven surface of the deposits between the channels.

the deposits becomes much smoother, the relief between the hummocks and the intervening depressions is much smaller. Dry channels, on the other hand, are common. On the mountain side north of this area is an irregular terrace about 100 m (aneroid) higher than the valley there (fig. 3.17). It is interpreted to be a lateral moraine.

This assemblage of hummocks, ridges, intervening depressions and dry channels is interpreted to be a terminal moraine. The circular depressions are distinct kettle-holes, strongly indicating glacial origin of the assemblage. The dry channels must be glacial melt water channels, they are situated in such a way that no other mode of origin is likely. This terminal moraine is much more conspicuous east of the stream which is compatible with the fact that on the eastern side of Núpsdalur there is plastered relatively thick till while the western side of the valley, below Grjótdalur, is totally devoid of till. The channel further east of Hvassihryggur, separated from it by what is interpreted to be ground moraine, indicates a position of the glacial margin during a glacial phase slightly more advanced than the one when the glacier built the main body of the terminal moraine. This earlier glacial phase did not build moraines in front of the ice margin. The terrace feature above the north-western part of the moraine is interpreted to be a lateral moraine.

The lowest part of this terminal moraine is at an altitude of 40 m $\pm$ 5 m (contour map, aneroid).

The Garðshlíðar - Mýrarfell area.

In both of the Garðshvilftir there is thick till but no end-moraines were observed.

In front of the two lakes in Vatnadalur there is a prominent ridge, about 5 m high. This is interpreted to be a terminal moraine.

Shoreline landforms and other evidences for water levels are abundant in the area between Garðshlíðar and Mýrarfell. The highest part of the road which runs through this pass is at an altitude of 90 m $\pm$ 5 m (contour map). Here are two sand and gravel quarries, one on each side of the road. The quarries expose thin deposits, 1 - 1.5 m thick overlying bedrock. The deposits are clearly bedded, and the stratigraphy is shown in fig. 3.19.

10 cm	Plain gravel, very few finer particles
30 cm	Sand and gravel, faint bedding
20 cm	Coarse sand, few pebbles
40 cm	Sand and gravel with a few pebbles

Fig. 3.19.

Three samples for particle size analysis were taken from southern quarry, nos. 3, 7 and 12 (see Appendix A). Fines constitute 5.25%, 1.10% and 1.52% of the samples respectively.

Kjartansson classified these deposits on this geological map as "ground moraine" or "glacial drift". This identification is challenged for many reasons:

(1) The deposits are bedded.

(2) The deposits are well sorted.

(3) The pebbles in the gravel are well rounded.

These features of the deposits render untenable the theory that this is ground moraine as defined in contemporary literature (e.g. Flint 1971, Embleton & King 1975). However, the possibility that the deposits are stratified glacial drift cannot be ruled out on these grounds alone, other factors must be considered. The surface of the deposits is smooth, uncharacteristic of glacial deposits. Furthermore, the landforms show many signs of having been formed by wave action: The only irregularities in the smooth surface of the deposits are small terraces and broad, low ridges (fig. 3.20. and 3.21.). These ridges, one on each side of the quarries, extend towards them from Mýrarfell and Garðshlíðar. Each is cut by small terraces. These ridges are interpreted as being either spits or remnants of a tombolo connecting Mýrarfell to the mainland when sea level was close to 90 m above present. Above these ridges on either side are small terraces. These extend up to an altitude of 110 m ± 10 m (contour map). The washing limit could be still higher up since above this altitude there are mostly steep bedrock slopes which do not preserve evidence for wave action. Apart from the end moraine complex and associated melt water channels at Núpsdalur, no other glacial landforms were observed below the 120 m contour. See also Appendix A.

Just west of Hrólfsnaust, on the eastern side of Mýrarfell (fig. 3.22.), are two distinct terraces. The backend of the upper terrace is the steep mountain slope and is at an

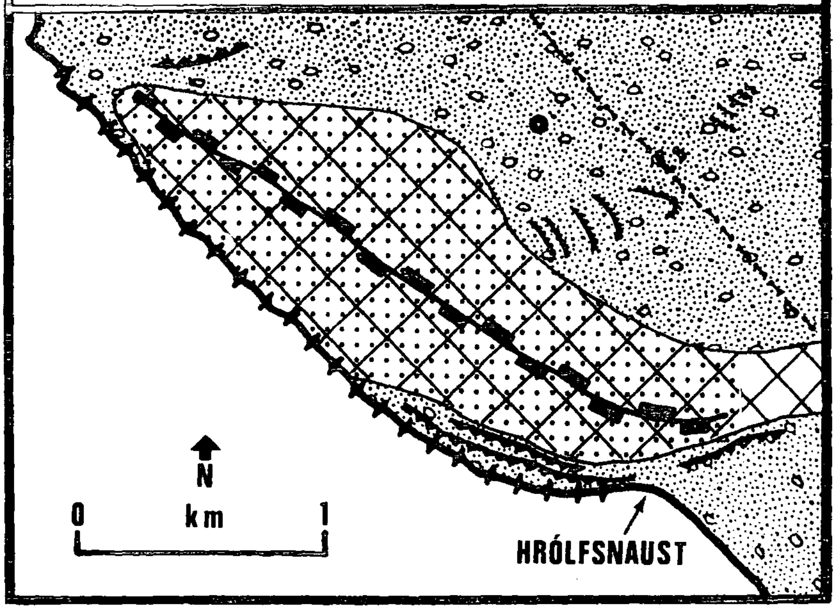
Fig. 3.20. View from Mýrarfell to Fell farm and Garðshlíðar
Arrow points to quarries and the low, broad ridge north of the road.

Fig. 3.21. Garðshlíðar. Arrows points to the broad, low ridge north of the road.

MÝRARFELL

Shorelines

FIG. 3.22



KLUKKULANDSFJALL

Topography

FIG. 3.23

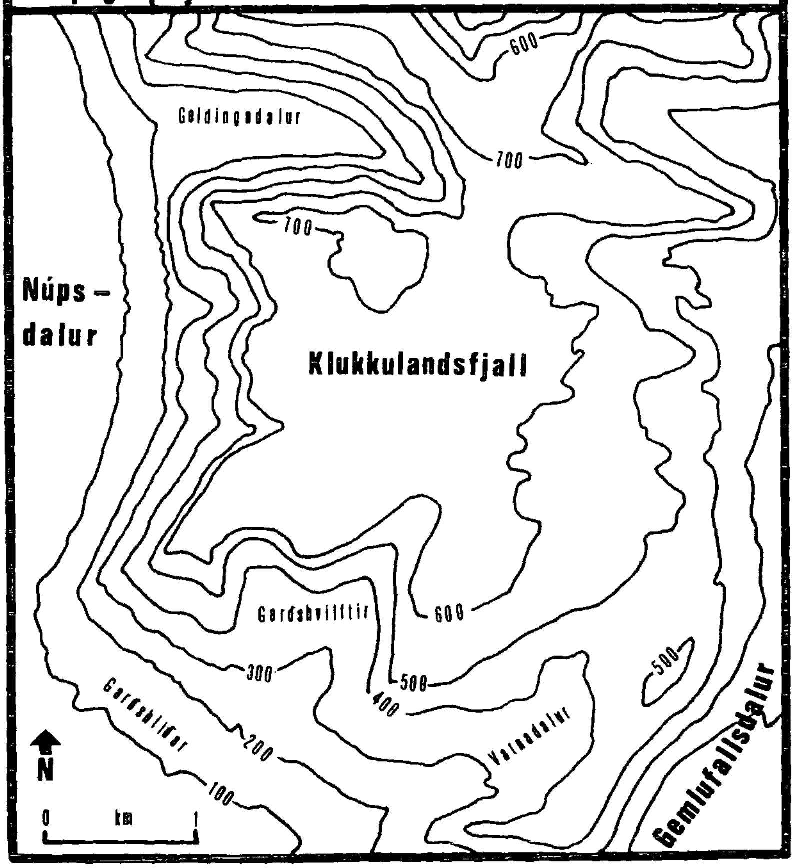


Fig. 3.8. The dykes near Gerðhamrar farm.

Fig. 3.9. Gerðhamrar farm and the dykes. Behind runs the lateral moraine Gerðhamrahryggur.

altitude of 70 m $\pm$ 10 m (contour map). The lower terrace is at 50 m $\pm$ 10 m (contour map). A terrace of similar height is found to the east of Hrólfsnaust.

Near the western end of Mýrarfell is a terrace at an altitude of 47 m $\pm$ 5 m (aneroid). The terrace is almost totally unvegetated, exposing very well rounded sands and gravels. This is probably the counterpart of the terrace on which Núpur farm stands, the altitudes are similar.

Just east of the mouth of Núpsá is another very distinct terrace at 5 m $\pm$ 2 m (estimated).

Discussion. In this discussion it is assumed that the 111 m $\pm$ 1 m terrace is the highest marine limit in the area. This is reasonable since in the Garðshlíðar - Mýrarfell area the marine limit is at a very similar altitude, 110 m $\pm$ 10 m.

In Núpsdalur a glacial readvance took place some time after the highest marine limit was formed. Since the Núpsdalur terminal moraine has not been affected by marine action, and the lowest part of the moraine is close to 40 m, it is concluded that the readvance took place when sea level was lower than 40 m. Nothing is known about the position of the glacier before the readvance and, therefore, it is not possible to say how far the glacier advanced before it halted at the mouth. It is pointed out here, however, that the valley floor is low, the 100 m contour extending to two thirds of the way up the valley. This fact is significant in as much as that when the sea stood at the marine limit it must have invaded the valley and greatly accelerated ablation by calving of the glacier which possibly occupied the valley at the time. It is, therefore, quite possible that the valley had become totally ice free before the readvance.

In Litlidalur a glacier readvance took place when sea level was between 30 and 15 m. This is based on the hypothesis that the stream which deposited Layer A in the Smiðjumór section came from Litlidalur. This hypothesis is reasonable in light of the fact that there is abundant field evidence for an active stream issuing from this cirque at the time when sea level stood close to 15 m above present s.l. and the fact that there is no surface drainage of Litlidalur at present. Maximum height of sea level during this period is the 30.5 m shoreline.

It is not possible to date the glacial landforms in Garðshvilftir and Vatnadalur in relation to height of sea level. No conclusive evidence for melt water streams was found in front of these cirques. In front of Vatnadalur there is a channel occupied by the stream which at present drains the valley, but this stream does not appear to be misfit and no signs of glacial drainage were observed.

Although Garðshvilftir are considerably smaller than Litlidalur, where there are such ample signs of glacial stream activity, one would expect to find some evidence for glacial stream activity in them. This is, however, not the case. This lack of evidence may indicate that these cirques were not glacierized after the formation of the marine limit in Garðshlíðar. Such negative evidence must be viewed in light of the existence of circumstancial evidence for the possibility that Garðshvilftir were occupied by quite small glaciers:

(1) The floor of Garðshvilftir west is mostly at an altitude of 350 - 400 m, the floor of Garðshvilftir east is mostly at 250 - 300 m while the floor of Litlidalur is

mostly at 300 - 400 m, i.e. the altitudes of the floors of these three cirques are comparable.

(2) Garðshvilftir are backed by a much more extensive plateau area, especially north-east of the cirques. This is significant if snow-drifting was an important source of accumulation, and north-easterly winds were prevailing, as they are at present, during the time of the glacial readvance stage in Litlidalur.

(3) During the glacial readvance in Núpsdalur the glaciation level must have been lower than the 620 - 700 m Klukkulandsfjall plateau behind Garðshvilftir. Otherwise the build up of a valley glacier cannot be explained in this valley where all the nine cirques opening into it have floors lower than about 400 m and where the 100 m contour crosses the valley two-thirds of the way up it. Consequently, Klukkulandsfjall plateau must have carried a small ice cap. The plateau slopes to the south-east (fig. 3.23.) and most likely ice movement was concentrated in that direction, very likely sending outlet glaciers into Garðshvilftir east and Vatnadalur. Evidence for this is the elongated shape of Garðshvilftir east and the rounded head-walls of this cirque and Vatnadalur, showing that they have been invaded by external ice, from the plateau. The moraine in front of the lakes in Vatnadalur, which is at an altitude of 360 m $\pm$ 20 m (contour map) would have been deposited then.

The conclusion is that there is strong, though circumstancial, evidence to show that Garðshvilftir east and Vatnadalur were invaded by external ice from an ice cap situated on Klukkulandsfjall at the time of the Núpsdalur glacial readvance.

The Núpsdalur cirque moraines must either date from the period of deglaciation of Núpsdalur after the readvance or from a later glacial readvance. It is very difficult to decide to which of these two periods the moraines belong. The curved moraine in Rangali, however, is a readvance moraine since it overrides older glacial landforms. The truncated lateral moraines in Grjótdalur and Hrútaskál most likely date from the Núpsdalur readvance. Had they formed at a time when there was no ice in Núpsdalur, i.e. after the Núpsdalur readvance, the glaciers depositing them would have left behind more landforms than the truncated moraines. These do not exist, however, so the truncated moraines show that there was ice in Núpsdalur, Hrútaskál and Grjót-dalur simultaneously, and that after the Núpsdalur readvance Hrútaskál did not contain significant glaciers. The moraine in Geldingadalur, on the other hand, could either date from the time of deglaciation of Núpsdalur after the readvance or from a later readvance.

Conclusion. There is certain limited evidence to suggest that the marine limit in the Núpur area may be as high as 148.4 m $\pm$ 1 m. In view of the lack of conclusive evidence for this marine limit it is suggested that the highest proven shoreline is at 111 m, and that is the minimum value for the marine limit in the area.

Distinct lower shorelines were found at 70 m $\pm$ 10 m, 50 m $\pm$ 10 m, 47 m $\pm$ 5 m, 44 m $\pm$ 3 m, 35 m $\pm$ 3 m, 30.5 m $\pm$ 4 m and 5 m $\pm$ 2 m. It is possible that these shorelines are parts of strandlines at 70 m, 44 - 47 m, 30 - 36 m and ca. 5 m. Because of the large error margin in the altitude figures, however, this is by no means certain.

A glacial readvance took place in Núpsdalur when sea level was lower than 40 m ± 5 m.

A glacial readvance took place in Litlidalur when sea level was between 30 and 15 m. The readvances in Litlidalur and Núpsdalur were probably roughly simultaneous, although this is not certain.

At the time of the Núpsdalur readvance there is circumstancial evidence for an invasion of ice from Klukkulandsfjall plateau into Garðshvilftir east and Vatnadalur.

A glacial readvance took place in Rangali after the Núpsdalur readvance. The lateral moraines in Grjótdalur and Hrútaskál date from the deglaciation after Núpsdalur readvance stage. The endmoraine in Geldingadalur could either date from the deglaciation after the Núpsdalur stage or from a later readvance.

3.8. GEMLUFALLSDALUR.

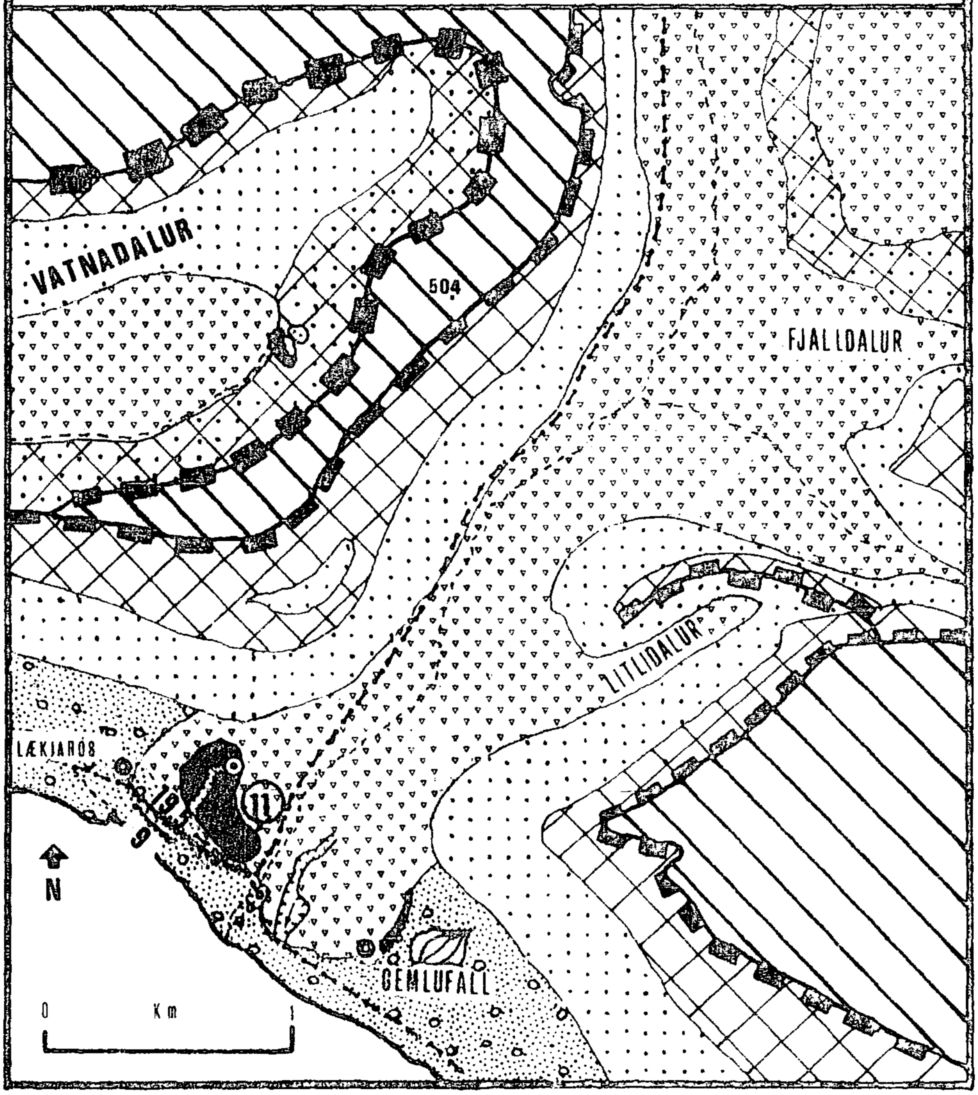
General morphology. The morphology of Gemlufallsdalur is shown in fig. 3.24. Gemlufallsdalur is the southern part of a valley which cuts right through the main mountain range between Önundarfjörður and Dýrafjörður. The northern part of the valley is called Bjarnadalur. The watershed in the valley, which is at a height of about 170 m, is located about 4 km from the mouth of Gemlufallsdalur and 6.5 km from the mouth of Bjarnadalur. Numerous cirques and valleys open into Bjarnadalur-Gemlufallsdalur.

Gemlufallsdalur is narrowest where Litlidalur opens into it (see fig. 3.24.), 1.3 km wide, while it is much wider where Fjalldalur opens into it, Fjalldalur itself being

FIG. 3.24.

GEMLUFALLSDALUR

Glacial Geomorphology and Shorelines



1.5 - 2 km wide.

The floor of Gemlufallsdalur rises rather steeply from the shore, the 100 m contour is crossed some 2 km from the shore and 1 km from the valley mouth, it then levels off, rising to 170 m at the watershed some 5 km from the shore.

Glacial geomorphology. The glacial geomorphology of Gemlufalldalur is shown in fig. 3.24.

Glacial deposits cover the valley floor everywhere and extend into the cirques. They are generally thick, exceeding 20 m in places. They are most prominent, however, just outside the valley mouth where they terminate in conspicuous ridges. Just north of farm Gemlufall there is a ridge, with a relative height of 3-5 m (fig. 3.25). West of the river the glacial deposits are bounded by a large ridge running parallel to the shore (fig. 3.26.). The ridge is 100-200 m wide and its relative height is mostly 5-10 m. On the ridge are occasional roundshaped depressions, typical kettle-holes.

Within the ridges are glacial deposits with a rough surface and generally the ground inside the ridges is higher than outside them.

Two dry channels were observed at the mouth of Gemlufallsdalur (see fig. 3.24.). One originates between two kettle-holes on the western ridge and runs right through the ridge. The other channel is located just east of the river, where it starts abruptly in the glacial deposits.

Immediately outside the western ridge is a terrace, the ridge forming its backend (fig. 3.27.). The terrace stretches all the way between Lækjarós farm and the stream, at an altitude of 19.5 m $\pm$ 3 m (aneroid). Below this terrace is another, less distinct and with more limited distribution

Fig. 3.25. The ridge by Gemlufall farm.

Fig. 3.26. The glacial deposits west of the stream at the mouth of Gemlufallsdalur. Arrow points to a ridge where the glacial deposits terminate. Sandafell in the background.

(fig. 3.28.). Its altitude is 9 m $\pm$ 2.5 m (aneroid). In unvegetated patches on both terraces rounded pebbles were observed everywhere.

The dry channel which runs through the western ridge ends on the upper terrace at a slightly lower altitude than the terrace itself, at 18.5 m $\pm$ 2.5 m (aneroid).

East of the eastern ridge is a *debris cone* below a gully in the mountain and other colluvium, while the glacial deposits inside the ridge terminate on the seaward-side at a terrace. The dry channel there also terminates on the terrace. The origin of this terrace, however, is in doubt since at present the road is located there and it was not possible to see if the terrace is the result of the roadbuilding or if it had been there before.

The landforms at the mouth of Gemlufallsdalur are interpreted thus:

The two ridges are interpreted as being end moraines, the western ridge as a terminal moraine and the eastern ridge as a lateral moraine. This interpretation is based on the position of the ridges, the fact that the glacial deposits terminate there, and the relationship of the ridges with other landforms. Both dry channels are interpreted as being melt water channels because they are in no way linked with the present day drainage of the area, while their position is such that glacial drainage very likely took place there.

The terraces in front of the western ridge are interpreted as being marine in origin. Many reasons account for this: The rounded pebbles indicate a high energy environment, the form of the terraces indicate wave action, the terraces are located near the present shore and are situated in such a way that the only likely wave environment is the sea.

Discussion. A glacial readvance has taken place in Gemlufallsdalur because the glacial landforms there, which have not been affected by marine action, are located well below the marine limit in Dýrafjörður (section 3.7.).

It is argued that sea level at the time of the readvance was close to 19.5 m $\pm$ 3 m for the following reasons:

(1) The terminal moraine west of the stream forms the backend of the upper terrace. This evidence alone is not conclusive, however, since it cannot be excluded that the terrace was formed during a transgression subsequent to glacial readvance.

(2) The fact that the melt water channel west of the stream peters out at the upper terrace shows that there was ice at the upper end of the channel at the same time as sea level stood at the upper terrace.

Furthermore, after the shoreline was displaced from the upper terrace, the channel must have dried since it only extends about 0.5 m below the surface of the terrace. This indicates that the glacier retreated from its most advanced position, leaving the channel dry, at about the same time as the shoreline was displaced from the upper terrace, otherwise the channel across the terrace would have been infilled.

Conclusion. Outside Gemlufallsdalur there is evidence for a readvance of a glacier in the valley at a time when sea level was about 19.5 m $\pm$ 3 m above present.

3.9. HJARÐARDALUR.

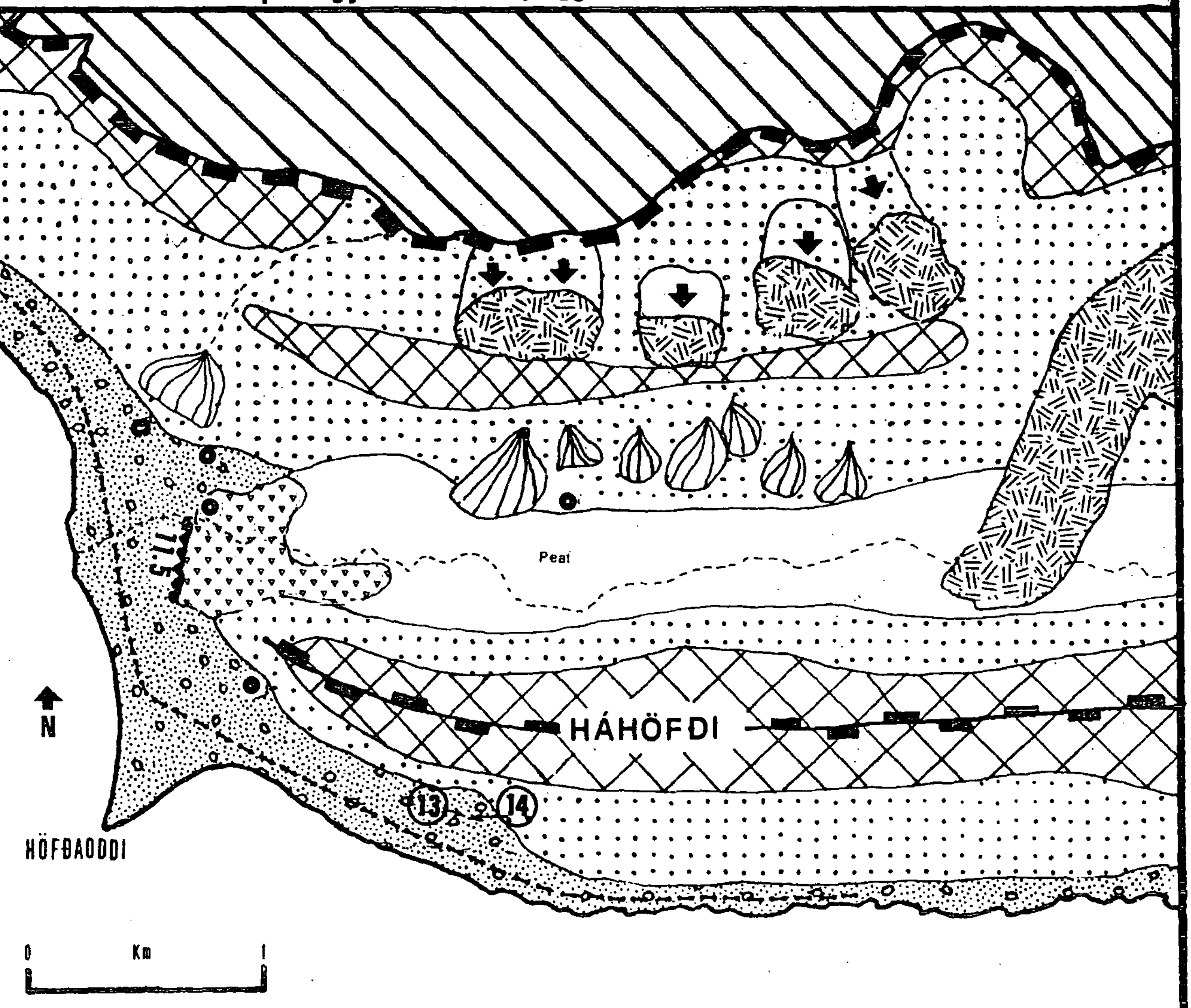
General morphology. Hjarðardalur is about 10 km long and mostly 2 km wide. It is separated from the fjord by a narrow ridge, Háhöfði, 200-300 m in height (figs. 3.29 and 3.30). From the shore Hjarðardalur runs west to east for some 5 km. It then t rns sharply to a NNE-SSW direction (fig.3.30), and rises rather steeply and gradually merges with the plateau without a well defined valley head.

The cross section of the valley is strongly asymmetrical (fig. 3.30), especially in its inner part. The north and west facing slopes are mostly steep, typically 30°, while the south and east facing slopes are relatively gentle, mostly 10-20°. Landsliding has affected most of the south facing slopes, in some cases on a large scale. On small cirque is situated some 3 km up the valley on the south facing slope.

Glacial landforms and shorelines. Till covers the ground everywhere in the upper part of the valley. The lower part, the E-W segment of the valley, is covered by thick peat under which are landslide debris and alluvium, while glacial deposits surface only near the mouth of the valley. The glacial landforms near the valley mouth do not form any special pattern and no definite ridges occur. South of the stream the glacial deposits end in a low cliff at the foot of which is a terrace (fig.3.31) at an altitude of 11.5 m ± 2.5 m (aneroid). Rounded pebbles abound on this terrace in contrast to the angular debris in the till which makes up the backend of the terrace. The terrace is interpreted an being marine in roigin for the following reasons: The rounded pebbles indicate high energy environment, the form of the terrace indicates wave action, it is located near

HJARÐARDALUR — HÁHÖFÐI **FIG. 3.29.**

Glacial Geomorphology and Shorelines



the shore and is situated in such a way that the only likely wave environment is the sea.

Discussion. A glacial readvance has taken place in Hjarðardalur. The glacial landforms have not been affected by marine action although they are well below the marine limit in Dýrafjörður.

The reason for the absence of end moraines could be that the glacier snout was in contact with the sea at the time and that some of the load was deposited at sea.

The glacial deposits at the mouth of Hjarðardalur were most likely deposited at and under the glacial snout when sea level was at 11.5 m ± 2.5 m. This is a maximum figure, however, since the possibility remains that the marine terrace was formed during a transgression post-dating the readvance.

Conclusion. A glacial readvance took place in Hjarðardalur when sea level was at about 11.5 m ± 2.5 m or lower.

3.10. HÁHÖFÐI.

General morphology. Háhöfði is narrow ridge, 200-300 m in height, which forms the interfluve between Hjarðardalur and Dýrafjörður (figs 3.29. and 3.30.). It is the extension of Tindafjall, the flattopped interfluve between Hjarðardalur and Lambadalur (fig. 3.35)..). The southern side of Háhöfði is flanked by a veneer of scree which terminates in the lower reaches where shoreline landforms are found.

Shoreline landforms. Quite conspicuous deposits cover parts of the southern slopes of Háhöfði (fig. 3.32.). They are located near the western end of the mountain, where they form a mantle of steeply (ca. 25°) inclined cross-bedded very well rounded sands and gravels. The upper limit of the sand and gravel deposits was found to be at 85.5 m ± 3 m (aneroid).

No distinct shorelines were observed. However, at an altitude of 65 m ± 3 m (aneroid) (fig. 3.33) a faint break of slope was observed above which the slopes become steeper and the sand and gravel deposits become only a few tens of cm thick. Further down the slope where the road crossed the deposits (fig. 3.33) there is possibly a terrace. The origin of this terrace is uncertain, however, since it could have been made during the roadbuilding.

Thus, assuming that the sand and gravel deposits are marine in origin, the marine limit lies at or above 85.5 m ± 3 m.

Immediately above the deposits are steep bedrock slopes with a thin veneer of scree. Just above the upper limit of sands and gravels bedrock is found to be rounded (fig. 3.34), which may indicate wave action. Such rounding, however, is often caused by weathering of the olivine basalts (Walker 1959). The author has observed similar rounding of basalt bedrock at the head of Hvammsdalur in Dýrafjörður at the height of 600 m, far above any wave action. At an altitude of 97 m ± 4 m on Háhöfði one small pothole was observed.

Two samples for particle size analysis were collected from Háhöfði. Sample 13, from an altitude of 65 m, contained 4.73% fines, and Sample 14, from an altitude of 55 m, contained 4.93% fines. The samples are discussed further in Appendix A.

Discussion. The tabular planar cross-bedded deposits on southern Háhöfði are interpreted to be marine in origin fact that their distribution is limited to the western end of Háhöfði.

(4) The structure and texture of the deposits indicate deposition in standing water with strong wave action. An alternative to a marine environment would be a large ice-dammed lake. It is not at all clear, however, how ice could have dammed up a lake at this locality, let alone a lake large enough to constitute a high energy environment.

The minimum marine limit on Háhöfði is 85.5 m ± 3 m, but could be as high as 97 m ± 4 m, as shown by the small pothole. Although similar potholes are frequently seen on the present day beaches in the area, this single observation cannot be taken as conclusive proof for wave action.

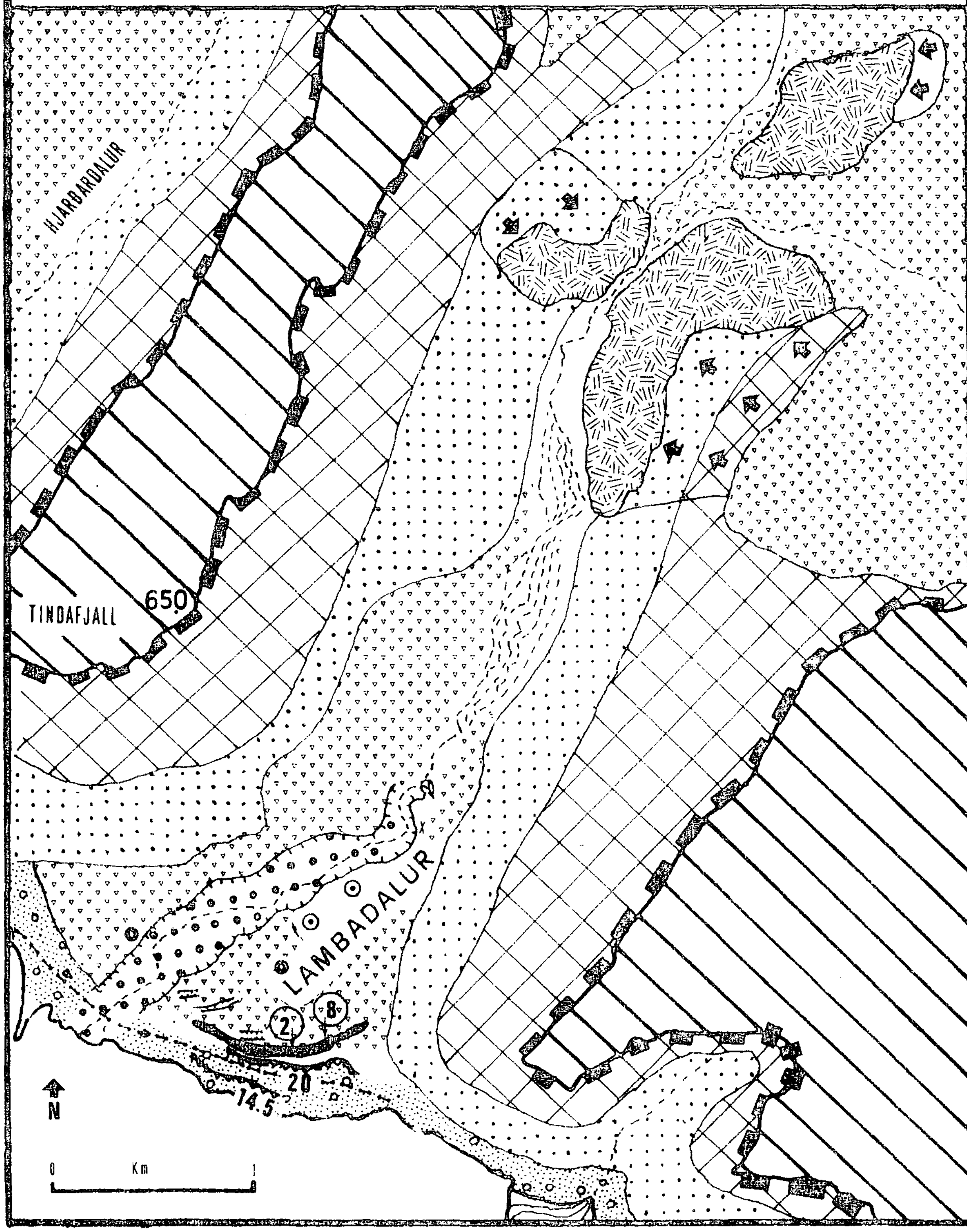
Conclusion. On the southside of Háhöfði, near the western end, are marine deposits with an upper limit at 85.5 m ± 3 m. Above this altitude there is inconclusive evidence for wave action up to an altitude of 97 m ± 4 m.
No distinct shorelines were observed but at an altitude of 65 m ± 3 m a faint break of slope was observed. The road is possibly built on a marine terrace.

3.11. LAMBADALUR.

General morphology. Lambadalur is about 2-3 km wide and about 8 km long. The 100 m contour crosses the valley about 4 km from the shore and there the valley floor starts to rise rather sharply, gradually merging with the plateau without an actual valley head. About 4-5 km from the shore there are three landslides. One of the landslides on the eastern side is very large, about 1.5 km wide (fig. 3.35.).

LAMBADALUR FIG. 3.35.

Glacial Geomorphology and Shorelines



Glacial geomorphology. In its upper reaches the floor of Lambadalur is covered by till of unknown thickness. The glacial geomorphology of the lower reaches is shown in fig. 3.35. Some 5 km from the shore most of the valley floor is covered with landslide debris. Shorewards of the landslides the present day stream is braided (fig. 3.35.) and till once more mantles the floor. At the valley mouth the glacial landforms become conspicuous, especially east of the stream. About 300 m from the shore there is a narrow ridge, about 5 m high (figs. 3.36 and 3.39.) (for location see fig. 3.35.). It ascends some way up the mountain slope to the east, but peters out when it approaches the stream. Inside the ridge is a smooth surface of till reaching Lambadalur farm. Further up the valley the surface of the till landforms is rougher, with small hummocks and depressions, some of which are circular. Just inside the moraine are five dry channels, they are short, ranging from 50-100 m in length, and narrow, up to 5 m wide. West of the stream the till surface is very smooth and some of it is covered with peat bogs.

The ridge east of the stream is interpreted to be a terminal moraine because of its association with the other glacial landforms. The dry channels are interpreted as melt water channels and the circular depressions are interpreted to be kettle-holes.

The channel of the present day stream is very large, 200-300 m wide and 5-10 m deep but exceeding 20 m in depth at its narrowest point. Most of the glacial drainage must have taken place in the channel since the present stream is clearly misfit as is shown by the fact that a small tributary seasonal stream has built a small fan on the channel floor diverting the course of the main stream, and also the channel floor is in many places vegetated and in one place it is utilized as a hayfield.

Immediately outside the terminal moraine is a terrace at an altitude of 20 m ± 2.5 m (aneroid) (figs. 3.37. and 3.39.). This terrace is very distinct, the steep backslope being the distal slope of the moraine. The terrace is 100 m wide at its widest, it ends abruptly on a rather steep bank which is the backslope of another terrace at 14.5 m ± 2 m (aneroid) (figs. 3.38. and 3.39.). This lower terrace is also well defined and in most respects similar to the upper one although the backslope is not so steep. On the surface of both terraces only well rounded sands and gravels could be seen. Both terraces are assumed to be marine in origin.

Rounded pebbles also occur inside the terminal moraine where they are common in the depressions but less so on the hummocks. Also, occasional rounded pebbles could be traced to an altitude of 60 m (aneroid) on the terminal moraine. No shoreline landforms, however, were observed inside the terminal moraine.

Shorewards of the area where the stream is braided it is bordered by high banks. At one place (marked x in fig. 3.35.), where the banks are over 20 m high is a good exposure. The stratigraphy is shown in fig. 3.40. The base of the section is at an altitude of close to 20 m. It was not possible to observe what was under Layer E.

Layer E is assumed to have been deposited in deep, still waters because of its fine grain size and the bedding. The top of Layer E is at a height of 28 m ± 3 m (aneroid) and the water level at the time of deposition must therefore have been much higher than this. In the case that Layer E was deposited in a freshwater environment, the lake was most likely associated with ice retreat, possibly a proglacial lake.

Layer D is badly exposed and nothing definite can be said about its origin.

Layer C does not display any indication of environment.

Layer B could be either fluvioglacial or marine in origin. The high degree of rounding, however, suggests marine origin, mainly because short transport distances argue against fluvioglacial origin, although it could be fluvioglacially reworked marine material.

Layer A is part of the till which is observed over most of the valley floor of Lambadalur.

Discussion. A glacial readvance has taken place in Lambadalur as shown by the glacial landforms down to 20 m which have not been affected by marine action although the marine limit in Dýrafjörður is at least 111 m (section 3.7.). Height of sea level at the time of the readvance was 20 m ± 3 m, or lower in the case that the marine terrace was formed during a marine transgression post-dating the readvance.

All layers in the section in fig. 3.39., with the possible exception of Layer B, are older than the terminal moraine, and therefore offer an opportunity to unfold glacial history in the valley prior to the readvance. In the case that Layer E was deposited in a lake, the lake-level at the time must have been higher than sea-level at the time. This requires that sea level was lower than about 30 m before the readvance which is very unlikely as will become apparent in section 4.4.3. In light of this it is very likely that Layer E is marine in origin. Unfortunately Layers C and D give little clue as to

	A	Till, varying thickness
	B 3 m	Well bedded sands and gravels. Very fine material. Mostly pebbles and cobbles, 5-10 cm and larger, all very well rounded. Thin (5-10 cm) sand-bed on top of this. Horizontal bedding.
	C 1 m	Sand
	D 8 m	The bed is badly exposed, but consists of gravel in fine matrix, very well consolidated. Cobbles and big boulders occur. Bedded. The matrix is fine sand. Horizontal bedding.
	3 m	Not exposed.
	E 7.5 m	Bedded fine sands and silts, sand beds thinner, 0.5-3 cm, silt beds 5-10 cm.

Fig. 3.40

their origin.

The rounded pebbles oberved occasionally on, and inside, the terminal moraine are interpreted to have been picked up from Layer B by the glacier during the readvance. This is based on the premise that Layer B is marine in origin which is reasonable in light of the high degree of rounding of the pebbles as discussed earlier.

It was shown earlier that the present stream is misfit and that most of the glacial drainage took place in this channel. The channel, however, is very low. The 20 m contour crosses the stream about 2 km from the shore (just upstream from the section in fig. 3.40.) and the channel slopes evenly to the shore. This relatively low channel floor is difficult to reconcile with sea level at 20 m when the terminal moraine was formed. The explanation for this could be one of the following:

(1) When the terminal moraine was formed sea level was much lower than 20 m, maybe 3-4 m. Later, a marine transgression took place and sea level stood at the 20 m terrace and falling later to 14.5 m.

(2) When the terminal moraine was being deposited sea level stood at 20 m. When the glacier started to retreat sea level fell rapidly, and had fallen to a level of a few metres whilst the valley glacier was still producing considerable amount of melt water hence maintaining the stream's erosive capacity. The channel was then eroded down to this low base level. Later, a marine transgression to the 14.5 m terrace took place.

(3) The channel was lowered in a flood caused by the sudden emptying of a lake which, after ice retreat, was

located where the braided stream deposits are now. This area is now lower than the area of the glacial deposits, and could well have been the site of a lake. No shorelines or other evidence for a lake there, however, were observed.

(4) The terminal moraine was formed during two sea level standstills, one with sea level at 14.5 m. The 20 m terrace would date from the time of the formation of the terminal moraine, while the 14.5 m terrace would date from a time when the glacier was slightly less advanced and on the retreat. This lower base level during ice retreat together with a flood caused by emptying of a lake could account for the low channel floor.

(5) There is the possibility that two or more of the hypotheses put forward above could combined account for the low channel floor.

Hypothesis (2) seems least likely since it requires very high rates of uplift during deglaciation which most likely occurred in a few years. In the case that rate of glacier was, say, 100 m/yr total deglaciation could have taken place in 50-80 yrs. An uplift of about 15 m in that short time span seems absurd. It is stressed that no field evidence was found to support or oppose any of these hypotheses. General considerations would argue against events involving complicated vertical crustal movements and eustatic sea level movements until evidence for these is forthcoming. This is discussed more fully in chapter 4.

Conclusion. Just outside the mouth of Lambadalur there is a terminal moraine which formed when sea level was at or lower than 20 m. The present stream is misfit. Its channel, which took most of the glacial drainage, is lower than 20 m. This is explained either by events involving a sudden flood from a dammed lake or a marine transgression to the 20 m level after deglaciation of the valley.

3.12. INNER DÝRAFJÖRÐUR.

General morphology. The innermost part of Dýrafjörður, between Lambadalur on the north side and Kjaransstaðadalur on the south side, is about 5 km long. On the north side of the fjord there is one valley east of Lambadalur, Hvallátradalur. The valley is short, about 4 km and its mouth is at a height of about 250-300 m. At the head of Dýrafjörður is a valley about 2 km long, behind which are some of the highest parts of Vestfirðir, the Gláma plateau. On the south side of the fjord are four cirques. These are north-facing and have lip altitudes of 300-400 m.

Glacial geomorphology. The glacial geomorphology is shown in fig. 3.41.

Most of the valley floor of Hvallátradalur is covered by till, but no end-moraines were observed.

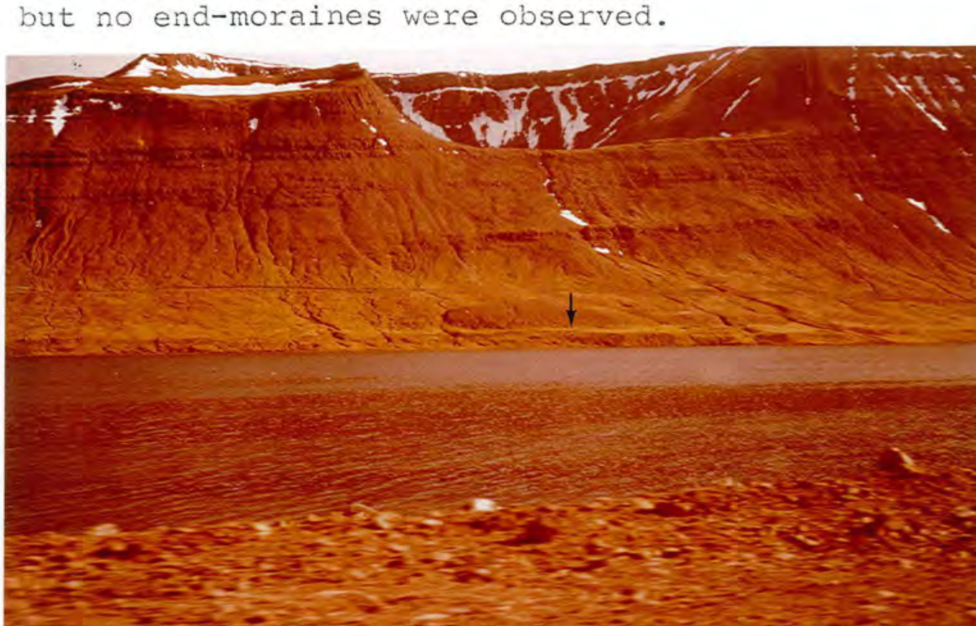
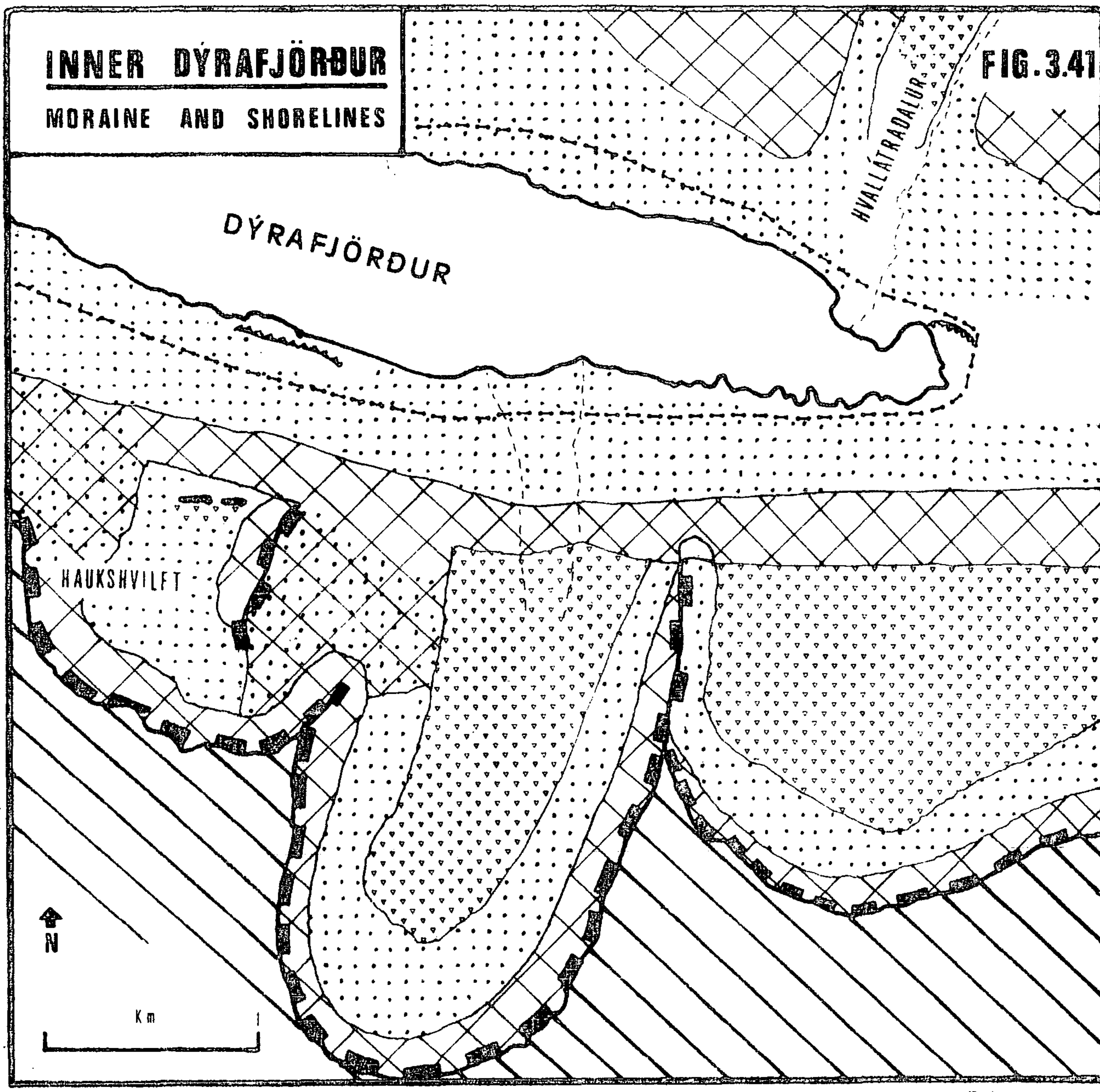


Fig. 3.42. View across the fjord to Haukshvilft, Arrow points to shoreline.



INNER DÝRAFJÖRÐUR

MORAINE AND SHORELINES

FIG. 3.41

In the valley at the head of the fjord drift is thin but the lowest part of the valley floor is covered by peat up to at least 3 m thick. No end-moraines were observed. Just at the head of the fjord, on the north side (fig. 3.41.), is a marine terrace about 5 m ± 3 m (estimated) above sea level.

The floors of all the cirques on the south side are covered by thin till. In Haukshvilft there is a ridge on the cirque lip interpreted to be a terminal moraine.

Below Haukshvilft, just above sea level, there are some deposits of unknown origin. They are cut by a distinct terrace (fig. 3.42.), clearly a shoreline, at an altitude of 7 m ± 3 m (estimated). The slopes beneath the cirques are steep and rocky in places, covered with a veneer of scree (fig. 3.42.).

Discussion. Only one end moraine, of unknown age, was found in the area, in Haukshvilft. Only two shorelines were found, both at altitudes of less than 10 m. The scarcity of shorelines in general, and at higher levels in particular, can be explained in at least two ways:

(1) The slopes are steep and loose deposits are scarce in the area. Conditions for shoreline formation, therefore, are poor. Also, this is the most sheltered part of the fjord and wave action must have been less here than in other parts of the fjord. In short, physical conditions for shoreline formation are not favourable.

(2) At the time when sea level was between, say, 30 and 10 m, there was a glacier in the fjord which would have destroyed the higher shorelines and only low shorelines would have formed in the wake of the retreating glacier.

Conclusion. In the inner part of Dýrafjörður there is one cirque moraine and two shorelines below 10 m.

3.13. KJARANSSTAÐADALUR.

General morphology. Kjaransstaðadalur is cut about 4 km SSE into the plateau between Dýrafjörður and Arnarfjörður (fig. 3.43.), and is 1.5 km wide. The valley-head is rounded.

Glacial geomorphology. In front of the valley there are large amounts of glacial deposits lying on a steep slope of about 10° (fig. 3.44.). The deposits have a rough surface, there are hummocks and depressions, some of which are circular. The deposits are interpreted to be ice marginal, the circular depressions being kettle-holes. The lack of end moraine ridges must be due to the relatively steep slopes.

At their foot the deposits are cut by a terrace (fig. 3.44. and 3.45.) at an altitude of 19.5 m ± 2.5 m(aneroid). This terrace is interpreted to be a marine shoreline. The terrace is a distinct feature, with a sharp break of slope at the backend and extends for about one km. Immediately west of the stream there is a raised delta with its highest point at the level of the backend of the marine terrace.

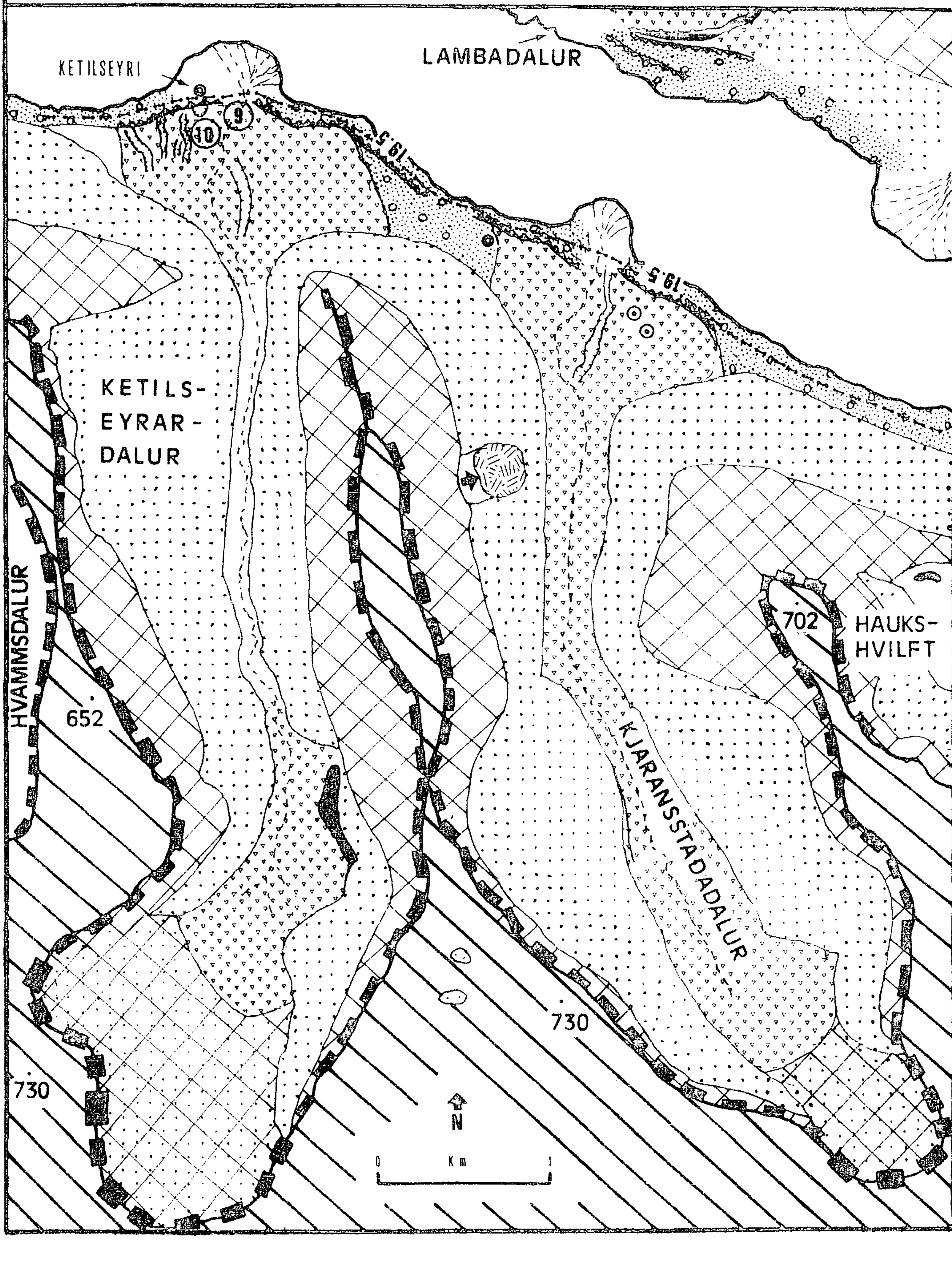
Discussion. A glacial readvance has taken place in Kjaransstaðadalur. The glacial landforms there have not been affected by marine action although they are well below the marine limit in Dýrafjörður.

The glacial readvance most likely took place when sea level was at the terrace which cuts the deposits at 19.5 m. The possibility remains, however, that the terrace was formed in a marine transgression post-dating the readvance.

Conclusion. A glacial readvance took place when sea level was at 19.5 m or lower.

KJARANSSTAÐADALUR — KETILSEYRARDALUR FIG.3.43

Glacial Geomorphology and Shorelines



3.14. KETILSEYRARDALUR.

General morphology (fig. 3.43.). Ketilseyrardalur is very similar to Kjaransstaðadalur in many respects, being only slightly longer, 5 km, and narrower, 1-1.5 km. The whole of the valley-head is rounded, indicating invasions of ice from the plateau. About 4 km up the valley there is a rock step and the valley turns sharply westwards and the valley floor becomes more extensive.

Glacial geomorphology. The glacial geomorphology is shown in fig. 3.43. The valley floor inside the step in the valley is everywhere covered with till. On the eastern side, at the step, there is a terrace with an uneven surface. It forms the upper limit of till on the mountain side there and is interpreted as being ice marginal, a lateral moraine.

Between the step and the mouth of the valley scree covers most of the slopes with only a narrow band of till along the stream.

Outside the valley mouth there are large amounts of loose deposits. They have an irregular surface of elongated hummocks and intervening depressions, some of which are dry channels. East of the stream are circular depressions. The deposits at the mouth of the valley are interpreted to be glacial in origin, the dry channels being melt water channels, they are not connected with the present stream, and the circular depressions being kettle-holes.

The glacial deposits are cut at their seaward end by a very distinct terrace, with a sharp break of slope at the backend (fig.3.46.). This terrace is interpreted to be marine in origin for reasons similar to the interpretation of other marine terraces in the area (see e.g. section 3.9. on Hjarðardalur). Its altitude is 19.5 m ± 3 m (aneroid).

Just south of the Ketilseyri farm the backend of the terrace has been partly dug away and turned into a sand and gravel quarry, exposing a section about 10 m in height. The section displays two sediment types. The lower sediment is well bedded sands and gravels, the beds dipping at an angle of 15-20° towards the sea.

Fig. 3.46. View to the SE across the terrace at 19.5 m at the mouth of Ketilseyrardalur towards Kjaransstaðadalur.

The pebbles and cobbles are very well rounded. The upper limit of this sediment is at an altitude of 27 m ± 3 m (aneroid). Overlying this is a 1 m thick bed of till. It has a greyish colour in contrast to the blueish colour of the underlying sediment. The till layer is unbedded an no size sorting of the particles was observed. The upper part of the till has been removed by quarrying. Samples were taken from each sediment type for particle size analysis. The results are tabulated and discussed in Appendix A, but it is mentioned here that in the lower sediment fines constitute 0.61% of the sample while fines constitute 18.04% of the sediment interpreted to be till.

Discussion. The till bed which overlies the cross bedded deposits in the quarry, and the glacial landforms , well below the marine limit in the area but having not been affected by marine action, show that a glacial readvance has taken place in Ketilseyrardalur. The glacial readvance must have taken place when sea level was at the marine terrace at 19.5 m or lower in the case that the terrace formed in a transgression post-dating the readvance.

The inclined beds of sands and gravels in the quarry are likely to be marine in origin because of their inclined bedding and high degree of rounding. They are older than the culmination of the glacial readvance since till covers them everywhere except where the marine terrace is. Modes of origin of the inclined beds include:

(1) They are reworked glacial deposits. Then they would have formed at a time of a retreating shoreline shortly after the deglaciation of the fjord by the fjord glacier. The great volume of the deposits, their structure, homogeneity and rather steep constant dip require that sea level stayed at the same level, 25-30 m, for a relatively long time. Such a low sea level at the time of deglaciation of the locality by the fjord glacier is very unlikely, however, in light of the fact that the marine limit in Dýrafjörður is at least 111 m (section 3.7.).

(2) The inclined beds are foreset beds of a delta. In this case sea level at the time must have been close to 27 m, the top of the inclined beds, or somewhat higher.

The great volume of the deposits suggests that a glacial stream was involved with the deposition. This means that a glacier must have been present in Ketilseyrardalur at the time.

In light of this discussion the cross-bedded sands and gravels are interpreted as delta deposits dating from a time when there was a glacier in Ketilseyrardalur. This glacial phase is most likely the same as the one which gave rise to the glacial landforms and deposits which now overlie the delta deposits, a glacial phase which has been shown to be a readvance stage. The two sea level stands indicated, close to 30 m and 19.5 m or lower, are not inconsistent. The marine terrace at 19.5 m $\pm$ 3 m is younger than the delta deposits and, if dating from the readvance stage, was formed towards its end.

Conclusion. In front of Ketilseyrardalur there is stratigraphic and geomorphological evidence for a glacial readvance. Two sea level stands can be related to the readvance, the former close to 30 m and the later 19.5 m or lower.

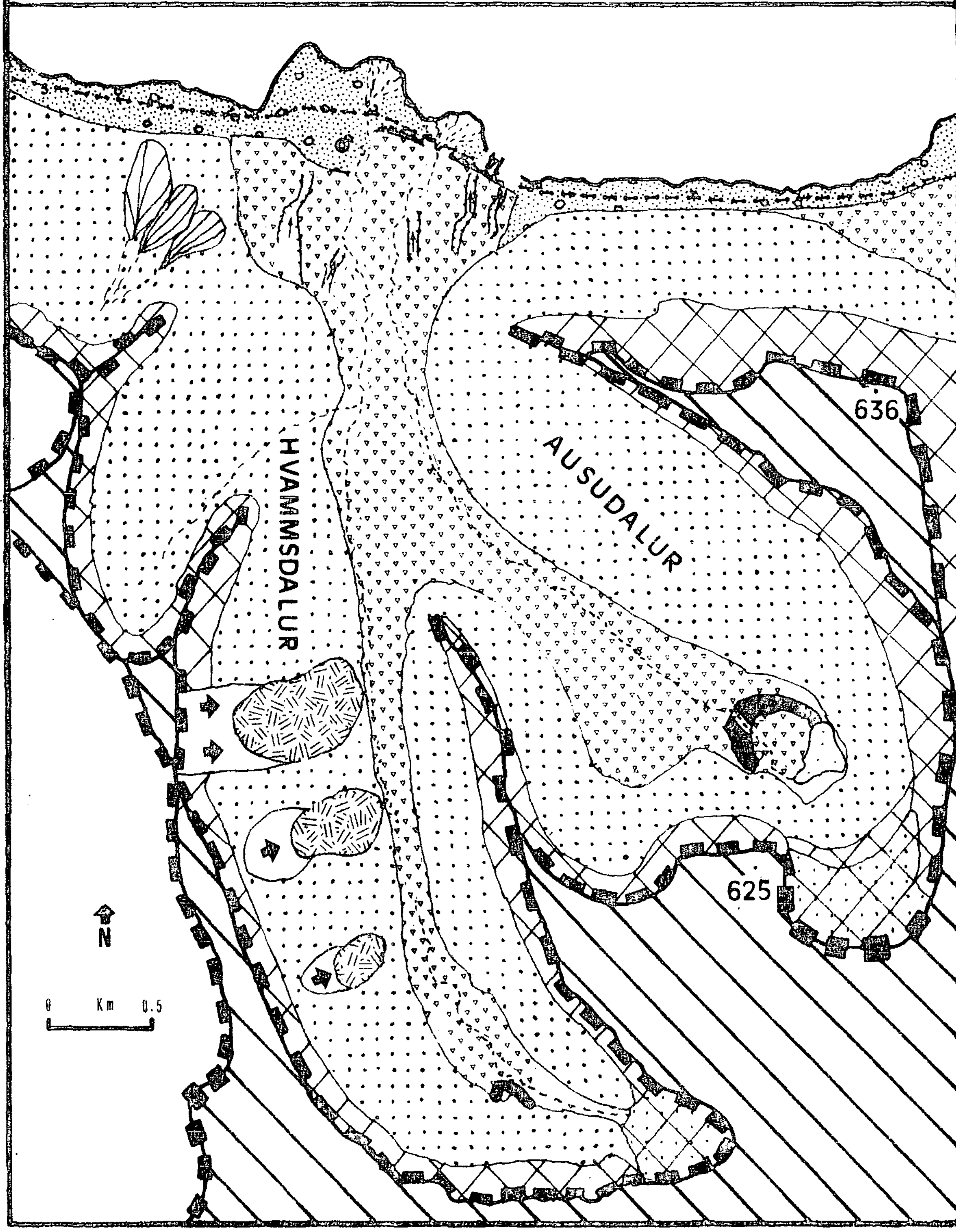
3.15. HVAMMSDALUR.

General morphology. The general morphology of Hvammsdalur is shown in fig. 3.47. Hvammsdalur, 4 km long and 1-1.5 km wide, cuts almost due south into the plateau but turns to south-east near its head. The valley-head is rounded from the invasion of ice from the plateau. On the western side of the valley are three landslides and one cirque. Towards the mouth of Hvammsdalur on its eastern side a tributary valley, Ausudalur, opens into it, being cut south-east into the plateau. At the head of Ausudalur are two cirques, one of which

HVAMMSDALUR

FIG. 3.47

Glacial Geomorphology and Shorelines



has a lake and a rounded head-wall.

Glacial geomorphology. Near the head of Hvammsdalur is a distinct, curved ridge (fig. 3.48). It is situated under the steepest cliff (fig. 3.47) and its aspect is almost due north. The relative height of the ridge is about 5 m. Its height above s.l. is 400 m ± 20 m (contour map). Because of its form and position the ridge is interpreted to be an end moraine.

In front of the cirque lake in Ausudalur is a curved ridge (fig. 3.49) with a relative height of about 5 m. The ridge merges with another which for a short distance ascends the slope on the NE-side. Because of its form and position this ridge is interpreted to be an end moraine.

A flat valley floor is only found where Ausudalur merges with the main valley. This valley floor is covered with till which in places is 20-30 m in thickness.

At the mouth of the valley glacial landforms abound. The till surface is irregular and is cut by 5 dry channels, interpreted as melt water channels. The glacial deposits are cut on the seaward side by a terrace, interpreted to be a marine shoreline (figs. 3.50 and 3.51). Two of the glacial melt water channels peter out at the terrace and are visibly cut into it. Two of the other channels enter the modern streams while the channel furthest west (fig. 3.47) peters out before the shoreline is reached. The backend of the shoreline is at 14 m ± 3 m (aneroid).

Discussion. In front of Hvammsdalur there is geomorphological evidence for a glacial readvance when sea level was about 14 m above present. This is shown by the glacial melt water channels which peter out at the terrace, thereby indicating that the presence of a valley glacier in front of the valley was synchronous with the formation of the terrace.

The age of the end moraine in front of the lake in the cirque is unknown, it could either date from the deglaciation of Hvammsdalur after the readvance or a later glacial readvance. The latter possibility is favoured because of the form and size of the moraine. In this case the moraine was built in the period between the Hvammsdalur readvance and the so called Little Ice Age (ca. A.D.1500-1900) since it is weathered and vegetated. Cirque moraines are discussed further in section 4.5.4.

The moraine near the head of Hvammsdalur is interpreted as representing a climatically induced readvance of a small glacier. The moraine is situated under the steepest cliffs in the valley, which face due north. The direction of flow of the glacier which built it was almost at right angles to the direction of the long axis of the valley, i.e. due north. It is reasonable to assume that the valley glacier margin retreated along the axis of the valley, and therefore this moraine must have formed after the revival of ice activity at the locality.

Conclusion. A glacial readvance culminated in Hvammsdalur when sea level was at 14 m ± 3 m. Later, a small glacier at the head of Hvammsdalur, and probably a cirque glacier at the head of Ausudalur too, advanced and built conspicuous moraines.

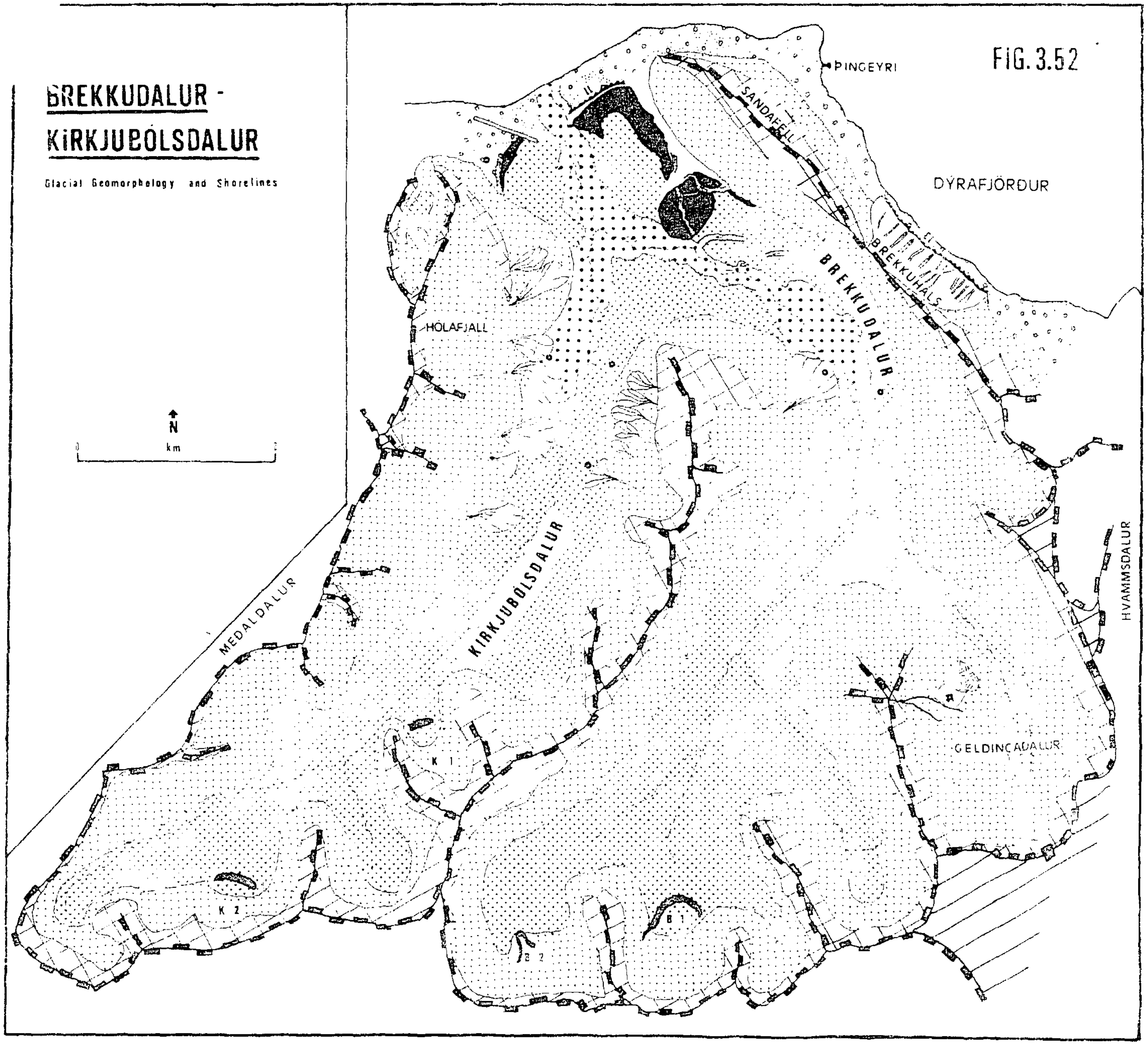
3.16. BREKKUDALUR - KIRKJUBÓLSDALUR.

General features. The valley system of Brekkudalur and Kirkjubólsdalur will be treated as a whole (fig. 3.52). These two valleys coalesce about 3 km from the shore to form the most extensive lowland area in Dýrafjörður with an area of about 10 km^2. The north-eastern side of these lowland is bounded by the rather low (367 m) mountain ridge Sandafell.

FIG. 3.52

BREKKUDALUR - KIRKJUBÓLSDALUR

Glacial Geomorphology and Shorelines



(fig. 3.26.).

Kirkjubólsdalur is one of the longest valleys in Dýrafjörður, about 11 km. It has a low floor, the 100 m contour crossing the valley about 7 km from the shore. On either side the valley is bounded by narrow mountain ridges, which, in effect, are series of aretes, since numerous cirques open into the valley and line the mountain ridges on either side. In total 10 cirques open into the valley.

Brekkudalur, 11 km long, is also one of the longest valleys in Dýrafjörður, and its floor is also low, the 100 m contour crossing the valley 7 km from the shore. The valley is bounded on the west by the arete which separates it from Kirkjubólsdalur, while its southern and eastern sides are dominated by large cirques and valleys. At the head of the tributary valley Geldingadalur there is the only extensive piece of plateau adjoining the Brekkudalur-Kirkjubólsdalur valley system, which otherwise is riddled with horns, aretes and cirques, all very typical alpine landforms.

The Brekkudalur-Kirkjubólsdalur valley system penetrates into the heart of the Hrafnseyri central volcanic complex. There is, therefore, a drastic change in the geology, and many more rock types are found here than in the more or less homogenous flood basalt areas dealt with in this chapter so far (see section 1.1.2).

Glacial geomorphology. Glacial deposits, alluvium and scree cover practically the whole area of the valley system. Glacial deposits, till, thickly cover almost the whole of the valley floors and most of the cirque floors too.

In two of the Kirkjubólsdalur cirques, referred to here as K-1 and K-2, are large ridges. The one on the lip of cirque K-1 is huge, 150 m wide and relative height about 20 m. The altitude of the ridge is 240-250 m and it is interpreted to be a terminal moraine because of its form and position. The ridge in cirque K-2 is sharp and very prominent, it is at a similar height to the one in K-1 but only about 100 m wide. This ridge is likewise interpreted to be terminal moraine. In front of the moraine there is thick fluted till reaching right down to the valley bottom. The flutes are orientated perpendicular to the moraine. The fluted till pre-dates the moraine.

Two Brekkudalur cirques also contain ridges interpreted to be end moraines. In B-1 there is a sharp and low lobe of terminal moraine. Outside the terminal moraine is a "pitted" till-cover characterized by numerous small "pits" which are interpreted as being kettle-holes. In cirque B-2 is a long and rather low lateral moraine ridge curving into a terminal moraine lobe. The glacier which deposited this moraine must have been very small since the moraine is located at the base of a scree slope. The altitude of the B-2 moraine is 460-560 m (contour map) while the one in B-1 is 300-360 m (contour map).

Away from the cirques, till covers most of the lower ground, and is usually thick with an irregular surface. These glacial deposits culminate on the lowlands in front of the valleys in two huge accumulations of deposits which are, as is related below, interpreted to be ice marginal deposits and end moraines.

North-east of the stream at the mouth of Brekkudalur, where it merges with Kirkjubólsdalur, are huge deposits, interpreted as a terminal moraine complex (fig. 3.53). The feature is 300 m wide and almost 40 m high at its highest. Three dry channels cut through the complex (fig. 3.53) and peter out just in front of it. The largest channel (NNW direction) "starts" about 1-2 m above the valley floor. The channels are interpreted as melt water channels. Kettle-holes, water-filled, are also observed (fig. 3.53.). On the northern side of the valley, on the slopes of Sandafell, is a smaller ridge attached to the moraine complex and interpreted as a lateral moraine. Inside the complex are also more melt water channels. On the other side of the stream is an area of thick hummocky till (fig. 3.53.).

Between the northern ends of Sandafell and Hólafjall there extends along the shore a ridge which continues along Sandafell. The ridge is broken in the middle by the present stream. East of the stream the ridge is rather large, 150-200 m wide over most of its length and mostly 15-20 m high (fig. 3.54.). The lateral part of the ridge almost joins up with the Brekkudalur end moraine complex. Inside the ridge the surface is smooth with occasional hummocks. Because of its form and its association with other landforms this ridge is interpreted as being an end moraine. Some minor (2-3 m wide) melt water channels occur between the lateral moraine and Sandafell. Where the stream passes the eastern part of the moraine is a section through the moraine, but only the lowest 5 m are exposed (fig. 3.55. and 3.56.). The exposure shows only well bedded sands and gravels, dipping very gently towards the valley.

West of the stream the terminal moraine is much less prominent and consists of low and irregulary spaced ridges and hummocks, with a melt water channel immediately outside it. Parts of the moraine were destroyed when the air-strip was built.

The terminal part of the end moraine east of the stream is cut by a terrace, interpreted to be marine, at an altitude of 11 m ± 3 m (aneroid).

Brekkudalur is separated from the fjord by the rather low mountain ridge Sandafell. At its lowest this ridge is called Brekkuháls, and is only 100-120 m a.s.l. (contour map).

Fig. 3.57. The terrace at 13 m below Brekkuháls. Arrow points to a melt water channel. Note the slight low in the terrace in front of the channel.

On the fjord side of Brekkuháls are many dry channels, most of which are less than 5 m in width. The channels all terminate on a terrace at an altitude of 13 m ± 3 m (aneroid) (fig. 3.57.). The terrace is interpreted to be marine for reasons similar to interpretations of other marine terraces in Dýrafjörður. Some of the channels are visibly cut into the terrace (just visible on fig. 3.57.) showing that the channels and the terrace are contemporaneous. The channels are interpreted as melt water channels, the melt water coming from the glacier in Brekkudalur. The reasons are that the channels are limited in distribution to the area below Brekkuháls which is the lowest part of the mountain ridge Sandafell. Also, the channels are found down to an altitude of about 13 m while the marine limit in Dýrafjörður is at least 111 m, which shows that the channels are signs of renewed glacial activity near the locality, most likely in Brekkudalur. The greatest relative altitude of Brekkuháls below which are melt water channels is 200 m ± 20 m (contour map) and this is a minimum thickness of the glacier in Brekkudalur at the locality during the readvance.

Discussion. In Brekkudalur there is geomorphological evidence for a glacial readvance. This most likely took place when sea level was at 13 m ± 3 m, on the premise that the Brekkudalur moraine is synchronous with the melt water channels which terminate on the marine terrace at 13 m ± 3 m below Brekkuháls.

In Kirkjubólsdalur there is also geomorphological evidence for a glacial readvance. This took place when sea level was 11 m ± 3 m as shown by the marine terrace which cuts the moraine at this height.

The end moraines in both valleys are very large compared with other end moraines in the Dýrafjörður-Arnarfjörður area. The volume of other loose deposits such as till-cover and alluvium is also out of proportion with what has been observed elsewhere in the area. Many factors could account for this although it is considered here to be related to the fact that the Brekkudalur-Kirkjubólsdalur valley system penetrates to the heart of the Hrafnseyri central volcano where the geology is very much different from that elsewhere. There is much more variety in rock types with the effect that easily eroded rocks like rhyolite, tephras and breccias are relatively abundant in the rock succession. It is therefore, argued here that the main reason for the large volume of loose sediments in these valleys is the bedrock factor. Other factors, especially the size of the valley glaciers, are also likely to have contributed to some degree to increasing the abundance of debris in the valleys.

End moraines, usually terminal moraine ridges, occur in four of the cirques in this valley system. Their age is unknown, they could either date from the deglaciation after the readvance in the valleys or date from a later readvance. The large size of the moraines in K-1 and K-2 suggests that they were formed during a climatically induced readvance. The moraines in B-1 and B-2 are smaller but still quite prominent and well defined, which again suggests that they formed in a climatically induced readvance. It is stressed again, however, that the age of these cirque moraines in Brekkudalur and Kirkjubólsdalur is unknown.

Conclusion. In Brekkudalur and Kirkjubólsdalur there is evidence for glacial readvances when sea level was at 13 m $\pm$ 3 m and 11 m $\pm$ 3 m respectively. Subsequent to the readvance in the valleys glacial advances, probably readvances, took place in at least four of the cirques resulting in the formation of prominent end moraines.

3.17. MEÐALDALUR.

General morphology. Meðaldalur is 7-8 km long, mostly 2 km wide, almost straight and is orientated almost due north-south (fig. 3.58.). It is separated from adjacent valleys Kirkjubólsdalur and Haukadalur by narrow, sharp-crested

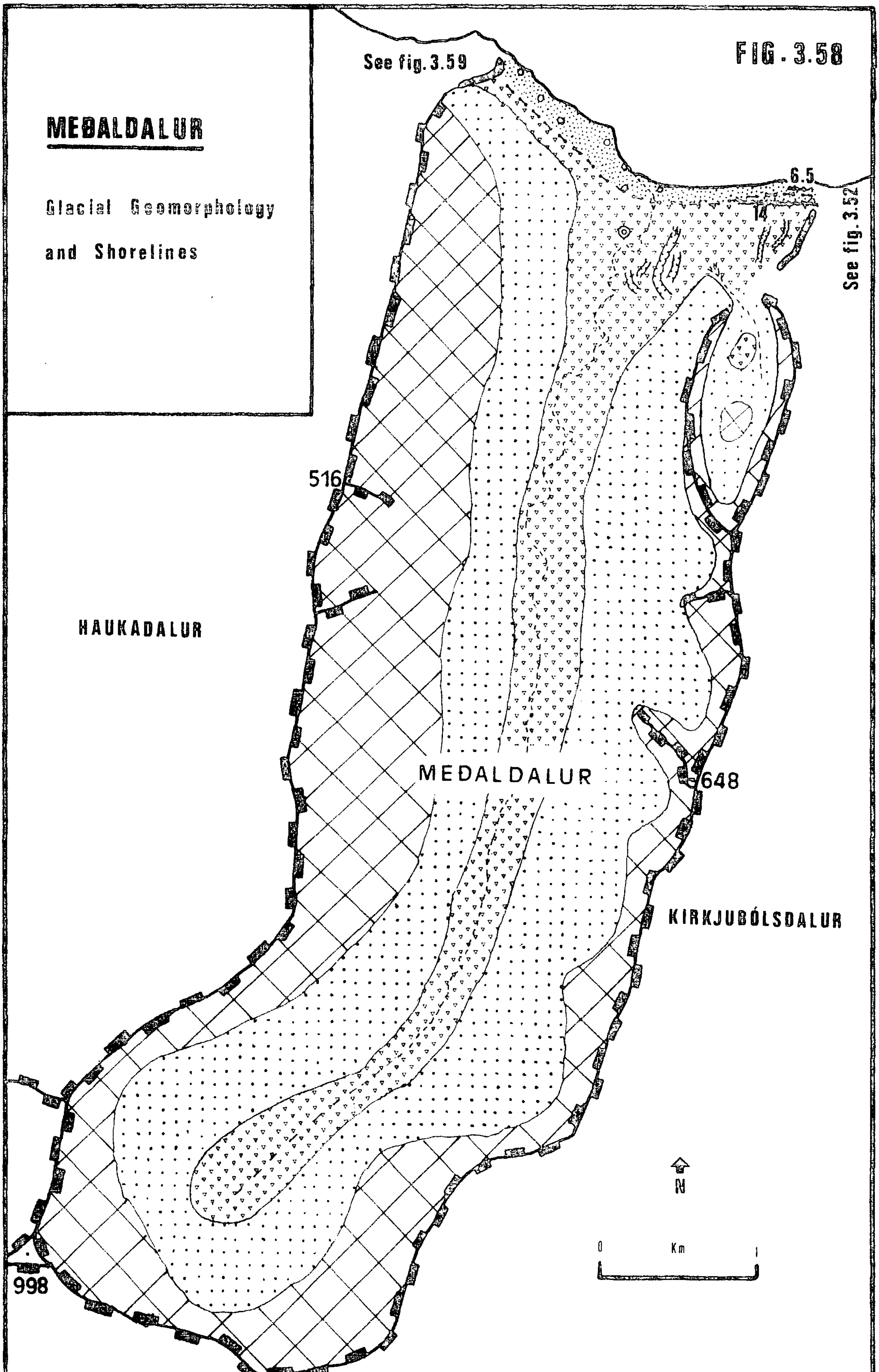


FIG. 3.58
MEÐALDALUR
Glacial Geomorphology
and Shorelines
See fig. 3.59
See fig. 3.52
6.5
14
516
HAUKADALUR
MEDALDALUR
648
KIRKJUBÓLSDALUR
N
0
Km
1
998

ridges up to 650 m in height. The valley head is half circular in outline, somewhat wider than the valley itself. At the head is the highest peak in Vestfirðir, Kaldbakur, 998 m. Three cirques open into the valley on the eastern side and one on the western side.

Glacial geomorphology. Screes cover most of the valley floor (fig. 3.58.) apart from a narrow band of till along the stream. At the valley mouth glacial deposits cover a larger area, but they are thin as shown by frequent exposures of bedrock on the beach and along the stream. At the valley mouth the irregular till surface is cut by dry channels. These are mostly minor features, less than 5 m in width, and short, apart from one which originates on the slope last of the stream and then peters out on the till on the valley floor.

On the eastern side the till terminates at a prominent ridge with a relative height of 6-7 m at its highest. Because of its form and its association with other landforms the ridge is interpreted as a lateral moraine. On the seaward side of the ridge is a terrace at an altitude of 14 m ± 2 m (aneroid). The terrace is poorly developed except where the moraine forms the backslope. Another poorly developed terrace at an altitude of 6.5 m ± 2 m (aneroid) is found there. Both terraces are interpreted to be marine for reasons similar to the interpretation of other shorelines in the area. Well rounded pebbles are rare on these terraces, they are also rare on the present day beaches, however. The moraine which forms the backslope of the upper terrace must have been truncated by marine action.

West of the stream the till surface is rather smooth and featureless. This is where the hayfields of the now deserted

Meðaldalur farm are located. No shorelines were observed west of the stream, but in front of the mountain ridge between Haukadalur and Meðaldalur is a prominent ridge discussed in section 3.18. on Haukadalur.

Discussion. The lateral moraine ridge east of the valley mouth must have formed during a glacial readvance when sea level was at or below 14 m ± 2 m (aneroid). The position of this lateral moraine shows that at the time of its formation the terminal part of the glacier was well advanced into the fjord, calving into the sea.

The faintness of the shorelines is accompanied with low degree of rounding of the terrace material. This is interpreted as being due to the fact that the coastal area here is well sheltered, even from the direction of largest fetch. This, together with the fact that the glacier calved into the sea during the readvance, largely explains the paucity of terminal moraines and shorelines in this area.

Conclusions. It is concluded that a glacial readvance took place in the valley when sea level was at or below 14 m ± 2 m.

3.18. HAUKADALUR.

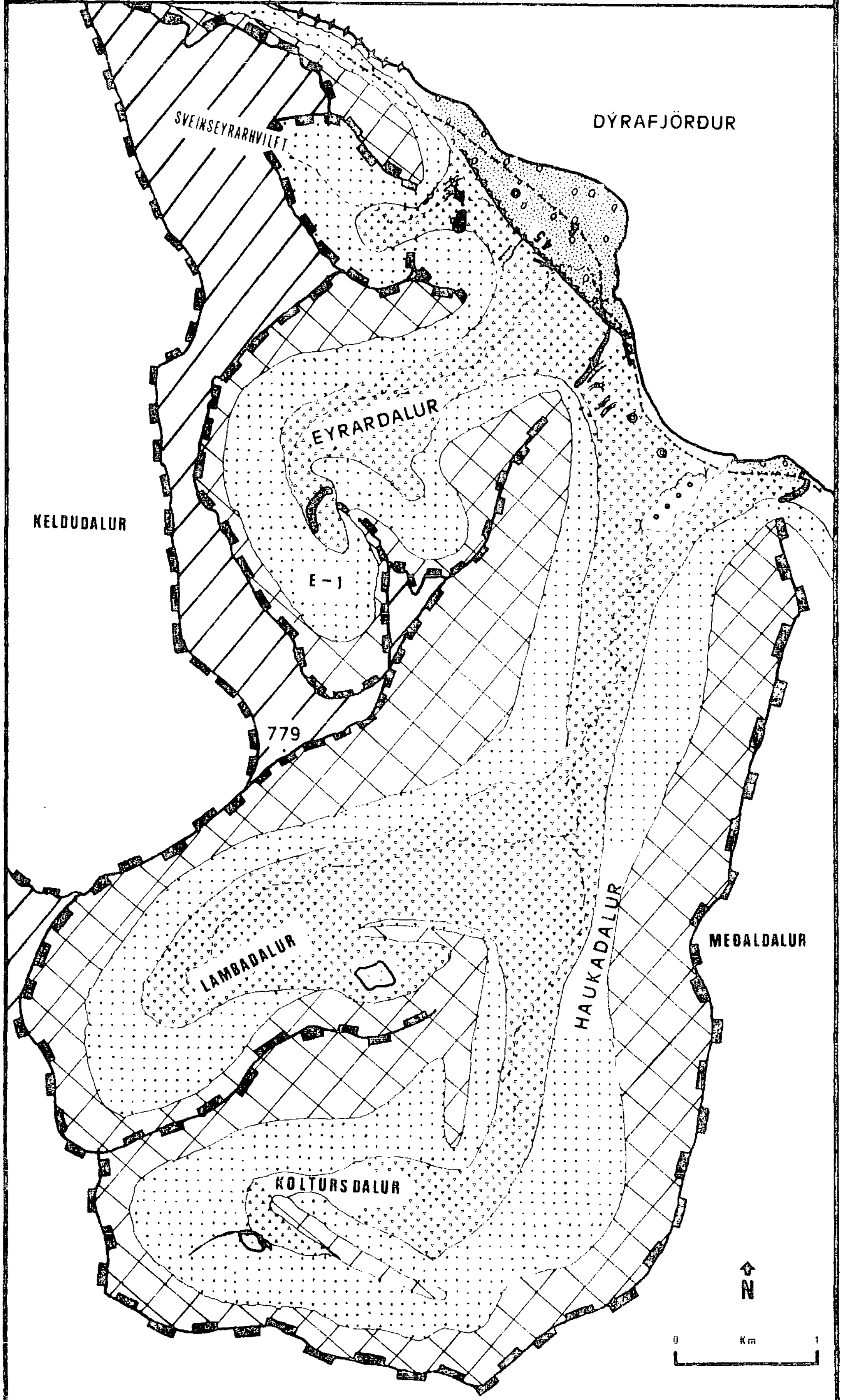
General morphology. Haukadalur is 7 km long, running south then turning sharply west for the last 2 km (fig. 3.59.). A hanging valley, Lambadalur, opens into it from the west. The inner part of Haukadalur is called Koltursdalur. Valley-head cirques occupy the heads of both Lambadalur and Koltursdalur. West of Haukadalur plateau areas reappear since this is outside the area of the Hrafnseyri central volcano.

Glacial geomorphology. Near the head of Koltursdalur

HAUKADALUR — EYRARDALUR — SVEINSEYRARHVILFT

FIG. 3.59

Glacial Geomorphology and Shorelines



is a long, curved ridge, about 2 m high and about 20 m wide. Inside it is a lake, approximately 100 x 200 m across. The ridge is interpreted to be an end moraine. It is at a height of 450-500 m while the height of the mountain forming the backwall is over 900 m.

Most of the valley floor is covered with thin, featureless till. Near the valley mouth, however, the valley floor is characterized by several low, roundshaped mounds. It was possible to examine the structure of two of the mounds in natural exposures. One is by the stream close to the shore, marked y on fig. 3.59, its top is at an altitude of 11.5 m ± 2.5 m (aneroid). The exposure showed about 1 m of alternating beds of silts, coarse sand and gravel. The beds are irregular, dipping in various directions, sometimes dipping up to 70° up the valley. The origin of the beds is uncertain, they could be marine or fluvio-glacial. In any case the irregular dips are interpreted as the beds having become contorted by pressure of overriding ice. The other exposure is in a mound further up the valley, about 600 m from the shore, marked x on the map. The stratigraphy observed there is shown in fig. 3.60.

The top layer is the till which covers most of the valley floor. The underlying layers are interpreted to be marine in origin because of the bedding and the generally well rounded gravels. The irregular dips are interpreted as being indicative of contortion of the beds by the pressure of overriding ice.

Just east of the mouth of Haukadalur is a curved ridge (fig. 3.58), about 20 m wide and for the most part rather low, although in one place it exceeds 5 m in relative height (fig. 3.60). The lower end of the ridge is at an altitude of 20 m ± 4 m (contour map). Because of its form, position

0.5 m		Till. Greyish silt with stones, occasional laminae of fine sand.
0.5 m		Coarse gravel, well rounded.
2.5 m		Sands and gravels, mostly horizontally bedded, but containing thin laminae of sand dipping gently in various directions.
0.05 m		Silt
		Mostly coarse gravel alternating with fine gravel. Rounding poor. Base not seen.

Fig. 3.60. Haukadalur stratigraphy.

and association with other landforms the ridge is interpreted as a lateral moraine. Inside the moraine is a thin, featureless cover of till reaching the stream. West of the stream is a featureless till cover stretching towards Eyrardalur, an area discussed in section 3.19. No shorelines were observed in the Haukadalur area.

dating from a time before the readvance when sea level was higher and the sea inundated the valley. The irregular dips indicate the beds have become disturbed after they were deposited and this disturbance is attributed to overriding ice. Most likely this took place during the same readvance which deposited the lateral moraine.

Ice marginal deposits are conspicuously sparse at the mouth of Haukadalur, there is only the lateral moraine east of the valley mouth. This is to be expected, however, since the position and the curved shape of the lateral moraine shows that during the readvance the glacier was well advanced into the fjord and must therefore have deposited most of its marginal load there.

The age of the cirque moraine in Koltursdalur is unknown. Because of its sharp outline, however, it is considered more likely that it was deposited during a climatically induced readvance post-dating the readvance in the valley than that it was formed during deglaciation of the valley after the readvance there.

Conclusion. There is geomorphological evidence for a glacial readvance in Haukadalur when sea level was below 20 m $\pm$ 4 m. After this readvance a cirque glacier in Koltursdalur probably advanced.

3.19. EYRARDALUR.

General morphology. Eyrardalur is a short valley, about 2.5 km long and about 1.5 km wide, cutting south-westwards into the plateau. At the head are two NNW-facing cirques with only a horn and an arete separating them from Haukadalur. The plateau remnants appear again west of Eyrardalur after being absent in all the area between Brekkudalur and Eyrardalur.

Glacial geomorphology. In the cirque here called E-1 is an inconspicuous ridge. It is interpreted as an end moraine.

Most of the valley floor is covered with thin, featureless till. Near the valley mouth, however, are large amounts of glacial deposits, especially east of the stream. The till surface there is characterized by several elongated hummocks or ridges with relief of the order of 3-4 m. The ridge furthest east is largest, rising about 5-7 m above the ground outside it. This ridge is interpreted as having been deposited at the lateral margin of a glacier in Eyrardalur. The ground inside this ridge is about 3 m higher than the ground east of it. East of the ridge are dry channels cutting through till. The position of the ridge, midway between Eyrardalur and Haukadalur, and its orientation suggest that at some time this ridge was a medial moraine between the glaciers in Haukadalur and Eyrardalur. This interpretation is plausible since it was shown in section 3.18. that during the readvance in Haukadalur the glacier there was well advanced into the fjord.

West of the stream the till is thinner and its surface is also characterized by irregular ridges, but relief is smaller. The only terminal moraine at the mouth of Eyrardalur is in this area, a short, narrow and inconspicuous ridge just west of the stream. The glacial deposits west of the stream end on the western side at a dry channel, interpreted as a melt water channel. The channel peters out before reaching the terrace at the foot of the glacial deposits.

The only shoreline observed in the Eyrardalur area is a marine terrace cutting the front of the glacial deposits very sharply, the backslope of the terrace is for the most part very steep, 25-30°, and about 5-10 m high. The terrace itself is very extensive and beach ridges are common there. The altitude of its backend is 4.5 m ± 2 m (aneroid).

Discussion. A glacial readvance has taken place in Eyrardalur, the glacial deposits at the valley, unaffected by marine action, are well below the marine limit of at least 111 m in Dýrafjörður.

The ridge east of the valley mouth is interpreted as a medial moraine between the glaciers in Haukadalur and Eyrardalur. The evidence for this is very strong: the medial moraine ridge is almost straight, it is located midway between the valleys, and till, well below the marine limit in Dýrafjörður, covers all the lowland area between the valleys. All this implies that the glacial readvances in Eyrardalur and Haukadalur occurred simultaneously.

The glacier at the mouth of Eyrardalur must have covered an area larger than the glacial deposits cover at the time of the readvance. This is shown by shape and position of the medial moraine, running straight almost down to the present shore. Also, the form and position of the terrace at 4.5 m shows that marine erosion has removed parts of the glacial deposits. All this indicates that the glacier snout covered parts of the area where the marine terrace is now. This implies that the marine terrace post-dates the glacial readvance in Eyrardalur.

Having established that the terrace post-dates the glacial readvance stage in Eyrardalur, the question arises as to the height of sea level during the readvance. This, however, remains unknown, due to lack of evidence. It is pointed out, however, that the intensity of marine erosion shown by the morphology of the terrace, was such that it may have removed all evidence of marine action contemporaneously with the readvance. In other words, sea level may well have been higher than the 4.5 m terrace during the readvance.

Conclusion. A glacial readvance took place in Eyrardalur. Height of sea level during the readvance is unknown. The glacial readvance occurred simultaneously with the one in Haukadalur, the glaciers in these valleys coalesced leaving behind them a medial moraine. A marine terrace at 4.5 m ± 2 m (aneroid), showing signs of vigorous marine activity, postdates the readvance. A glacial readvance may have taken place in the cirque E-1 after the readvance in the valley.

3.20. SVEINSEYRARHVILFT.

General morphology. This is a large cirque, 1 km long and 1 km wide at the mouth, located just east of Eyrardalur (fig. 3.59). The NW side wall is rounded by the invasion of ice from the plateau. A consequence of this invasion is that the width of this cirque now exceeds its length.

Glacial geomorphology. Outside the cirque lip, on the rather steep slope of about 25°, is a feature which is interpreted to be a terminal moraine on the basis of its characteristics desribed below. The feature forms a platform on the slope outside the cirque and is breached in the middle by a small stream. On the platform are small kettle-holes, moraine hummocks, and melt water channels. The lowest part of this moraine is at an altitude of 42.5 m ± 4 m (aneroid).

The only shoreline in the area is a marine terrace also seen in front of Eyrardalur, at 4.5 m ± 2 m (aneroid). Above this terrace are smooth slopes up to the morainic deposits. Occasional small exposures into the surface of the deposits forming this smooth slope show rounded pebbles. Because of the smoothness of the surface of the deposits, and the rounded pebbles, they are interpreted to be marine in origin. The melt water channels are situated inside the moraine and to the side of it, but not on the smooth slopes below it. It was not possible, therefore, to determine the height of sea level when the moraine was formed except to say that it formed when sea level was lower than 42.5 m ± 4 m (aneroid).

Discussion. A glacial readvance has taken place in Sveinseyrarhvilft since the moraine in front of it is lower than the marine limit of at least 111 m in Dýrafjörður. Sea level during the readvance must have been lower than the lowest part of the moraine, 42.5 m ± 4 m.

Conclusion. A glacial readvance took place in Sveinseyrarhvilft when sea level was lower than 42.5 m ± 4 m (aneroid).

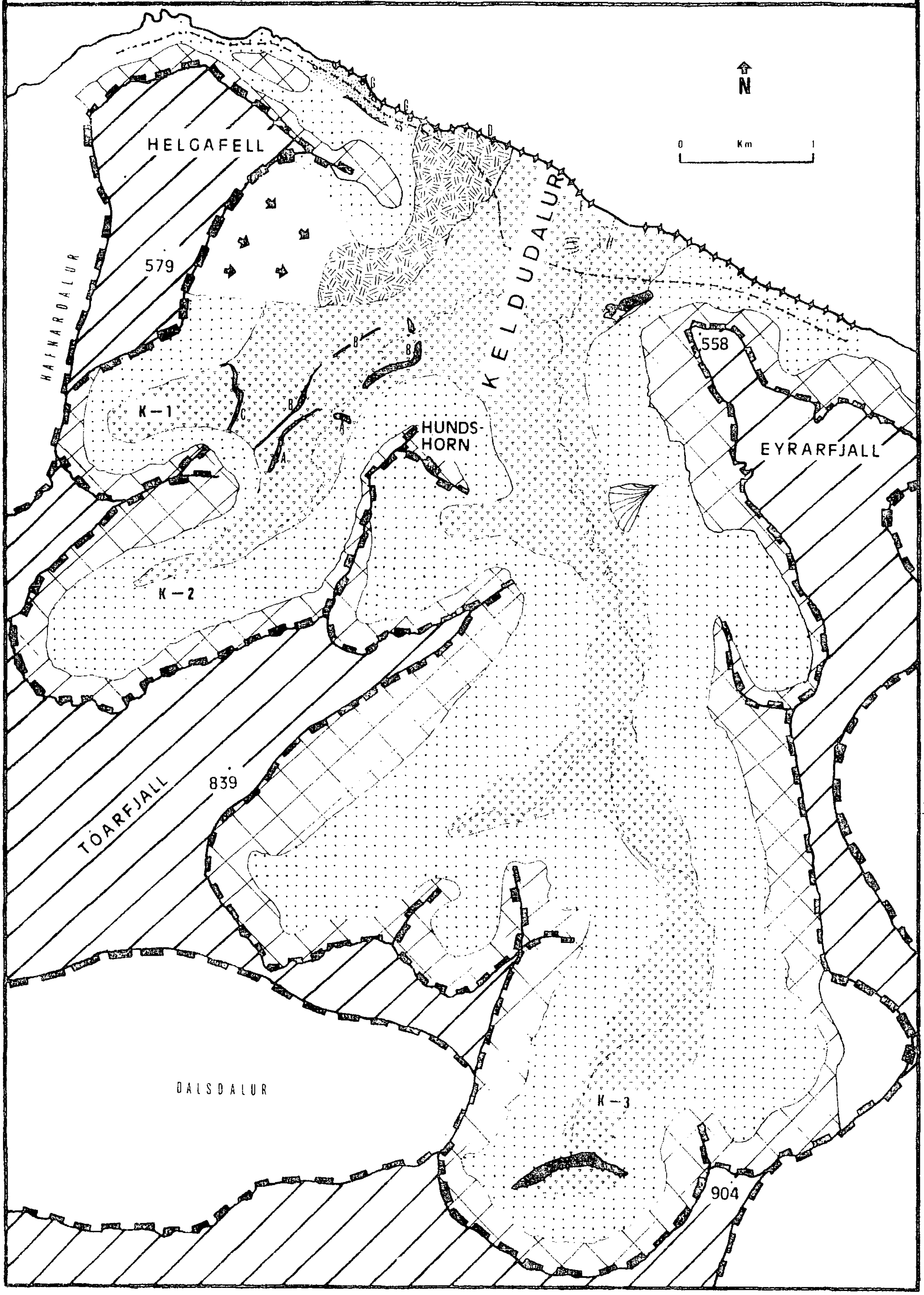
3.21. KELDUDALUR.

General morphology. Keldudalur is 7-8 km long. The main valley is cut south into the plateau and is lined by 5 cirques. Near the mouth a tributary valley opens into it from the west near the head of which are two cirques (fig. 3.61.).

KELDUDALUR

FIG.3.61

Glacial Geomorphorphology and Shorelines



Glacial geomorphology. At the head of K-3 (Geldingadalur) is a long and prominent ridge, double in places. It faces due north and is located behind a 900 m high plateau remnant. Because of its form and location it is interpreted as an end moraine.

The valley floor below K-3 is covered with featureless till.

Just outside the mouth of K-2 (Gjálpardalur) is a 4-5 m high, curved ridge, broken where the stream runs through. It is interpreted as a terminal moraine merging into a lateral moraine (marked A-A on fig. 3.61.). Outside lateral moraine A, higher up the slopes in front of cirque K-1, is a terrace with an uneven surface continuing on the gentler slopes shorewards as a ridge about 2 m high and 5 m wide (marked B-B in fig. 3.61.). On the other side, on the lower slopes of Hundshorn below terminal moraine A, is another terrace, with an uneven surface and curving at its lower end into a ridge about 5 m high and 20 m wide (marked B in fig. 3.61.). The ridge is broken where the stream runs through it. This feature is interpreted as a lateral moraine merging into a terminal moraine.

The floor of cirque K-1 (Strengbergshvilft) is covered with relatively thick till with an uneven surface and a relief of about 2-4 m. On its lower end the till is bounded by a low ridge (marked C in fig. 3.61.), about 2-3 m higher than the ground immediately inside the ridge but about 5-7 m higher than the ground outside it. This ridge is interpreted as a terminal moraine.

At the mouth of Keldudalur is a relatively large lowland area covered with thick loose deposits. On the western side landslide debris covers the floor, the landslide originating on Helgafell, the mountain west of the valley. East of the landslide is a large area of till having an uneven surface. Both the landslide debris and the till terminate at the shore in cliffs mostly 30-40 m high (aneroid, contour map). In these cliffs are many small, discontinuous exposures. At a place marked D in fig. 3.61. the coastal cliffs are 28 m $\pm$ 3 m (aneroid) high and an exposure showed that the landslide debris there is about 5 m thick. The underlying deposits are badly exposed, at the most each section was about 2-3 m in height. Along the entire coastal cliffs the same was observed: bedded silts are exposed at the base while higher up well rounded and bedded sands and gravels are exposed. The sands and gravel deposits were found to be highest just west of the stream (marked F on fig. 3.61.) where they are at an altitude of 30 m $\pm$ 2 m (aneroid), and are overlain by till. The deposits underlying the till and the landslide debris are interpreted to be marine because of their great rounding, sorting and the bedding. The landslide debris and the till are older than the marine deposits. No stratigraphic evidence was found, however, to indicate age relations between the till and the landslide debris. The lowest altitude at which till was observed in the cliff-face is at 17.5 m $\pm$ 2.5 m (aneroid).

On the eastern side of the valley, along the side of the mountain Eyrarfjall, is a very narrow terrace with an uneven surface which dips towards the sea (fig. 3.62.). The feature is on a scree slope while the slopes below it are till-covered. It is interpreted as a lateral moraine.

Discussion. A glacial readvance has taken place in Keldudalur, the glacial landforms there, unaffected by marine action, are well below the marine limit in Dýrafjörður. During the readvance the glacier must have advanced into the fjord because the till reaches the sea cliff.

Because no shorelines were observed it was not possible to determine the height of sea level when this readvance took place. However, the lowest altitude at which the till in the cliff-face was observed is at 17.5 m $\pm$ 2.5 (aneroid). This indicates that sea level during the readvance was lower than this altitude. This, if true, accounts for the lack of shorelines in the Keldudalur area since the coastal cliffs are everywhere 20 m or higher.

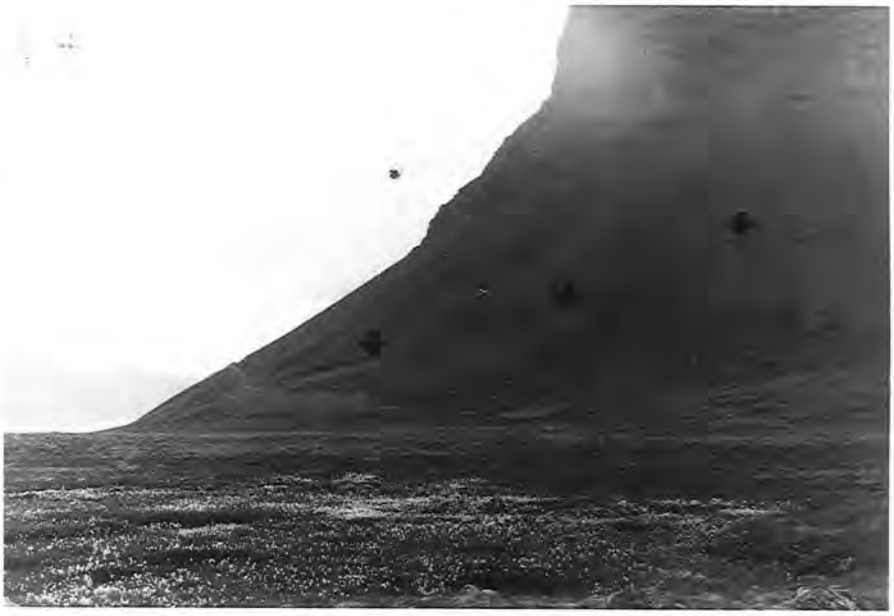


Fig. 3.62. Eyrarfjall seen from Keldudalur.Arrows point to sloping terrace feature.

The deposits underlying the till and the landslide debris in the coastal cliffs are argued to be marine in origin.

This is supported by the structure and texture of the deposits as related earlier. The distribution of the deposits, they are exposed in cliffs 1 km long, also suggests marine origin. Furthermore, the deposits are located very close to the present shore, and sea must have inundated the valley to some degreee prior to the readvance.

In front of cirque K-2 there are end moraines (A and B in fig. 3.61) indicating two glacier positions post-dating the culmination of the readvance stage in Keldudalur. The age of the moraines is unknown, they could have formed during the ice retreat after the readvance stage in Keldudalur, or during a readvance post-dating this. The same applies to the end moraine at the mouth of K-1. The cirque moraine in K-3 is a very prominent feature, it is likely that it formed in a climatically induced readvance post-dating the readvance in Keldudalur.

The age-relation of the landslide debris to the till is unknown, but both are younger than the marine deposits underlying them.

Conclusion. There is geomorphological and stratigraphical evidence for a readvance of a glacier in Keldudalur. Very likely it took place when sea level was lower than 17.5 m $\pm$ 2.5 m. It is likely that in one, and possibly three, cirques local glaciations took place after the readvance.

3.22. HELGAFELL.

General features. Helgafell is the mountain between Keldudalur and Hafnardalur (fig. 3.61). On the side open to the sea this mountain slopes steeply down to the sea level.

Recent roadcuttings, marked G-G on fig. 3.61, offer in many places good exposures in the deposits covering the lower reaches of the mountain slope.

The deposits. The exposures along the road are mostly 3-5 m in height and show everywhere very well rounded coarse gravel and cobbles with occasional beds of well sorted, coarse sand. The beds dip at an angle of 20-25° towards the fjord. The cobbles are commonly 10-20 cm across, and larger ones not uncommon. Above this exposure along the road the slopes are covered with talus until a terrace with the backend at an altitude of 89 m ± 6 m (aneroid) is reached. The backslope of the terrace is the bedrock slope of the mountain. The surface of the terrace is covered with talus, mostly angular cobbles, so that its original surface is perhaps 2-3 m lower. The terrace has limited distribution as shown on fig. 3.61. West of the terrace the slopes are steeper and loose deposits on them thinner, and mostly covered with a veneer of talus. Occasionally there are exposures through the talus into well rounded gravels. The highest exposure of these rounded gravels was found at height of 77 m ± 5 m (aneroid). Above this are bedrock cliffs.

Interpretation. The deposits exposed along the road on the northern slopes of Helgafell are interpreted to be marine in origin. The reasons are:

(1) The tabular planar cross-bedding of the deposits indicates deposition off a bank, in this case down the outer slopes of a marine terrace.

(2) The high degree of rounding of the material and its coarseness indicate that it was formed in a high energy

environment.

Wave action on a large scale must be attributed to ocean waves with large fetch. This effectively rules out the possibility of deposition in an ice-dammed lake, since fetch, and, therefore, wave action would in that case have been very small and, in any case, ice-dammed lakes are short-lived phenomena.

It has been suggested to the author (Haukur Tómasson, pers. comm. 1978 and M.J. Alexander, pers comm. 1978) that the deposits under discussion represent a kame terrace, fluvio-glacial deposition along the margin of the fjord glacier. The tabular planar cross-bedding, the coarseness and the shape of the deposits argues strongly against this possibility. Besides, the slopes are so steep that had a kame terrace formed it very likely slumped when the glacier retreated.

The upper limit of these deposits must be taken as a minimum value for wave action on these slopes. The marine limit could well have been higher. Because the slopes are so steep the beach material could have been easily eroded away by marine action during the regression.

Conclusion. On the northern slopes of Helgafell there is evidence, argued to be conclusive, for marine action up to 77 m ± 5 m. This figure is a minimal value for marine wave action on these slopes.

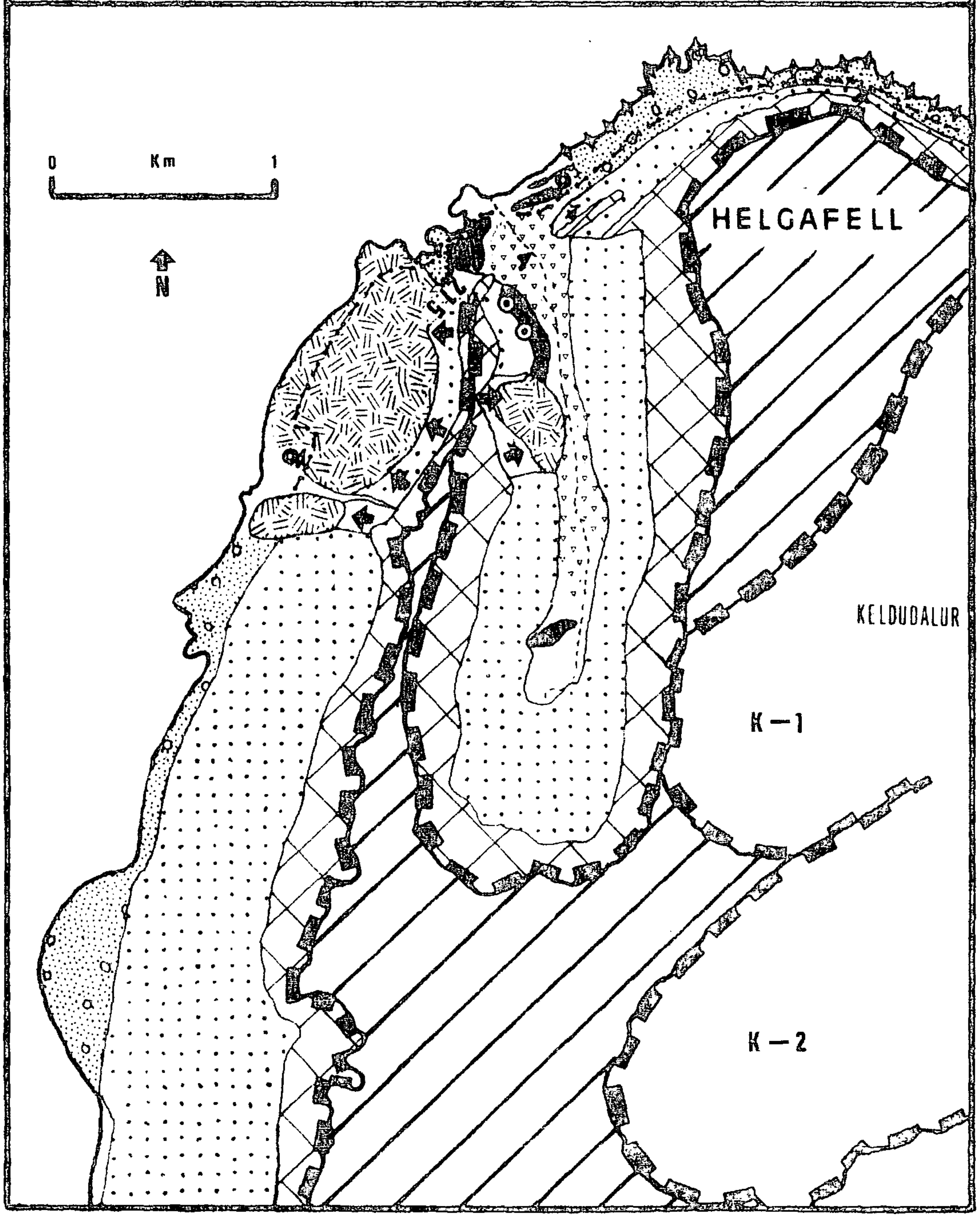
3.23. HAFNARDALUR.

General morphology. Hafnardalur is a hanging valley some 2.5 km long and cuts almost due south into the plateau on the tip of the peninsula between Dýrafjörður and Arnarfjörður with its mouth ending at 90 m ± 10 m (contour map) (fig. 3.64).

HAFNARDALUR — HELGAFELL

FIG.3.64

Glacial Geomorpology and Shorelines



Glacial geomorphology. Near the head of the valley is a low, 1-2 m high, wide ridge. Inside it is the site of a former lake, now filled with peat. The ridge is interpreted to be a terminal moraine because of its form and position.

In front of Hafnardalur is a very prominent ridge, over 10 m in height and 100- 200 m wide, and double in places. It is broken in the middle where the stream has cut through it. Near the western side the ridge curves around and continues to the step at the valley mouth where it breaks but continues in the valley for a short distance before it disappears under debris from a large landslide. This ridge is interpreted as an end moraine, a lateral moraine merging into a terminal moraine. Circular depressions on the lateral moraine are interpreted as kettle-holes.

West of the lateral moraine part in front of the valley is a well developed terrace where the moraine forms the back-slope. Its backend is at an altitude of 21.5 m $\pm$ 3 m (aneroid). The terrace is strewn with very well rounded pebbles and cobbles. It is interpreted to be marine in origin. This shoreline was not found further east because the coastal cliffs there exceed 20 m in height. Most of the coastal cliffs are in bedrock.

At the mouth of Hafnardalur, at an altitude of 86 m $\pm$ 5 m (aneroid) (Grid. ref. UP131135) (marked y on fig. 3.64.) was observed a small patch (about 10 m^2) of very well rounded pebbles directly on the bedrock. The rounded pebbles were in obvious contrast to the rather angular glacial deposits surrounding them. This rounded material is thin, mostly less than 1 m.

Just east of Hafnardalur, on a steep slope of Helgafell covered with talus (Grid.ref. UP718138) (marked Z in fig. 3.64.)

very well rounded gravels were observed at an altitude of 94.5 m ± 4 m (aneroid). The deposits are less than 1 m thick and were observed in one place only, their area being about 15-20 m^2.

Discussion. A glacial readvance has taken place in Hafnardalur, the glacial landforms in front of the valley, unaffected by marine action, are well below the marine limit in the area. The marine terrace at 21.5 m may have been formed simultaneously with the moraine, but there is also the possibility that the terrace was formed during a later transgression after the formation of the moraine.

Explanation for the presence of the rounded pebbles at the mouth of Hafnardalur (y on fig. 3.64.) could include some of the following:

(1) The deposits are marine in origin and must, therefore, because of their height, 86 m ± 5 m, predate the glacier readvance. In that case they could be remnants of formerly more extensive deposits which were later partially removed during the glacier advance. The reason why all of the deposits were not removed could be that perhaps the advanced state of the glacier was short-lived. It is much more likely, however, that the deposits, which are on the steep slope just below the valley floor, could have survived in the lee under a cavity in the ice. This cavity would have formed because the ice could not yield to the sharp break of slope above.

(2) The deposits are related to the activity of the glacier. In that case the pebbles most likely got their high degree of rounding through transport by the glacial melt water stream. This interpretation is unlikely because it is improbable that their high degree of rounding could have been

achieved over the very short transport distances available, the valley only being about 2 km in length. Also, the fact that the deposits are very localized and that they are situated on a slope, makes this interpretation untenable because one would expect to find them in many more places.

(3) The deposits were formed in much the same way as in (1) but in a lacustrine environment, in a ice-dammed lake.

Comparing these three hypotheses it seems that (2) is least likely. The available evidence, however, does not make it possible to distinguish between marine or lacustrine environment.

Similarly, the deposits just east of Hafnardalur at an altitude of 94.5 m $\pm$ 4 m could either have been deposited in a marine or a lacustrine environment. The available evidence is not sufficient to make it possible to distinguish between the two. It is pointed out, however, that in light of the evidence for a marine limit at 111 m, at least, in the Núpur area, and the difficulty in envisaging an ice-dammed lake at the locality, a marine origin for these lower deposits in Hafnardalur is very probable.

Conclusion. A glacial readvance took place in Hafnardalur when sea level was at or lower than 21.5 m $\pm$ 3 m. Well rounded deposits at an altitude of 86 m $\pm$ 5 m at the mouth of Hafnardalur, and at 94.5 m $\pm$ 4 m just east of the valley are most likely marine in origin.

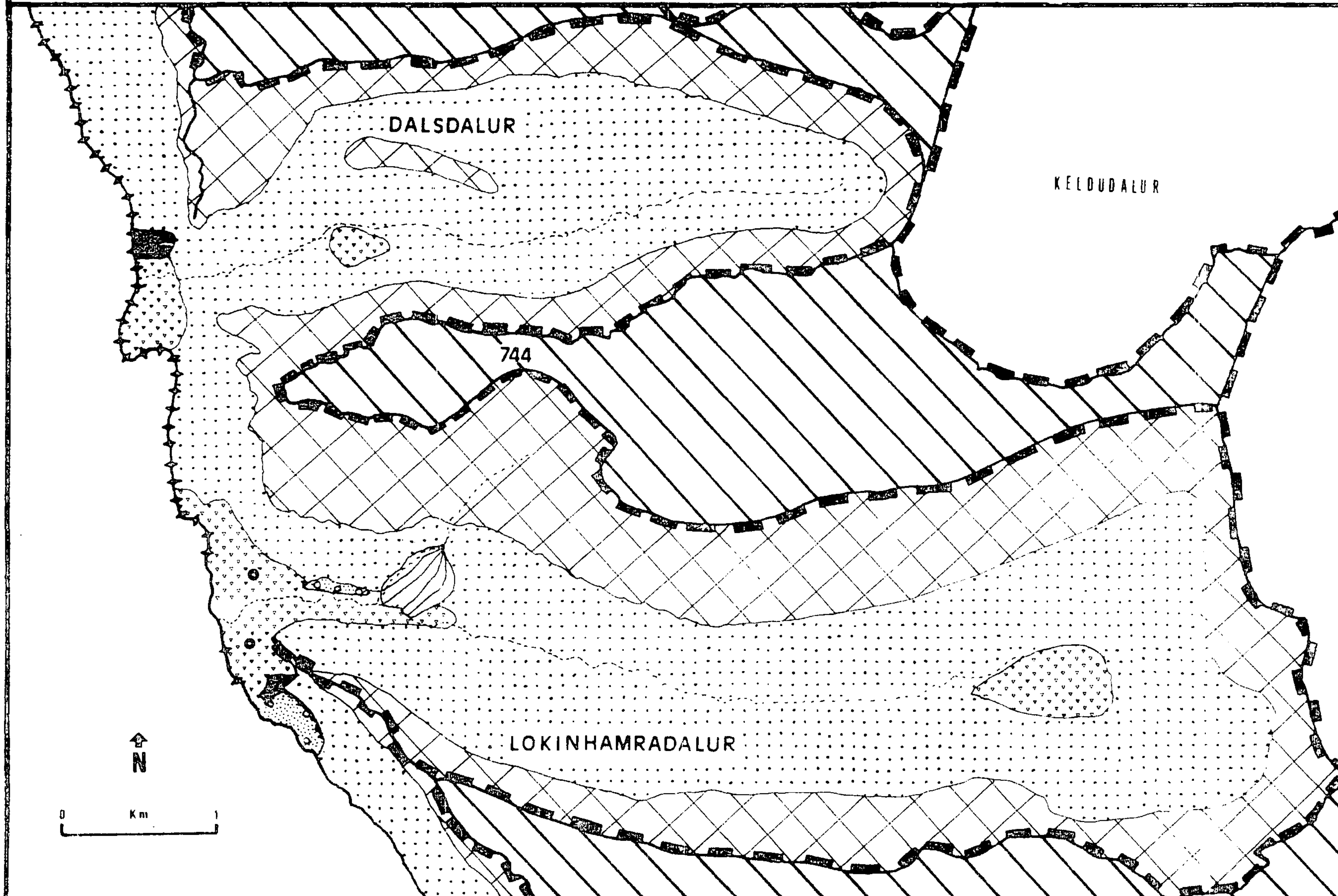
3.24. DALSDALUR.

General features. The coastal area between Hafnardalur and Dalsdalur (figs. 3.64. and 3.65.) is mostly covered with talus which in many places reaches right down to sea level.

DALSDALUR — LOKINHAMRADALUR

FIG. 3.65

Glacial Geomorphology and Shorelines



shorelines or glacial landforms were not observed there.

Dalsdalur is 4 km long and is cut due west and almost straight into the plateau from Arnarfjörður. It is separated from the cirque K-3 Keldudalur only by an arete. North of Dalsdalur is an extensive plateau area, Tóarfjall, sloping west, the same way as Dalsdalur (fig. 3.61.).

Glacial geomorphology. Just north of the stream, outside the valley mouth is a prominent but short, double ridge. It is about 100-150 m wide and rises 15-20 m above the surrounding ground, at its highest it is over 40 m above sea level (contour map). No shoreline landforms were observed in the area, probably because all the coastal cliffs are higher than 20 m.

Discussion. Little fieldwork was done in the Dalsdalur because no shorelines were observed and the relevant height data could be read from the contour map.

The double ridge just outside the mouth of the valley is interpreted to be a lateral moraine, formed during a glacial readvance. This readvance took place when sea level was lower than 20 m, this being the height of the coastal cliffs, and there are no signs of sea level above them.

Conclusion. A glacial readvance took place in the valley when sea level was lower than 20 m.

3.25. LOKINHAMRADALUR.

General morphology. Cutting west into the plateau Lokinhamradalur is 6 km long and averages 1.5- 2 km wide (fig. 3.65.). At the head of the valley are two small cirques. The mountains at the head of the valley reach a height of over 900 m.

Glacial geomorphology. South of the valley mouth there is a prominent ridge, interpreted to be a lateral moraine (fig. 3.65). The moraine is situated 500 m south of the stream and in front of a mountain ridge which defines the southern side of the valley. Directly above the moraine the mountain ridge has a height above sea level of 200 m (contour map). There is evidence on the ridge that it has been overridden by ice, but no way of telling if this was during the main glaciation or the readvance. In any case, the glacier must have been over 200 m thick less than 300 m from the shore to overrun the ridge. This is unlikely to have happened during the readvance and probably the glacier came around the ridge at that stage.

Inside the moraine there is a rough till surface extending to the stream. North of the stream this till surface is much smoother and has been extensively cultivated. No end moraines were found there. Outside the lateral moraine is a very well developed terrace, interpreted as a marine shoreline. Its altitude is less than 20 m (contour map).

The valley floor is everywhere covered with till except where there are debris cones and talus. However, about 500-800 m from the shore, on the north side of the stream, west of the alluvial fan, is an extensive body of well rounded, bedded gravels. The gravels are coarse, 10 cm cobbles being not uncommon. The beds are horizontal. The surface of these gravels is at an altitude of about 60 m ± 10 m (aneroid) and they extend for some 300 m along the river. Local relief there is very low and therefore it was not possible to see if the deposits were overlain by till or colluvium from the mountain slope above.

Discussion. A glacial readvance took place in the valley when sea level was lower than about 20 m. The location of the lateral moraine shows that during this readvance the glacier must have been advanced into the fjord, possibly calving.

The presence of the gravel deposits at an altitude of 40-60 m well inside the limits of the readvance seems problematical. The bedding, high degree of rounding and the coarseness of the deposits indicate a high energy environment. It is argued that this must have been a marine environment, the valley being exposed totally to the south-west and west and fetch therefore being very large. Also, alternative high energy environments are not obvious in this valley. Assuming that the deposits are marine in origin the glacier must have overridden them during the readvance without totally destroying them.

The backslope of the terrace outside the moraine is partly the lateral moraine, partly the mountain slope. The moraine and the terrace are, therefore, assumed to be synchronous although the possibility that the terrace was formed during a transgression after the readvance, cannot be ruled out.

Conclusion. A glacial readvance took place in Lokinhamradalur when sea level was lower than 20 m.

3.26. STAPADALUR.

General morphology. Stapadalur is a straight valley, 5,5 km long with a ENE orientation (fig. 3.66).

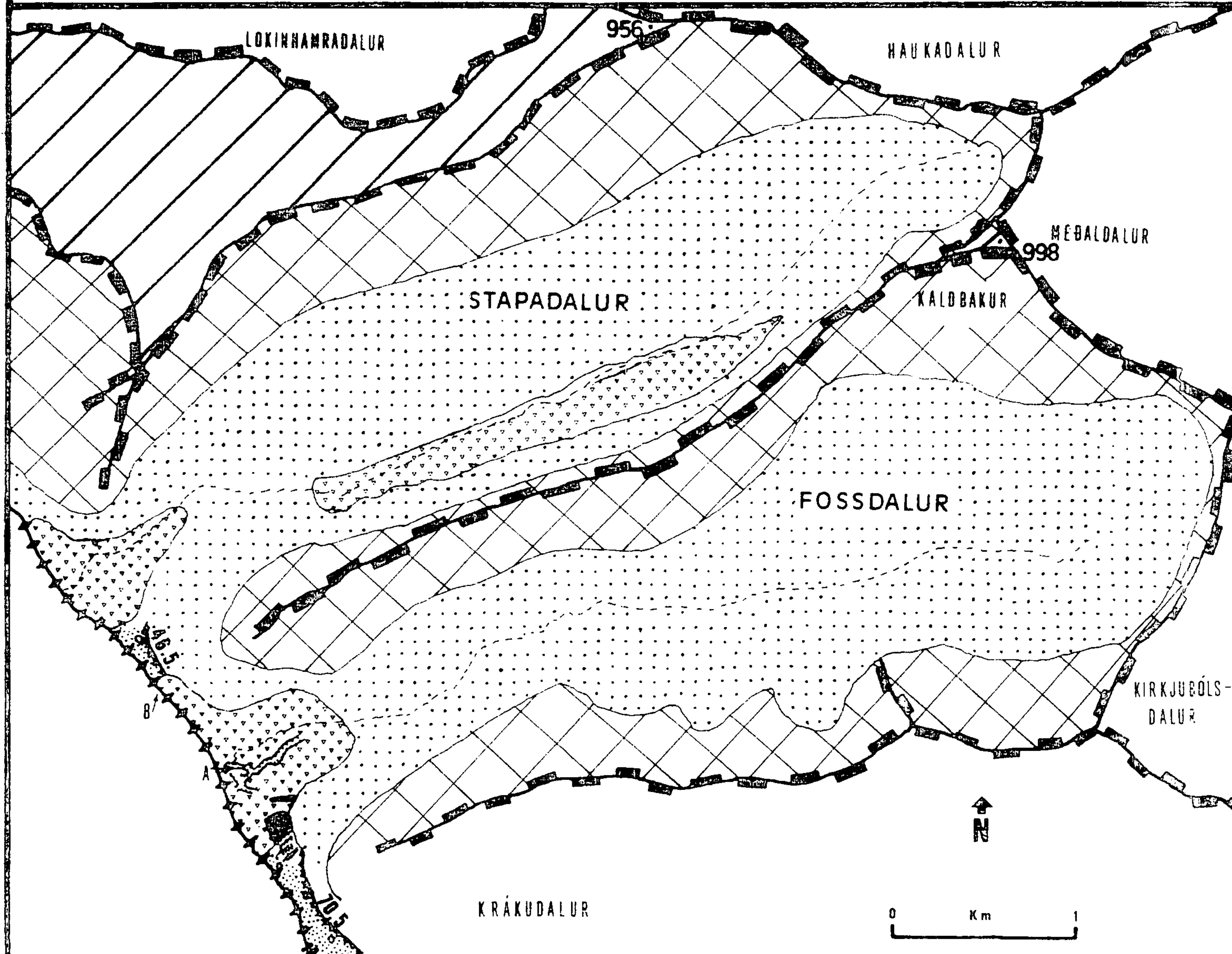
Glacial geomorphology. Stapadalur was visited only briefly in the field and no obvious landforms of glacial deposition or shorelines were observed (fig. 3.66). Air-photo interpretation, however, has revealed that the valley floor near the mouth is covered with thick deposits which from the surface morphology are in all probability glacial.

Discussion. Neither end moraines nor shoreline landforms were observed in the field or detected on the air-photos.

FIG. 3.66

STAPADALUR — FOSSDALUR

Glacial Geomorphology and Shorelines



The landforms in front of the valley are rather smooth, but are most likely glacial in origin. These landforms are at an altitude of 20-50 m (contour map) and are, therefore, well below the marine limit of 111 m at Núpur which indicates that they were formed after the marine limit was reached.

The lack of end moraines suggests the possibility that these landforms were formed during the deglaciation of the main glacier in the fjord. This possibility can be ruled out, however, on the ground that it necessitates that deglaciation of Arnarfjörður was much slower than that of Dýrafjörður. That this is not tenable is concluded from the evidence presented in the next sections.

In view of this, and assuming that these landforms are glacial, a readvance must have taken place and these glacial landforms formed then. Sea level must have been lower than 20 m then because shoreline landforms were not detected above this altitude. The landforms are so vague, however, that they are not conclusive indications of a glacial readvance.

Conclusion. There are certain indications that a glacial readvance took place in the valley when sea level was lower than 20 m. It is by no means certain, however.

3.27. FOSSDALUR.

General morphology. Fossdalur is aligned parallel to Stapadalur and these two valleys are separated only by a narrow and sharp mountain ridge mostly about 500 m high. Fossdalur widens towards its head where there is a very large valley-head cirque (fig. 3.66.).

Glacial geomorphology. At the mouth of Fossdalur are thick deposits. South-east of the valley mouth are two ridges (fig. 3.66.). The outer one has a relative height of about 5-6 m and is c. 100 m wide. The inner one is lower, 2-3 m high and much narrower. The altitude of these ridges is 50-60 m (contour map). Because of their form and association with other landforms, they are interpreted as being lateral moraines. Outside the outer moraine is a marine terrace with a backend at an altitude of 70.5 m $\pm$ 3 m (aneroid) with the mountain side forming the backslope. Immediately east of the lateral moraine are three short but quite deep (ca. 2 m) melt water channels which are incised into the terrace surface which shows that the channels are younger than the terrace (fig. 3.68.). The channels are separated by till. The front of the terrace has been heavily gullied (fig. 3.67.) and there are many sections exposing the deposits, albeit discontinuous. Generally these sections show bedded sands and gravels, everywhere very well rounded. The beds are inclined at an angle of about 15-20° and the dip is towards the sea. In one place, at an altitude of 41.5 m $\pm$ 2.5 m (aneroid) is a section showing bedded silts.

Inside the inner moraine is a rough till surface cut right through just east of the stream by a deep melt water channel which starts abruptly in the till about 400 m from the shore and joins the channel of the present stream close to the shore. In the steep river bank near the mouth, well inside the lateral moraines, is a section showing very well rounded pebbles and cobbles, marked A in fig. 3.66. It was not possible to see if these deposits are bedded. These deposits have a very sharp upper limit at an altitude of 44 m $\pm$ 2 m (aneroid) and are overlain by till.

North-west of the stream, at the valley mouth, are moraine hummocks stretching half way towards Stapadalur. West of these is the backend of a marine terrace with most of the terrace itself having been removed by recent marine action. The terrace backend is at an altitude of 46.5 m $\pm$ 3 m (aneroid). The surface of the terrace is covered with rounded pebbles. The backslope of the terrace is the mountain side. It is apparent that the glacial deposits east of the terrace were laid down on the terrace (fig. 3.69.). In front of the terrace is a steep coastal cliff. In one place, marked B on fig. 3.66., is a section containing bedded silts at an altitude of 25.5 m $\pm$ 2.5 m (aneroid). The silts are overlain by well rounded, coarse gravels containing occasional boulders. The gravels and the silts continue eastwards far enough to actually underly the glacial deposits.

they indicate four different positions of the ice margin during the readvance. The distance from the western-most lateral moraine to the easternmost channel, however, is only about 300 m, so these different ice marginal positions only reflect minor oscillations of the ice margin during the readvance stage.

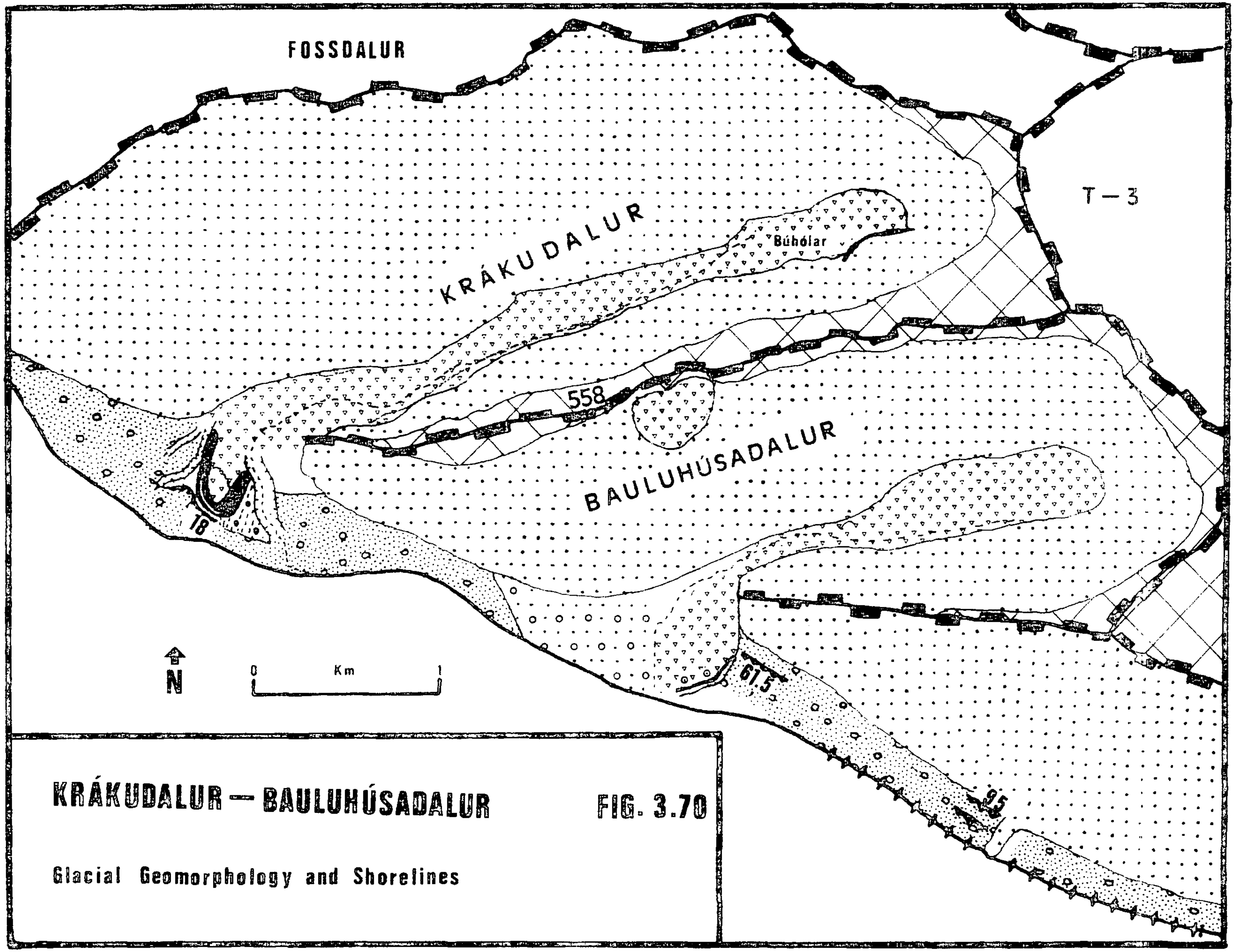
The position of the lateral moraines and the till inside them, which has been truncated on the seaward side, shows that the glacier was advanced into the fjord during the readvance stage.

Conclusion. There is geomorphological and stratigraphic evidence at the mouth of Fossdalur for a glacial readvance in the valley. Sea level during this readvance was lower than 46.5 m $\pm$ 3 m (aneroid). There is evidence for four different positions of the ice margin during the readvance.

3.28. KRÁKUDALUR.

General morphology. Krákudalur is 4 km long and 1 km wide, with a cirque at its head. The bedrock geology is much influenced by the Hrafnseyri central volcano with its varied rock types. The mountain side is completely covered with talus and other colluvium (fig. 3.70.) which shows how prone the rock formations are to weathering and erosion. Talus covers most of the south-east mountain slope as well.

Glacial geomorphology. Outside the mouth of Krákudalur is a prominent, curved ridge which is double in places (fig. 3.70.). West of the ridge there are some dry channels which issue from the ridge and peter out on a terrace. The ridge is, because of its form and position, interpreted as an end moraine and the dry channels are interpreted as melt water



KRÁKUDALUR — BAULUHÚSADALUR **FIG. 3.70**

Glacial Geomorphology and Shorelines

channels for similar reasons. The terrace, interpreted as a marine shoreline, has its backend at an altitude of 18 m $\pm$ 3 m (aneroid). The terrace and the channels formed simultaneously since the channels peter out on the terrace and are slightly incised into it.

Near the head of Krákudalur are numerous, large hummocks, called Búhólar. These Búhólar attain in places relative heights of about 20 m. Inside these hummocks, below a NW orientated scree slope, is a long, curved ridge, mostly 10-20 m wide and about 3 m higher than the ground outside it but 1 m higher than the ground inside it. The ridge could either be an end moraine or a protalus rampart.

Discussion. A glacial readvance took place in Krákudalur when sea level was close to 18 m $\pm$ 3 m as shown by the glacial melt water channels which peter out at this altitude. The glacier must have been very thin at the terminus at this time since it did not spread out in front of the valley, but only formed a narrow lobe.

The hummocks Búhólar could either be moraine hummocks or be landslide debris. No scar or other evidence for them being landslide debris was observed so they are assumed to be glacial, possibly the result of ice stagnation. Possibly the hummocks are a mixture of landslide debris and till, a result of a minor landslide onto a glacier. A minor landslide need not to have left a scar which is easily recognizable to-day.

The ridge inside the Búhólar could either be an end moraine, in which case the glacier depositing it must have been very thin, the ridge located at the base of a scree slope, or a protalus rampart. In either case, its age is unknown.

Conclusion. A glacial readvance took place in Krákudalur when sea level was at 18 m $\pm$ 3 m. Possibly another readvance took place after this in the valley head cirque.

3.29. BAULUHÚSADALUR.

General morphology. Bauluhúsadalur is very large for a cirque, 2.5 km long and 1.5 km wide, and is surrounded by aretes and horns on all sides. On top of the ridge between Krákudalur and Bauluhúsadalur is a cirque remnant, with the headwall and most of the side-walls removed but the floor left intact (fig. 3.70.).

Glacial geomorphology. Outside the mouth of the valley is a lobe of till. The till has an uneven surface, with innumerable low hummocks and occasional small kettle-holes. A ridge, about 2 m high and about 15-20 m wide, borders the till on the south side and outside it is a steep cliff. The ridge is interpreted as an end moraine. West of the till colluvium hides the underlying deposits.

Along the eastern bank of the stream are four terraces, sloping a little gentler than the channel of the present stream (their location is marked A in fig. 3.70.). The uppermost terrace is the most prominent one, about 13-20 m wide. It ends in a steep coastal cliff at an altitude of 26 m $\pm$ 2 m (aneroid). The one below is also prominent, about 10-15 m wide and ends in the cliff at an altitude of 20 m $\pm$ 2.5 m (aneroid). The two lowest terraces are minor features, they were just visible. The terraces are interpreted as river terraces because of their location, along the present stream, and the fact that they have a similar slope as the channel of the present stream.

East of the moraine very well rounded material is observed everywhere and the landforms are smooth. Two shorelines were noted, one is a faint break of slope at an altitude of 51 m ± 2.5 m (aneroid) and the other is the backend of a terrace at an altitude of 61.5 m (aneroid).

Discussion. A glacial readvance has taken place in Bauluhúsadalur as shown by the till surface outside the valley well below the highest shorelines in the area (see later sections).

The river terraces must have formed when base level was higher than at present. Furthermore, they indicate that the base level was more or less stable for some time, while in between it fell sharply (although the possibility of oscillating sea level cannot be ruled out). The two highest terraces are such prominent features that glacial melt water was almost certainly involved in their formation, which means that the glacier was still in the valley when they were formed. The altitude of the end of the river terraces, therefore, should indicate the height of sea level during this readvance, sea level being lower than the end of the terrace when it formed. It can be concluded, therefore, that the uppermost terrace was formed when sea level was either near to 20 m ± 2.5 m, the height of the second terrace, or lower than the end of the uppermost terrace, 26 m ± 2 m. This is based on the reasonable assumption that the terraces were formerly more extensive and that marine erosion has removed their original lower end. Glacier retreat must have started before the terraces started to form, unless they were formed under the glacier which is not likely. It is concluded, therefore, that the glacier had started to retreat when sea level was between 20 and 26 m.

Conclusion. A glacial readvance has taken place in Bauluhúsadalur, The glacier had retreated from in front of the valley when sea level was between 20 and 26 m.

3.30. BAULUHÚSASKRIÐUR.

General morphology. Between Bauluhúsadalur and Tjaldanesdalur there is a 4 km long mountain side covered with talus, which in places almost extends down to the shore. Two large gullies are on the slope (fig. 3.71).

Shorelines. Immediately east of the largest gully, about 2 km east of the mouth of Bauluhúsadalur, shorelines occur. Their height was not measured in the field. They are all clear features on the air-photos, however, and their alitude range could be read with ease on the contour map. There are at least two shorleines in the altitude range 60-100 m. The altitude of the upper shoreline is 95 m ± 5 m (contour map). The exact marine limit could not be determined.

Conclusion. At least two shorelines occur in Bauluhúsa-skriður between the 60 m and 100 m contours. The upper shoreline is at an altitude of 95 m ± 5 m.

3.31. TJALDANESDALUR.

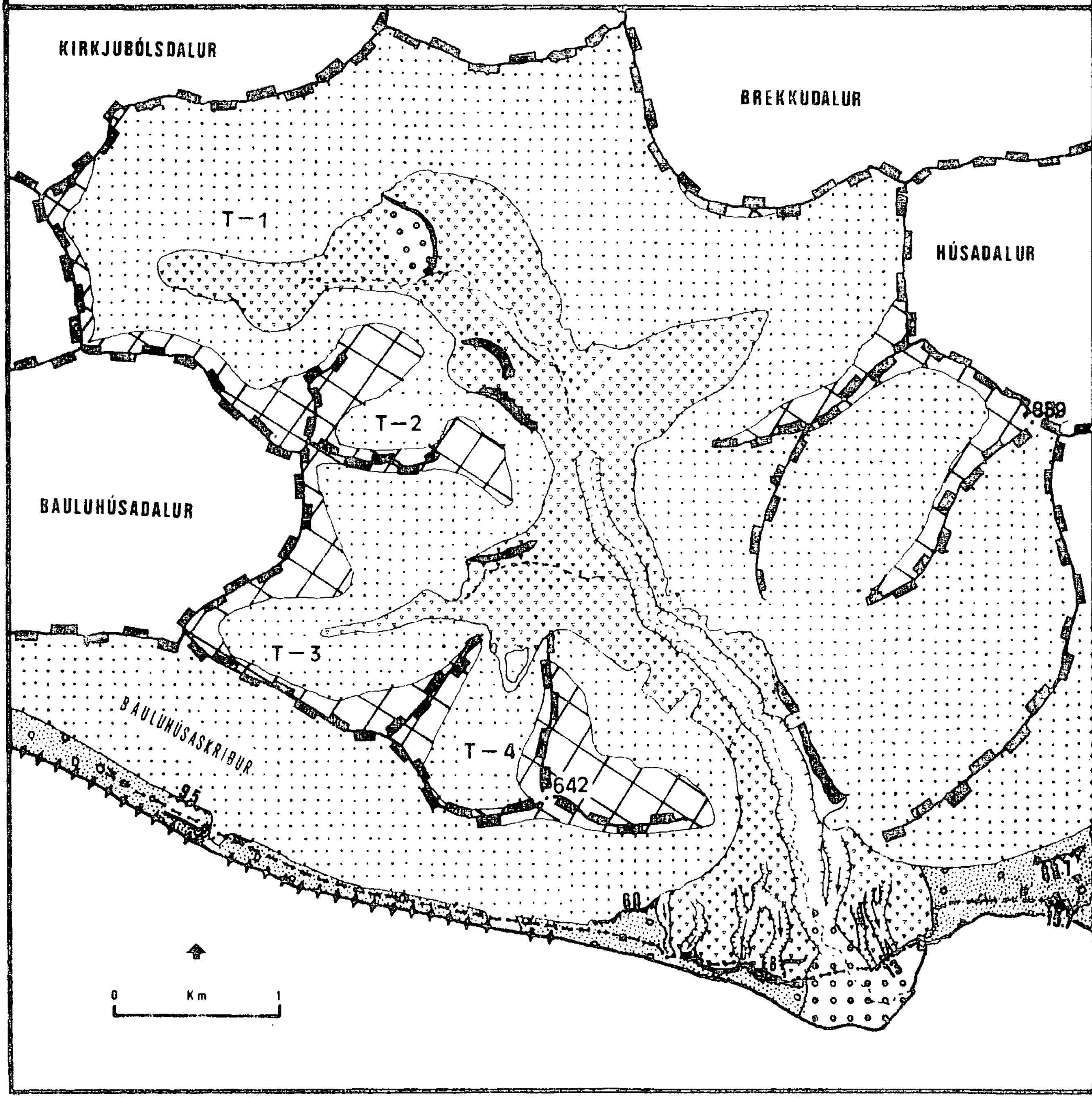
General morphology. Tjaldanesdalur is about 6 km long (fig. 3.71). Six cirques open into it. This system of valley and cirques is surrounded by aretes and horns. The bedrock geology is very varied with gabbroes and rhyolites outcropping in many places (Kjartansson, 1969). This is the centre of the Hrafnseyri central volcano.

Glacial geomorphology. At the head of the long valley-head cirque, here called T-1, is a low narrow ridge. In front of it is smooth till, characterized by wide, low ridges, possibly flutes, which are orientated in the direction of ice flow. Inside the ridge, however, there is drastic change in the landforms with typical ice-disintegration features

TJALDANESDALUR — BAULUHÚSASKRIDUR

FIG. 3.71

Glacial Geomorphology and Shorelines



predominant. These are mostly moraine hummocks with occasional kettle-holes in between. The ridge separating the two different landform types is interpreted as being an end moraine.

In front of cirque T-2 there is also a prominent end moraine lobe.

In front of cirques T-3 and T-4 there is a terrace made of till just above valley floor. It has an uneven surface and is because of its morphology and position interpreted as being a lateral moraine.

Very thick drift everywhere covers the valley floor. This is best exposed along the stream, the channel being more than 40 m deep in places, showing loose deposits everywhere. Lateral terraces, similar to the one associated with T-3 and T-4, and interpreted as lateral moraines, occur near cirque T-2 and near the valley mouth on the eastern side, the latter one only about 20 m above the valley floor.

In front of the valley there is also very thick drift which spreads out on both sides of the valley. The deposits there have innumerable small hummocks and short ridges on their surface. Several large melt water channels cut through the deposits, sometimes up to a depth of over 20 m. (figs. 3.74., 3.75., 3.76.).

The deposits are bordered at their western end by a melt water channel which is incised to a depth of 3-5 m into a terrace (fig. 3.72.). The terrace, which must be older than the channel, is very well defined (fig. 3.73.) and is strewn with rounded pebbles on its surface. The altitude of its backend is 60 m $\pm$ 5 m (contour map). The terrace is interpreted as marine because of its form and position.

In front of the glacial

mouth indicates that ice must have been very thin when it was deposited. This is taken to indicate that the glacier was retreating at the time, and most likely it was stagnant. This suggests that the features interpreted here as lateral moraines are really kame terraces. No signs of fluvio-glacial activity, however, were observed.

The end moraine in the valley-head cirque, with its associated ice-disintegration features, could have been formed during a readvance and later rapid glacier wastage. In that case, however, in light of the abundance of loose material, one would have expected the end moraine produced to be more prominent. It is more likely, therefore, that these landforms were formed during a halt and a later ice stagnation during general glacier retreat. The other possibility cannot be ruled out at all, however.

The great volume of drift in Tjaldanesdalur is explained by the varied rock types present. Easily weathered and eroded rocks such as rhyolites and tephras are interbedded with the basalts and andesites. A succession of interbedded resistant and non-resistant rocks is especially susceptible to mass-wasting.

Conclusion. A glacial readvance took place in the valley when sea level was at 13.0 m $\pm$ 1 m (level). Possibly a later cirque glaciation took place in the valley-head cirque (T-1).

3.32. HÚSADALUR - GILDRÖG.

General morphology. Húsadalur is a narrow valley, about 1 km wide, 5 km long and curved over most of its length. Gildrög lies just east of Húsadalur and is separated from it by a low ridge which, at its maximum, rises about 200-300 m above the floors of these valleys, gradually lowering towards the valley mouths (fig. 3.77.).

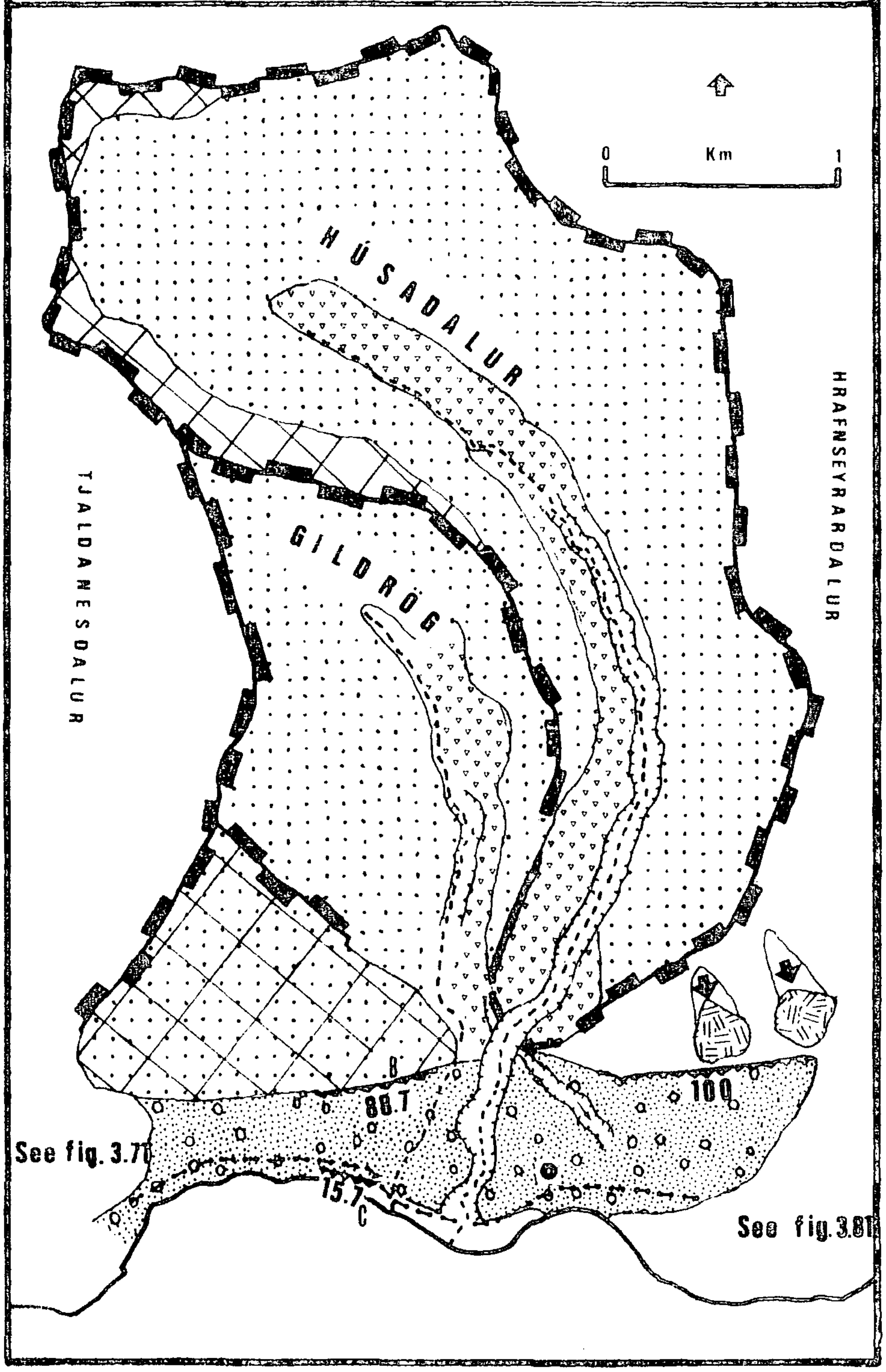
Glacial geomorphology. At the mouth of Húsadalur there is a distinct ridge which runs along the western side of the valley parallel to the stream for about 500 m before curving eastwards and crossing the valley, extending for some 200 m east of the gap formed by the present stream. The straight leg of the ridge is low and narrow, about 1 m high and 5 m wide. Further down, where the ridge is curved, it rises to about 2-3 m in height and a width of about 10-15 m (fig. 3.78.). The ridge is interpreted to be an end moraine, a lateral moraine curving into a terminal moraine at the front. Inside the lateral moraine is an uneven till surface of low relief, the maximum amplitude being of the order of 0.5 - 1 m. Outside the lateral moraine and in Gildrög the till surface is much smoother. This is taken to indicate that the lateral moraine was not a medial moraine between glaciers in Gildrög and Húsadalur, rather that only the glacier in Húsadalur was involved with its formation.

In front of both valleys, and stretching both east and west of the mouths, are very thick deposits and shoreline landforms. No good exposures revealed the structure of the deposits, but in the steep and high river-bank of Húsadalur river (marked A in fig. 3.77.) it was observed that the deposits are mostly coarse, large pebbles and cobbles commonly well rounded. Just east of the mouth of Húsadalur a melt water channel cuts through the deposits (fig. 3.79.). The channel starts immediately in front of the terminal moraine at the valley mouth and gradually peters out and merges with shoreline landforms without any clear break. The lowest signs of this channel were observed at an altitude of 19 m $\pm$ 2.5 m (aneroid) and it is deduced that sea level was at or close to this

HÚSADALUR — GILDRÖG

FIG. 3.77

Glacial Geomorphology and Shorelines



altitude when the channel was being cut.

The shoreline landforms east of Húsadalur are discussed under the section on Hrafnseyrardalur (3.32.).

Immediately east of the stream from Gildrög (marked B-C on fig. 3.77.) there are series of little terraces cut into the deposits up to a well defined

3.80. The terrace at 88.7 m west of Gildrög.

terrace at a height of 88.7 m $\pm$ 1 m (level) (fig. 3.80.). The backslope of this terrace is the bedrock slope of the mountain. Well rounded pebbles are common right up to it. The bedrock slope above the terrace is convex in profile, a clear indication of undercutting of the bedrock slope. Further up the bedrock slope, at an altitude of 135.2 m $\pm$ 1 m (level) there is a small abrasion terrace, very similar to the one at 148.4 m above Núpur. The terrace is only a few metres wide and it slopes outward rather steeply. It can be traced for most of the way to Tjaldanesdalur, a distance of 1 km.

At the base of slope B-C in fig. 3.77. is a well developed terrace at 15.7 m $\pm$ 1 m (level).

Discussion. A glacial readvance took place in Húsadalur when sea level was at 19 m ± 2.5 m, the height at which the melt water channel merges with the raised beach landforms. Since no particular shoreline was observed at this altitude sea level was probably not stationary at the time. The channel was probably occupied by melt water for only part of the time of the readvance and only when the glacier was at the terminal moraine. This is deduced because the channel starts to grow outside the terminal moraine (fig. 3.79.). The channel of the present stream is situated in such a way that most of the melt water must have been contained there.

The origin of the abrasion terrace at 135.2 m is uncertain. Further research is necessary including specialized investigations of the strength or weakness of the bedrock together with levelling the altitude of the feature at many points to find out if, and in which direction it slopes. At the present state of knowledge, however, it can only be considered likely that the predominant process involved in the formation of this terrace was wave action.

The terraces at 88.7 m and 15.7 m are interpreted to be marine in origin for two reasons mainly:

(1) The high degree of rounding and the coarseness of the deposits render untenable the possibility of genesis by wave action in a relatively small, ice-dammed lake, the only other wave environment.

(2) The locality is very exposed and no possible site for such a lake is present.

The lack of evidence for a glacial readvance in Gildrög, reasonably assuming that the smooth glacial landforms there are older than the glacial deposits in Húsadalur, is curious because the valley-head is at an altitude of 500 m, which is higher than the lip of the valley-head cirque in Húsadalur. Over most of its length, however, Gildrög faces almost due south, which renders it less susceptable to glaciation.

Conclusion. A glacial readvance took place in Húsadalur when sea level was at 19 m ± 2.5 m. Well developed shorelines were found at altitudes 15.7 m ± 1 m and 88.7 m ± 1 m. The marine limit could be as high as the abrasion terrace at 135.2 m ± 1 m.

3.33. HRAFNSEYRARDALUR.

General morphology. Hrafnseyrardalur is about 2 km wide and 6 km long with a wide, flat floor. Five cirques open into it. In the mountains east of the valley flood basalts gradually replace the varied rock types stemming from the Hrafnseyri central volcano and, consequently, large plateau areas become common again. Numerous large landslides line the western side of the valley (fig. 3.81.).

Glacial geomorphology. In Geldingadalur cirque (fig. 3.82.) is a very prominent ridge right at the head of the cirque (fig. 3.83.). The ridge is about 6-7 m high with steep sides (c. 25°) and is located near the foot of the scree slope. This ridge is interpreted to be a terminal moraine. Outside this is another ridge about 3-4 m high. At its northern end it turns abruptly to the north-east and lies there very close to the foot of the scree slope. The ridge is made of till and is also interpreted to be a terminal moraine.

Most of the valley-floor is covered with till except where landslide debris reaches the floor, but several landslides line the western side of the valley.

At the mouth of the valley is a very large and prominent,

HRAFNSEYRARDALUR

FIG. 3.81

Glacial Geomorpology and Shorelines

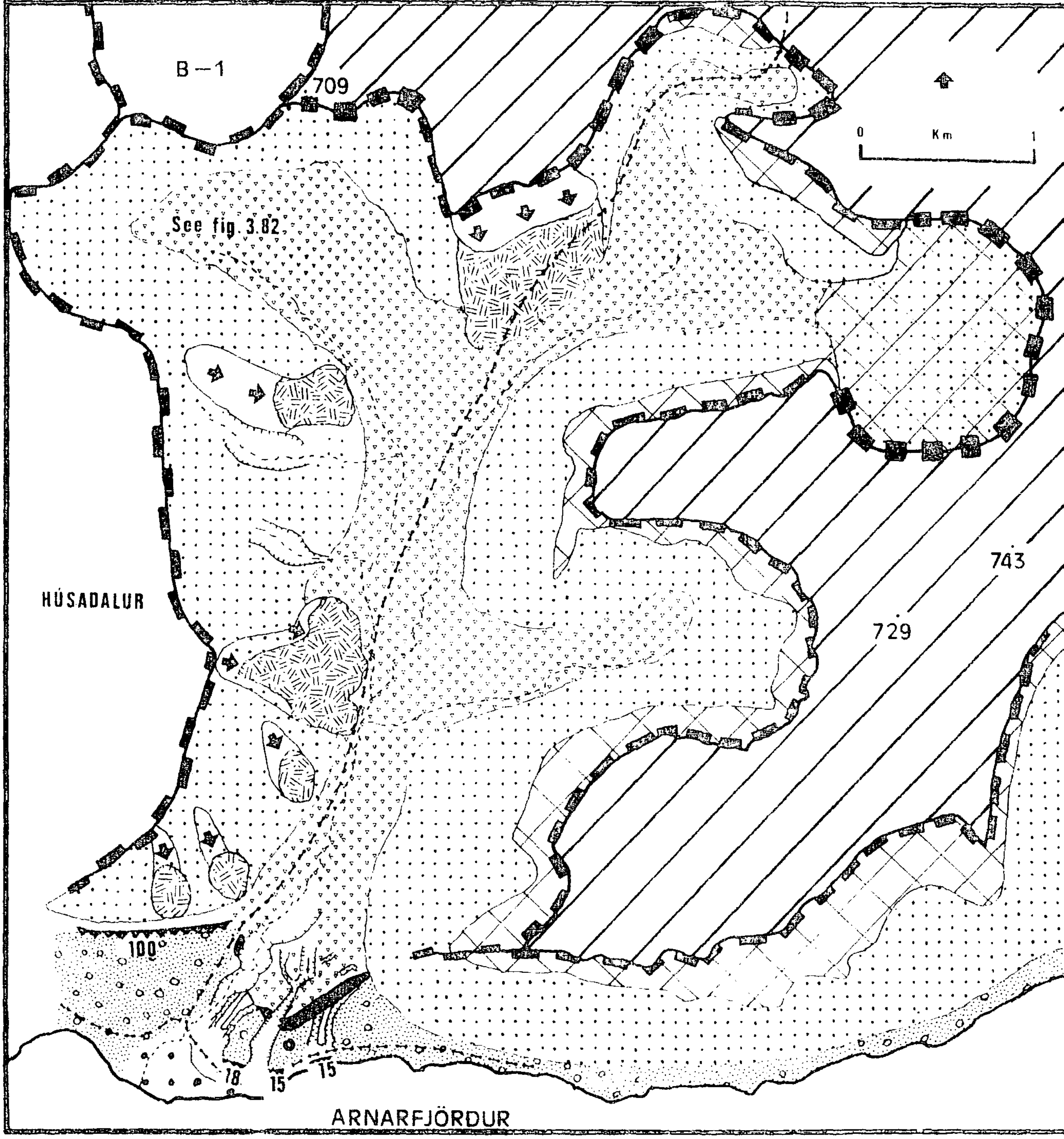
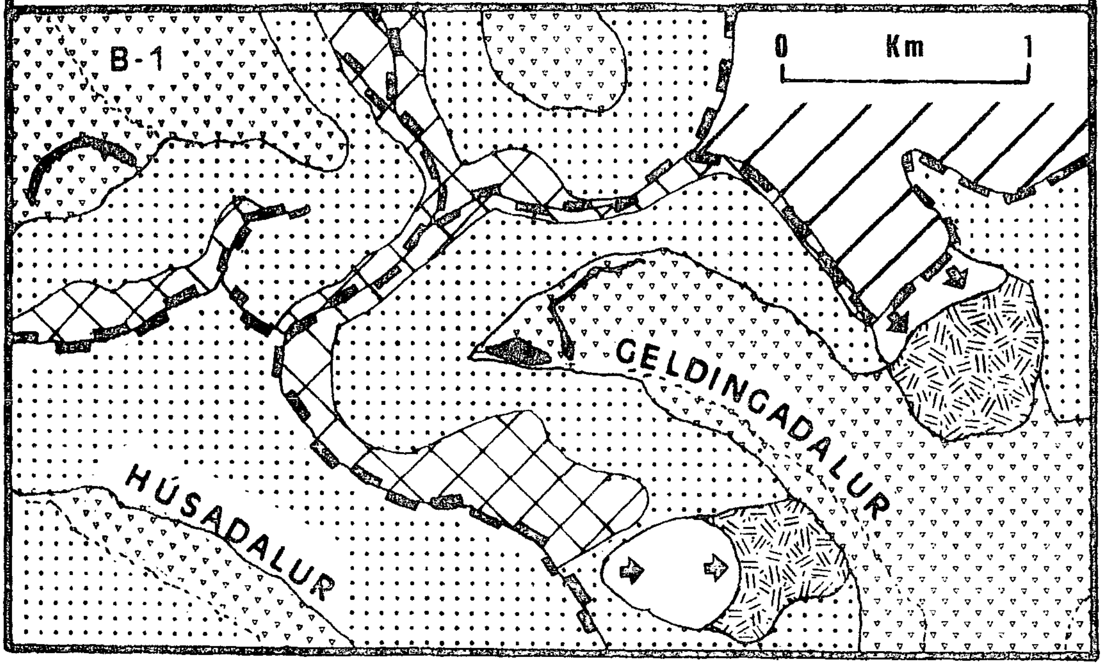


FIG. 3.82

GELDINGADALUR

MORAINES



curved ridge, exceeding in places 10 m in height. Almost all of it is located east of the stream, a short and less conspicuous segment lies west of the stream. The middle part of the ridge is broken by a dry channel. Several other dry channels rise right in front of the ridge. Because of their form, position and association with other landforms the dry channels are interpreted as melt water channels and the ridge as a terminal moraine. In front of the terminal moraine are shoreline landforms which at some time were smooth but are now variously dissected by the melt water channels. The one furthest east opens onto a terrace at an altitude of 15 m ± 3 m (aneroid). Two metres below the terrace edge is a section showing 1 m of bedded sands and gravels. The largest melt water channel is just west of the farm house. The backend of the terrace west of the channel is at 18 m ± 3 m while the backend of the one east of the channel is at 15 m ± 3 m (aneroid). The backends of the terraces are clearly a little higher than the floor of the channels. The channel peters out and merges with the terrace at an altitude of 13 m ± 3 m (aneroid). Although the error margins imply the possibility of equivalence of height of the terrace backends and the channel floor, the error in their relative altitudes is much less than their difference in height. The other channels also merge with the terrace. Because of its form, location and association with other landforms the terrace is interpreted to be marine in origin.

West of the stream there is only small moraine hummock, probably part of the end moraine.

Between Hrafnseyrardalur and Húsadalur there extends a terrace. Its backend is partly covered with talus and is therefore not very well defined. Its altitude is estimated as 100 m ± 10 m (contour map). Below this uppermost terrace is a straight slope down to 20 m, everywhere covered with peat-bog (fig. 3.84). Drainage ditches in the bog expose well rounded gravels beneath the peat cover.

Discussion. A glacial readvance took place in Hrafnseyrardalur. Sea level at the time can be determined as being the altitude where two melt water channels merge with their terraces, at or between the altitudes of 15 m ± 3 m and 13 m ± 3 m. The terrace altitudes at 18 m ± 3 m and 15 m ± 3 m match up, broadly speaking, with the channel heights. The mean of these four figures is about 15 m with a standard deviation of 1.8 m.

The terrace between Hrafnseyrardalur and Húsadalur at an altitude of 100 m ± 10 m is a prominent feature. It is

formed either in a marine or a lacustrine environment. Because there are no exposures into the deposits worth speaking of it is not possible to distinguish between the two environments on the basis of sediment structure and texture. A marine environment is favoured, however, since this location is an unlikely site for an ice-dammed lake.

The age of the moraines in Geldingadalur is unknown. It is considered likely, however, that the inner moraine, because of its size, was formed in a significant glacial advance rather than that it formed during a minor halt in the deglaciation of the valley after the readvance in Hrafnseyrardalur. The outer moraine is less conspicuous and hence it is less likely that it formed during a significant glacial advance.

Conclusion. A glacial readvance took place when sea level was close to 15 m ± 2 m. A wave-cut terrace is observed at an altitude of about 100 m ± 10 m and is likely to be marine in origin. At the head of Geldingadalur are two moraines of unknown age.

3.34. SUMMARY OF PROCESSES.

The main contents of this chapter are synthesized and developed further in subsequent chapters. In this section is presented a summary of the processes during the deglaciation of the area which gave rise to the present landforms.

The oldest landforms are the marine limits around 110 m in the Núpur-Garðshlíðar-Mýrarfell area. They are believed to be formed at the instant of deglaciation (see sections 4.4.5 and 4.4.6). Layer E of the Smiðjumór section (see section 3.7), interpreted to have formed at least partly under floating ice, is probably similar in age, but may be somewhat younger.

Then comes a period of unknown duration during which sea level fell. Then were formed shorelines of intermediate heights (c. 30-90 m). The implications of the spatial distribution of these shorelines are discussed in section 4.5.3.

When sea level had fallen below c. 30 m glacial readvances took place in all the valleys in the area with the possible exception of Stapadalur. Then were formed the glacial landforms and shorelines which are so prominent at the mouth of many of the valleys. The age relations of the glacial landforms and shorelines and the question of the synchronicity of the glacial readvances are discussed in section 4.5.2.

Finally, some time after the deglaciation of the valleys there very likely occurred glacial readvances in many of the cirques. This is discussed in section 4.5.4.

CHAPTER 4. GLACIAL CHRONOLOGY AND SHORELINE DISPLACEMENTS IN VESTUR-ÍSAFJARÐARSÝSLA: SYNTHESIS.

4.1. INTRODUCTION.

In this chapter field evidence for glacial variations and shoreline displacements is analysed and synthesized for the purpose of establishing glacial chronology. The absence of absolute dates in Vestfirðir and the scarcity of Late Glacial dates in Iceland in general makes this task difficult, and makes it necessary to resort to indirect means of establishing the glacial chronology.

Previous work on the Late Glacial chronology in Iceland and the glacial history of Vestfirðir is related and critically analysed. Then follows a discussion on the pattern and age of the highest marine limits in Iceland and comparison is made with the marine limits in the field area, Vestur-Ísafjarðarsýsla. The course of the shoreline displacements, or uplift, is analysed with reference to equidistant diagrams, one for shorelines associated with ice margins and one for all shorelines in Dýrafjörður and N-Arnarfjörður. On the basis of all this a tentative glacial chronology for Vestur-Ísafjarðarsýsla is constructed. Finally, there is a brief discussion on the chronological position of the cirque moraines.

4.2. LATE GLACIAL CHRONOLOGY IN ICELAND.

Þ. Einarsson (1978), in his latest review of the Quaternary chronology of Iceland, has divided the Late Glacial substage (ca. 13 000 - 10 000 C^{14} years B.P.) into the following chronozones:

Zone	Approximate ages of boundaries.
	10 000 years B.P.
Búði	
	11 000 "
Saurbær	
	12 000 "
Álftanes	
	Age unknown
Kópasker	
	13 000 years B.P.

The ages of the boundaries are approximations only. During the Búði and the Álftanes chronozones glacial readvances are considered to have taken place (Þ. Einarsson 1978) while the Saurbær and the Kópasker zones he considers were periods of general ice retreat.

4.2.1. The Álftanes chronozone. This zone is named after the peninsula Álftanes near Reykjavík where there is a moraine ridge first observed by Tryggvason and Jónsson (1958). In his review Þ. Einarsson (1978) states that moraines belonging to this chronozone are found at Hvalfjörður, Melasveit and the north-facing valleys in the Borgarfjörður area in western Iceland. In western north Iceland, between Hrútafjörður and Blönduós, is a discontinuous end moraine which Þ. Einarsson believes was formed during the Álftanes.

Recently, Tr. Einarsson (1977) has argued that the end moraine on Álftanes "shows the rand (margin) of a local Older Dryas glacier extending from the mountain chain on the Reykjanes peninsula" (p. 11-12). The fact is that the moraine on Álftanes has not, to the author's knowledge, been dated by any means. The same applies to the discontinuous end moraine between Hrútafjörður and Blönduós. In the Borgarfjörður -

Melasveit area Þ. Einarsson reports fossiliferous marine sediments associated with the end moraines there with a C^{14} age of about 12 000 years B.P., dating the Álftanes readvance. No details are given how the end moraines are related to the marine sediments.

Þ. Einarsson (1978) also states that in many places in Vestfirðir there were valley and cirque glaciers during the Álftanes chronozone. The statement, however, is not discussed further and no examples are mentioned.

On the whole, the evidence for a glacial readvance during the Álftanes chronozone is very sparse and has not, to the author's knowledge, been presented and analyzed in research papers.

4.2.2. The Búði chronozone. This zone is named after the waterfall Búði on the river Þjórsá in southern Iceland where a prominent terminal moraine is exposed. The moraine is seen there to overlie marine sediments (Kjartansson 1943). Kjartansson (1939, 1943) mapped this terminal moraine and traced it across the lowlands of western south Iceland from Fljótshlíð in the east to Efstadalsfjall in the west. He suggested that sea level at the time of the formation of the moraine was close to 100 m above present sea level. Later, Kjartansson (1964) traced the ice limit north from Efstadalsfjall to the Langjökull area. In all papers he argued for a Younger Dryas age of this ice limit, although this interpretation was not based on radiometric or other datings.

In this context it is significant to review some early work on varve chronology in Iceland. De Geer (1928) analyzed four varve diagrams which Wadell measured in the year 1919 from two places in southern Iceland. De Geer attempted to correlate these diagrams with the Swedish Timescale with very good results. Two of the diagrams are from Valá near Tindafjöll, located inside the Búði moraines, and correlated with the varves 974-1066 of the Swedish Timescale with a similarity of 83%. The two diagrams from Sólheimar in the Hreppar district, just outside the Búði moraines, fitted with the years 1093-1147 of the Swedish Timescale with a similarity of 87%. On the Swedish Timescale the Finiglacial limit is fixed at the year 1073. Accordingly, the Valá diagrams belong to the Finiglacial and the Sólheimar ones to the Gotiglacial, the Gotiglacial/Finiglacial boundary being equivalent to the Late-Weichselian/Flandrian boundary of Mangerud et al. (1974). These results strongly indicate a Younger Dryas age for the Búði moraine.

In the Mývatn area in northern Iceland Thorarinsson (1951) observed a discontinuous terminal moraine which he could trace for tens of kilometres. He argued that the moraine had formed when sea level was at 52 m in Laxárdalur and has formed during a glacial readvance which he called the Hólkot stage. He suggested that the Hólkot stage was of the same age as the Búði moraines in southern Iceland, or Younger Dryas in age. Although this correlation is tenable, it has not been proven.

In his reviews Þ. Einarsson (1968, 1978) states that in Vestfirðir, during the Búði stage, there were small ice caps with outlet glaciers in the valleys, which in places calved in the sea, and southern Arnarfjörður is mentioned as an example.

On the whole, it seems that the moraines considered to belong to the Búði/Hólkot stages in Iceland have been dated only in the southern part of the country, where it has also been shown that this chronozone was one of a glacial readvance. In other parts of the country moraines considered to be of the same age have not yet been dated. However, referring to the work of Kjartansson (1943) it can be concluded that the Búði moraines in southern Iceland were formed during a period of a significant glacial readvance, and that this readvance very likely, considering De Geer's varve dating, has a similar age to the Younger Dryas moraines in Sweden.

4.2.3. Summary. The investigation of Late Glacial chronology in Iceland is still in its infancy. Two chronozones with glacial readvances have been postulated, the Álftanes and the Búði chronozones. To the author's knowledge, however, the end moraines assigned to the Álftanes chronozones have not been dated. The moraines belonging to the Búði chronozone can be dated with fair certainty in southern Iceland but not elsewhere. The apparently little known varve dates of the moraines by De Geer (1928) indicate that their age is equivalent to the Younger Dryas end moraines in Sweden.

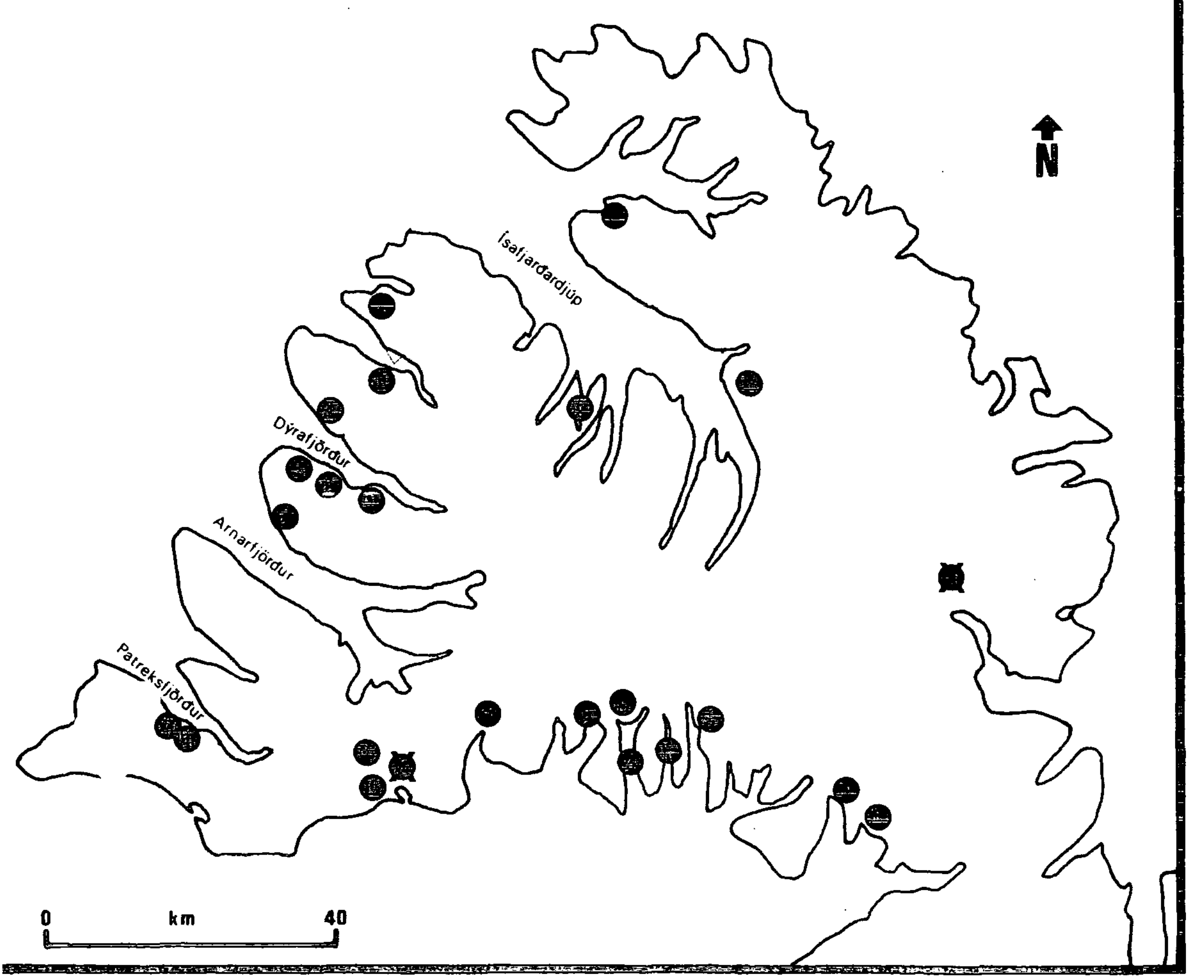
4.3. THE GLACIAL HISTORY OF VESTFIRÐIR.

4.3.1. Previous work. Thoroddsen (1906) concluded after his travels around the whole of Iceland that end moraines are particularly abundant in Vestfirðir. He reported end moraines from many areas in Vestfirðir, and his work is summarized below and in fig. 4.1.

Along the southern coast of Vestfirðir he reported moraines from the following places: In Berufjörður and Króksfjörður prominent moraines occur behind well developed marine terraces. In Kollafjörður an inconspicuous moraine stretches across the valley Kálfadalur. Large moraines occur along the mountain

FIG.4.1.

LOCATION OF END MORAINES IN VESTFIRÐIR REPORTED BY THORODDSEN (1906) ● & KJARTANSSON (1969)



sides in Kvígindisfjörður and Skálmarfjörður. In Vattardalur there is a moraine on a rockhill. A large moraine runs along the mountain side in Kerlingarfjörður. In front of the lake in Vatnsfjörður a moraine stretches across the valley. Moraines occur in Vaðaldalur and Arnarbýlisdalur. In Keflavík there is a marine terrace at 66 m where he observed striated stones and suggested this was a washed moraine. He found traces of moraines in Breiðavík, Örlygshöfn, Vatnadalur and Kvígindisdalur. In Vatnsdalur the moraine is in front of a small lake. In Patreksfjörður, Tálknafjörður and Arnarfjörður he observed moraines only by Lokinhamrar where a prominent moraine was reported. About Dýrafjörður he made the following remarks (p. 326, author's translation from the German): "In the long Dýrafjörður, moraines large and small, occur at the mouth of all the valleys, the ones by Sandar (Brekkudalur), Haukadalur, Hraundalur (Keldudalur) and Gerðhamrar being expecially noticible. The mouth of Hraundalur (Keldudalur) is filled with an enormous moraine with large blocks, and in the valley west of Gerðhamrar particularly beautiful terminal - and lateral moraines are visible". In Önundarfjörður the largest moraines were found in Valþjófsdalur. In Súganda-fjörður he found the mouth of Sunndalur filled with moraines, and in Vatnadalur he observed moraines in front of the lakes there. In Hestfjörður he mentions that a large moraine occurs. In Skjaldfannardalur he observed the following: North of Melgraseyri gravel deposits stretch across the valley cut by two marine terraces. Behind the terraces is a massive moraine with many large kettle-holes. Behind the moraine is an old sea bottom. By Staður in Grunnavík many moraines cross the valley floor.

The summary above contains all the essentials of Thoroddsen's descriptions of the sites.

Many of Thoroddsen's reports of moraines in Vestfirðir seem suspect. Firstly, on his geological map of Vestfirðir, Kjartansson (1969) indicates only two end moraines (fig. 4.1.), in Selárdalur in Steingrímsfjörður and near Hagavaðall which is probably the same as Thoroddsen's Vaðaldalur site. This can only mean that Kjartansson rejected Thoroddsen's work except in this one case. Secondly, the present author failed to notice any prominent terminal moraines in Keldudalur and Gerðhamradalur. Thirdly, Rafferty (1974) failed to observe any moraines on the valley floors in Sunndalur and Vatnadalur. However, Thoroddsen's statement that there are end moraines in all the valleys in Dýrafjörður is remarkably accurate. Also, the author's investigations agree with Thoroddsen's in Grunnavík (unpublished). Thoroddsen's investigations must be viewed with the point in mind that in the 1880's, at the time he made his observations, the Glacial Theory was still being disputed and the knowlegde of moraines was in its infancy.

Bárðarson (1921), during his investigations in the Saurbær area, made a quick visit to south-eastern Vestfirðir and made the following observation there: "The marine terraces are best developed at the altitude of 50-60 m, especially at the mouths of the valleys, e.g. in front of the valley-mouths of Garpsdalur, Geiradalur and Bæjardalur, where the terraces must have stretched right across the valley mouths, but have now been breached by streams. The main valley floor is often at lower altitudes than the terraces in front of the valleys, and up the valleys the terraces are less conspicuous. Possibly these threshold-forming terraces in front of the valleys were originally end moraines in front of glaciers which in

Late Glacial time occupied the valleys ..." (p. 369, the author's translation from the Danish). In Saurbær he had observed a similar situation and inferred it in three other valleys in the area just south of Vestfirðir.

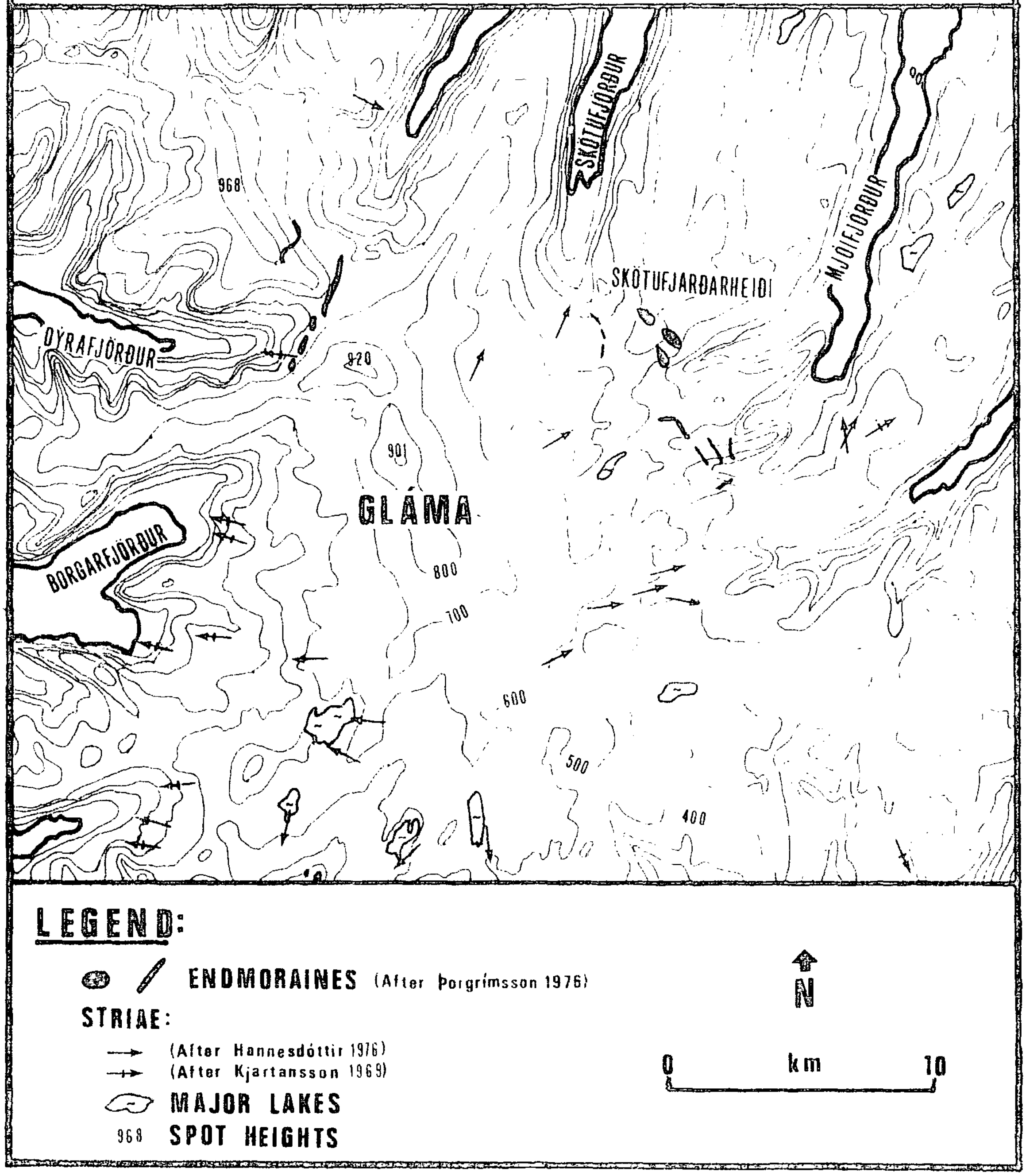
Tómasson (1964, quoted in Guðmundsson et al. 1978) suggested that near the mouth of Gilsfjörður there is a submarine end moraine correlating with a lateral moraine on the south side of the fjord in Saurbær. Seismic refraction studies by Guðmundsson et al. (1978) seem to confirm this. Guðmundsson (1979) observed a similar situation in Þorskafjörður where a lateral moraine seems to correlate with a zone of shallow depths about half-way up the fjord.

In the mid-seventies Orkustofnun launched a project of prospecting for water power and building materials in the Gláma district of Vestfirðir. During the course of these investigations Hannesdóttir (1976) mapped striae and Þorgrímsson (1976) mapped end moraines. Þorgrímsson found that drift in the area is generally very thin (less than 1 m) and, indeed, absent in most places. He found several end moraines, all minor ones with the exception of the ones on Skötufjarðarheiði, where he estimates their volume as greater than 200,000 m^3. The moraines mapped by Þorgrímsson (1976), together with the striae mapped by Hannesdóttir (1976) and Kjartansson (1969) are shown in fig. 4.2. The age of these moraines is not known. Þorgrímsson (1976), however, observed that most of the drift in the area, which he indentified as till, is weathered down to a depth of at least 20 cm, which is the depth at which the till was sampled. This weathering of the drift suggests an earlier date than the Little Ice Age (A.D. ca. 1600-1900).

As related earlier, Þ. Einarsson (1968, 1971, 1978)

FIG.4.2.

ENDMORAINES AND STRIAE IN THE GLÁMA AREA



states that during the Álftanes chronozone there were valley glaciers and cirque glaciers in Vestfirðir. He maintained the same for the Búði chronozone but added that many valley glaciers calved in the sea during that chronozone and mentioned southern Arnarfjörður as an example of the location of these glaciers.

The Durham University Vestfirðir Project (DUVP) started in 1974 after reconnaissance in 1973. Very little of the results have been published yet, but one of the main aims was to elucidate glacial chronology. Lárusson (1975) reported his preliminary results on the glacial chronology of Dýrafjörður. He found moraines in tributary valleys linked with two shorelines at heights of about 20 m and 14 m. He tentatively suggested a Búði age for the moraines. John (1975) found nine glacial stages in Reykjafjörður north of Drangajökull. He tentatively suggested two of the moraines to be "Late Glacial" in age, from the Álftanes and Búði chronozones. Sea level when the moraine of suggested Álftanes age was formed he found to have been 32 m above present, while sea level when the moraine assigned Búði age was formed remains unknown. Of the other seven moraines he suggested an early Neoglacial age (c. 7500-2500 B.P.) for three of them, a Little Ice Age to another three and one formed in 1939 A.D. Alexander (1975), in discussing some initial results of studies made into the soil chronosequences developed on the moraine ridges in Reykjafjörður, came to the following conclusion: "preliminary investigation of the soil chronosequence in Reykjafjörður strongly supports the tentative glacial chronology proposed by John" (p. 60).

A common feature in all the work on glacial history in Vestfirðir is the lack of dates (exceptions are the Little Ice Age moraines not dealt with in this thesis). Relative dating, by linking moraines with higher sea levels, has, however, been accomplished by Bárðarson (1921), John (1975) and the present author (chapter 3), Bárðarson described delta moraines associated with terraces at an altitude of 50-60 m in south-eastern Vestfirðir and John reporting a moraine which formed when sea level was 32 m above present in Reykjafjörður. The work of the present author, reported in detail in chapter 3, is summarized and analysed in the next section.

4.4. MARINE LIMITS IN ICELAND AND VESTUR-ÍSAFJARÐARSÝSLA.

4.4.1. Introduction. The purpose of the present section is to compare the heights of the marine limits in Vestur-Ísafjarðarsýsla to marine limits in Iceland. An attempt will also be made to establish the relationship of the marine limit with the distance from the former ice margin.

The recognition and measurement of marine limits is of great importance. It forms the necessary framework within which to consider post glacial uplift. If the age of the marine limit is known it is possible to estimate the height of the eustatic sea level at the time of formation of the marine limit which, when subtracted from the marine limit elevation gives the amount of postglacial uplift. Post-glacial uplift is the glacio-isostatic recovery of the earth´s crust between the instant of deglaciation and the present. Also, it has been shown (Andrews 1970) that variation in the elevation of the marine limit is a function of distance from the former ice margin, date of deglaciation and the rise of eustatic sea level since deglaciation. Recent work has demonstrated that

variation

in the elevation of the marine limit is also dependent on the gravitational attraction of massive ice sheets which caused the oceans to rise locally relative to the land (e.g. Clark 1976, Farrell and Clark 1976). Also, increased water loads due to eustatic rise in sea level can cause coastal downwarping of the crust (e.g. Bloom 1965) and the shift of mass from land areas to the oceans during deglaciation causes changes in the shape of the geoide and differential rise in sea level (e.g. Farrell and Clark 1976, Jensen 1972).

Delimiting the marine limit is often difficult. The problem has been reviewed by Sim (1960), Stephens and Synge (1966) and Andrews (1970) and is summarized here.
The marine limit may be delimited by:

(1) The lowest altitude at which undisturbed ground moraine can be recongnized.

(2) The lowest altitude at which perched boulders are found.

(3) The highest elevation at which marine organic remains are found.

(4) The upper limit of bare rock on rocky hills with a thin drift cover.

(5) The highest elevation at which beach ridges or rolled cobbles of deltaic origin are found.

(6) The lower limit of channels dissecting the surface of a delta.

To this can be added (7) the highest marine terraces. There is little doubt that if all these criteria were found at the same locality they would be found at different altitudes. Subfossil marine organic remains in Iceland are found at altitudes far below the local marine limits (see section 4.4.5.), rolled cobbles are often found well below the marine limit, and deltas also occur well below the marine limit. Of the criteria which have been found in the field in Dýrafjörður and northern Arnarfjörður, namely (1), (3), (5) and (6), Andrews (1970) makes the following reservations:

(1) Mass-movement of the ground moraine may override the marine limit.

(2) Lateral/sublateral meltwater erosion can result in a demarcation line between bedrock and ground moraine.

(3) Beach ridges, rolled pebbles and deltas cannot be used per se to distinguish between a marine and a lacustrine environment. The problem of separating these two is especially acute in localities where the glacier ponded water in tributary valleys and in such a case it is very difficult to recognize the marine limit as opposed to lacustrine strands or deltas. The same applies to terraces. In the case of Dýrafjörður and northern Arnarfjörður, no landforms or other evidence for wave action have been found in the tributary valleys with the exceptions of rounded pebbles and cobbles in Gerðhamradalur, Lambadalur, Haukadalur and Lokinhamradalur which, on the basis of their size or the structure of the deposits, are concluded to be marine in origin. It may seem curious that no evidence for ice-dammed lakes was found in the study area. The cause for this, however, is no doubt the fact that in all the valleys, with the exception of Stapadalur, glacial readvances have been shown to have taken place and the glaciers would then have destroyed the evidence for such ice-dammed lakes.

4.4.2. The marine limits in Vestur-Ísafjarðarsýsla. The highest altitudes of possible marine limits in the area are the rockbenches above Núpur at 148.4 m $\pm$ 1 m and near Gildrög at 135.2 m ± 1 m. The origin of these features, however, is uncertain. The highest probable marine limits are 111 m ± 1 m, the terrace above Núpur farm and 110 m ± 10 m in Garðshlíðar and Mýrarfell. These values for the marine limit must be considered minimum values for the upper limit of wave action, since the back-slope of the uppermost terraces is made of steep bedrock, which does not preserve evidence for wave action very well. This applies to all marine limits above about 70 m. All marine limits in Dýrafjörður and northern Arnarfjörður which are higher than 70 are shown on fig. 4.3.

Below 70 m there are numerous other marine limits, especially the ones associated with end moraines and other glacial landforms and deposits in most of the tributary valleys. These are, however, not relevant when comparing the highest marine limits in the area with the highest marine limits in Iceland as a whole.

4.4.3. Marine limits elsewhere in Iceland. The most recent reviews of heights of marine limits in Iceland have been presented by Þ. Einarsson (1968, 1971). The highest marine limit indicated by him is at 110 m in the Hreppar district of southern Iceland (Þ. Einarsson 1971, mynd (fig.) 25-22 (p. 228)). Elsewhere in Iceland the marine limit is much lower, in most places between 40 and 52 m. Þ. Einarsson's map is redrawn here as fig. 4.4. As can be seen when the results of the author's work (fig. 4.3.) on marine limits in Vestur-Ísafjarðarsýsla are compared with the map compiled by Þ. Einarsson (fig. 4.4.) the author's results are much higher than would be expected from Einarsson's work. This conflict is of a serious nature since in Vestur-Ísafjarðarsýsla there are, according to the author, marine limits at altitudes

FIG.4.3.

THE HIGHEST MARINE LIMITS (>70m) IN VESTUR–ÍSAFJARDARSÝSLA

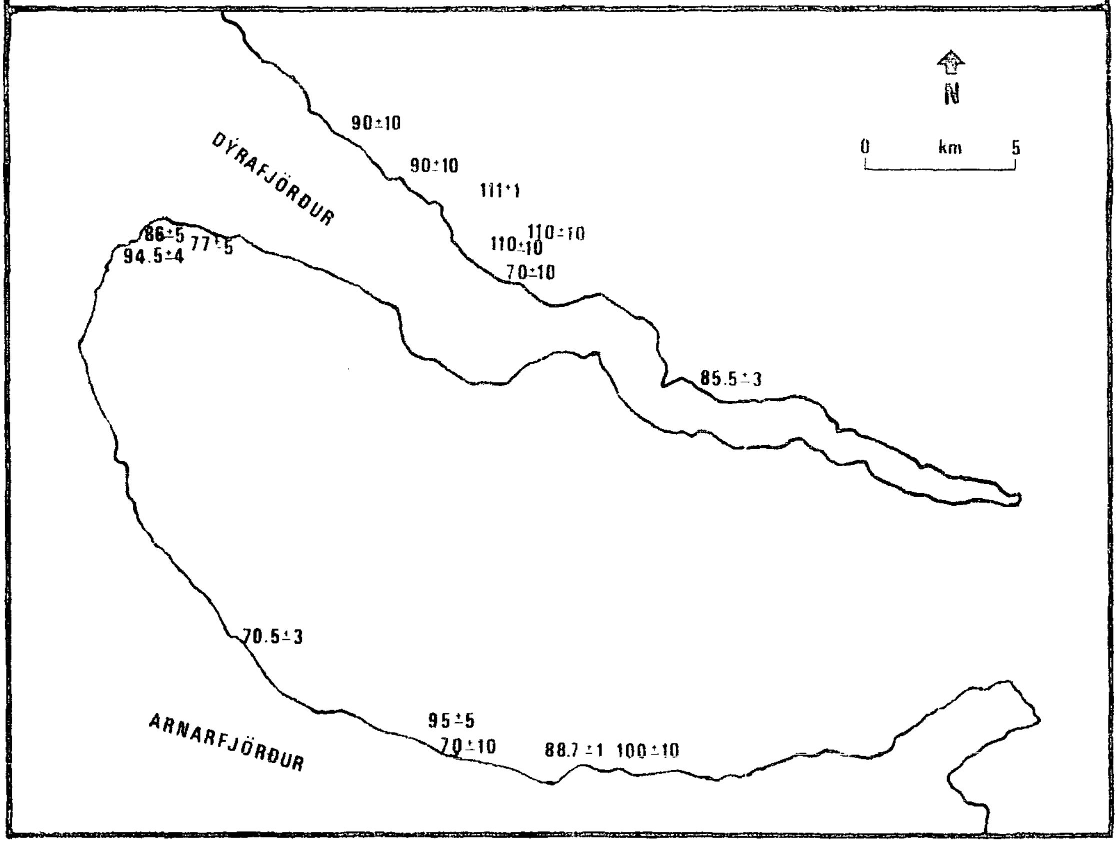
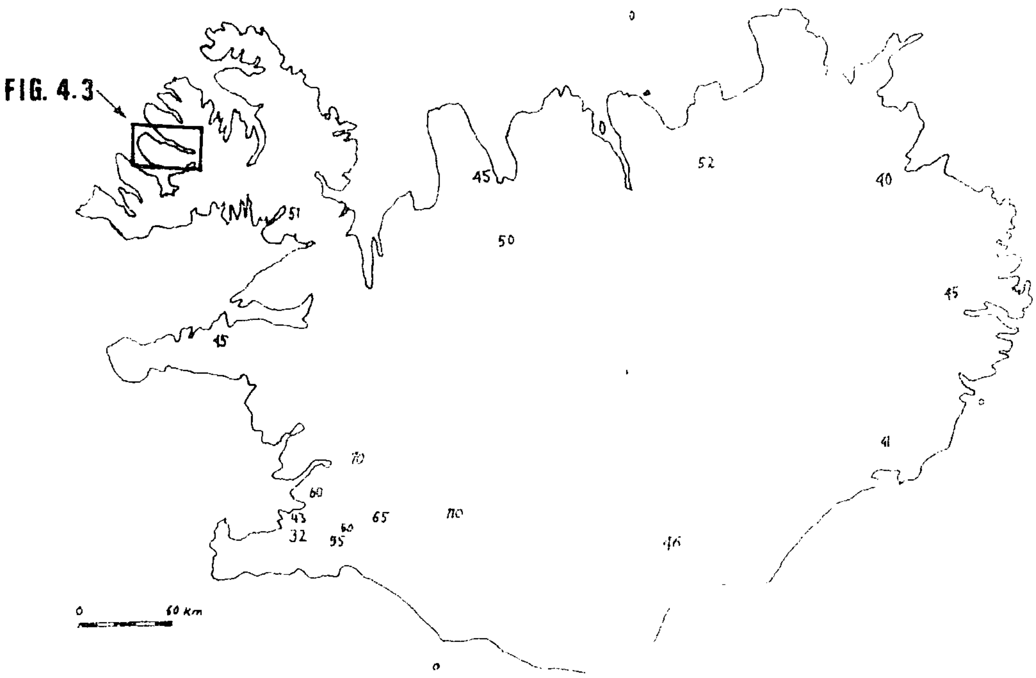


FIG.4.4.



comparable to the highest marine limits on Þ. Einarsson's map. This is in spite of the fact that Vestur-Ísafjarðarsýsla is closer to the presumed periphery of the ice-sheet of the last glaciation. Because of this apparent conflict of opinions it was decided to independently review the literature on marine limits in Iceland. The information so gathered is presented on fig. 4.5. and in table 4.1. is a key to the literature quoted.

Some of the sites on fig. 4.5. need to be commented on. At site 4, in the Hreppar district in southern Iceland, various authors have reported a wave cut rockbench at altitudes 120-230 m. Kjartansson (1958), however, concluded that the feature is at an altitude of 110 m, the same height as a washing limit in a nearby terminal moraine of Búði age.

Site 10 is Stóri-Sandhóll in Skorradalur (Ashwell 1967, 1975). He observed marine molluscs (for their age see section 4.4.5.) in a thick silt-till deposits at the height of 111-235 m in the hill Stóri-Sandhóll which he concludes formed when sea level was well above 145 m, which is the height of the hill. Þ. Einarsson (1968, p. 284) interprets the evidence differently. He argues that the silt-till layer with the molluscs had been deposited at the bottom of Skorradalsvatn, (now a lake some 3.5 m up the valley) at a time when Skorradalur was a fjord. The silt-till deposits, which Þ. Einarsson suggests is a moraine hummock, was then, according to him, pushed up from the bottom of the lake and brought to its present position by a readvancing glacier. This is supposed to have taken place during the Álftanes readvance. Þ. Einarsson does not, however, present any arguments to support this interpretation and does not mention Ashwell's work. According to Ashwell (1967, 1975) the silt-till was deposited by melt

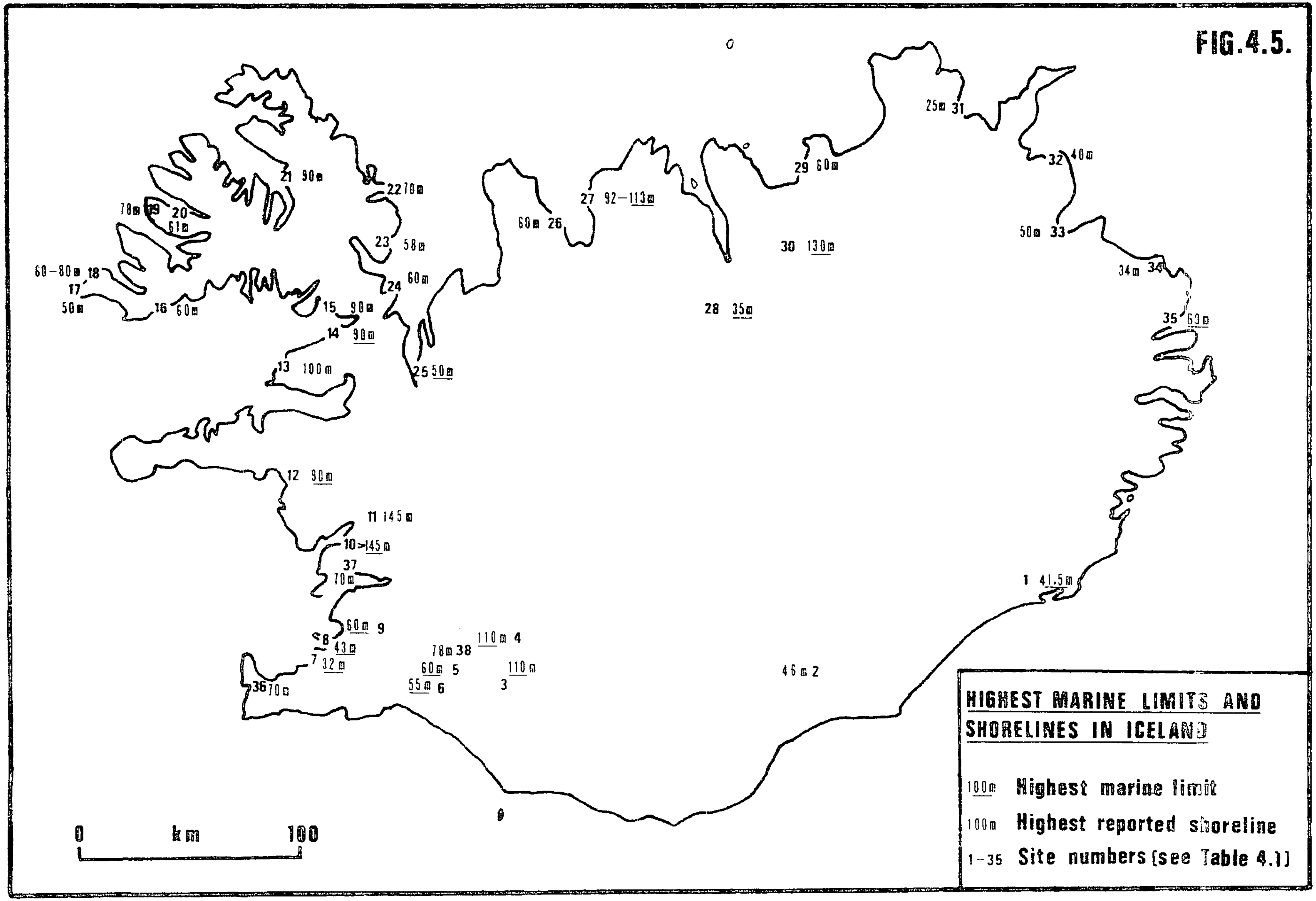

HIGHEST MARINE LIMITS AND SHORELINES IN ICELAND
100m Highest marine limit
100m Highest reported shoreline
1-35 Site numbers (see Table 4.1)
0 km 100
21 90m
22 70m
78m 19 20
61m
23 58m
24 60m
60-80m 18
17
50m
16 60m
15 90m
14 90m
13 100m
25 50m
60m 26
27 92-113m
28 35m
29 60m
30 130m
25m 31
32 40m
50m 33
34m 34
35 60m
12 90m
11 145m
10 >145m
37
70m
60m 9
8
43m
7 32m
36 70m
78m 38
110m 4
60m 5
55m 6
110m
3
46m 2
1 41.5m

FIG.4.5.

water streams and melt from the base of an ice-shelf, the ice shelf being a floating piedmont glacier which was located there when sea level stood well above the 135 m level of shells. One of his observations argues strongly against Þ. Einarsson's interpretation

TABLE 4.1.

Guide to the literature used to compile fig. 4.5.

Site No.	Reference	Site No.	Reference
1	Jónsson, 1957	19	Thoroddsen, 1892
2	- " -	20	Kjartansson, 1969
3	Kjartansson, 1958	21	Bout, 1955
4	Áskelsson, 1930	22	Kjartansson, 1969
4	Pjeturss, 1901	23	- " -
4	Kjartansson, 1958	24	- " -
4	Kjartansson, 1943	25	Bárðarson, 1910
5	Kjartansson, 1943	26	Thoroddsen, 1892
6	Þ. Einarsson, 1960,	27	Bodéré, 1973
	Kjartansson, 1943	28	Tr. Einarsson, 1959
7	Þorkelsson, 1935	29	Thoroddsen, 1892
8	- " -	30	Thorarinsson, 1951
9	Sæmundsson, 1965	31	Sæmundsson, 1977
	Sæmundsson &	32	- " -
	S. Einarsson, 1980	33	- " -
10	Ashwell, 1967	34	- " -
11	Ashwell, 1966	35	Thoroddsen, 1892
12	Áskelsson, 1961	36	Sæmundsson &
13	Pjeturss, 1907		S. Einarsson, 1980
14	Bárðarson, 1921	37	- " -
15	Áskelsson, 1950	38	- " -
	John, 1975		
	Kjartansson, 1969		
16	Friedrich, 1966		
17	Kjartansson, 1969		
18	Keilhack, 1933		

(Ashwell 1975, p. 236): "At a height of about 125 m a stone was found with Balanus plates in contact with most of the periphery, which seems an unlikely event if the surrounding deposit had undergone considerable pressure and movement".

Until further evidence is forthcoming, it is concluded that at site 10, Stóri-Sandhóll, there is evidence for a marine limit higher than 145 m and that this is the highest marine limit reported from Iceland so far.

Sites 15 (85 m), 17, 20, 22, 23, and 24 are from Kjartansson's (1969) geological map of Vestfirðir (scale 1:250 000). This is the only map in the series compiled by him where altitudes are assigned to the shorelines. He does not indicate what evidence he used to delineate shorelines.

Sites 31-34 are from Sæmundsson's (1977) geological map of north-eastern Iceland in the same series (1:250 000). Like Kjartansson, he does not indicate what evidence he used to define shorelines either.

Apart from these exceptions most of the marine limits are identified from terraces. An exception is site 30 where Thorarinsson (1951, p.80) found shell fragments at the height of 127 m in Laxárdalur and concluded that "the marine limit is at least 127 m - probably nearer 130 m".

The map of the highest marine limits and shorelines in Iceland compiled by the author (fig. 4.5.), differs in two respects from the map compiled by Þ. Einarsson (fig. 4.4.):

(1) The author's map shows 35 sites while Þ. Einarsson's map shows only 17 sites.

(2) The author's map shows many more "high" (>90 m) marine limits than Þ. Einarsson's.

4.4.4. Comparison of altitudes of marine limits and high shorelines in Vestur-Ísafjarðarsýsla with those elsewhere in Iceland. Many of the "high" marine limits in Iceland are within 10 km from the coast (sites 10, 11, 12, 13, 14, 15, 18, 19, 21, 27) and are therefore relatively close to the periphery of the ice-sheet of the last glaciation. The highest marine limits in Vestur-Ísafjarðarsýsla (fig. 4.3.) are of comparable elevations and also in coastal locations. The nature of the evidence is, however, different. Only in a few areas, apart from Vestur-Ísafjarðarsýsla, has a systematic search been undertaken for the upper limit of wave action, namely in Holt, Hreppar (sites 3,4), the Reykjavík area (sites 7 and 8), Borgarfjörður (sites 10, 11), Saurbær (site 14) and in Eyjafjörður (site 28). Most of the other sites are haphazard findings, where the upper limit of wave action could well be higher than indicated on the map.

In light of all this it is concluded that although the marine limits in Vestur-Ísafjarðarsýsla are high, they are not anomalously high compared with marine limits in the rest of Iceland.

4.4.5. The age of the marine limits. No dates are available on the age of the marine limits in Vestur-Ísafjarðarsýsla due to lack of datable material. To arrive at an estimate of this, therefore, it is necessary to examine the ages of the marine limits in the rest of Iceland.

In his review of shorelines displacements in Iceland Þ. Einarsson (1968, 1971) concludes that the age of the marine limit seems to be the same everywhere in Iceland, c. 11 000 C^{14} years B.P. In his latest review (1978) he concludes that the marine limits in Iceland date from the Saurbær chronozone, 11 000 - 12 000 years B.p. In all his reviews he also concludes that the marine limit was formed at a time when, for a considerable period, the rate of post glacial uplift was the same as the rate of eustatic sea level rise because large terraces are frequently found at the highest marine limit. In general, it can be stated that the marine limit forms either at the instant of deglacierization of a locality or during a subsequent transgression which exceeded the marine limit which formed at the instant of deglacierization (e.g. Andrews 1970, Donner 1978). For the marine limit to be synchronous over most of Iceland it is necessary that one of the following conditions prevailed:

(1) The ice sheet over Iceland disappeared everywhere in an instant. Then the date of deglacierization would be the same everywhere and the age of the marine limit synchronous.

(2) The marine limit was formed during a general transgression at the time of deglaciation of coastal areas. This implies that eustatic rise of sea level exceeded the rate of post-glacial uplift at the time of deglaciation of coastal areas. Early workers on shoreline displacements in Iceland, e.g. Bárðarson (1921, 1923), held this to be true without, however, presenting any arguments for it.

(3) Some time after the deglaciation of coastal districts a transgression took place which formed marine limits, higher than the ones which formed immdeiately following deglaciation.

Possibility (1) is absurd and needs no further discussion. Possibility (2) can be argued against on the ground that it has been shown (Þ. Einarsson 1964, 1968, 1971, 1978) that post-glacial uplift rates were high, in some areas at least of the order of 5 m/100 years in the period 10 500 - 9 000 C^{14} years B.P., which exceeds by far any known rates of eustatic sea level rise in the same period. For possibility (3) much the same applies, i.e. the known, high uplift rates are against it. For lack of evidence it cannot be conclusively proven that none of these conditions prevailed but it must be considered very unlikely that they did. The alternative, that the marine limit was formed at each locality at the instant of deglacierization and that it is, therefore, metachronous is therefore preferred.

In light of these arguments and the conclusion that the marine limits in Iceland are metachronous it was decided to undertake a search for published radiocarbon dates relating to shoreline displacments, in research papers and laboratory reports published in Radiocarbon. It was hoped that these dates might throw some light on the question of the ages of marine limits in Iceland. These dates are shown in table 4.2. and fig. 4.6.

In all the dates the half-life of C^{14} used is 5570 years. Only two of the shell dates have been corrected by the laboratory for the apparent age of sea water, T-343 and T-362, by subtracting 410 years from the original results (Mangerud & Gulliksen 1975, Gulliksen, pers. comm. 1977). These two dates are therefore inconsistant with the others and cannot be directly compared with them. It was decided not to attempt to correct the other dates for apparent age of sea water (sea correction) because it is not known how

Table 4.2. Radiocarbon dated samples relating to shoreline displacements in Iceland.

AGE	LAB.NO.	HEIGHT	MATERIAL	REFERENCE	LOCATION	COMMENTS
12830±170	U-2225	0-4 m	shells	10	Kópasker	Inner 35% of shell dated
12800±220	S-291	15-21 m	"	2	Borgarfjörður	
12290±160	U-641	5 m	"	9	- " -	Inner 60% of shell dated
12270±150	I-1824	111-135 m	"	1	- " -	Stóri-Sandhóll
12240±200	I-1825	16-24 m	"	1	- " -	Andakílsárvirkjun
12100±250	S-289	21-26 m	"	2	- " -	Efri Hreppur
12100±150	S-290	25-30 m	"	2	- " -	Grjóteyri
11710±210	U-2226	0-4 m	"	10	Kópasker	Outer part of U-2225
11630±160	U-2227	25 m	"	10	Kaldárbrú	Inner 80% of shell dated
11620±240	U-2019	15 m	"	7, 8	Saurbær	Inner 65% of shell dated
11330^{+540}_{-510}	U-726	25 m	"	10	Kaldárbrú	Surrounding 20% of U-2227
10450±160	U-414	13 m	"	4, 6	Reykjavík	Surrounding 45% of U-415
10310±260	U-412	13 m	"	4, 6	Reykjavík	Inner 18%
10230±190	U-415	13 m	"	4, 6	Reykjavík	Inner 21%
9940±260	U-413	13 m	"	4, 6	Reykjavík	Surrounding 14% of U-415
9930±190	T-362	55 m	"	4, 3	Hreppar	Brúará
9800^{+2600}_{-2000}	U-725	15 m	"	10	Víðidalur	Surrounding 5% of U-724; Árnes
9800±150	U-417	75 m	"	4, 6	Hreppar	Inner 29%; Hellisholtalækur
9730±160	U-724	15 m	"	10	Víðidalur	Árnes
9580±140	U-416	75 m	"	4, 6	Hreppar	Surrounding 54% of U-417; Hellis
9460±100	U-2224	-43 m	peat	10	Faxaflói	64°13.5´N;22°19´W, Dredged.

continued

Table 4.2. continued. Radiocarbon dated samples relating to shoreline displacements in Iceland.

AGE	LAB.NO.	HEIGHT	MATERIAL	REFERENCE	LOCATION	COMMENTS
9120±180	U-750	-43 m	peat	10	Faxaflói	Humus from U-2224
9030±280	Y-247	-4 m	"	11	Reykjavík	Seltjörn
8780±150	H-404/370	-4 m	"	12	Reykjavík	Seltjörn
8210±310	U-524		"	7, 8	Þjórsárbrú	Dates Þjórsár-lava
8190±190	U-525		"	7, 8	Þjórsárbrú	- " -
8065±400	W-482		"	5	Þjórsárbrú	- " -
7970±180	T-343	62 m	shells	3	Hreppar	Kópavatn
6510±100	U-2	-2 m	peat	5	Hornafjörður	
3140±140	U-2088	3 m	shells	9	Hrútafjörður	Bæjará
1910±250	W-909	-1.5 m	peat	5	Stokkseyri	
1240±100	U-2051	-3 m(,)	driftwood	9	Dyrhólaós	

References: 1 - Ashwell 1967; 2 - Ashwell 1975; 3 - Nydal et al. 1964; 4 - Þ. Einarsson 1964; 5 - Kjartansson 1964; 6 - Olsson & Piuanuj 1965; 7 - Kjartansson 1966; 8 - Olsson et al. 1967; 9 - Olsson et al. 1969; 10 - Olsson et al. 1972; 11 - Thorarinsson 1956; 12 - Thorarinsson 1958.

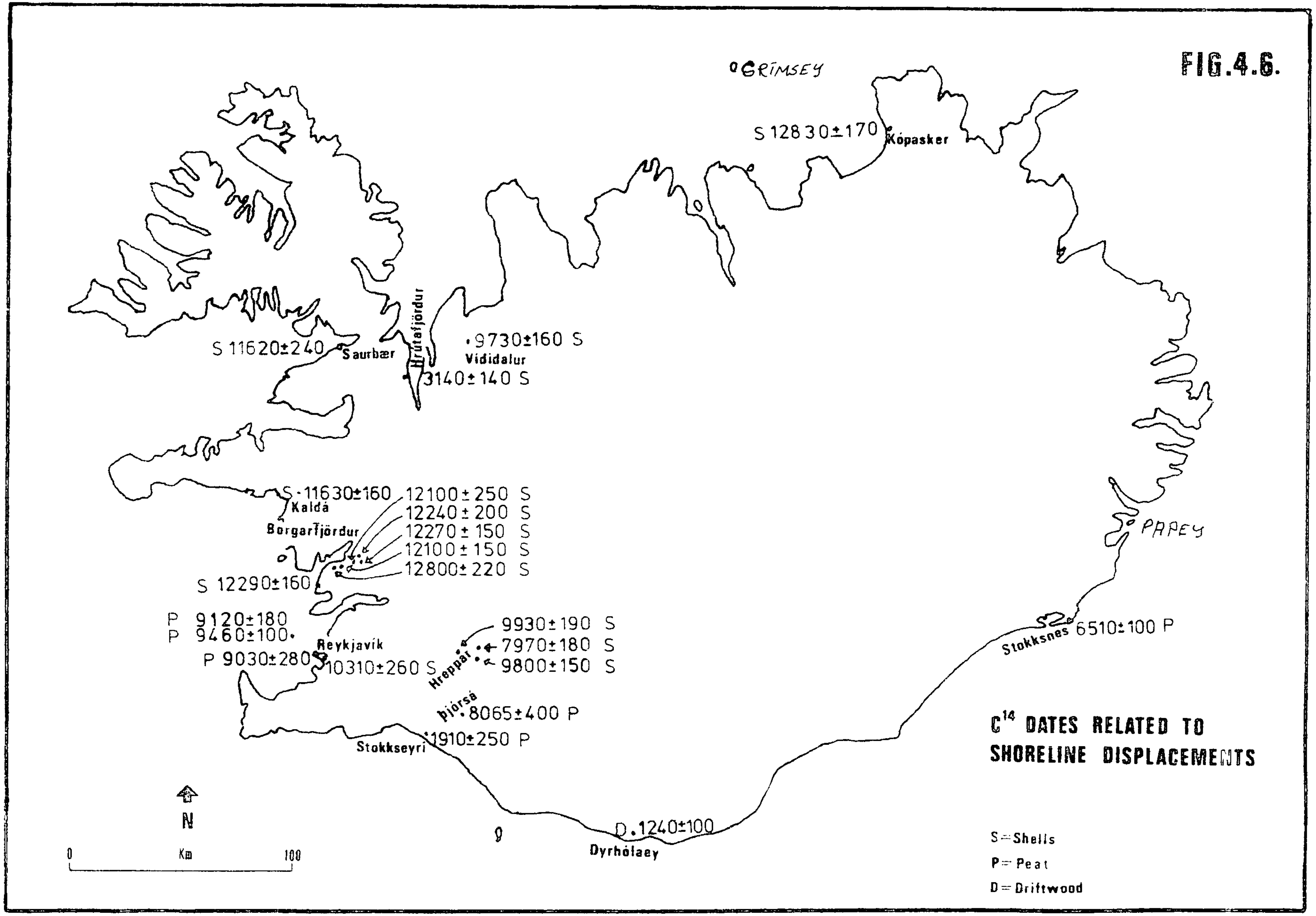


FIG.4.6.
GRÍMSEY
S 12830±170
Kópasker
S 11620±240
Saurbær
Hrútafjördur
•9730±160 S
Vididalur
3140±140 S
S·11630±160
Kaldá
Borgarfjördur
12100±250 S
12240±200 S
12270±150 S
12100±150 S
12800±220 S
S 12290±160
P 9120±180
P 9460±100
P 9030±280
Reykjavík
10310±260 S
Hreppar
9930±190 S
7970±180 S
9800±150 S
Þjórsá
8065±400 P
1910±250 P
Stokkseyri
PAPEY
Stokksnes
6510±100 P
D.1240±100
Dyrhólaey
N
0
Km
100
C14 DATES RELATED TO SHORELINE DISPLACEMENTS
S = Shells
P = Peat
D = Driftwood

great this correction should be. Apparent age of living and very recent shells and sea water has been measured in a few localitites in the Iceland area. The results are shown in table 4.3.:

Table 4.3.

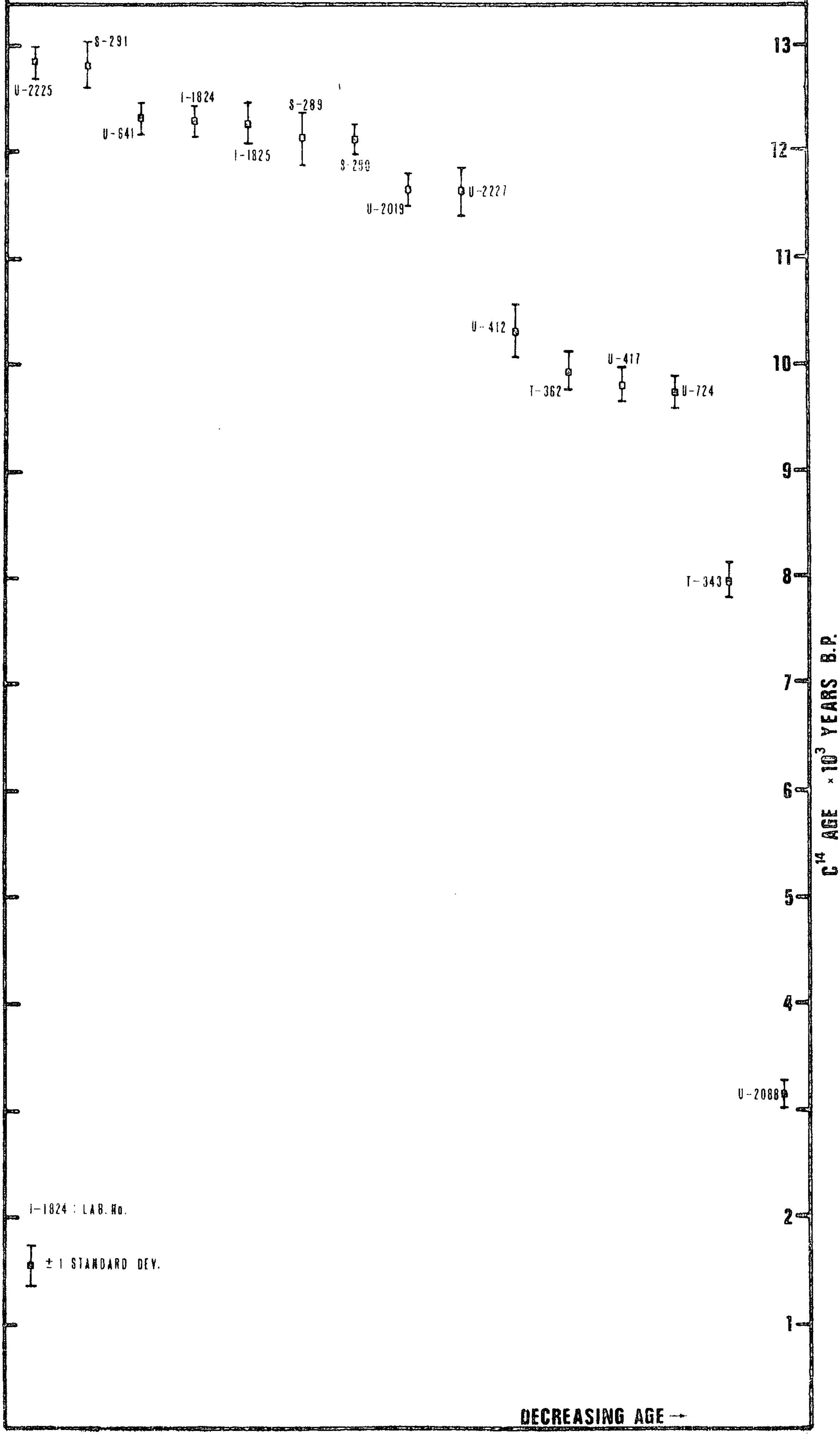
Apparent ages of sea water near Iceland.

Apparent age	Lab.No.	Material	Location	Reference
425	St-332	Sea water	Denmark Strait (65.5°N;25.6°W)	Fonselius & Östlund 1959
600±48	L-576i	Gastropod	Faxaflói (64°N;22°W)	Mangerud & Gulliksen 1975
570±48	L-576h	- " -	- " -	- " -

Mangerud & Gulliksen (1975) suggested apparent age of 590 for sea water near Iceland while Gulliksen (pers. comm. 1977) expressed the view that different regions of Iceland, depending on local oceanographic conditions, will show apparent ages, ranging from 500-600 years, characterizing mixed Atlantic and Arctic water, down to ca. 400 years of Atlantic water. This shows that much more research is necessary and it was decided not to attempt to correct dates in table 4.2. for apparent age of sea water.

The ages of radiocarbon dated shell samples from sites in Iceland are plotted in fig. 4.7. against order of decreasing age with the error limits given by each laboratory as shown in table 4.2. Disregarded in plotting this figure are the following samples because they are dates

FIG.4.7. C^{14} DATES ON SHELLS IN ICELAND



of outer layers of shell samples: U-414, U-413, U-416, U-725, U-726. The outer layers of shells are more likely to be contaminated and therefore the innermost layers are most likely to give reliable dates (e.g. Olsson 1974). A striking feature of fig. 4.7. is that the samples tend to form distinct groups although there is some overlapping.

In plotting figure 4.7. dates of 15 samples are used. Nine of those show an age greater than 11 380 C^{14} years B.P. This makes it difficult to accept the hypothesis that the marine limits are only 11 000 C^{14} years old. Also, five samples show an age greater than 12 040 C^{14} years which does not comply with Þ. Einarsson's contention that Icelandic marine limits are no older than 12 000 C^{14} years. In the Borgarfjörður 6 samples have been dated and their ages range from 11 850 to 13 020 C^{14} years. It is significant that the highest marine limits are also in this area (145 m in Stóri-Sandhóll). However, all but one of the samples from Borgarfjörður are from altitudes lower than about 30 m and height of sea level when they lived is therefore not known. Sample I-1824 (12 270 $\pm$ 150) is from an altitude of 111-135 m in Stóri-Sandhóll. The marine limit there is in excess of 145 m. According to Ashwell (1967) the age of sample I-1824 is somewhat younger than the age of the marine limit in Stóri-Sandhóll.

Other samples from high altitudes are T-343 (62 m), T-362 (55 m) and U-417 (75 m) all from the Hreppar area. The age of these samples is, however, not simply related to altitude as is apparent from fig. 4.8.:

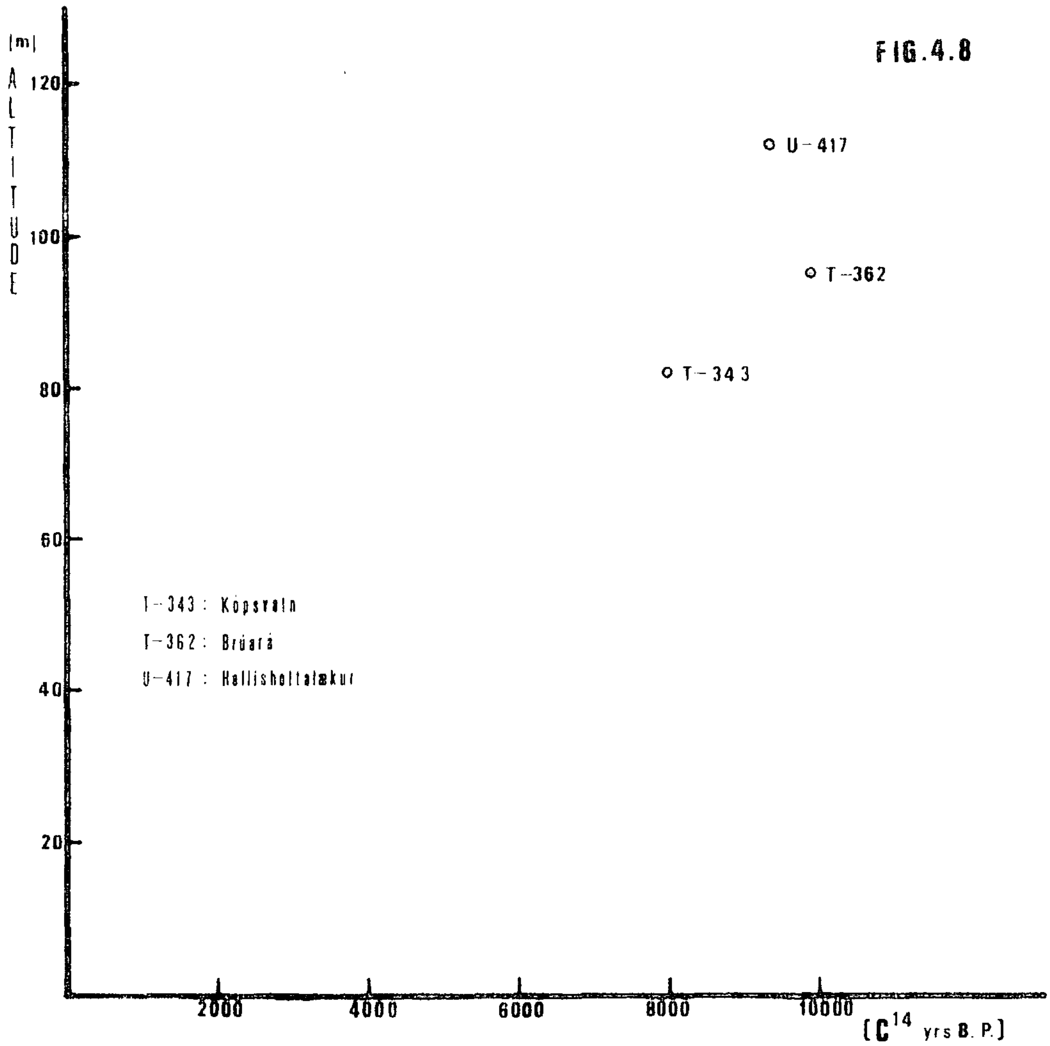


Fig. 4.8. An altitude/age plot of the three samples from the Hreppar district.

A sea correction of 410 years was applied to U-417 to make the age consistant with the other samples. For a eustatic correction Mörner's (1971) curve of eustatic sea level rise was applied. Hundreds of such curves have been published and Mörner's was chosen because it has a mean position for, at least, the earlier curves. The marine limit in the Hreppar district is 110 m and is associated with a terminal moraine of Búði age. The three dates from Hreppar are just outside the limits of the Búði advance. The age of the marine limit in Hreppar is, therefore, probably a little earlier than the age of sample T-362, maybe c. 10 500 C^{14}

years.

Other dated samples are far below the local marine limits and the dates therefore only give minimum estimates for the age of the marine limits. The age of the oldest samples should therefore be taken as a minimum age for the oldest marine limits in Iceland.

In conclusion it can be said that the age of the marine limits in Iceland varies. In Hreppar it is in the region of 10 500 C^{14} years B.P. In the Borgarfjörður area it is at least 11 860 ± 150 years (I-1824 with a sea correction of 410 years) and probably as high as 12 390 ± 220 (S-291 with a sea correction of 410 years). It must be stressed, however, that so far relatively very few Late Glacial shell samples have been dated from Iceland. Drawing far-reaching conclusion based on these few samples in dangerous.

4.4.6. The age of the marine limits in Vestur-Ísafjarðarsýsla. Estimating the age of the marine limits in Vestur-Ísafjarðarsýsla from ages of marine limits elsewhere in Iceland is riddled with difficulty. The main difficulties are:

(1) The Late Glacial dates are very few, only 14.

(2) The height of sea level when the dated shells lived is only rarely known.

(3) Most of the dated samples are far from Vestur-Ísafjarðarsýsla.

Some inferences, however, can be made. First, samples U-2225 (12 830 ± 170) from Kópasker and S-291 (12 800 ± 220) from Borgarfjörður show that about 13 000 C^{14} years B.P. parts of the coasts of north-eastern and western Iceland had become deglacierized. Secondly, after the formation of the highest marine limits in Vestur-Ísafjarðarsýsla a glacial readvance took place in most of the valleys in the area. The age of this readvance is not known, but it must either be the equivalent of Álftanes or the Búði readvances. In either case, it can be assumed that the higher marine limits are older than about 11 000 C^{14} years B.P. It is suggested here that the upper limit of the age is at least in the region of about 13 000 C^{14} years. This is based on the considerations that since Borgarfjörður had become deglacierized by at least 12 800 C^{14} years B.P. it is not unreasonable to assume that parts, at least, of Vestur-Ísafjarðarsýsla had also become deglacierized, that area being much further away from the central area of the main Icelandic ice sheet.

In conclusion it can be said that the age of the higher (70 m) marine limits in Iceland is at least 11 000 C^{14} years B.P. The upper age bracket could well be in the region of 13 000 C^{14} years B.P.

4.5. THE GLACIAL CHRONOLOGY OF VESTUR-ÍSAFJARÐARSÝSLA.

4.5.1. Introduction. The field evidence from Dýrafjörður and northern Arnarfjörður, presented in Chapter 3, is in this section analysed in an attempt to establish a glacial chronology for the area.

The field work concentrated on mapping end moraines and other ice marginal features, and searching for means of dating the ice margins, absolutely and/or relatively. Unfortunately, no organic material suitable for radiometric dating of events was discovered. Thus, since an absolute chronology could not be established, an attempt has been made to establish a relative chronology. During fieldwork it soon became apparent that in many cases it was possible to relate the end moraines and other ice marginal features to sea levels at the time of their formation. Much of the fieldwork, therefore, was concentrated on mapping and measuring the height of features indicating former higher sea levels and elucidating their relationship with former ice margins, and in this way establishing a relative chronology. In fig. 4.9. is shown the distribution of end-moraines from glacial readvances in valleys in Dýrafjörður and Arnarfjörður and in fig. 4.10. is a location map for the same area.

The evidence used to link higher sea levels with former ice margins in the area is varied and can be classified thus:

a) At some localities there is a marine terrace cut into the distal side of an end moraine or ice marginal deposits. This situation was observed in the valleys of Gemlufallsdalur, Hjarðardalur, Lambadalur, Kjaransstaðadalur, Ketilseyrardalur, Hvammsdalur, Kirkjubólsdalur, Meðaldalur, Eyrardalur, Hafnardalur, Lokinhamradalur, Krákudalur, Tjaldanesdalur. However, this evidence alone is not conclusive as regards determining the height of sea level at the time of formation of the moraine or ice marginal deposits in question because the possibility that the marine terrace was formed during a marine transgression post-dating the moraine or ice marginal deposits. cannot be ruled out.

b) In some cases it was observed that glacial melt water channels, issuing from end moraines, petered out on marine terraces situated on the distal side of moraines.

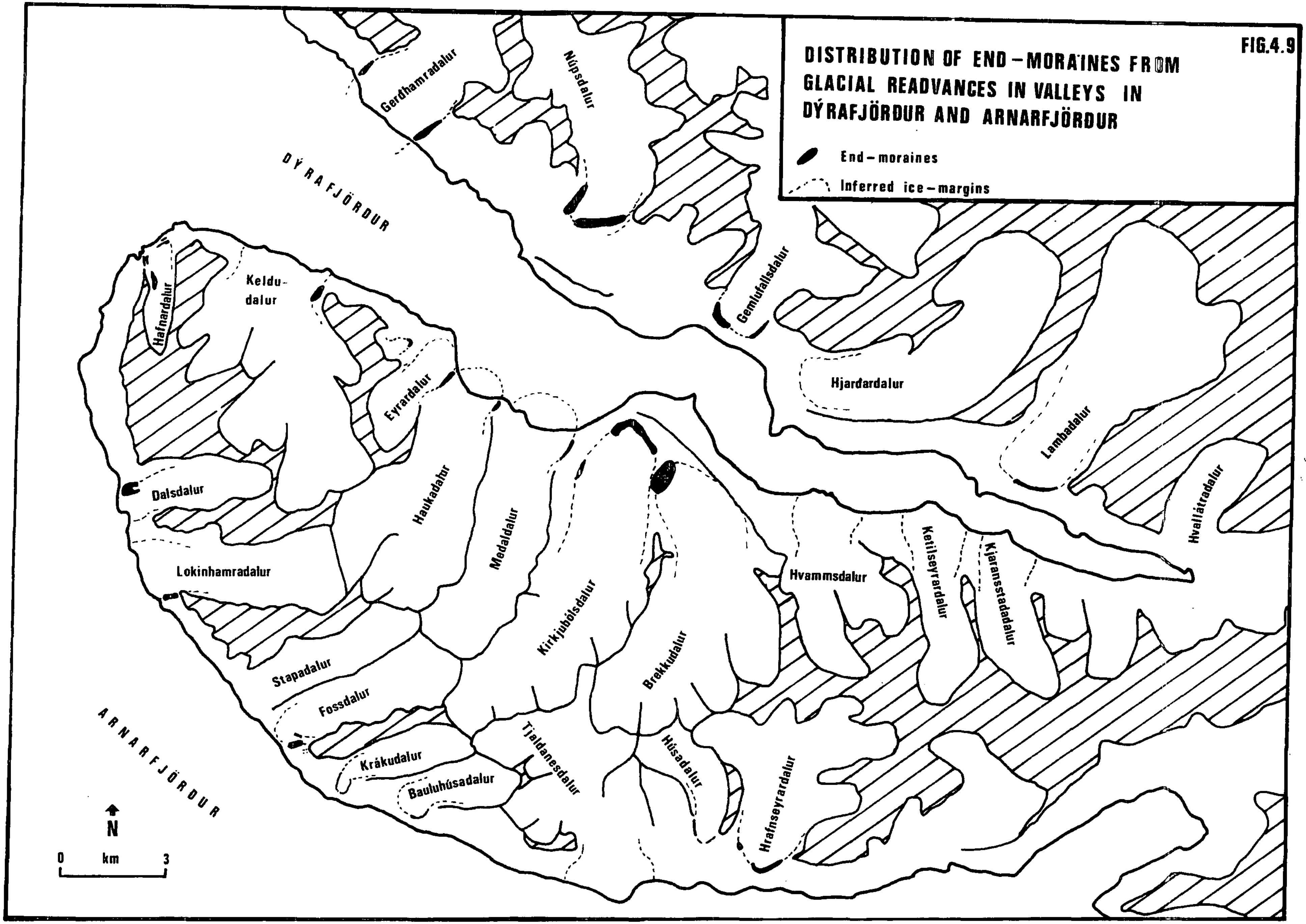


FIG.4.9
DISTRIBUTION OF END-MORAINES FROM GLACIAL READVANCES IN VALLEYS IN DÝRAFJÖRDUR AND ARNARFJÖRDUR
End-moraines
Inferred ice-margins
DÝRAFJÖRDUR
ARNARFJÖRDUR
Gerdhamradalur
Núpsdalur
Gemlufallsdalur
Hjardardalur
Lambadalur
Hvallátradalur
Hafnardalur
Keldu-dalur
Eyrardalur
Dalsdalur
Haukadalur
Medaldalur
Lokinhamradalur
Kirkjubólsdalur
Brekkudalur
Hvammsdalur
Ketilseyrardalur
Kjaransstadadalur
Stapadalur
Fossdalur
Krákudalur
Bauluhúsadalur
Tjaldanesdalur
Húsadalur
Hrafnseyrardalur
N
0 km 3

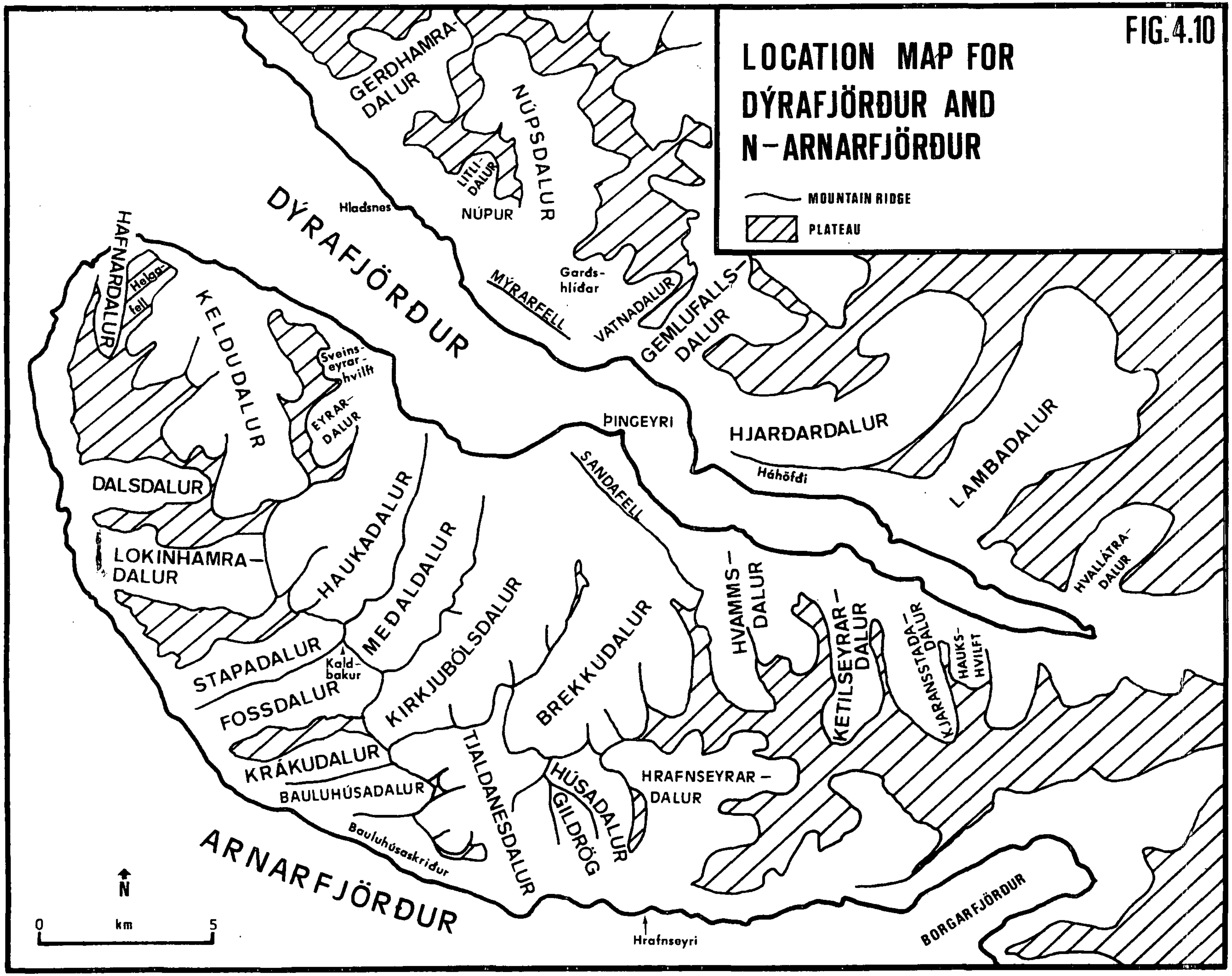


FIG. 4.10
LOCATION MAP FOR DÝRAFJÖRÐUR AND N-ARNARFJÖRÐUR
MOUNTAIN RIDGE
PLATEAU
GERÐHAMRA-DALUR
NÚPSDALUR
LITLI-DALUR
NÚPUR
Hlaðsnes
DÝRAFJÖRÐUR
MÝRARFELL
Garðs-hlíðar
VATNADALUR
GEMLUFALLS-DALUR
HAFNARDALUR
Helga-fell
KELDUDALUR
Sveins-eyrar-hvilft
EYRAR-DALUR
ÞINGEYRI
HJARÐARDALUR
Háhöfði
LAMBADALUR
SANDAFELL
DALSDALUR
LOKINHAMRA-DALUR
HAUKADALUR
MEÐALDALUR
KIRKJUBÓLSDALUR
BREKKUDALUR
HVAMMS-DALUR
KETILSEYRAR-DALUR
KJARANSSTAÐA-DALUR
HAUKS-HVILFT
HVALLÁTRA-DALUR
STAPADALUR
Kald-bakur
FOSSDALUR
KRÁKUDALUR
BAULUHÚSADALUR
TJALDANESDALUR
HÚSADALUR
GILDRÖG
HRAFNSEYRAR-DALUR
Bauluhúsaskriður
ARNARFJÖRÐUR
Hrafnseyri
BORGARFJÖRÐUR
N
0 km 5

This evidence is considered to give a very strong indication of the height of sea level at the time of formation of the moraines concerned, because the channels are cut to local base level, operative at the time. This situation was observed in Gemlufallsdalur, Hvammsdalur, Krákudalur and Tjaldanesdalur.

c) In some instances glacial melt water channels, issuing from moraines, ended on marine terraces lower than the moraine concerned. This situation was observed in Húsadalur and Hrafnseyrardalur. A similar situation was observed in Litlidalur although no shoreline was observed.

d) In a few places it was not possible to determine the height of sea level when the ice marginal features were formed. This was the case in Gerðhamradalur, Núpsdalur, Haukadalur, Sveinseyrarhvilft, Keldudalur, Dalsdalur and Fossdalur. Nevertheless, it was possible to ascertain that sea level had been lower than a certain level when the ice marginal features were formed. It is significant to note that in all these valleys the ice marginal features are located at altitudes higher than about 20 m. An exception here is Keldudalur. There till was observed lowest at an altitude of 17.5 m $\pm$ 2.5 m exposed in the coastal cliffs. It is concluded that sea level must have been lower than this when the till formed.

e) At Brekkudalur it could not be decided if the moraine formed at the same time as the melt water channels which issued from the side of the glacier and terminate on the marine terrace below Brekkuháls. However, viewing the evidence from Kirkjubólsdalur and Brekkudalur as a whole it is very reasonable to assume that the channels and the moraine did form practically simultaneously.

f) In Bauluhúsadalur river terraces were used to attemt to establish the height of sea level when the moraine there was formed. It was concluded that the glacier had retreated from in front of the valley when sea level was between about 20 and 26 m. The evidence, however, is difficult to evaluate.

The results of the investigations of relating ice marginal features to shorelines are now analysed with two aims in mind:

Firstly, to find out significant age differences, if there are any, between the ice marginal features.

Secondly, to elucidate the course of the shoreline displacements and determine the position of the moraine shorelines in this (moraine shorelines are defined as shorelines which can be linked with ice marginal features). The purpose is to throw light on the relations between the moraine shorelines and the highest marine limits and will thus be the basis for absolute chronology when, eventually, it will be possible to date shorelines in the area.

On the basis of their altitude the moraine shorelines can be divided into two groups (see Table 4.4.).

Table 4.4.

Altitudes of moraine shorelines in Vestur-Ísafjarðarsýsla.

Group	Locality	Height of moraine shorelines	Height range
Group 1:	Higher shorelines, max. range 24.5 - 17 m.		
	Hafnardalur	21.5 m ± 3 m	18.5 - 24.5 m
	Lambadalur	20 m ± 2.5 m	17.5 - 22.5 m
	Kjaransstaðadalur	19.5 m ± 2.5 m	17 - 22 m
	Ketilseyrardalur	19.5 m ± 2.5 m	17 - 22 m
	Gemlufallsdalur	19.5 m ± 2.5 m	17 - 22 m
	Intermediate shorelines, max. range 21.5 - 15 m.		
	Húsadalur	19 m ± 2.5 m	16.5 - 21.5 m
	Krákudalur	18 m ± 3 m	15 - 21 m

Group	Locality	Height of moraine shorelines	Height range
Group 2:	Lower shorelines, max range 17 - 8 m.		
	Hrafnseyrardalur	15 m ± 2 m	13 - 17 m
	Hvammsdalur	14 m ± 3 m	11 - 17 m
	Meðaldalur	14 m ± 3 m	11 - 17 m
	Brekkudalur	13 m ± 3 m	10 - 16 m
	Tjaldanesdalur	13 m ± 1 m	12 - 14 m
	Hjarðardalur	11.5 m ± 3 m	8.5 - 14.5 m
	Kirkjubólsdalur	11 m ± 3 m	8 - 14 m

The moraine shoreline outside Eyrardalur has been discarded for reasons related in section 3.19.

The highest moraine shoreline is in Hafnardalur at 21.5 m ± 3 m while the lowest are in Kirkjubólsdalur and Hjarðardalur at 11 m ± 3 m and 11.5 m ± 3 m respectively. If the measurement errors are taken at the extremes (21.5 m - 3 m and 11 m + 3 m) then the difference is only about 4 m. Considering that the highest marine limit in the area is at least 111 m, this is a very small difference.

In the other valleys where there are moraines not cut by shorelines it was possible by various means to find out the maximum possible sea level position. These valleys are listed in Table 4.5.

Table 4.5.

Valleys where moraine shorelines were not observed

Valley	position of sea level during readvance
Gerðhamradalur	20 m contour
Haukadalur	20 m contour
Dalsdalur	20 m contour
Lokinhamradalur	20 m contour
Keldudalur	17.5 m ± 2.5 m
Bauluhúsadalur	20 - 26 m
Litlidalur	30 - 15 m
Núpsdalur	40 m ± 5 m
Sveinseyrarhvilft	42.5 m ± 4 m
Fossdalur	46.5 m ± 3 m

In all these valleys sea level was lower than 50 m and in five valleys lower than 29 m when the moraines were formed. In the cirques Litlidalur and Bauluhúsadalur there is evidence that sea level was in the vicinity of 20 m for some of the time when the cirques were occupied by glaciers.

In the classification of altitudes of moraine shorelines in Table 4.4. the possibility of differential uplift is not taken into account. To do that an equidistant diagram is presented and analysed in the next section.

4.5.2. Equidistant diagram for moraine shorelines in Vestur-Ísafjarðarsýsla.

The term shoreline is here defined as the line of former intersection of the land with the sea. Strandline is here defined as the shoreline fragments which can be shown to have formed simultaneously in an area. Isobases are defined as lines joining points of equal post-glacial emergence. An equidistant diagram is defined as "a diagram drawn in a plane that is orthogonal to the local system of isobases. On this graph the y axis is elevation above present sea level and the x axis, distance" (Andrews 1970, p. 7).

The equidistant diagram has been used extensively in areas of former ice and water loads to analyse the spatial distribution of shorelines. By projecting a strandline of this plane, the extent and geometry of crustal deformation becomes apparent. For the construction of an equidistant diagram it is necessary to determine the correct direction of the plane of projection, and the site elevations used to project a strandline must be synchronous. Because of the lack of dates in many areas and the consequent difficulty in finding out which shorelines constitute a strandline many workers (e.g. Gray 1974, England and Andrews 1973, Boulton and Rhodes 1974) have used the equidistant diagram to correlate shorelines of a similar height in a small area to delineate possible strandlines and, conversely, to demonstrate which shorelines are not synchronous. In this respect, especially, the present equidistant diagram is a potentially powerful tool to find out if there are significant age differences between the ice marginal features in the area.

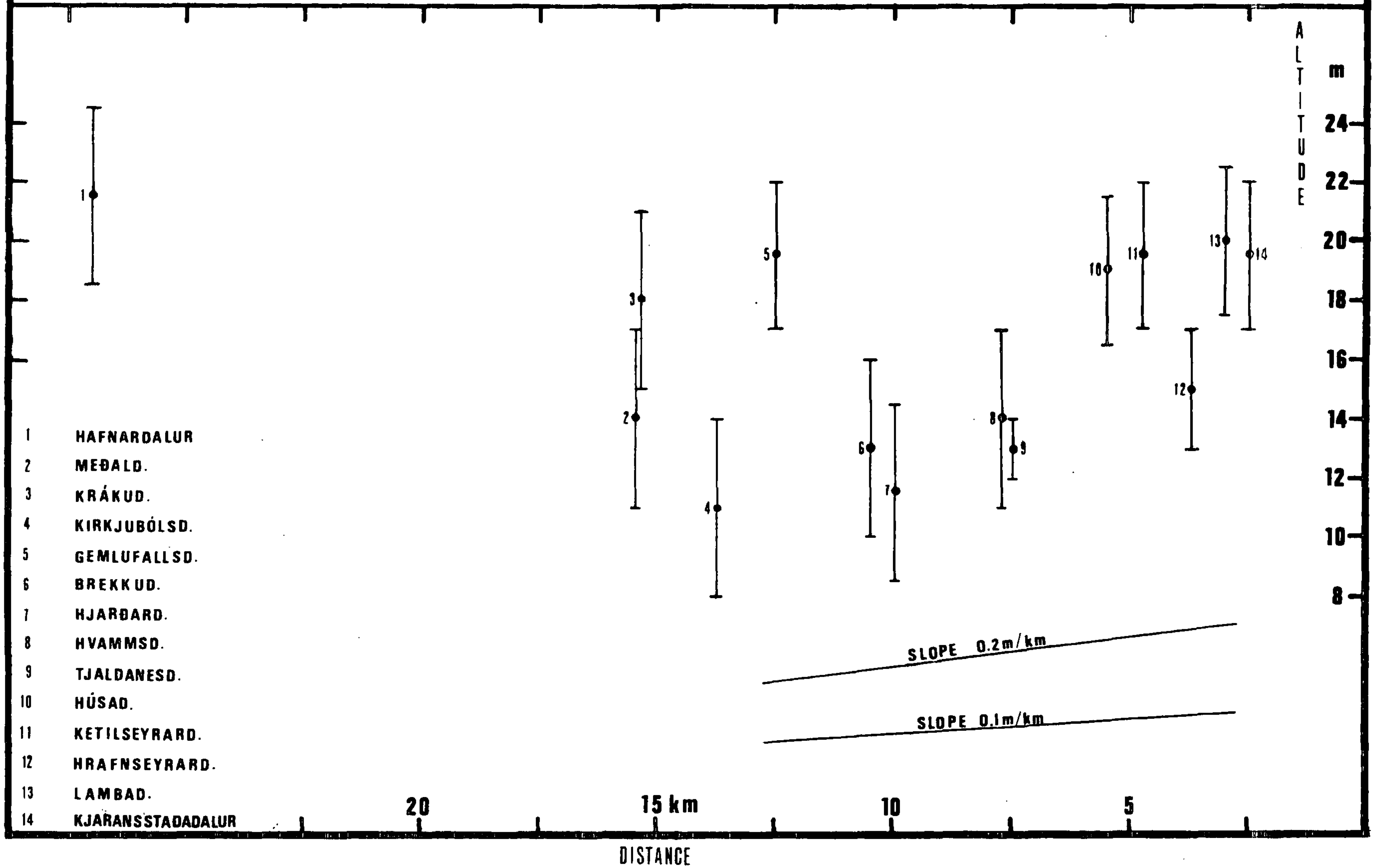
An equidistant diagram for moraine shorelines for the Dýrafjörður and northern Arnarfjörður area is presented in fig. 4.11. The diagram is tentative since it is based on the following assumptions:

Firstly, it is assumed that the retreat of the ice body which caused the crustal deformation proceeded along a line with the direction N117°E. This line is parallel with the direction of Dýrafjörður and is in the direction of the Gláma plateau, a likely centre of uplift assuming that Vestfirðir was indeed a centre of uplift. The line is also in the direction of Hofsjökull in central Iceland, a likely centre of uplift in Iceland.

Secondly, it is assumed that curvature of the isobases in the area is negligible. This assumption is reasonable because the area is relatively small, the localitites area all within 8 km of the projection line and the error limits of the moraine shorelines are relatively large anyway.

FIG.4.11

EQUIDISTANT DIAGRAM FOR MORAINE SHORELINES IN VESTUR—ÍSAFJARÐARSÝSLA



4.5.2.1. Results. The main features of the equidistant diagram of moraine shorelines in Dýrafjörður and northern Arnarfjörður are the following:

(1) The moraine shorelines are at least at two different "levels". This agrees with the conclusion drawn from Table 4.4.

(2) A least squares regression line through points 4, 6, 7, 8, 9, 12 has the equation $x = 16.46 - 0.4y$ and has the slope 0.4 m/km and $r = 0.9$ significant at the 0.05 level.

(3) A least square regression line through points 1, 3, 5, 10, 11, 13, 14 has the equation $x = 19.1 + 0.05y$ and has the slope 0.05 m/km towards the head of the fjords. The $r = 0.43$ not significant at the 0.05 level. Omitting point 1 (Hafnardalur) which causes the reverse slope, a least squares regression line through points 3, 5, 10, 11, 13, 14 has the equation $x = 19.93 - 0.093y$ and the slope 0.09 m/km and $r = 0.73$ not significant at the 0.05 level.

(4) The moraine shorelines are lowest along the middle of the fjords. A smooth, curved, line drawn from Hafnardalur (point 1) to Kjaransstaðadalur (point 14) goes through the error margins of all the points except point 5 (Gemlufallsdalur) and point 12 (Hrafnseyrardalur).

4.5.2.2. Discussion. The ice marginal features in the valleys of Dýrafjörður and Arnarfjörður are all at altitudes lower than 50 m. This shows that they were formed during readvances because the highest marine limits are higher than this, at least 111 m in Dýrafjörður and 90-100 m in Arnarfjörður. Besides, in Gerðhamradalur, Lambadalur, Ketilseyrardalur, Haukadalur, Keldudalur and Fossdalur there is stratigraphic evidence for readvances. The key question now is do these readvances in the valleys belong to the same chronozone or is there a significant difference in age between them?

At least two different levels can be identified in the altitudes of the moraine shorelines. To find out if these levels are actual strandlines a regression analysis is undertaken. The results of this are presented above (p. 251). The regression line for the higher shorelines slopes towards the head of the valley. This makes no sense since strandlines are everywhere seen to slope away from the area of greatest crustal load which in this case could not have been located near the tips of the peninsulas between the fjords. To amend this situation Hafnardalur, which weighted very heavily in the analysis, was omitted. This improved the results considerably, the slope is now in the desired direction and the correlation coefficient rose from 0.43 to 0.73, though not significant at the 0.05 level. Some degree of subjectivity, however, has been introduced by omitting an "undesirable" variable. The slope of the regression line this time, 0.09 m/km, is not unreasonable. The coefficient of determination, r^2, is still only 0.53 and only 53% of the variance is accounted for. It is not very likely, therefore, that the shorelines used for the analysis are parts of a strandline. The regression line for the lower shorelines has a much higher r, 0.90, and it is significant at the 0.05 level and 81% of the variance is accounted for. The slope of the line, however, is unreasonably high, 0.4 m/km, since it is not compatible with the slope of the line for the higher shorelines; the slope of the lower line should be lower than the slope of the higher line. The regression analysis shows, therefore, that although the moraine shorelines are at two separate levels, they are not parts of two strandlines. The possibility that one strandline is present cannot be excluded.

The two "levels" of the moraine shorelines are closely spaced and it is argued that they could not have formed at significantly different times. The same is argued for the moraines which have been shown to have formed when sea level was close to 20 m (see Table 4.5.). The reason for this is that the highest marine limits in the area is at least 111 m in Dýrafjörður and 90-100 m in Arnarfjörður. This point is discussed further in section 4.5.3. The reasons for the slightly different heights of sea level during the readvances could include the following:

In Hafnardalur, Dalsdalur and Krákudalur there is evidence for two positions of the ice margin during the readvances, This shows that in these valleys, at least, the ice margin oscillated during the readvances. These glacier oscillations were most likely due to climatic oscillations. That glaciers respond differently to climatic inputs is well known (e.g. Paterson 1969, Thorarinsson 1956, 1964). The main factors which are likely to affect different responses of glaciers include the size and the morphology of the valley, the aspect of the glacier accumulation area, the setting of the glacier, if it is fed by cirques or ice from the plateu. All these factors are highly variable in the area and this could explain that different glaciers peaked at different times during the readvances. And some glaciers surge. This factor alone could explain variable height of moraine shorelines in many cases.

In 21 valleys (see Tables 4.4. and 4.5.) there is evidence that sea level was close to or lower than 20 m and higher than about 11 when readvances took place in them. And sea level was very likely lower than 20 m in Eyrardalur when the moraine there formed. The question now is, did the readvances in Núpsdalur, Sveinseyrarhvilft and Fossdalur occur during the same stage as the readvances in the other valleys, i.e. when sea level was close to or a little lower than 20 m. The moraines in these valleys are located at altitudes of about 40 m or a little higher, and sea level could not be linked with them. It is argued that the readvances in these three valleys took place during the same readvance stage which affected the other valleys. The reason for this contention is that the setting of Núpsdalur and Fossdalur is much the same as the other valleys where readvances took place when sea level was close to or lower than 20 m, and therefore that a readvance must have taken place in all the valleys. And the cirque Sveinseyrarhvilft is at a low altitude, its lip is at about 120 m, and glacial readvances in adjacent valleys would have affected it too.

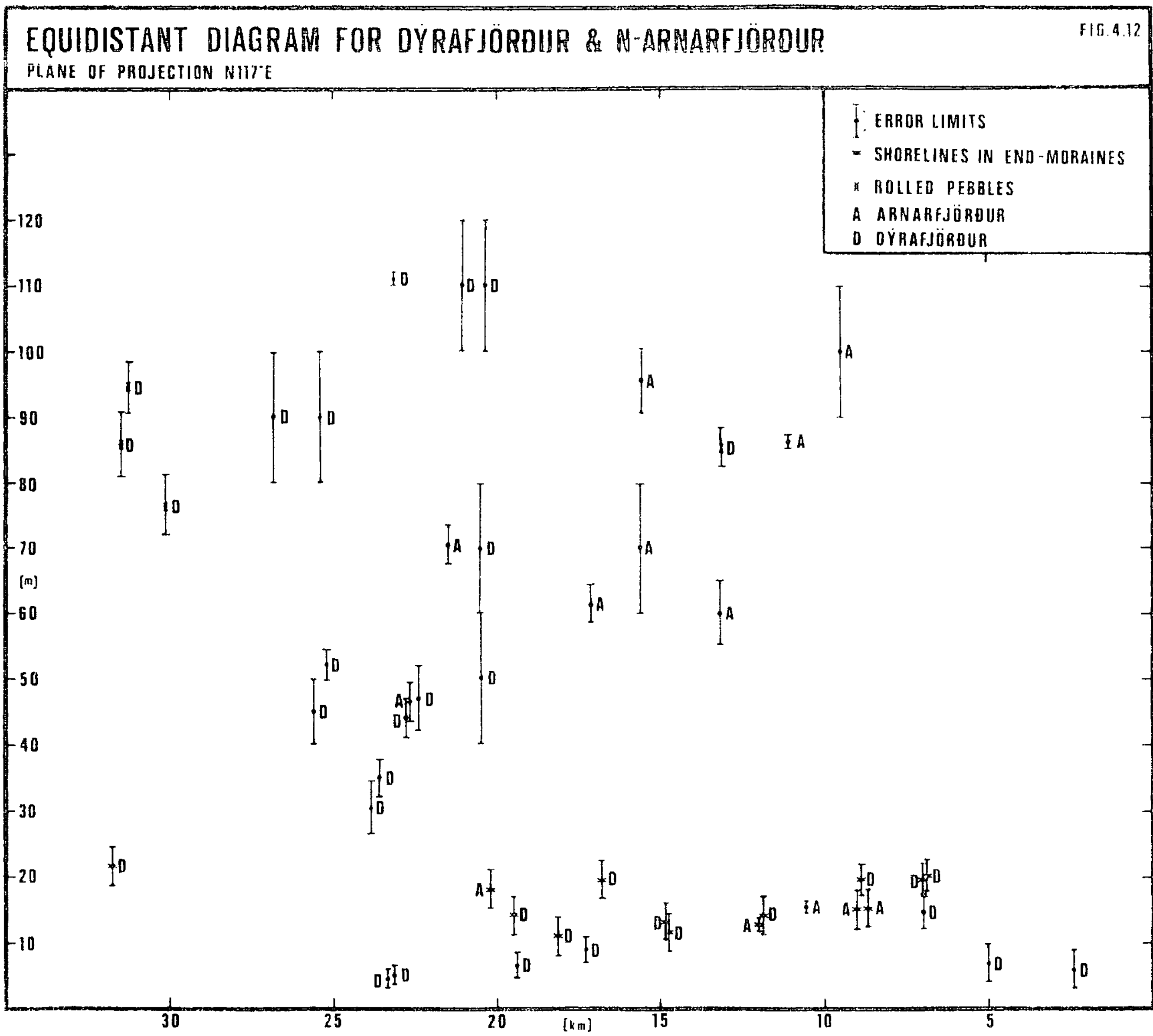
The conclusion is that when sea level was between 11 and 21 m a glacial readvance took place in 22 valleys and in 4 discrete cirques in the area of Dýrafjörður and northern Arnarfjörður. It is suggested here that the stage during which the readvances took place be called the Tjaldanes readvance stage, since in Tjaldanesdalur evidence for a readvance is strong and height of sea level during the readvance is known with great accuracy.

4.5.3. Equidistant diagram for all shorelines in Vestur-Ísafjarðarsýsla.

4.5.3.1. Introduction. The aim of this section is to elucidate the course of shoreline displacements and to understand the position of the moraine shorelines in this. This may throw light on the age relations of the readvance stage to the highest marine limits and possible strandlines and could thus be the basis for absolute chronology when, eventually, shorelines in the area will be dated. This aim is approached by presenting and analysing an equidistant diagram for the shorelines in Vestur-Ísafjarðarsýsla.

4.5.3.2. Results. In fig. 4.12. a tentative equidistant diagram for Dýrafjörður and northern Arnarfjörður is presented. The assumptions underlying the construction of the diagram are the same as for the diagram for the moraine shorelines and are listed in section 4.5.2.

A striking feature of the diagram is the great scatter of the shoreline altitudes. They are found at almost all altitudes from just above the present sea level to the highest marine limits around 111 m. They are most common at heights between about 10 and 20 m with most of these being the moraine shorelines. One other minor cluster of shorelines is in the height range 44-50 m where there are 5 shorelines within 5 km of the plane of projection. In the height range 22-44 m there is a noticible paucity of shorelines, only two shorelines occur there, those at 30.5 m and 35 m. Shorelines are also lacking in the range c. 70-90 m although the large error margins of the shorelines in the vicinity of these heights make it difficult to ascertain that the lack of shorelines there is real.


EQUIDISTANT DIAGRAM FOR DÝRAFJÖRÐUR & N-ARNARFJÖRÐUR
PLANE OF PROJECTION N117°E
FIG. 4.12
ERROR LIMITS
SHORELINES IN END-MORAINES
ROLLED PEBBLES
A ARNARFJÖRÐUR
D DÝRAFJÖRÐUR
(m)
(km)

The highest marine limits in both Dýrafjörður and Arnarfjörður are found near the middle of the fjords.

4.5.3.3. Discussion. The lack of dates of shorelines in the area makes it difficult to reconstruct the course of shorelines displacements in the area. A further difficulty is the large error margins for many of the shorelines, especially the ones whose height had to be estimated from the contour maps and could not, for various reasons, be measured in the field.

In spite of the lack of dates and lack of accurate height measurements some important inferences can be made from the equidistant diagram.

The equidistant diagram can be divided into altitude zones according to the lack or abundance of shorelines. Such a zonation is shown in Table 4.6.

Table 4.6.

Altitude zonation of shorelines in V-Í.

Altitude zone	shoreline occurrence
5 - 22 m	shorelines abundant, 14 are moraine shorelines, 8 are not.
22 - 44 m	Only 2 shorelines
44 - 70 m	Shorelines rather abundant, 11 in all.
70 - 90 m	No shorelines, 3 occurrences of rolled pebbles.
90 - 111 m	Seven shorelines and marine limits and 2 occurrences of rolled pebbles.

The boundaries between the altitude zones in Table 4.6.

are not well defined because of large error margins of the shoreline heights. Nevertheless, possible strandlines can only occur in the altitude zones 5-22 m and 44-70 m, the higher shorelines and marine limits are considered to be metachronous (see section 4.4.6.). The paucity of shorelines in the altitude zones 22-44 m and 70-90 m is also noticable. These main features of the equidistant diagram will be the focus of this discussion.

At least three explanations for the mode of origin of strandlines have been introduced: (1) Wright (1914) put forward the isokinetic theory which maintains that strandlines form when the rate of post-glacial uplift is equalled or exceeded by the rate of eustatic sea level rise. (2) Several workers (e.g. Løken 1962, Sugden and John 1965) have maintained that prominent strandlines were formed during glacial advances. (3) Andrews (1970) suggested that strandlines in Arctic Canada are related to climatic changes, the type of climate required being one of cool and wet summers.

The isokinetic theory is not a plausible explanation for the origin of strandlines in areas where post-glacial uplift has been rapid (Andrews 1970). This is because it is unlikely that rate of eustatic sea level rise equalled to rapid uplift. In Iceland there is trong evidence to suggest that post-glacial uplift was very rapid. Þ. Einarsson (1968) has shown that in southern Iceland a vertical shoreline displacement of over 100 m occurred in less than 2000 years (c. 10000-8000 B.P.), with average uplift rate of at least 6 m/100 yr. Also, Tr. Einarsson (1966) and Tryggvason (1973) have suggested that mantle viscosity under Iceland is anomalously low which implies high rates of post-glacial uplift (e.g. O'Connell 1971).

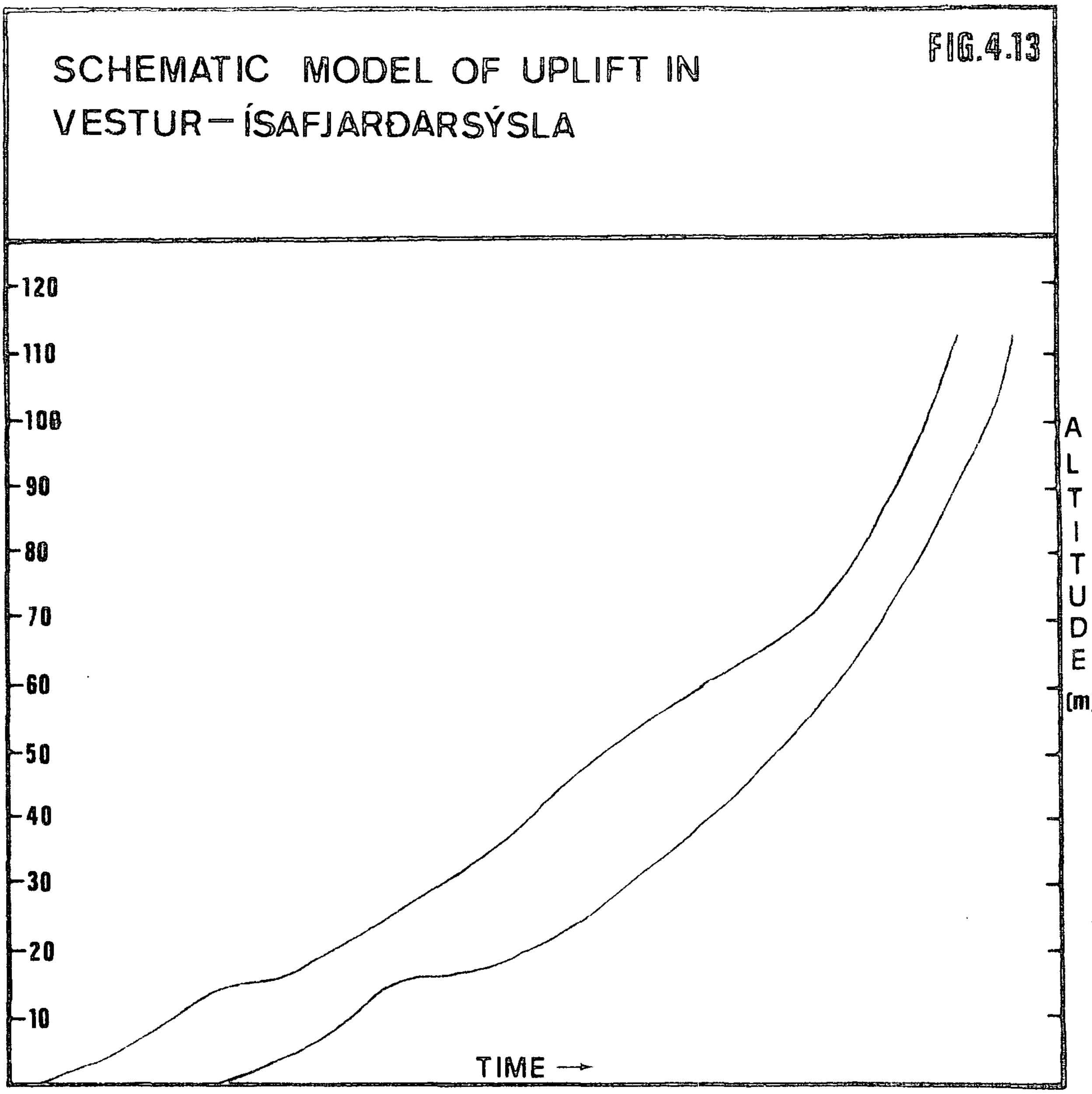
The glacial advance explanation for the mode of origin of strandlines is more relevent to Iceland. This is because of great crustal sensitivity to loads due to the low viscosity. Thorarinsson (1951) has suggested that glacial advance during his Hólkot stage in northern Iceland led to renewed downwarping of the crust which led to the formation of prominent shorelines at 40-50 m in northern Iceland. In any event, it must be considered highly likely that renewed downwarping of the crust did take place in Iceland during glacial advances. This suggests that the moraine shorelines in Vestur-Ísafjarðarsýsla were formed during a marine transgression. No field evidence for marine transgressions during glacial advances were found atlhough there are indications in the case of Lambadalur that a marine transgression took place there during or after the readvance there.

If glacial advances were the most important mode of origin of strandlines and shorelines in the area, which is very likely, the altitude zones of abundant and scarce shorelines become very important. Where shorelines are scarce or absent high rates of uplift and relatively fast glacial retreat can be inferred. Also, in altitude zones where shorelines are relatively abundant slower uplift rates can be inferred and possibly glacial advances. Apart from the altitude zone 5-22 m, where the moraine shorelines are dominant, the only other altitude zone where strandlines could be inferred is the zone 44-70 m. The shorelines altitudes within this zone, however, exhibit a considerable scatter.

It seems that the only possibility for a strandline in this zone in the range 44-50 m where there are 5 shorelines within 5 km of the plane of projection. A least squares regression line for these shorelines was computed and found to be $x = 67.45 - 0.92y$, with the slope 0.9 m/km and the correlation coefficient $r = 0.73$ not significant at the 0.05 level. The slope of the line seems high, although it is difficult to evaluate since no strandlines are known in Iceland. The correlation coefficient is not statistically significant and only explains about 52% of the variance. It is concluded that when sea level was between 70 and 90 m and 22 and 44 m uplift was rapid and glacial retreat fast, while when sea level was between 44 and 70 m uplift was slower, probably due to slower glacial retreat or, possibly, because of minor glacial advances.

Marine limits, when formed at the instant of deglaciation of a site, can give information on the course of glacier retreat. As has been mentioned before (section 4.4.2.), conditions for the formation of marine limits in Vestur-Ísafjarðarsýsla are rather poor because of the abundance of steep, rocky slopes. Because of this it is dangerous to draw far-reaching conclusions from the scanty data present. The fact that the highest marine limits in both Dýrafjörður and Arnarfjörður are found around the middle of the fjords need therefore not be of great significance. Furthermore, considering that the best conditions for marine limits to form in both fjords is along their middle sections because here gentle slopes are most common, it is clear that the locations of the highest marine limits say more about where conditions for the formation of the marine limits are best rather than saying anything significant about glacier retreat.

With the lack of dates it is difficult to reconstruct the course of shoreline displacements, or uplift. It has been shown, however, that it is very likely that when the moraine shorelines were formed a marine transgression took place. And there are no indications that marine transgressions took place when sea level was higher than about 20 m. Considering this, and also that crustal sensitivity in Iceland is great, it is reasonable to infer that crustal uplift had the form of a slowly decelerating curve down to a height of about 20 m when submergence took place to be followed by decelerating uplift again. This model of uplift in Vestur-Ísafjarðarsýsla is shown schematically in fig. 4.13. Two possible curves are drawn there. One which assumes continuous uplift and another which assumes a slowing down in uplift around the formation of the shorelines in the altitude zone 44-70 m. At the present state of knowledge the second curve is probably closer to the truth. If rate of uplift is taken to be 5 m/100 years from the formation of the marine limit to the formation of the moraine shorelines (average height say 16 m) then uplift at this rate would have taken about 2000 years. Similarly, with the extremely high uplift rate of 10 m/100 years uplift would have taken about 1000 years. With no dates available it is not possible to envisage any uplift rates. However, it is suggested that the age of the readvance stage in Vestur-Ísafjarðarsýsla, which can be called the Tjaldanes stage, and occurred when sea level was between approximately 11 and 22 m is similar in age to the Búði readvance stage in southern Iceland and the Hólkot stage in northern Iceland. This is based on the following considerations:



SCHEMATIC MODEL OF UPLIFT IN
VESTUR—ÍSAFJARÐARSÝSLA
FIG.4.13
120
110
100
90
80
70
60
50
40
30
20
10
TIME →
ALTITUDE (m)

(1) There is strong geomorphological evidence and some stratigraphic evidence that the Tjaldanes stage was a prominent readvance stage and that it led to renewed downwarping of the crust or, at least, a considerable retardation in uplift.

(2) There is firm evidence for only one Late Glacial readvance stage in Iceland (see section 4.2).

(3) There is evidence to indicate that immediately prior to the Tjaldanes stage there was relatively fast glacial retreat and rapid uplift. This complies with the evidence available for conditions during the Saurbær chronozone elsewhere in Iceland (Þ. Einarsson 1978).

(4) Widely in the North Atlantic area there is evidence for only one prominent Late Glacial advance: In East Greenland a major glacial advance to the so-called B-line culminated around 10 300 years B.P. Glaciers were then more extensive than during the Middle Weichselian (Hjort 1979). In Svalbard, the Billefjorden readvance stage took place with its maximum between 11 000 and 10 000 B.P. (e.g. Boulton 1979). According to Boulton (1979) this was the most important glacial event in Svalbard during the last 40 000 years at least. In western Norway only one prominent readvance stage has been recognized (e.g. Mangerud et al. 1979). This was during the Younger Dryas. Similarly, in Scotland only one prominent readvance stage is recognized (e.g. Sugden 1972, Clapperton 1972, Sissons 1972, 1976). This is the Loch Lomond stage which took place during Zone III (ca. 10 800 - 10 300 B.P., Sissons 1976).

This shows that during the Late Glacial (13 000 - 10 000 B.P., see Mangerud et al. 1974, Mangerud and Berglund 1978) there is evidence for only one prominent readvance stage in the North Atlantic area culminating between 11 000 and 10 000 B.P. At the present state of knowledge it is very reasonable to correlate the Tjaldanes readvance with this stage. An alternative would be to correlate the Tjaldanes readvance to a supposed glacial advance during the Álftanes chronozone (c. 12000 B.P., see section 4.2.1. and Þ. Einarsson 1978). Such a correlation is untenable, however, for the following reasons: (1) The evidence for a glacial readvance during the Álftanes chronozone is very sparse and conclusive evidence has not been presented. (2) A glacial readvance in Vestur-Ísafjarðarsýsla when sea level was between 11 and 22 m earlier than 12 000 B.P. would imply unacceptably high uplift rates or an unlikely early age for the highest marine limit. (3) A prominent readvance seems not to have occurred elsewhere in the North Atlantic area at this time.

4.5.4. The cirque moraines. In this section the position of cirque glaciations in relation to valley glaciations is considered. Their location is shown in fig. 4.14.

In Chapter 3 two ages were tentatively suggested for the cirque moraines. Dating the cirque moraines is difficult because only in exceptional cases could they be related to former sea levels. These cases are discussed in section 4.5.1. where it is concluded that they belong to the Tjaldanes stage. In Chapter 3 two ages are tentatively suggested for the other cirque moraines:

(1) Moraines formed during minor glacial advances or stillstands in the deglaciation of the cirques after the Tjaldanes stage.

(2) Moraines formed during phases of local glaciations post-dating the Tjaldanes stage.

The basis for this grouping is the size and morphology of the moraines. Large and prominent moraines are hypothesized to have formed during climatically induced readvances while less conspicuous moraines are hypothesized to merely reflect minor glacier oscillations during general retreat. This age

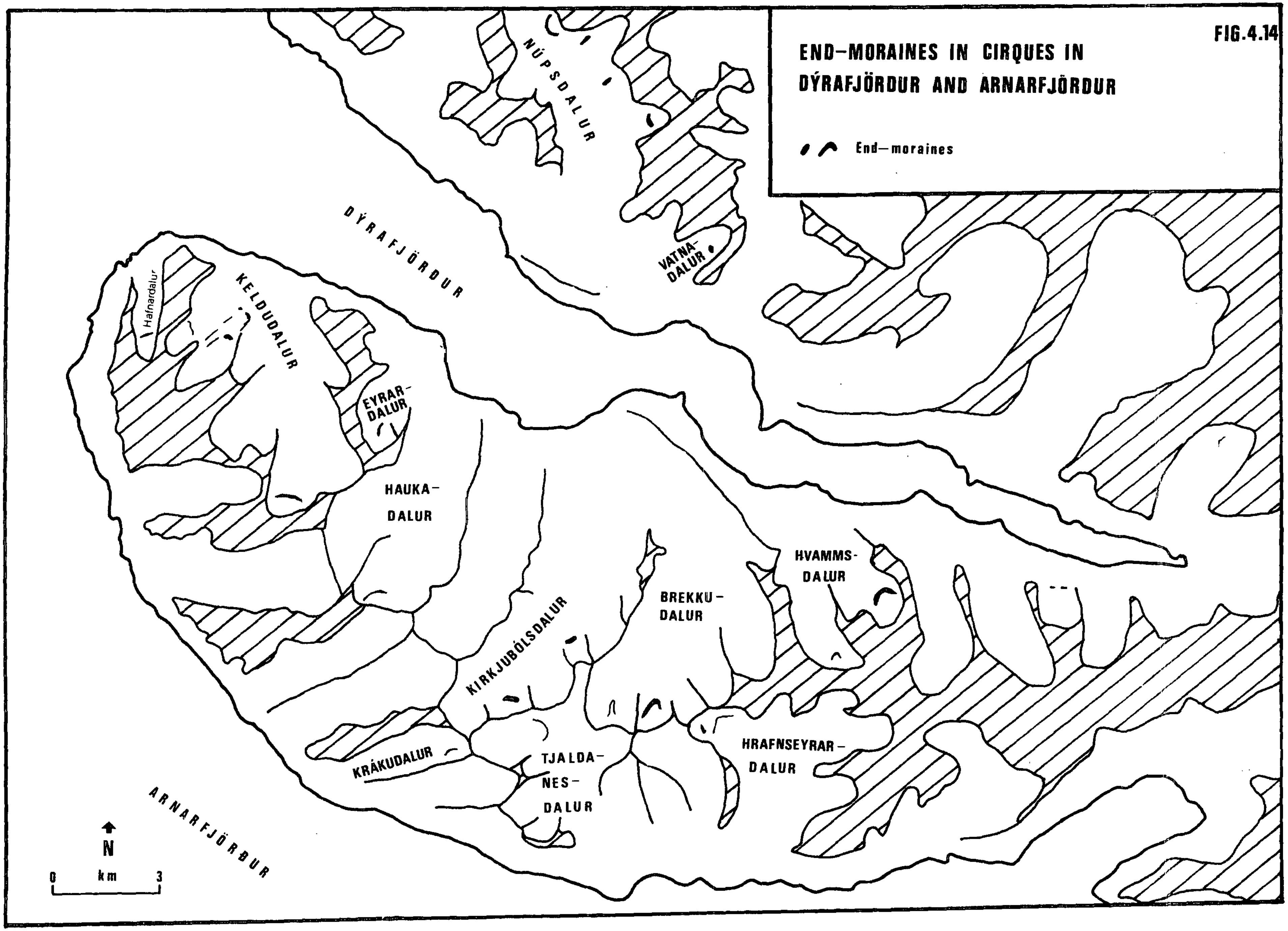


FIG.4.14
END-MORAINES IN CIRQUES IN DÝRAFJÖRDUR AND ARNARFJÖRDUR
End-moraines
NÚPSDALUR
DÝRAFJÖRDUR
VATNADALUR
Hafnardalur
KELDUDALUR
EYRARDALUR
HAUKADALUR
KIRKJUBÓLSDALUR
BREKKUDALUR
HVAMMSDALUR
HRAFNSEYRARDALUR
KRÁKUDALUR
TJALDANESDALUR
ARNARFJÖRDUR
N
0 km 3

division of the cirque moraines is very tentative, of course, as there is no sharp dividing line between the two groups and a considerable degree of subjectivity is involved with using concepts such as prominence and size when these have not been measured directly. Conditions for moraine building also vary according to the size and availability of loose deposits and different resistance of the rocks to erosion. To divide the cirque moraines into rigid groups on this basis is, therefore, hardly warranted. It is maintained, however, that in some cases, at least, the size of the moraines is such that they very likely formed during prominent advances of cirque glaciers. And it is argued that the moraines which are less conspicuous could belong to either of the two groups mentioned above, they either formed during the waning of the Tjaldanes stage or during cirque stage(s) post-dating this. In some cases the setting of the moraines is such that it is almost certain that they formed at the end of the Tjaldanes stage. It is suggested, therefore, that the cirque moraines can be conveniently divided into three groups according to their age. In Table 4.7. all the cirque moraines which have been mapped in Vestur-Ísafjarðarsýsla are classified according to this. In the table R means that the moraine is believed to have formed during a significant readvance of a cirque glacier, T that it was formed during the waning of the Tjaldanes stage and R/T means that it could belong to either of the aforementioned groups.

The moraines which are believed to have formed at the end of the Tjaldanes stage are all in the Núpsdalur area. Only in Grjótdalur and Hrútaskál, however, is there strong field evidence for this, the evidence for Garðshvilftir and Vatnadalur being circumstancial.

Of the 10 moraines which are believed to have formed during significant readvances of cirque glaciers after the Tjaldanes stage 8 are located in the area where rocks from the Hrafnseyri central volcano are found. This is an area where, on the whole, loose deposits are abundant. The

Table 4.7.

Age grouping of cirque moraines in Vestur-Ísafjarðarsýsla.

Núpsdalur:	Rangali	R		
	Grjótdalur			T
	Hrútaskál			T
	Geldingardalur		R/T	
Vatnadalur				T
(Garðshvilftir)				T
Haukshvilft			R/T	
Ausudalur		R		
Hvammsdalur (head)		R		
Kirkjubólsdalur:	K-1	R		
	K-2	R		
Brekkudalur:	B-1	R		
	B-2	R		
Koltursdalur		R		
Eyrardalur			R/T	
Keldudalur:	K-1		R/T	
	K-2		R/T	
	K-3	R		
Krákudalur			R/T	
Tjaldanesdalur:	T-1		R/T	
	T-2		R/T	
	T-3		R/T	
Hrafnseyrardalur:	Geldingadalur	R		
		10,	10,	4, total 24.

building of large moraines at the end of the Tjaldanes stage should have been easier there than in other areas. The size of some of the moraines concerned, however, is such that even allowing for this abundance of loose deposits it is very likely that the moraines must have been formed during a significant readvance of the cirque glaciers. Only in Rangali is there stratigraphic evidence for a cirque moraine overlying older deposits. This, however, shows that after the Tjaldanes stage an independent cirque glaciation took place in this cirque. Very likely this cirque glaciation also affected other cirques.

In ten cirques the age of the moraines remains very difficult to estimate.

It is concluded that there is conclusive evidence for a significant cirque glacier advance in one cirque, and very likely significant glacier advances occurred in at least 9 others, possibly as many as 19 others. There is very strong evidence in two cirques that the moraines in them formed at the end of the Tjaldanes stage and a similar age is very likely in two more cirques and possibly as many as 10 more.

4.6. SYNTHESIS AND CONCLUSIONS: GLACIAL HISTORY OF VESTUR-ÍSAFJARÐARSÝSLA.

The author's field work in Vestur-Ísafjarðarsýsla has led to the recognition of two stages of glacial readvances in the area, at least:

(1) The Tjaldanes readvance stage which occurred when sea level was between 11 and about 22 m. This readvance stage is argued to be the time equivalent of the Búði readvance stage in southern Iceland, or date from the Younger Dryas chronozone.

(2) At least one readvance stage has very likely taken

place in the cirques in the area. This took place after the Tjaldanes stage.

Other possible stages during the last glaciation of the area are the moraines discovered by Ólafsdóttir (1975) on Látragrunn. This stage can be called the Látragrunn stage. The age of the Látragrunn stage is unknown but is discussed in Chapter 5. It is also possible that the moraines discovered by Þorgrímsson (1976) near the head of Dýrafjöróur at a height of about 600-700 m were formed during a glacial readvance although this is considered unlikely because the moraines are very inconspicous.

CHAPTER 5. THE EXTENT OF THE MAXIMUM GLACIATION IN VESTFIRÐIR.

5.1. INTRODUCTION. The aim of this chapter is to reconstruct the extent of the maximum glaciation in Vestfirðir.

Firstly, the literature on ice extent in Iceland is reviewed.

Secondly, ice thickness in Vestfirðir is estimated by projecting theoretical ice cap profiles onshore from the furthest known glaciated point off the Vestfirðir coast.

Thirdly, the evidence supplied by the highest marine limit is used to estimate ice thickness, and this is compared with the evidence from the ice cap profiles.

5.2. THE NUNATAK HYPOTHESIS AND RECENT WORK ON EXTENT OF THE GLACIATION OF ICELAND. Thoroddsen (1906, 1911) was the first to systematically search for evidence concerning the extent of ice in Iceland. His mapping of striae in all parts of Iceland led him to the following conclusion:

(1) On the whole, striae seem to radiate from the centre of Iceland.

(2) There was a local centre of glaciation in Vestfirðir, possibly throughout the Pleistocene, with an ice thickness of 400-500 m.

(3) His search for striae on table-mountains in north-east Iceland revealed that only on the highest one, Bláfjall, 1225 m, did he fail to find any striae, which led him to the conclusion that the main ice sheet had been 700-800 m thick there.

(4) The overall conclusion was that during maximum

glaciation, apart from a few unimportant areas, Iceland was completely ice covered.

In this context it is necessary to bear in mind that Thoroddsen believed there had been only one glacial period during the Pleistocene.

In the 1930's four workers put forward independant evidence for large unglaciated enclaves during, at least, the last glaciation in Iceland. By this time the Nunatak Hypothesis was already well established in Scandinavia (Mangerud 1973). Lindroth (1931) based his arguments on the composition and distribution of insect genera. Gelting (1934) and Steindórsson (1937) used the distribution of higher plants and Thorarinsson (1937) used the distribution of alpine and cirque landscapes.

Lindroth (1931) considered it impossible for the insects to have migrated to Iceland during Post Glacial times. To account for the presence for at least half of the genera he stated that there must have been unglaciated areas along the coastal stretches. On the basis of their present distribution he proposed two fauna centres, one in middle southern Iceland (the Mýrdalur area), and the other in south-east Iceland (the Hornafjörður area).

Thorarinsson's (1937) geomorphological evidence mainly consisted of the presence or absence of cirques and "alpine" landscapes. Thus, the areas he proposed as potential biota refugia are also the main cirque areas. He argued that the presence of cirques was in itself sufficient evidence to show that these areas had not been inundated by an ice cap or an ice sheet. This argument is based on the assumption that the "cirques were most likely formed during the maximum of the last glaciation".(p. 171). He also observed from the topographic maps that the numerous cirques of Vestfirðir are located close to the coast, no cirques for instance being observed in the inner part of Ísafjarðardjúp. Gelting (1934) pointed to the vicinity of Eyjafjörður in northern Iceland as a nunatak area because here "the landscape is distinctly alpine and a large number of species occur which have not otherwise been found in Iceland"(Gelting 1934, p. 28). Steindórsson also expressed the view, based on the distribution of some higher plants, that some species would have survived the Ice Age in Iceland.

Several other botanists have since expressed the view that to account for the distribution of some higher plants in Iceland certain parts of the country must have been ice free during the last glaciation at least. Most of this work is summarized by Steindórsson (1962). There he collected all that was known at the time about the distribution of 304 plant species. Of these he considers 214 as native and to have survived at least the last glaciation. The total number of species in the Icelandic flora is only about 440. He noticed that the great majority of the less common species appeared to be confined to a few areas or at least having their central distribution there and then appearing to disperse from these centres. From this he suggested that it was possible to recognize 6 major possible refugia and 13 single nunataks. The major refugia all coincide with the "alpine" areas inferred by Thorarinsson (1937) to have been ice free as well as the two areas in southern Iceland which Lindroth (1931) had claimed were ice free. The main botanical arguments are that certain plants are more or less confined to the refuge areas, but are rare or not found elsewhere in the country.

While the botanists added more and more evidence to support the Nunatak Hypothesis, very little work was done on the geomorphological side. Kjartansson (1943) mapped striae over a wide area in Árnessýsla in southern Iceland, and especially searched for them on high mountains. He found no evidence for ice free areas.

Tr. Einarsson (1959) published the results of his extensive investigations in the area around Eyjafjörður in northern Iceland. He argues for large unglaciated areas as well as numerous nunataks. The evidence consisted of the upper limit of lateral moraines, gravel terraces and striae coinciding with the lower limit of deeply weathered bedrock. His conclusion was that all through the Pleistocene there had been nemerous nunataks rising above the ice, and during the last glaciation, especially, coastal areas could be shown to have been ice free. Significantly, on the remote island of Grímsey (location in fig. 4.6) he found "no signs of a glaciation and very likely the island has never been glaciated "(Tr. Einarsson 1959, p.11).

Þ. Einarsson (1961) added further support for the Nunatak Hypothesis with his pollen analytical studies. He was able to show that the birch (Betula pubescens) appeared in his oldest pollen zone (Zone A) in north and eastern Iceland but not in south-west Iceland. This implies that the birch had survived longer in the north an east. Subsequent C^{14} dating, however, has shown that Zone A in north Iceland is only older than 8000 years B.P. and that the start of Zone B in southern Iceland dates back to about

9000 years B.P. Because of this it is possible that the birch has not had a longer history in the north of Iceland than in the south (Þ. Einarsson 1967).

Kjartansson (1955) reported on his studies of striae in many parts of Iceland and concluded that the ice-divide during the Late Glacial Búði stage (roughly equivalent to the Younger Dryas chronozone, see section 4.2.2.) lay some 50 km south of the present water divide. If similar conditions prevailed during the last glaciation, it would seem likely that the ice sheet would be thinner in northern Iceland than in southern Iceland.

Tr. Einarsson (1962 (a)) envisaged a large unglaciated area in eastern Iceland, mainly on the grounds of lack of glacial landforms and striae and what he interpreted as deeply weathered rock. His main points were rejected by Kjartansson (1962) who observed striae at relatively high altitudes, which greatly restricted the area which could possibly have been ice free. Tr. Einarsson (1962 (b)) accepted his arguments. It is significant in this context that neither worker visited Papey, an island 7 km off the area they investigated.

A different line of evidence for ice extent came from Thorarinsson (1951) who found shell fragments at an altitude of 127 m in Laxárdalur in northern Iceland, and concluded that the marine limit was probably close to 130 m. Such a high marine limit is difficult to tie up with a stage of valley glaciation in northern Iceland. This point is discussed further in section 5.4. Strangely enough, this observation seems to have gone unnoticed in the literature.

Friðriksson (1962) presented the first botanical objections against the Nunatak Hypothesis. He pointed out that the centric plants are almost all alpine plants and that it was not surprising, therefore, that they are at present confined to alpine areas. He also pointed out that there are no endemic species in Iceland as would be expected, had part of the flora survived several glaciations. Friðriksson also thought that, considering the Icelandic flora as a whole, everything seemed to indicate that it was easier to explain its origin by colonization in Late and Post Glacial times than that part of it had survived the Ice Age. Steindórsson (1964) discussed the points made by Friðriksson and rejected his conclusion on the basis that Tr. Einarsson (1959) had "proven" that there were ice free areas in the Eyjafjörður district during the last glaciation.

By the mid-sixties the Nunatak Hypothesis had become well established. But as Þ. Einarsson (1967) pointed out, it had not really been tested with systematic research. He suggested to this end the need for pollen analysis coupled with C^{14} dating of Late Glacial bog sites on the one hand and a search for evidence of glaciation on offshore islands and high mountains on the other. In line with this he presented the results of his work on Grímsey island and the Tjörnes peninsula in northern Iceland. As mentioned earlier, Tr. Einarsson had not found any traces of glaciation on Grímsey, but Þ. Einarsson found glacial striae in three places, but no other evidence. He concluded that the age of the striae could not be very great, and certainly not older than the maximum of the last glaciation, since if they had been exposed for a long time they would have become destroyed by weathering. He also found striae near the top of the 760 m high Búrfell on Tjörnes, 15 km from the coast. On both Grímsey and Búrfell and on the outer part of the Tjörnes peninsula, the striae have a direction of NW-SE. On the basis of this evidence, he concluded that there had been no ice free plant refugia in the Eyjafjörður area during the maximum of the last glaciation.

Hoppe (1968) also visited Grimsey and apart from observing striae in 12 localities, he also found an abundance of melt water channels, areas with a thin till cover and roches moutonnées. Hoppe's conclusions are as follows: "The ice border at the glacial maximum stood at least tens of kilometres north of Grímsey. With Grimsey covered by ice from the southerly mainland the area around Eyjafjörður and Skjálfandi must have been heavily glaciated; nunatak areas, however, cannot be excluded" (Hoppe 1968, p. 22).

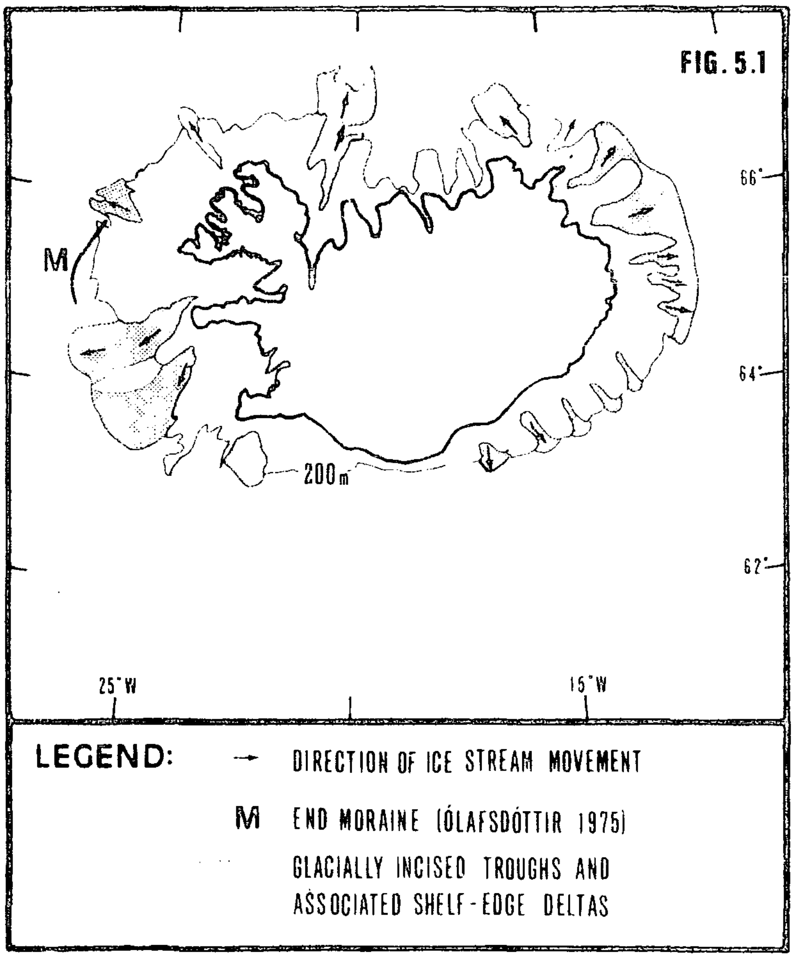
Hoppe (1972) also paid a visit to the island of Papey off the coast of eastern Iceland and observed "that much of the landscape is made up of well-preserved roches moutonnées. No clear evidence of glacial striae was found, but this may have been due to hazy weather at the time. In any event it seems likely that the whole of Papey was ice-covered during Würm time" (Hoppe 1972, p. 28). Thus the evidence from these two islands is in direct disagreement with evidence based on weathering of bedrock and absence of glacial erosional landforms (Tr. Einarsson 1959, 1962). The age of the traces of glaciation on Grímsey and Papey is unknown, but, as Kjartansson (1943, 1955, 1962) has shown, glacial striae are not preserved for a long time after they become exposed in Iceland, because weathering, mainly frost shattering, quickly destroys them. Therefore, it can be assumed that almost all striae found at present in Iceland date from the last main glaciation or more recent local glaciations. Sometimes a striated pavement is found beneath the older, interbasaltic tillites, but only on surfaces which have obviously been recently exposed. However, although the striae in Grímsey very likely date from the last glaciation, it has not been conclusively proven. The date of ice overriding Papey is even more uncertain.

More conflicting evidence is coming to light as research on the sediments and physiography of offshore areas develop.

Ólafsdóttir (1975) reported the presence of a 100 km long, 20-30 m high ridge about 130 km off the mouth of Breiðafjörður. The evidence, which consists of more than 40 fathometre records of crossings over the ridge and four grab samples of the sediments in it, overwhelmingly indicates a glacial origin of this ridge. There is no evidence as to its age, but Ólafsdóttir and Þ. Einarsson (1978) interpret it to have formed during the maximum of the last glaciation. This interpretation is in line with workers such as King (1969) working off the coast of Nova Scotia, and Holtedahl and Sellevoll (1972) and Andersen (1979), discussing the numerous moraine ridges on the Norwegian shelf, who all assigned a tentative Wisconsin/Weichselian age to the submarine moraine ridges.

Recently Egloff and Johnson (1979) have reported many end moraines near the shelf edge off western and south-western Iceland. Their evidence is based on seismic reflection data. They also stated that "Iceberg plough marks are widespread" (p. 45). It seems most likely that ice bergs leaving plough marks on the shelf originated in ice derived from Iceland. Egloff and Johnson (1979) came to the following conclusion about ice action on the shelf: "The insular margin of southwestern Iceland has been extensively modified by glacial erosion and morainal depositon with 10 to 30 km of shelf-edge progradation" (p. 48).

Geophysical studies of other offshore areas around Iceland have increased greatly recently (e.g. Kristjánsson 1976, Vogt and Perry 1978, Perry et al. 1977, Vogt et al. 1980, Johnson and Pálmason 1980). Vogt et al. reviewed the data from north of Iceland, which consists of bathymetry seismic reflection profiles, aeromagnetic surveys and sediment thicknesses, and came to the following conclusion: "The Iceland Plateau" (defined as the relatively shallow area bounded by the shelf edges of Greenland and northern Iceland, by the Jan Mayen ridge in the east, and the Jan Mayen Fracture Zone in the north) "is indented by numerous shallow U-shaped valleys, many of which appear to be submarine extensions of fjords and other embayments of the Iceland coastline. It is most reasonable to explain these submarine valleys as the work of glacial erosion by grounded ice streams flowing radially from an ice dome culminating in central Iceland. The bathymetric chart shows recognizable arcuate salients of the shelf edge located at the mouths of the submarine valleys. These salients most likely represent ice-front deltas composed of debris transported to the shelf edge by grounded ice streams. In most cases the 400 m isobath is deflected seaward where the 200 m isobath shows an embayment. This suggests the ice streams were grounded to depths between 200 and 400 m" (p. 76). Fig. 5.1. (redrawn from Vogt et al. 1980, figs. 1 & 8) shows



the submarine valleys they interpret as glacially eroded, the offshore area off northern Iceland which they suggest was occupied by grounded ice streams during the Pleistocene glacial maximum, and the direction of ice stream flow and submarine sediment transport along valley floors. Also shown is the moraine ridge found by Ólafsdóttir (1975). According to this map the offshore area north of Vestfirðir was glaciated to a distance of some 130 km from the coast.

<u>5.2.1. Discussion</u>. Table 5.1. summarizes the evidence used by various workers in their attempts to delimit the extent of ice during the last glaciation. The evidence is divided into indirect evidence and direct evidence. In this sense "direct evidence" gives conclusive results as regards

TABLE 5.1.

Lines of evidence used to delimit the extent of ice during former glaciation

SUGGESTIVE EVIDENCE:

- Present distribution of centric plant species
- Past distribution of plants
- Present distribution of animals
- Past distribution of animals
- Lack of signs of glacial erosion
- Products of prolonged weathering (mountain top detritus, felsenmeer, tors, chemical weathering, extensive clay mineral development, weathering zones)

CONCLUSIVE EVIDENCE:

- End moraines
- striae, grooves, ice polished surfaces
- Roches moutonnées
- Melt water channels
- Till
- Erratics
- Dated high marine limits and lower shorelines indicating amount of glacio-isostatic rebound and minimum ice thickness

ice extent, while "indirect evidence" can only be suggestive. A classification like this, however, is bound to be arbitrary to some extent. For instance, past distribution of plants is here classified as indirect evidence. Löve (1963), however, discussing the diminishing of the Icelandic flora since the first interglacials and the extinction of species, concluded that "Logically, this must be regarded as fully satisfactory proof that plants and animals have been able to survive the Pleistocene glaciations" (p. 392). The present author cannot see how diminishing of the flora and the extinction of species can prove glacial overwintering, it could be explained by e.g. deteriorating climate or that some species did not migrate back to Iceland at the end of a glacial. There is also disagreement on the strength of the evidence of the centric plant distribution with Friðriksson (1962) in Iceland and Berg (1963) in Scandinavia claiming that glacial overwintering is not required to account for the distribution.

Lack of signs of glacial erosion has been used to argue for ice free areas, while e.g. Ives (1974) has pointed out that cold-based, inert, ice would most likely accomplish no erosion.

Past distribution of animals was used by Lindroth (1963) in discussing the fauna in deposits most likely dating from the last interglacial.

Tr. Einarsson (1959) used signs of prolonged weathering to argue for ice free areas. His observations, however, need to be tested with detailed studies like those of R. Dahl (1966) and Andrews and Miller (1972).

In Iceland, high marine limits have never entered the discussion of ice extent, in spite of their obvious relevance (e.g. Andrews 1970). This, however, is a complicated problem and is discussed in detail in section 5.4.

Until about the mid-sixties all the evidence collected about ice extent was what is here classified as indirect, and had been used to demonstrate limited ice extent. Since then work has shifted to collecting direct evidence, which is here classified as conclusive: Signs of glaciations on high coastal mountains (Þ. Einarsson 1967), on offshore islands (Þ. Einarsson 1967, Hoppe 1968, 1972) and end moraines on the shelf (Ólafsdóttir 1975). The findings of these workers, together with the work of Vogt et al. (1980), render the possibilities for large unglaciated enclaves as very slim indeed.

The question of unglaciated enclaves, nunataks and biological refugia can be investigated in light of the known minimum limits of ice extent furnished by conclusive evidence of end moraines and other glacial depositional landforms and glacial landforms. By projecting theoretical ice cap profiles from such sites, towards the presumed ice centre, this question can at least be partly solved. This is the subject of the next section.

5.3. THEORETICAL ICE CAP PROFILES AND THE MAXIMUM EXTENT OF ICE IN VESTFIRÐIR.

5.3.1. Introduction. The method of projecting theoretical ice cap profiles to investigate the possibility of unglaciated enclaves and nunataks has been used in Baffin Island (e.g. Buckley 1969), Labrador-Ungava (Mathews 1974), Greenland (Sugden 1974) and all along the periphery of the Laurentide ice sheet by Sugden (1978). Sugden (1978) was able to show that his alpine landscapes had protruded above the Laurentide ice sheet in most areas. In both Baffin Island and Greenland it was shown confidently that the highest coastal mountains must have protruded above the ice streams of the main ice sheet, at a given ice limit, so that the possibility of plant refugia on nunataks must have been very high. The situation was probably similar to the present day Antarctic nunataks. If it so happens that it can be shown that no mountain tops protruded above the ice sheet, the possibility of unglaciated enclaves can be ruled out. Care must be taken when interpreting results in marginal cases, especially where the ice is likely to have been thin in the vicinity of rough topography of high relief. This is because ice thickness is closely related to the slope of the ice surface and, to a lesser extent, to the slope of the underlying bed. If bedslope is very steep, ice free slopes might occur if the ice in general is thin. In general, this would be most likely to happen in the vicinity of high coastal cliffs.

5.3.2. Theory and assumptions. Paterson (1969, 1972) has reviewed the use and derivation of theoretical ice sheet profiles. He showed that three types of steady-state profile equations, hyperbola, parabola and an ellipse can be applied with very reasonable accuracy to approximate profiles of the Antarctic ice sheet. A hyperbola of the form

$$\left(\frac{h}{H}\right)^{2.5} - \left(\frac{x}{L}\right)^{1.5} = 1$$

(where the total ice sheet width is 2L, h is ice thickness at x and H is ice thickness at the centre) best fits most of the actual Antarctic profiles, while a parabola of the form

$$h = A\ x^{1/2}$$

(A is a constant related to basal shear stress, density of ice and gravitational attraction and h is ice thickness at x) has a lower profile. Since the purpose of this investigation is to find out minimum ice thickness to draw conclusions about minimum ice extent, the parabolic equation was chosen. Several assumptions underly the derivation of the parabola:

(1) The profile should follow a flow line.

(2) The base of the ice sheet should be horizontal.

(3) The ice sheet should be in a steady state.

(4) Stresses and velocities should vary only slowly with horizontal distance.

(5) Mass balance should be constant over the ice sheet.

(6) Temperature, roughness of the bed and other factors which might influence the velocity should be constant over the ice sheet.

The first four assumptions are taken to hold approximately. The mass balance would be far from constant over the ice sheet, but it has been shown (Nye 1959) that ice thickness is extremely insensitive to changes in mass balance. The effects of factors which might influence the velocity are difficult to assess. Paterson (1969) points out that the theoretical profiles agree surprisingly well with observed ones in view of the approximations made, "which supports the basic idea that the shape of an ice sheet is largely determined by the plastic properties of ice. Variations in accumulation, temperature, the nature of the bed and other factors are relatively unimportant in many cases " (Paterson 1969, p. 153-154).

The equation for an ice sheet profile preferred here has the following form:

$$h = (2Ax)^{1/2} \qquad (1)$$

where A is a constant equal to S/dg where S is basal shear stress, d is density of ice and g is the acceleration due to gravity. Since d and g can be regarded as constants, the basal shear stress becomes very important in determining the height of the profile. Equation (1) can be derived from the relation $S = dgh \sin a$ (where a is the slope of the surface) (Nye 1952) which shows that the basal shear stress can be calculated where ice thickness and surface slopes are known. This has been done for many glaciers and the great majority of the values for the basal shear stress lie between 0.5 and 1.5 bar (Nye 1952, Paterson 1969, Andrews 1972). When the basal shear stress becomes low, the surface profile also becomes low. Since predicting the shear stress in a Pleistocene ice sheet is very difficult, it has to be conjectured. The lower limit for it was taken as 0.5 bar, as for values lower than 0.5 bar the strain rate would be very low and, hence, velocities would become very low as well.

5.3.3. Results and discussion. In fig. 5.2. ice sheet profiles are plotted with basal shear stresses of 0.45, 0.5, 0.8, 1.0 and 1.5 bar. The bed constituting the continental shelf was taken to be horizontal, which is reasonable taking isostatic depression into account. The lowest profile, with basal shear stress of 0.5 bar, would be about 120 m above Vestfirðir's highest summit, Kaldbakur, 998 m. In this the landmass has been ignored, but taking the landmass into account the profile would become higher. The effect of the landmass on the profile was calculated using a method used by Nye (1952).

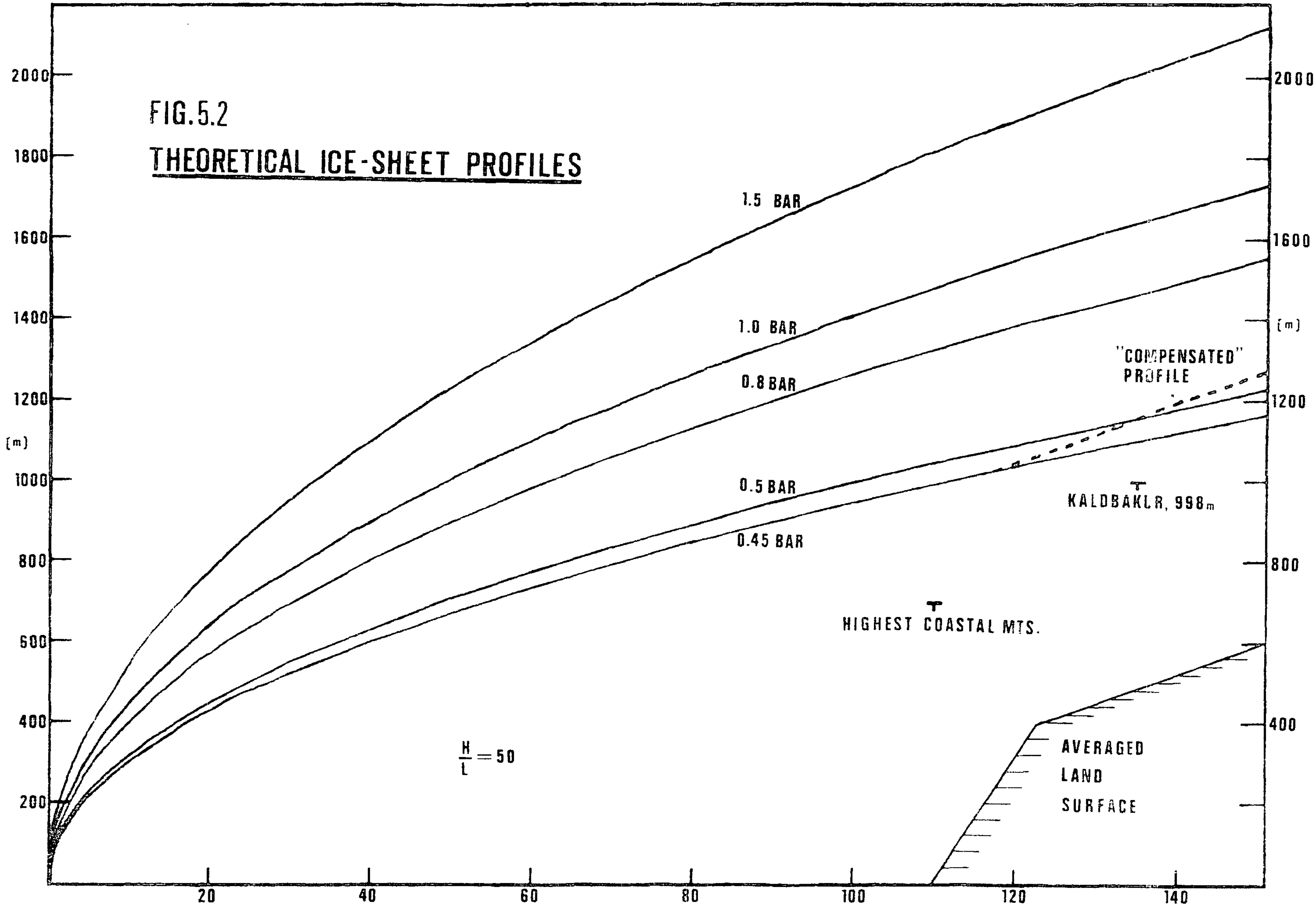


FIG.5.2
THEORETICAL ICE-SHEET PROFILES
1.5 BAR
1.0 BAR
0.8 BAR
0.5 BAR
0.45 BAR
"COMPENSATED" PROFILE
KALDBAKUR, 998m
HIGHEST COASTAL MTS.
AVERAGED LAND SURFACE
H/L = 50
(m)
2000
1800
1600
1400
1200
1000
800
600
400
200
20
40
60
80
100
120
140

The following assumptions are made: The area between Patreksfjörður and Önunarfjörður was chosen to take the profile on land. It was necessary to average the height of the land to compensate for the concentrated flow of ice in the fjords. The average land surface was taken to rise steadily to an elevation of 400 m 13 km from the coast, and then to rise to 600 m over the next 28 km. All estimates of the average height are minimal. This compensated profile is shown in fig. 5.2. for the very low basal shear stress of 0.45 bar. As can be seen the compensation for the landmass does not change the profile drastically, but further emphasizes the conclusion that the coastal mountains would be deeply buried by ice and that the 998 m summit of Kaldbakur would be buried by at least 100 m of ice. The ice over Kaldbakur was probably much thicker in view of all the minimal estimations made. In the event, however, very unlikely though it is, that all the minimal estimations are realistic, only 100 m of ice over Kaldbakur is hardly enough to exclude that there were ice free areas. This is because the topography is rough, and the largest fjords would be the sites of major ice streams which would have the effect of lowering the surface of the ice sheet near them. Nevertheless, Kaldbakur is by far the highest summit in the area where the mountains rarely exceed about 700 m and would, according to the profile, be buried under thick ice even though all the minimal estimations were realistic.

5.3.4. Conclusion. At the time when the ice sheet built the terminal moraines on the outer continental shelf on Látragrunn, the ice sheet edge-point used to draw the theoretical profile, it can be concluded that almost certainly, unless some very special conditions prevailed, there were no ice free areas in this part of Vestfirðir.

5.4. ESTIMATION OF ICE THICKNESS FROM THE HEIGHT OF THE MARINE LIMITS. Variability in the height of the marine limit is a function of factors listed in section 4.4. In the case of Vestur-Ísafjarðarsýsla none of these variables is known. It may be possible, however, to arrive at reasonable estimates. This will be attempted here since, in general, heights of the marine limit have large potential interpretive value.

Distance from the former ice sheet margin, one of the factors affecting variability in the altitude of the marine limit, is a measure of ice thickness. It was concluded in earlier sections (4.6 and 5.2) that the submarine terminal moraine ridge on Látragrunn off Breiðafjörður very likely dates from the maximum of the last glaciation (perhaps in the region of 20 000 B.P.). Ice thickness at this time was in section 5.3 estimated by projecting theoretical ice sheet profiles from this terminal moraine onto Vestfirðir. Estimating ice thicknesses from such profiles is, however, difficult. The height of the profile depends entirely on the basal shear stress, which is an unknown quantity, and the distance from the ice margin. Nevertheless, it will be attempted to estimate the minimum ice thickness in Vestur-Ísafjarðarsýsla from these profiles. The results are shown in Table 5.2. The middle of the fjords, Dýrafjörður and Arnarfjörður, is used as a point of reference:

Table 5.2.

Estimation of ice thicknesses in Vestur-Ísafjarðarsýsla from theoretical ice sheet profiles in fig. 5.2.

Basal shear stress	ice thickness
0.5 bar	690 m
0.8 bar	990 m
1.0 bar	1170 m
1.5 bar	1520 m

As was shown in section 5.3. the most likely basal shear stress is 1.0 bar while it can not be lower than 0.5 bar. Consequently, minimum estimated ice thickness lies between 700 and 1170 m, this latter thickness being more likely.

To get a reliable estimate of the age of the marine limit in Vestur-Ísafjarðarsýsla is difficult since so little is known about the ages of the marine limit elsewhere in Iceland (section 4.4.5.) and no dates are available from the field area. The ages of the marine limits elsewhere in Iceland appear to be within a range close to 10 500 - 12 500 yrs. B.P. (section 4.4.5.). On the basis of this information and the assumption that the marine limit at Núpur, at least 111 m, located near the middle of Dýrafjörður, is representative for Vestur-Ísafjarðarsýsla, the amount of post-glacial uplift in Vestur-Ísafjarðarsýsla can be estimated. The results are shown in table 5.3. where Mörner's (1971) curve is used for correcting for eustatic change of sea level:

Table 5.3.

Estimated ages of marine limits and amount of post-glacial uplift in Vestur-Ísafjarðarsýsla.

Estimated age of marine limits	Altitude of marine limit	Eustatic correction	Estimated amount of post-glacial uplift
10500 B.P.	111 m	43 m	154 m
11500 B.P.	111 m	42 m	153 m
12500 B.P.	111 m	52 m	163 m
13000 B.P.	111 m	60 m	171 m

Although the range of estimates for the age of the marine limit is large, the range in the estimates of the amount of post-glacial uplift is small, 18 m.

Post-glacial uplift only forms a part of the total glacio-isostatic recovery, the other part, that took place before deglaciation, is called restrained rebound. Since the restrained rebound is unknown it is not possible to estimate the amount of the total glacio-isostatic recovery using uplift data only. However, assuming isostatic equilibrium prior to unloading of the crust, glacio-isostatic recovery is a function of ice thickness:

$$R_e = d_i Z_e / d_r$$

where R denotes depression under ice load, Z the thickness of ice at the point concerned, d_i density of ice, d_r density of rock displaced and e denotes the state of equilibrium (Bergquist 1977). Using values arrived at in Table 5.2. on ice thickness and taking density of displaced rock to be 3.0 (a mean of 2.7 the density of crust and 3.3 the density just below the Moho) and density of ice to be 0.9, the following results are obtained for glacio-isostatic recovery (see Table 5.4):

Table 5.4.

Basal shear stress	Ice thickness	Glacio-isostatic recovery
0.5 bar	690 m	210 m
0.8 bar	990 m	300 m
1.0 bar	1170 m	350 m
1.5 bar	1520 m	460 m

Conversely, it is possible to arrive at minimum estimates of ice thickness by multiplying 150 m, the lower estimate of the amount of post-glacial uplift, by 3.0/0.9 and arrive at the value 500 m as a minimum for the thickness of ice in the Núpur area. This minimum value compares well with the ice thickness values in Table 5.2. By subtracting the value of estimated amount of post-glacial uplift in Table 5.3. from 390 m (Table 5.4.) a value for the likely amount of restrained rebound (220-240 m) is arrived at. This exercise indicates that possibly more than half the glacio-isostatic recovery took place by restrained rebound in the Núpur area. This exercise also shows that the estimated ice thickness over Núpur area is, in broad terms, compatible with the marine limits in the area. Thus, it reinforces the conclusion that the ice margin during the last glaciation stood near the edge of the continental shelf off Vestfirðir. Although this conclusion is arrived at in spite of many imponderables and various assumptions it is believed that the marine limit in a given area can give important clues as to ice thickness in that area. Also, during this exercise many areas of neglected research have become apparent and this could be a guide to future research.

5.5. SYNTHESIS AND CONCLUSION: MODELS OF GLACIATION IN VESTFIRÐIR.

The evidence presented and analysed in previous sections on cirque distribution, cirque elevation, zeolite zonation, distribution of landscape types of glacial erosion, glacial history, marine limits, ice cap profiles and shelf moraines will now be synthesized for the purpose of formulating a hypothetical model of glaciations in Vestfirðir.

The models proposed by Thorarinsson (1937), Þ. Einarsson (1968) and Sugden and John (1976) all assume that there were ice free areas in Vestfirðir. These models, if taken to represent conditions during maximum glaciations, can now be rejected for the following reasons:

(1) The projection of theoretical ice cap profiles using the terminal moraine on Látragrunn reported by Ólafsdóttir (1975) as an ice cap margin, has shown that the cirque area in the western part of Vestfirðir, between Patreksfjörður and Álftafjörður, were submerged beneath the ice cap at this stage (sections 5.3. and 5.4.).

(2) The large western troughs from Patreksfjörður to Jökulfirðir have been affected by selective linear erosion beneath an ice cap. This applies especially to the troughs Patreksfjörður, Tálknafjörður, Arnarfjörður, Ísafjarðardjúp and Jökulfirðir (section 2.5.).

(3) Landscapes of areal scouring, with or without selective linear erosion, are widespread all over Vestfirðir and also offshore in most of Breiðafjörður and Húnaflói (section 2.5.). This can be taken as evidence that the base of the ice cap must have been at pressure melting point except in

the cirque areas. Other things being equal, the thicker the ice the more likely it is that it will be at the pressure melting point (e.g. Budd et al. 1969, Sugden 1977). The presence of these widespread areas of areal scouring can be taken as a strong indication of great ice thickness, and therefore great extent of ice.

On these grounds an alternative model of maximum glaciation is proposed:

During maximum ice extent the whole of Vestfirðir was covered by ice. No nunataks protruded above it. The continental shelf around Vestfirðir was covered with ice as well. On the shelf, ice marginal positions are known to a depth of 260 m on Látragrunn, and the 200 m isobath is a reasonable minimum extent of this apparent maximum ice cover.

During maximum ice extent all the cirques were submerged beneath an ice cap. This raises the question when were the cirques formed? This must have been during more marginal conditions, when the snowline was well below the present one and higher than during maximum ice extent. Indeed, as was shown in section 2.4.2., there is evidence, from the great range in cirque lip altitudes, for large oscillations of the snowline in Vestfirðir. When exactly did these marginal conditions prevail? To answer this a few possibilities, all hypothetical, are suggested. In all of them it is assumed that during the last 3 million years many glaciations have occurred intermittently:

(1) Possibly extensive glaciations, like when the ice stood at the terminal moraines on Látragrunn, are relatively late phenomena, with marginal glaciations prevailing during the time interval say about 1-3 million years ago.

This would give ample time for cirque formation, but would imply that the cirques were largely fossil landforms.

(2) Possibly extensive glaciations, like the Látragrunn stage, are of relatively short duration only and occur at the end of glacial periods. The conditions hypothesized here would give ample time for cirque formation, but would not give precise indications as to the ages of cirques.

(3) Possibly marginal conditions, favourable for cirque glaciers to form existed at the onset of glaciations and during deglaciation. This can be interpreted in terms of a hemicycle: cirque glaciation - ice cap glaciation - cirque glaciation. It can be argued, however, that it is unlikely that important cirque glacier activity accompanies the decay of ice sheet (e.g. Sugden and John 1976, chapter 7). Instead, many authors (e.g. Evans 1974, Sugden 1969) favour the onset of glaciations as a time of cirque glaciation and formation.

(4) Possibly extensive glaciations, like the Látragrunn stage, only occurred every now and then during the last 3 million years, with perhaps most of the glacials dominated by more marginal glaciations.

Fig. 3.83. The two ridges in Geldingadalur.

Fig. 3.84. View from the terminal moraine at the mouth of Húsadalur towards the mouth of Hrafnseyrardalur and the terrace at 100 m.

Fig. 3.78. View westwards along the terminal moraine ridge east of the stream at the mouth of Húsdalur. Note kettle-holes inside the moraine.

Fig. 3.79. View southeastwards from the terminal moraine at the mouth of Húsadalur showing a melt water channel starting in front of the moraine.

Fig. 3.76. The channel marked C in fig. 3.71.

landform assemblage there is another terrace. All the glacial melt water channels open onto this terrace and merge with it but are not cut into it. It is considered, however, that the channels and the terrace are contemporaneous, because of the morphology of the channels, they spread out and get very wide at their mouths, and the fact that the terrace does not have a backend in the channels. The altitude of the mouth of the easternmost channels (fig. 3.74.) is the same as that of the backend of the terrace, 13.0 m $\pm$ 1 m (level). One traverse with the aneroid in unfavourable weather conditions gave the height as 13.5 m $\pm$ 3.5 m.

Discussion. A glacial readvance took place in Tjaldanesdalur; the glacial landforms at the valley mouth, well below the highest shorelines in Arnarfjörður, are unaffected by marine action. Also, the melt water channel west of the deposits is incised into the terrace at 60 m $\pm$ 5 m and must therefore post-date it. The altitude of the terrace in front of the glacial deposits, onto which the melt water channels open, is a measure of the height of sea level when the melt water was still actively flowing in these channels.

The lateral moraine at the eastern side of the valley

Fig. 3.74. The channel marked A in fig. 3.71.

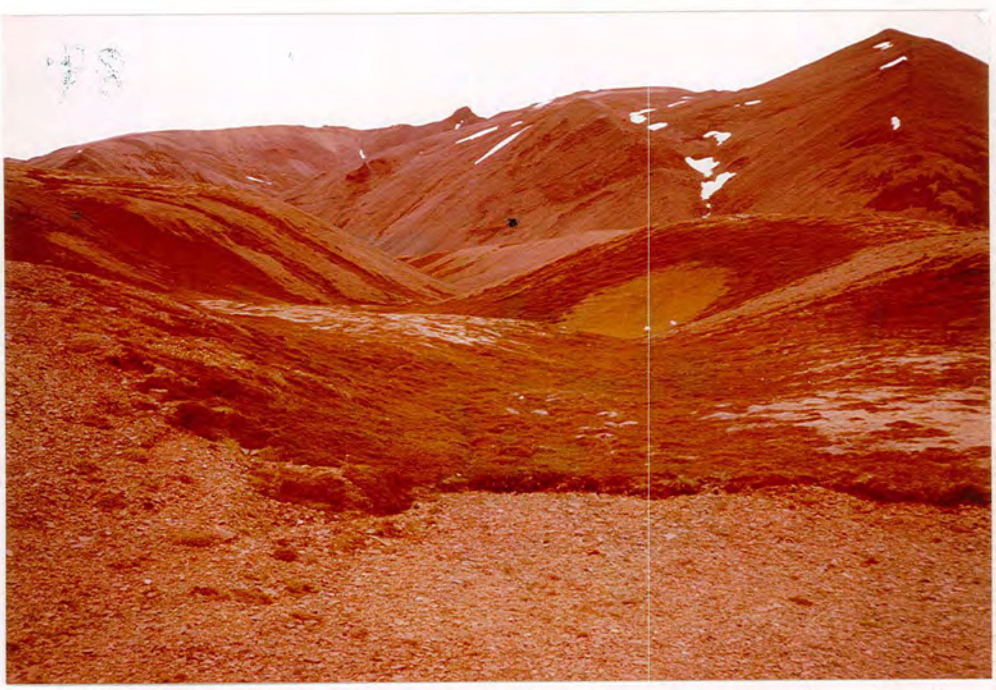


Fig. 3.75. The channel marked B in fig. 3.71.

Fig. 3.72. The western end of the glacial deposits west of Tjaldanesdalur separated from the terrace at 60 m in the foreground by a dry channel.

Fig. 3.73. The terrace at 60 m west of Tjaldanesdalur.

Fig. 3.69. Arrow points to where glacial deposits west of Fossdalur end and the terrace at 46.5 m takes over.

Discussion. A glacial readvance has taken place in Fossdalur, the glacial landforms there, unaffected by marine action, are well below the marine limit in Arnarfjörður (see later sections). Height of sea level during this readvance is unknown. It was, however, lower than the shorelines on either side of the valley mouth, lower than the terrace at 70.5 m because melt water channels are incised relatively deeply into it, and lower than the terrace at 46.5 m because till was deposited onto it.

The section just east of the river mouth, A in fig. 3.66., showing very well rounded pebbles and cobbles overlain by till, gives stratigraphic evidence for the glacial readvance in the valley. The same applies to the sections west of the stream (B in fig. 366.), where there are bedded silts overlain by well rounded, coarse gravels containing occasional boulders, underlying the glacial deposits.

The three melt water channels east of the valley mouth must have formed at the ice margin because they are separated by till. Together with the two lateral moraines west of them

Fig. 3.67. The gullied front of the terrace at 70.5 m east of Fossdalur.

Fig. 3.68. Arrows point to the three channels east of the mouth of Fossdalur and a lateral moraine.

Fig. 3.60. The lower part of the ridge east of the mouth of Haukadalur.

Discussion. The lateral moraine just east of Haukadalur is interpreted as having been deposited during a glacial readvance in the valley. The moraine has not been affected by marine action (fig. 3.60.) and must therefore have been formed after the formation of the highest marine limit, which is at least 111 m, in the Núpur area on the opposite side of the fjord. The lack of shorelines makes it impossible to determine the height of sea level during the readvance. Since the moraine has not been affected by marine action sea level could not have been higher than the lowest part of the moraine during its formation. Sea level must then have been lower than 20 m $\pm$ 4 m.

The mounds on the valley floor near the mouth of the valley are interpreted to be made predominantly of marine sediments

Fig. 3.55. The terminal moraine at the mouth of Kirkjubólsdalur, Sandafell in the background.

Fig. 3.56. A close-up of fig. 3.55 showing the section in the terminal moraine.

Fig. 3.53. View from Sandafell to the junction of Brekkudalur on the left and Kirkjubólsdalur. Arrows point to kettle-hole and melt water channels in the moraine complex. Hummocky till in area marked x.

Fig. 3.54. View from Sandafell to the mouth of Kirkjubólsdalur.

Fig. 3.50. View east across the terrace at 14 m in front of Hvammsdalur.

Fig. 3.51. The backend of the terrace at 14 m in front of Hvammsdalur.

Fig. 3.48. The end moraine near the head of Hvammsdalur.

Fig. 3.49. The cirque with the lake at the head of Ausudalur. Arrow points to the end moraine.

Fig. 3.44. View across the fjord to Kjaransstaðadalur. Note the large amounts of glacial deposits at the valley mouth. Arrow points to terrace at 19.5 m.

Fig. 3.45. The backend of the terrace at 19.5 m at Kjaransstaðadalur. In the background from left: Sandafell, Mýrarfell, Háhöfði.

Fig. 3.38. The terrace at 14.5 m in front of Lambadalur.

Fig. 3.39. View across the fjord to Lambadalur. Arrows point to the terraces at 20 m and 14.5 m and the terminal moraine.

Fig. 3.36. View down the ridge east of the stream at the mouth of Lambadalur.

Fig. 3.37. The terrace at 20 m at Lambadalur with the terminal moraine forming the backslope.

Fig. 3.34. The upper limit of sand and gravel deposits at 85.5 m and parts of the rounded bedrock outcrops above.

for several reasons:

(1) Tabular planar cross-bedding originates from deposition off a bank and can take place in a variety of environments including dunes, ripples, bars, fans, small deltas or the beach face (Blatt et.al. 1972). Of these dunes and ripples can be excluded forthwith. The case of fans or small deltas is excluded since large enough streams could not have formed on this low mountain. This leaves the environments of bars and beaches as the only likely ones to have been present on Háhöfði at the time of formation of the deposits.

(2) The well rounded pebbles indicate a high energy environment. Again a marine environment is most likely.

(3) From the example of the present day spit Höfðaoddi, it is argued that when relative sea level was considerably higher, and assuming that longshore drift was eastward as at present, then a similar feature would have developed on the slopes some way east of the western tip of Háhöfði. This hypothesis accounts for the location of the deposits and the

Fig. 3.32. View from across the fjord towards Háhöfði.
Note the location of the sand and gravel deposits
Arrows point to the sand and gravel deposits.

Fig. 3.33. View down from the top of the sand and gravel deposits on Háhöfði. The poles stand where the change of slope at 65 m was observed.

Fig. 3.30. View from top of Sandafell (374 m) towards Hjarðardalur and Háhöfði. Arrow points to the deposits at Háhöfði.

Fig. 3.31. The terrace backend at 11.5 m in Hjarðardalur.

Fig. 3.27. The terrace at 19.5 m in front of Gemlufalls-dalur with the ridge behind it.

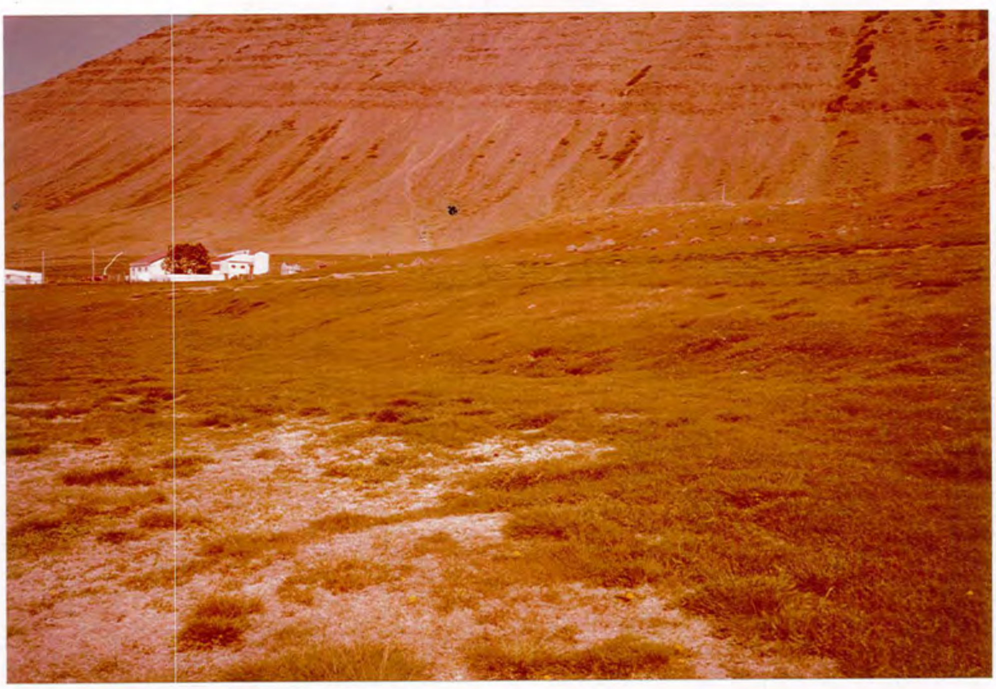


Fig. 3.28. Lækjarós farm, the terrace at 9 m, the terrace at 19.5 m and the ridge behind it.

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APPENDIX A

GRAIN SIZE ANALYSIS

Purpose.

During fieldwork in Vestur-Ísafjarðarsýsla in total 14 samples were collected for particle size analysis. The purpose of this sampling was twofold:

1) Samples were collected for the general purpose of comparing field identifications of sediments and landforms with genetical information revealed from the analysis of grain size.

2) Samples were collected for the purpose of checking certain field observations.

Sample descriptions.

Sample 1. Núpur area (location shown in fig. 3.11). From a sediment identified in the field as a top of a marine terrace.

Sample 2. Lambadalur (location shown in fig. 3.35). From a sediment identified in the field as till in a terminal moraine.

Sample 3. Núpur area (location shown in fig. 3.11). From a section in a sand and gravel quarry, middle layer, identidied in the field as marine deposits.

Sample 4. Núpur area (location shown in fig. 3.11). From a sediment identified in the field as till in a terminal moraine.

Sample 5. Gerðhamradalur (location shown in fig. 3.1). From a sediment identified in the field as till in a lateral moraine.

Sample 7. Núpur area (location shown in fig. 3.11). From a section in a sand and gravel quarry, bottom layer, identified in the field as marine deposits.

Sample 8. Lambadalur (location shown in fig. 3.35). From a sediment identified in the field as till in a terminal moraine.

Sample 9. Ketilseyrardalur (location shown in fig. 3.43). From an altitude of 27 m in a section in a sand and gravel quarry. From the middle of a sediment 1 m thick identified in the field as till.

Sample 10. Ketilseyrardalur (location shown in fig. 3.43). From an altitude of 26 m in a section in a sand and gravel quarry. From a sediment identified in the field as delta deposits.

Sample 11. Gemlufallsdalur (location shown in fig. 3.24). From a sediment identified in the field as till in a terminal moraine.

Sample 12. Núpur area (location shown in fig. 3.11). From the bottom in a section in a sand and gravel quarry. Sediment identified in the field as marine deposits.

Sample 13. Háhöfði (location shown in fig. 3.29). From a sediment at 65 m identified in the field as marine deposits.

Sample 14. Háhöfði (location shown in fig. 3.29). From a sediment at 55 m identified in the field as marine deposits.

Sample 15. Gerðhamradalur (location shown in fig. 3.1). From a sediment identified in the field as marine deposits.

Analytical procedures.

Samples were collected from a depth of about 40 cm and care was taken that they were unweathered and that each sample was from one sedimentation unit only. Most of the sediments sampled were coarse and hence large samples, 1-2 kgs, were collected.

In the laboratory each sample was placed in a drying-cupboard at about 80-90°C until thoroughly dry. Then each sample was passed through a 3/4" mesh to eliminate pebbles and coarse gravel particles. The samples were split by quartering by hand (Krumbein and Pettijohn 1938).

Sieving was done in two lots on an automatic sieving machine using sieve sizes shown in Tables A 1 and A 2.

Results and discussion.

The results of the sieving are shown in Tables A 1, A 2 and fig. A 1. Statistics of the grain size distribution are shown in Table A 3.

There is a close correspondance between field identification of the sediments and the percentage of fines in the samples (Table A 3). The marine deposit sample with the highest percentage of fines is Sample 1, 6.42%, while the till sample with the lowest precentage of fines is Sample 4, 6.72%. There is hardly a significant statistical difference between these two percentages, but there is a distinct difference in the sorting values of the two samples, 1.7 and 2.5 respectively, the marine deposit being better sorted. Table A 3 shows that percentage of fines in a sample is a powerful means of differentiating between marine and glacial origin of the sediments. The lower percentage of fines in the marine deposits can be explained by the washing effect of wave action, finer particles are kept in suspension and are only deposited in calm waters.

Sorting is another value useful in differentiating marine and glacial environments. The sorting mean for the six samples identified in the field as from glacial sediments is 2.61 while for the 8 samples from marine deposits the sorting mean is 2.01, significantly lower. Only one till sample, Sample 9, has a sorting value close to the mean of the sorting values for the marine samples. The high percentage of fines, however, 18.04%, leaves no doubt about the glacial origin of the sample. Only one marine sample, Sample 3, has a sorting value close to the sorting values for the till samples. The low percentage of fines, however, 5.25%, leaves little doubt about the marine origin of the deposit.

Conclusion.

Field identification of the origin of sediments is firmly supported by the grain size distribution of 14 samples analysed with reference to percentage of fines in each sample and sorting of the samples.

TABLE A 1

GRAIN SIZE DISTRIBUTION: PERCENTAGES.

MESH	Ø	Sample No´s. 1	2	3	4	5	7	8	9	10	11	12	13	14	15
1/2	-3.67	2.09	9.20	9.04	10.89	8.71	9.44	7.87	5.67	2.91	2.95	5.79	1.74	3.96	7.77
1/4	-2.67	3.48	13.78	23.78	13.00	15.11	18.44	8.42	8.65	14.64	6.90	23.51	6.73	6.11	15.29
3/16	-2.25	1.94	7.30	8.97	6.42	5.54	6.83	5.94	2.81	5.17	6.58	8.80	5.21	4.87	5.88
1/8	-1.67	3.00	10.18	8.72	9.56	7.93	9.35	6.75	5.48	10.26	7.50	11.80	8.00	8.75	10.63
8	-1.05	5.18	10.57	5.22	10.53	9.62	11.85	10.30	8.18	14.38	9.28	13.40	12.38	13.75	12.72
14	-0.25	15.32	11.47	4.72	11.57	12.64	15.77	10.62	12.19	16.94	12.08	11.59	18.13	24.21	14.61
25	0.75	27.08	10.20	9.27	11.88	11.14	13.47	10.99	14.17	14.92	13.78	6.14	18.77	20.42	13.77
36	1.30	8.07	3.94	6.38	5.22	4.40	3.69	2.37	6.08	6.56	6.40	3.18	7.68	3.32	4.66
52	1.75	6.87	3.58	7.09	4.58	3.70	3.93	2.27	4.35	4.28	5.07	3.56	5.02	1.63	3.41
72	2.30	8.74	3.33	4.24	3.57	3.22	3.73	2.54	4.05	3.52	5.02	5.24	4.04	1.75	2.59
100	2.75	7.10	2.82	2.21	2.27	2.43	1.49	2.95	3.79	3.19	4.97	3.75	3.33	2.51	2.19
150	3.24	2.80	3.18	2.38	1.97	2.77	0.60	3.15	3.11	1.72	4.21	1.15	2.12	2.26	1.47
200	3.75	1.23	2.04	1.77	1.25	1.99	0.25	3.22	2.94	0.82	3.61	0.51	1.48	1.52	1.25
240	4.00	0.68	1.34	0.96	0.56	1.06	0.05	1.62	0.60	0.03	0.90	0.06	0.64	0.53	0.54
rest		6.42	7.06	5.25	6.72	9.74	1.10	21.04	18.04	0.61	10.76	1.52	4.73	4.39	3.21
Weight of sample, g		1160.0	1104.9	760.28	653.7	584.43	636.49	228.15	131.96	294.21	197.24	431.42	344.89	358.46	460.89

TABLE A 2

GRAIN SIZE DISTRIBUTION: CUMULATIVE PERCENTAGES.

MESH	Ø	Sample No´s. 1	2	3	4	5	7	8	9	10	11	12	13	14	15
1/2	-3.67	2.09	9.20	9.04	10.89	8.71	9.44	7.87	5.67	2.91	2.95	5.79	1.74	3.96	7.77
1/4	-2.67	5.57	22.98	32.82	23.89	23.82	27.88	16.29	14.32	17.55	9.85	29.30	8.47	10.07	23.06
3/16	-2.25	7.51	30.28	41.79	30.31	29.32	34.71	22.23	17.13	22.72	16.43	38.10	13.68	14.94	28.94
1/8	-1.67	10.51	40.46	50.51	39.87	37.25	44.06	28.98	22.61	32.98	23.93	49.90	21.68	23.69	39.59
8	-1.05	15.69	51.03	55.73	50.40	46.87	55.91	39.28	30.79	47.36	33.21	63.30	34.06	37.44	52.31
14	-0.25	31.01	62.50	60.45	61.97	59.51	71.68	49.90	42.98	64.30	45.29	74.89	52.19	61.65	66.92
25	0.75	58.09	72.70	69.72	73.85	70.65	85.15	60.89	57.15	79.22	59.07	81.03	70.96	82.07	80.69
36	1.30	66.16	76.64	76.10	79.09	75.05	88.84	63.26	63.23	85.81	65.47	84.21	78.64	85.39	85.35
52	1.75	73.03	80.22	83.19	83.65	78.75	92.77	65.53	67.58	90.09	70.54	87.77	83.66	87.02	88.76
72	2.30	81.77	83.55	87.43	87.22	81.97	96.50	68.07	71.63	93.61	75.56	93.01	87.70	88.77	91.35
100	2.75	88.87	86.37	89.64	89.49	84.40	97.99	71.02	75.42	96.80	80.53	96.76	91.03	91.28	93.54
150	3.24	91.67	89.55	92.04	91.46	87.17	98.59	74.17	78.53	98.52	84.74	97.91	93.15	93.54	95.01
200	3.75	92.90	91.59	93.81	92.71	89.16	98.84	77.39	81.47	99.34	88.35	98.42	94.63	95.06	96.26
240	4.00	93.58	92.93	94.77	93.25	90.22	98.89	79.01	82.07	99.37	89.25	98.48	95.27	95.59	96.80
SUM		100.00	99.99	100.02	99.99	99.96	99.99	100.05	100.11	99.98	100.01	100.00	100.00	99.98	100.01

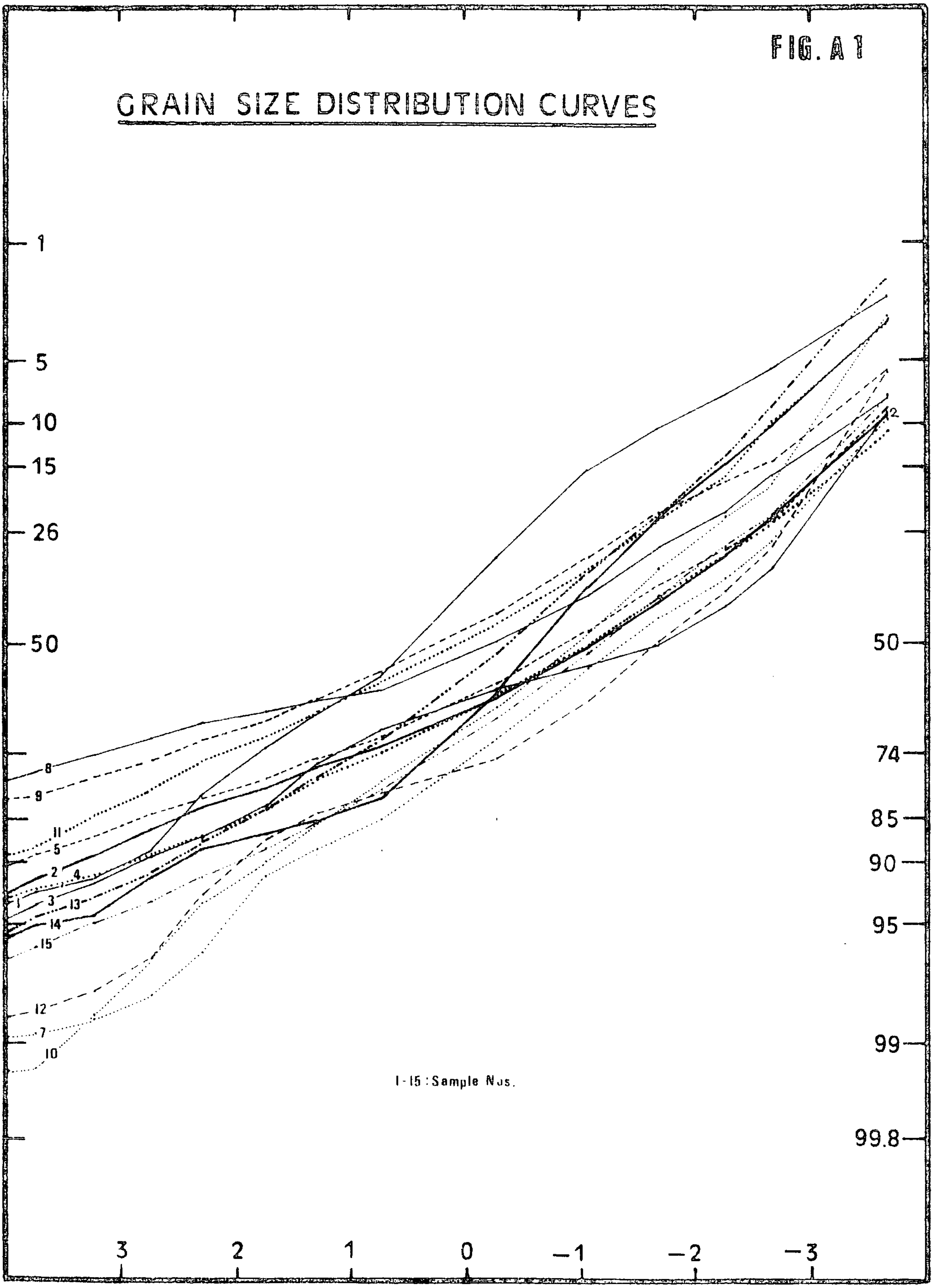
TABLE A 3

GRAIN SIZE DISTRIBUTION: STATISTICS.

SAMPLE No	FIELD IDENTIFICATION	CONTENT OF FINES Ø4	MEAN $\frac{Ø20+Ø50+Ø80}{3}$	SORTING $\frac{Ø84-Ø16}{2}$	LOCATION
10	DELTA DEPOSIT	0.61%	-0.9	1.9	Ketilseyrardalur, quarry
7	MARINE DEPOSIT	1.10%	-1.37	1.81 1)	Núpur area, southern quarry, bottom layer
12	- " -	1.52%	-1.37	2.18	Núpur area, northern quarry, bottom layer
15	- " -	3.21%	-1.1	2.03	Gerðhamradalur
13	- " -	4.73%	-0.28	2.01 1)	Háhöfði, altitude 65 m
14	- " -	4.93%	-0.63	1.85 1)	Háhöfði, altitude 55 m
3	- " -	5.25%	-1.1	2.58	Núpur area, southern quarry, middle layer
1	- " -	6.42%	0.62	1.7	Núpur area
4	TILL	6.72%	-0.9	2.5	Núpur area, Hvassihryggur end moraine
2	-"-	7.06%	-0.75	2.73	Lambadalur end moraine
5	-"-	9.74%	-0.6	2.88	Gerðhamradalur lateral moraine
11	-"-	10.76%	0.23	2.73	Gemlufallsdalur end moraine
9	-"-	18.04%	0.58	2.1 2)	Ketilseyrardalur, quarry
8	-"-	21.04%	0.7 3)	2.7 2)	Lambadalur end moraine

1) $\frac{Ø84-Ø16}{4} + \frac{Ø95-Ø5}{6.6}$ 2) $\frac{Ø75-Ø25}{1.35}$ 3) $\frac{Ø25+Ø75}{2}$

FIG. A1


GRAIN SIZE DISTRIBUTION CURVES
1
5
10
15
26
50
74
85
90
95
99
99.8
8
9
11
5
2
4
1
3
13
14
15
12
7
10
1-15 : Sample Nos.
3
2
1
0
−1
−2
−3
DIAMETER IN PHI UNITS

LEGEND FOR MAPS IN FIGS. 3.1—3.82

- PLATEAU
- CLIFFS, BEDROCK
- THIN TALUS
- TALUS
- GLACIAL DEPOSITS
- MARINE DEPOSITS, " " LANDFORMS
- ALLUVIUM
- LANDSLIDE SCAR & " " DEBRIS
- DEBRIS CONE
- COASTAL CLIFFS
- SEDIMENT SAMPLE
- MOUNTAIN RIDGE
- PLATEAU EDGE, SHARP
- " " ROUNDED
- SHORELINE & HEIGHT
- END MORAINE
- MELT WATER CHANNEL
- STREAM
- " AND DELTA
- BRAIDED STREAM
- DEEP CHANNEL
- RAISED DELTA
- KETTLE-HOLES
- LAKE
- FARM
- AIR STRIP
- ROAD
- QUARRY
- 998 SPOT HEIGHTS IN METRES

LEGEND FOR MAPS IN FIGS. 3.1—3.82

- PLATEAU
- CLIFFS, BEDROCK
- THIN TALUS
- TALUS
- GLACIAL DEPOSITS
- MARINE DEPOSITS, 〃 〃 LANDFORMS
- ALLUVIUM
- LANDSLIDE SCAR & 〃 〃 DEBRIS
- DEBRIS CONE
- COASTAL CLIFFS
- SEDIMENT SAMPLE

- MOUNTAIN RIDGE
- PLATEAU EDGE, SHARP
- 〃 〃 ROUNDED
- SHORELINE & HEIGHT
- END MORAINE
- MELT WATER CHANNEL
- STREAM
- 〃 AND DELTA
- BRAIDED STREAM
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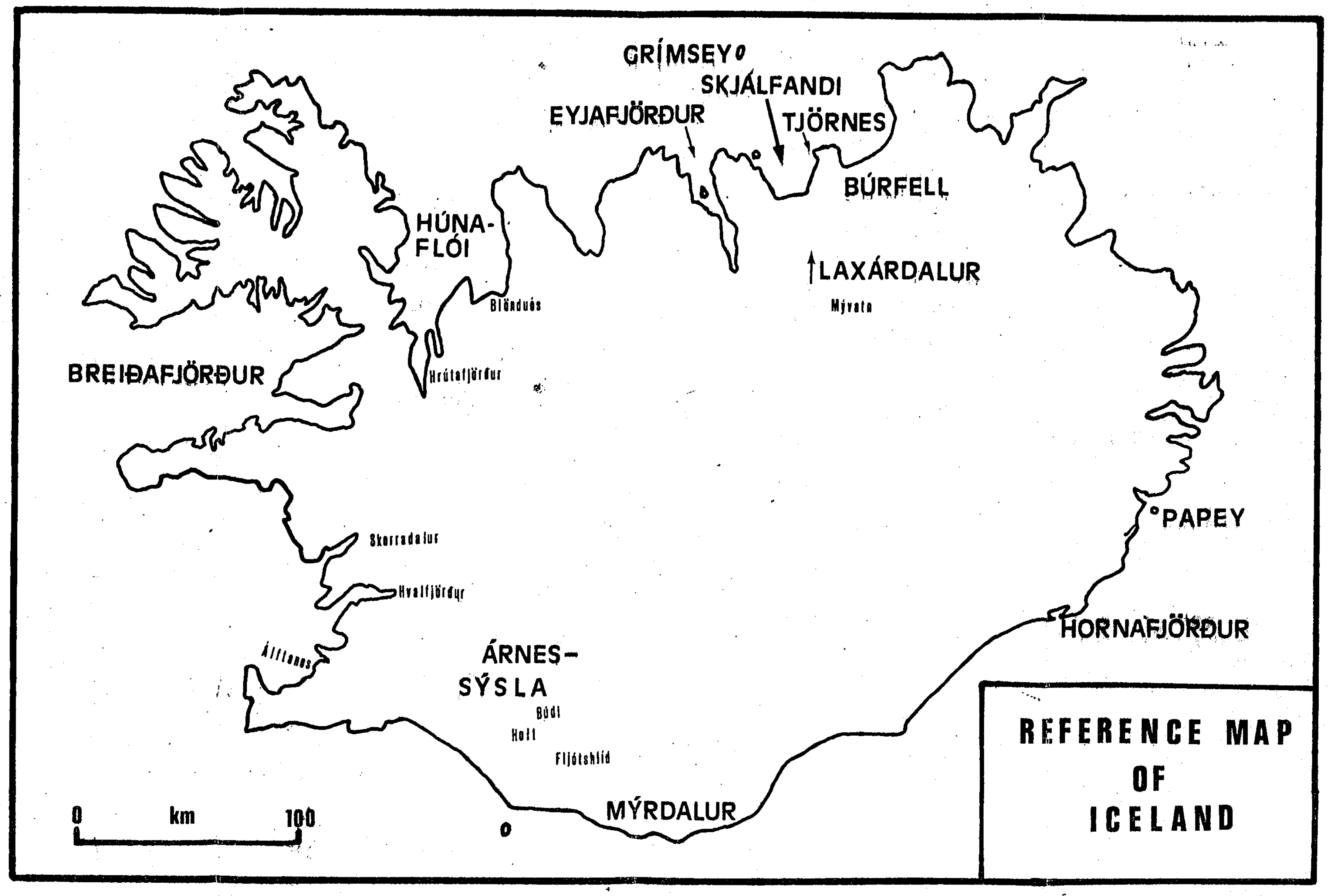
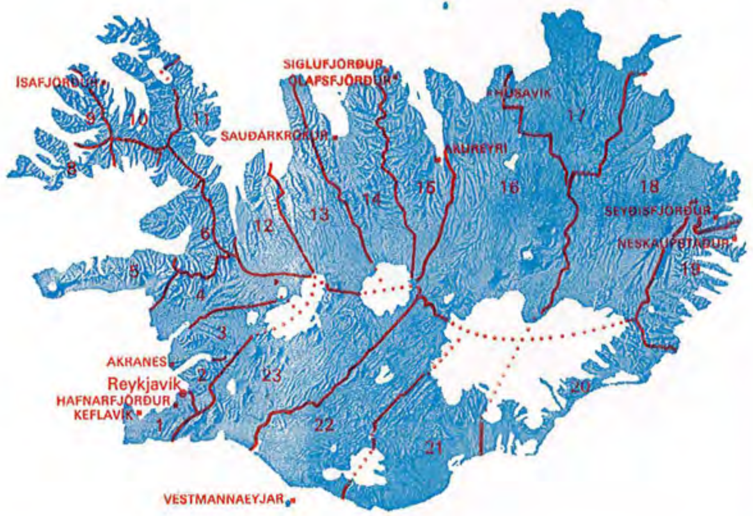
- RAISED DELTA
- KETTLE-HOLES
- LAKE
- FARM
- AIR STRIP
- ROAD
- QUARRY
- 998 SPOT HEIGHTS IN METRES



REFERENCE MAP OF ICELAND

Kaupstaðir og sýsluskipting

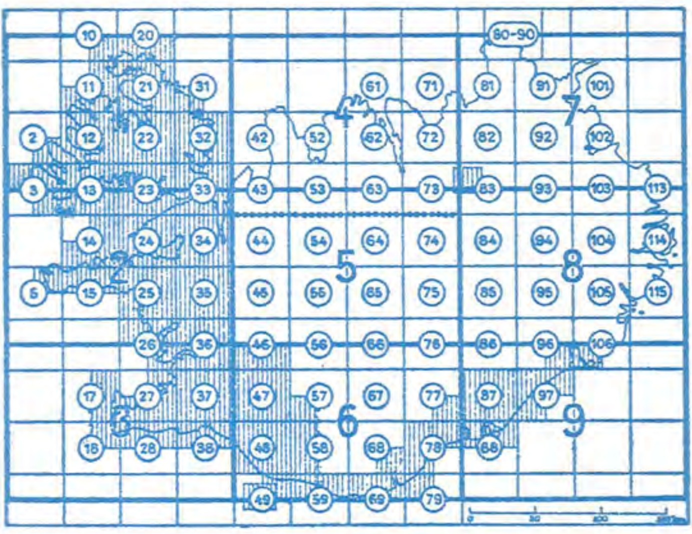
1 Gullbringusýsla
2 Kjósarsýsla
3 Borgarfjarðarsýsla
4 Mýrasýsla
5 Snæfellsnes- og Hnappadalssýsla
6 Dalasýsla
7 Austur-Barðastrandarsýsla
8 Vestur-Barðastrandarsýsla
9 Vestur-Ísafjarðarsýsla
10 Norður-Ísafjarðarsýsla
11 Strandasýsla
12 Vestur-Húnavatnssýsla
13 Austur-Húnavatnssýsla
14 Skagafjarðarsýsla
15 Eyjafjarðarsýsla
16 Suður-Þingeyjarsýsla
17 Norður-Þingeyjarsýsla
18 Norður-Múlasýsla
19 Suður-Múlasýsla
20 Austur-Skaftafellssýsla
21 Vestur-Skaftafellssýsla
22 Rangárvallasýsla
23 Árnessýsla



UPPDRÁTTUR ÍSLANDS

AÐALKORT BL. 1
NORÐVESTURLAND
1:250 000

UPPDRÆTTIR ÍSLANDS



(42) Atlasblöð mælikv. 1:100 000.

[2] Aðalkort, mælikv. 1:250 000.

(48) Fjórðungsblöð sem út eru komin; mælikv. 1:50 000. Hvert nr. er 4 blöð: NV, SV. NA, SA.

Atlasblöðin, 87 að tölu, í mælikvarða 1:100 000, taka yfir allt landið. Hvert kort tekur yfir 1760 km² og er 40×44 cm að stærð.

Fjórðungsblöðin, mælikv. 1:50 000, taka yfir 440 km² hvert. Fjögur þeirra taka yfir sama svæði og eitt atlasblað. Útgáfu þessara blaða verður ekki haldið áfram fram yfir það sem sýnt er á yfirlitskortinu. Fjórðungsblöðin eru af sömu stærð og atlasblöðin.

Aðalkort yfir Ísland á 9 blöðum, tekur yfir allt landið; mælikv. 1:250 000. Hvert blað tekur yfir 21 120 km² og er 48×70,4 cm að stærð. Á kortinu sjást bæir, vegir, ár, fjöll o. s. frv. Það er einkar hentugt fyrir ferðamenn og fyrir þá sem vilja kynnast landinu yfirleitt. Kortið er í hentugu vasabókarbroti með spjöldum til hlífðar, en fæst einnig slétt til þess að hafa á vegg.

Sérkort í mælikv. 1:25 000 yfir þjóðgarðana að Þingvöllum og Skaftafelli og 1:50 000 yfir Mývatn með umhverfi þess, samanbrotin eða ósamanbrotin.

Landslagskort, mælikv. 1:350 000. Veggjakort yfir allt Ísland á 4 blöðum. Stærð kortsins er hér um bil 110×160 cm. Kortið sýnir hið sama og aðalkortið, að svo miklu leyti sem mælikvarðinn leyfir. Mismunur á hæðum og djúpum er sýndur með litbreytingum.

Landslagskort, mælikv. 1:500 000, og **Staðfræðilegt yfirlitskort**, mælikv. 1:500 000. Veggjakort yfir allt Ísland, hvort fyrir sig á einu blaði, 77,5×111 cm að stærð. Í aðalatriðum er landslagskortið minnkuð útgáfa landslagskortsins með mælikv. 1:350 000. Á staðfræðikortinu er hæðamunur ekki sýndur með litum heldur með hæðarlínum með 100 m hæðarmun.

Uppdráttur Íslands, mælikv. 1:750 000, útgefinn af Ferðafélagi Íslands. Brotið eða slétt.

Staðfræðilegt yfirlitskort, mælikv. 1:1 000 000, að stærð 38×53,5 cm.

Alþjóðakortblöð, mælikv. 1:1 000 000, N. P. 27 Reykjavík, og 28 Hekla, ósamanbrotið.

Sérkort af Surtsey, mælikv. 1:10 000.

Upphleypt kort af Íslandi, mælikv. 1:1 000 000, prentað á plastefni.

Skólakort 1:1 000 000, 1:2 000 000 og 1:3 000 000.

KORT OVER ISLAND

Atlasbladene i 1:100 000 omfatter hele landet på 87 blade. Hvert blad er 40×44 cm og indeholder 1760 km².

Kvartbladene i 1:50 000 indeholder 440 km², således at 4 kvartblade dækker samme terræn som et atlasblad. Udgivelsen af disse blade vil ikke blive fortsat ud over, hvad der er vist på oversigtskortet. Kvartbladene har samme størrelse som atlasbladene.

Generalkort over Island i 9 blade omfatter hele landet og er i målestokken 1:250 000. Hvert blad indeholder 21 120 km² og størrelsen er 48×70,4 cm. På kortet er gårde, veje, vandløb, fjelde o. s. v. angivet. Det egner sig ypperligt til rejsekort og til studium af landet i almindelighed. Det er i lommeformat med kartonomslag, men findes også plant.

Særkort i 1:25 000 over Þingvellir Nationalpark og Skaftafell Nationalpark og 1:50 000 over Mývatn med nærmeste omgivelser, falsede eller plane.

Fysisk kort i 1:350 000, vægkort over hele Island i 4 blade. Kortets størrelse ca. 110×160 cm. Indeholdet er som generalkortets i det omfang målestokken tillader. Højde- og dybdeforhold er fremhævet ved farvetoner.

Fysisk kort i 1:500 000, og **Topografisk oversigtskort i 1:500 000**, vægkort over hele Island, hvert i et blad, 77,5×111 cm. Hovedsagelig en mindre udgave af kortet i 1:350 000. På det topografiske kort er højdefarvetoning udeladt, men højdekurver med 100 m ækvidistance.

Turistkort over Island i 1:750 000, udg. af Islands Turistforening, falset eller plant.

Topografisk oversigtskort i 1:1 000 000, 38,5×53,5 cm.

Internationale kort i 1:1 000 000, N. P. 27 Reykjavík og 28 Hekla, plant.

Særkort over den nye vulkaniske ø Surtsey i 1:10 000.

Plastic reliefkort over Island i 1:1 000 000.

Kort til skolebrug i målestok 1:1 000 000, 1:2 000 000 og 1:3 000 000.

MAPS OF ICELAND

The Atlas Sheets, on the scale of 1:100 000, cover the whole country in 87 sheets, each sheet measures 40×44 cm and comprises 1760 sq.kilometres (680 sq.miles).

The Quarter Sheets, 1:50 000, cover 440 sq.km (170 sq.m), whereby four quarter sheets represent the same area as one atlas sheet. Publication of these sheets will be confined to those indicated on the key-plan. The dimensions are the same as those of the atlas sheets.

The General Map of Iceland, in nine sheets, comprises the whole country on the scale of 1:250 000. Each sheet covers 21120 sq.km (8160 sq.m.), its dimensions being 48×70 cm. Farms, roads, watercourses, mountains, etc. are all shown. It is most suitable for travellers and for a general study of the country. It is available in pocket-form with cardboard cover or flat.

Special Sheets, 1:25 000 of the National Park Þingvellir and Skaftafell and 1:50 000 of the Mývatn with its surroundings, folded or flat.

Physical Map, 1:500 000. Wall map of all Iceland, in four sheets. Total dimensions about 110×160 cm. Contains the same information as the general map as far as the scale permits. Heights and depths shown in colours tones.

Physical Map, 1:500 000, and **Topographical Map**, 1:500 000. Wall maps of all Iceland, each in one sheet, 77,5×111 cm. Mainly reduced edition of the 1:350 000 map. On the topographical map the height colouring is omitted.

Tourist Map of Iceland, 1:750 000, publ. by The Tourist Association of Iceland, foldet or flat.

Topographical Map, 1:1 000 000, 38,5×53,5 cm.

International Maps, 1:1 000 000, N. P. 27 Revkjavík and 28 Hekla. Flat.

Special Sheet, 1:10 000, of the vulcanic island Surtsey.

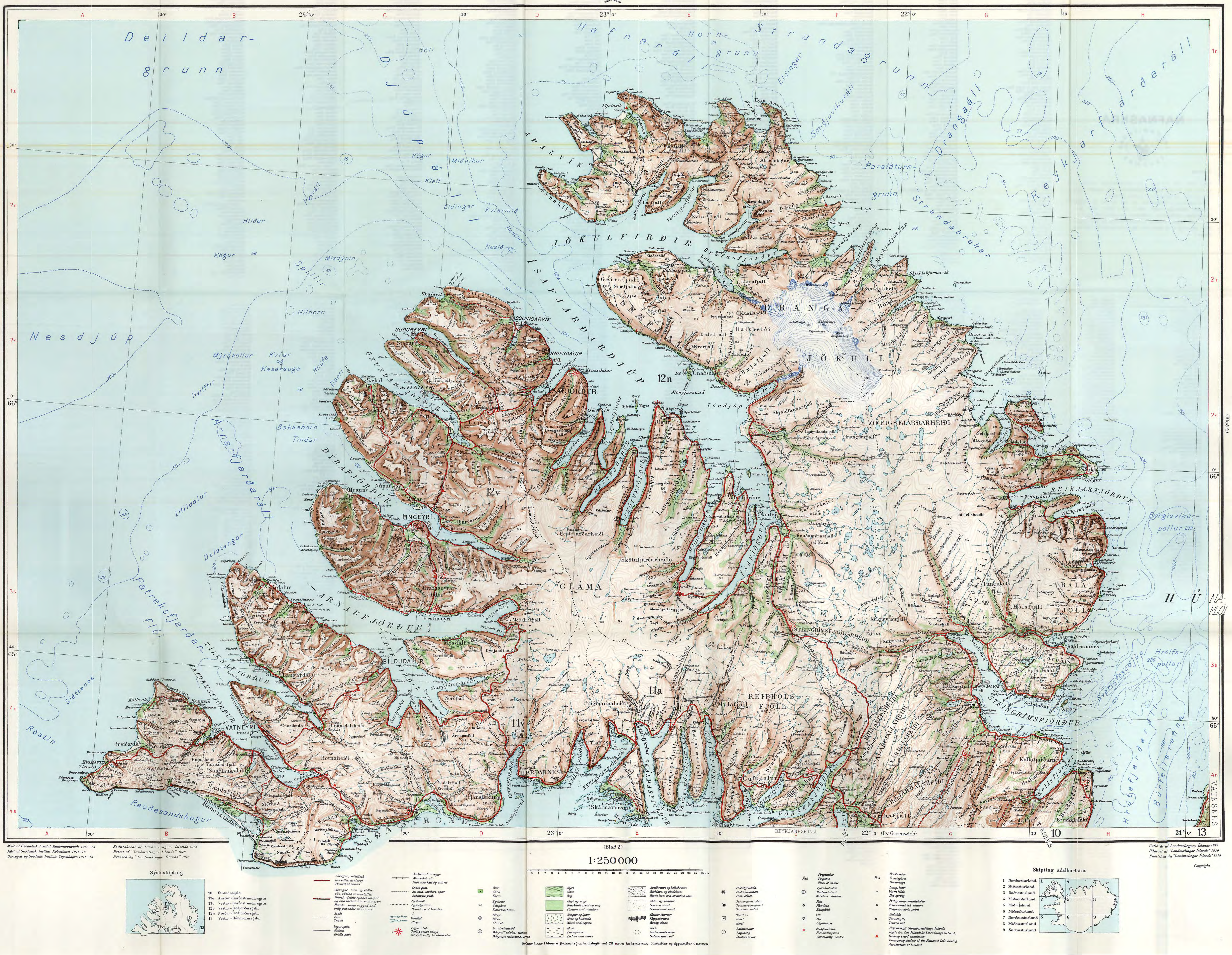
Plastic relief Map of Iceland, scale 1:1 000 000.

Maps for public scools, scales 1:1 000 000, 1:2 000 000 and 1:3 000 000.

UPPDRÁTTUR ÍSLANDS

GEODÆTISK INSTITUT

AÐALKORT BLAÐ 1. NORÐVESTURLAND



NAFNASKRÁ

Skýringar:

Reitir þeir, sem breiddar- og lengdarbaugar mynda á kortinu eru notaðir sem tilvísunarreitir og merktir með rauðum bók- og tölustöfum í ramma kortsins.

Aukastafirnir í tilvísuninni, nv, na, sv og sa merkja hugsaða skiptingu hvers reits í fjóra jafna hluta, þ.e. norðvestur-, norðaustur-, suðvestur- og suðausturhluta.

Ef nafn liggur í tveimur tilvísunarreitum, er þeirri reglu fylgt, að vísað er til þess reits, sem upphafsstafur nafnsins liggur í.