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Facies analysis of the Breidavík Group sediments on Tjörnes, North Iceland

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Abstract. Thick Quaternary sediments of the Breidavík Group are intercalated between lava flows and tuffs on Tjörnes, North Iceland. The vertical column of strata displays a rhythmic character. The present paper contains a model for sedimentation during glacial–interglacial cycles in a volcanic environment. The facies record is analyzed with reference to observations at the margins of modern glaciers, and fourteen separate glaciations are indicated by tillite horizons. The tillites are typically associated with kame and outwash conglomerates, followed at first by glaciolacustrine and glaciomarine mudrocks and diamictites, and then by deltaic and/or bar-lagoon assemblages, fluvial sediments and subaerial lava flows. Depositional environments are reconstructed for several steps in the geological history of the Breidavík Group. The oldest tillite has been dated at ca. 2 Ma. Several of the tillite beds are succeeded by marine sediments with fossils, especially in the lower part of the sequence. Facies analysis of the lithologies and fossils leads to the conclusion that the Breidavík Group cycles reflect glacial–interglacial cyclicity with a frequency of the order of one glaciation every 100–150 thousand years. During the first million years the deposition took place in a transitional environment while the area was subsiding, but the latter part of the geological record reflects terrestrial deposition and volcanism.

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INTRODUCTION

Quaternary sections on land are generally incomplete. Repeated glaciations have tended to devastate the record of the immediate geological past. Therefore the story of continental glaciations within a given region must often be pieced together from short, isolated sections from various localities. This task is difficult in the absence of reliable dating techniques for pinning down absolute ages of individual glacial–interglacial cycles, and the history may be incomplete. The problem is particularly acute in regions where proximal glacial environments have prevailed during glacials throughout the Quaternary. Frequent erosional unconformities characterize many sequences from such environments. Deposits from the glacio-marine environment, while promising a better continuity, are generally not accessible for mapping and dating except through geophysical profiling. Although raised marine sediments often yield important evidence about deglaciation patterns, they span only a very limited time relative to a full glacial–interglacial cycle.

It has been suggested that deep sea records provide a yardstick, against which the fragmentary continental records might be placed (Shackleton 1977). The deep sea sediments have continued to accumulate outside the glacial environments, irrespective of glacial events. Oxygen isotope curves derived from deep sea sediments show recurrent changes of sea-water properties, that have been interpreted as reflecting global ice-volume changes (Olausson 1965, Shackleton and Opdyke 1973). Although the oxygen isotope curves and the stages defined for them may evolve as a global framework for the Quaternary cyclicity in ice volume changes, they do not offer many clues to local or regional patterns of glaciation. However, the accumulating evidence from the deep sea floor of the North Atlantic constitutes a challenge to those who investigate Quaternary sections on land. The records must be compared and explanations sought if discrepancies exist.

Most of the land masses of the Northern Hemisphere are tectonically stable shields, where the conservation potential of sediments is typically low. This is also true of mountainous tectonically active zones of intensive uplift, but local basins may develop in collision related tectonic settings (Mitchell and Reading 1978). More extensive basins are likely to develop along transform faults, subduction zones and divergent plate margins. Plate tectonic processes can be assumed to operate independently of climate, and it may be assumed that the present configuration of plate margins and processes have prevailed throughout the Quaternary. Thick Quaternary sequences of sediments may probably be expected to be associated with some plate margins. Unfortunately, plate margins in the Northern Hemisphere tend to be either mountainous areas of intensive relief and erosion, such as the Rockies, the Alps, and the Himalayas, or submarine ridges or trenches.

Although divergent plate margins exist on land elsewhere in the Northern Hemisphere (California Bay, Afar), the only one to have been subjected to Quaternary glaciations is located in Iceland, where the axial zones of rifting and volcanism feature several characteristics that have contributed towards the production and conservation of the exceptionally thick Quaternary sequence. Processes associated with plate margins in Iceland were reviewed by Pálmason and Saemundsson (1974) and by Saemundsson (1978, 1980). The key elements are the relatively constant (over thousands of years) rate of pouring out of volcanics within the zones, coupled with subsidence and related tilting of flanking rock units towards the axial zones. These elements are significant for the conservation potential of the geological record because the resistant lava flows form a shield against future erosion and weathering of any underlying sediments, and the subsidence reduces the likelihood of erosion as well as reducing the available energy for erosion of a particular rock unit if erosional circumstances do arise. In the absence of sediments, facies of volcanic rocks may yield important information about the physical conditions during eruptions. Piling up of hyaloclastite ridges and table mountains indicates subglacial or subaqueous conditions whereas ice free environments on land permit lavas to flow freely and crystallize without brecciation.

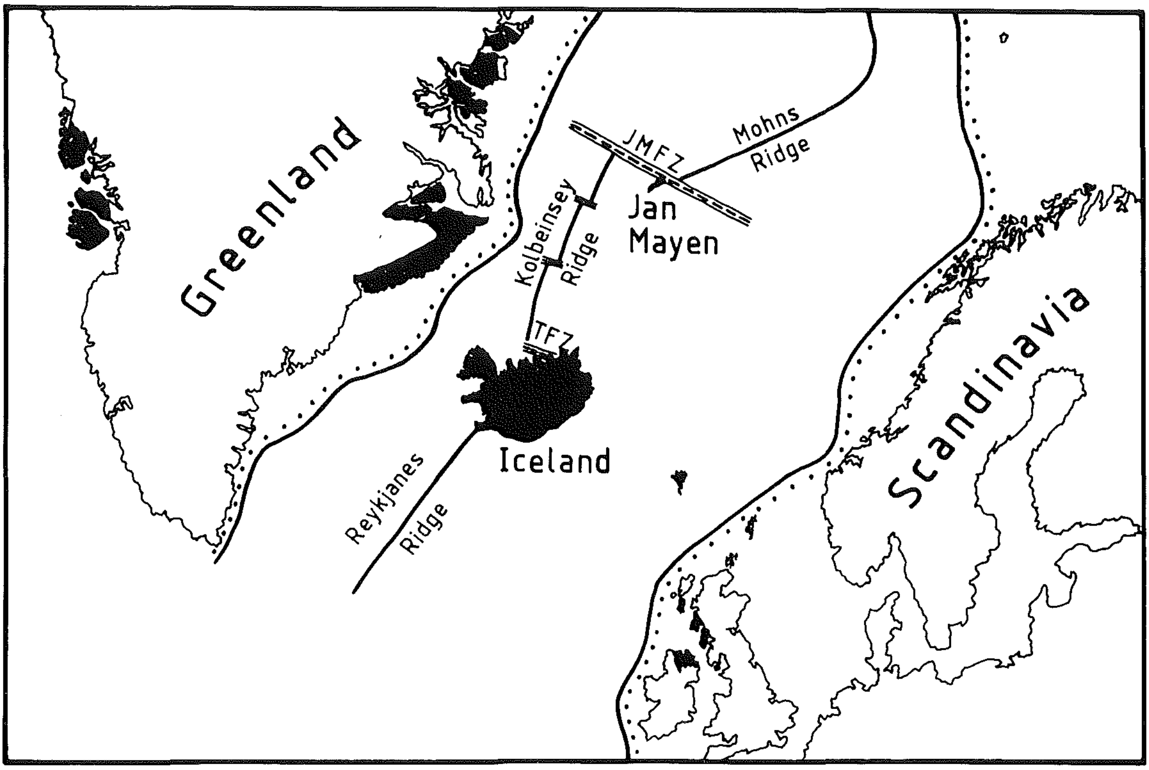

Fig. 1. Tectonic map of the North Atlantic showing the location of Iceland with respect to spreading ridges (Reykjanes, Kolbeinsey and Mohns), fracture zones (Tjörnes and Jan Mayen), and adjacent continental margins (dotted lines). Plateau basalt areas shown in black.

When the plates move away from the rifting zones, erosion and weathering supersede the constructive processes, and thick tilted sequences are exposed in tectonically distal fjords and valleys. Clearly, the tectonic and volcanic processes at work in Iceland provide a conservation factor which makes sections there promising for the study of actual glacier ice variations throughout the Quaternary. Remanent rock magnetism and K/Ar dating provide absolute ages for the lava sequences.

Iceland is located in the North Atlantic directly in the path of the high altitude westerly jet streams (Fig. 1). The climate is cold-temperate and maritime, and over 10% of the island's area of 103,000 km^2 are covered by glaciers. The present day climatic conditions are considered to be analogous to Quaternary interglacial conditions, and any changes in the latitude or in the shape of the path of the low depressions across the northern hemisphere are very likely to be reflected in the mass balance of glaciers or an ice sheet in Iceland.

The location of Iceland within a sensitive climatic zone and the favourable tectonic environment enhance the potential of Quaternary sections in Iceland.

THE BREIDAVÍK GROUP. GEOLOGICAL SETTING AND RESEARCH METHODS

Tjörnes Peninsula (Fig. 2) is a tectonically active horst bounded in the east by the axial zone of rifting and volcanism in Öxarfjördur, and in the south by the Húsavík faults which belong to the Tjörnes Fracture Zone (Fig. 2), along which the plate boundary across North Iceland is shifted westward to continue along the Kolbeinsey Ridge (Saemundsson 1974). Tjörnes exposes a basal unit of Tertiary flood basalts (Thoroddsen 1902, Aronson and Saemundsson 1974, Albertsson, 1978) followed by over 1000 m thick sediments and lavas of Pliocene and Quaternary age (Bárdarson 1925, Áskelsson 1941 and 1960, Einarsson, T. 1957a and 1957b, Th. Einarsson et al. 1967).

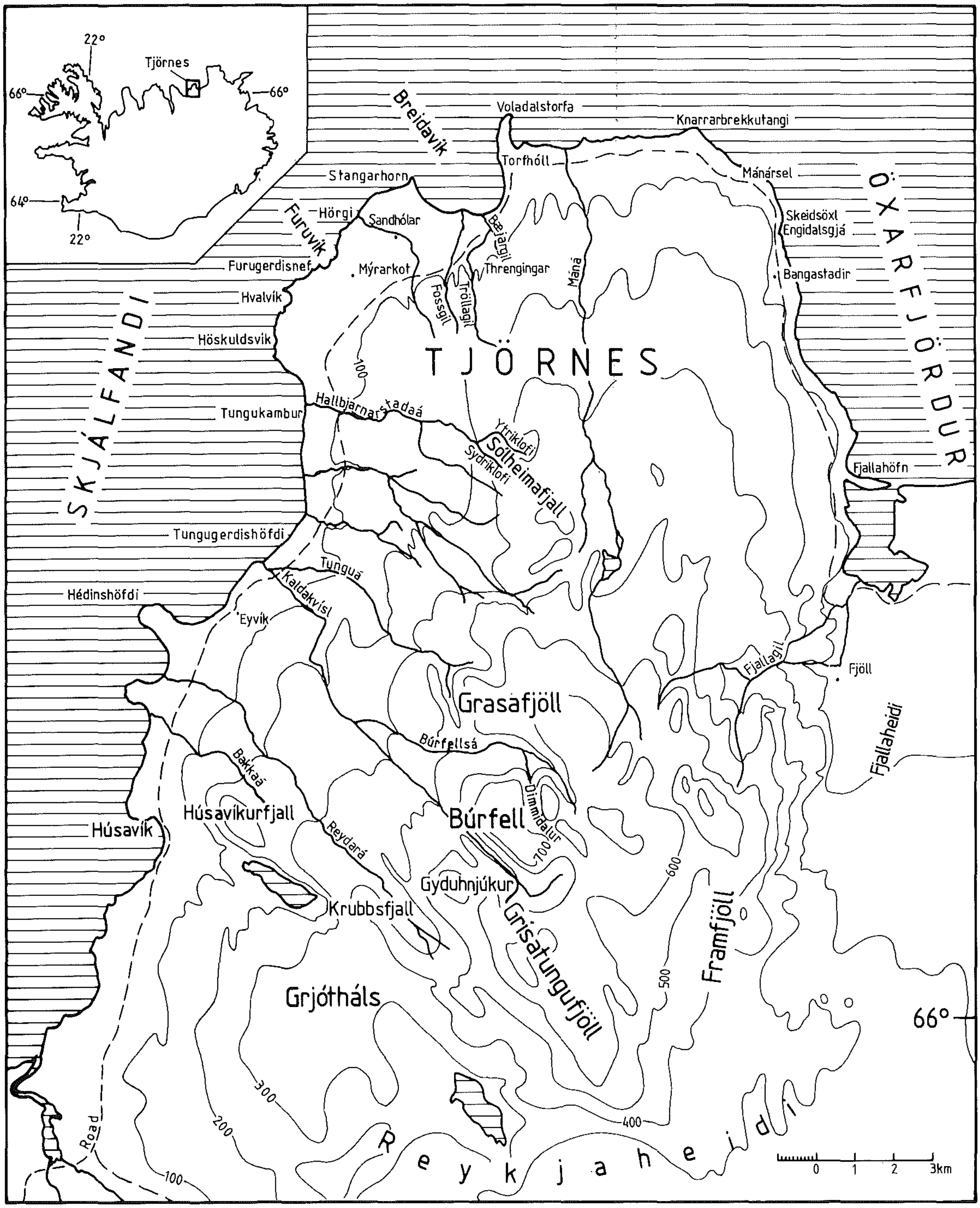

Fig. 2. Index map of Tjörnes (after Eiríksson 1981b).

During Postglacial time, lavas have flowed along the eastern and southern margins of the Tjörnes horst. Lava flows predominate in the uppermost part of the Tjörnes sequence and are intermingled with sedimentary units throughout the Breidavík Group. While the Pliocene Tjörnes basin may have formed along a transform fault well away from volcanic zones, lavas began to flow into the basin in upper Gauss time (Albertsson 1976), and since then lava flows appear to have had access to the Tjörnes area whenever environmental factors such as sea level or ice cover permitted. Palaeocurrent data from the Pliocene Tjörnes sediments (Strauch 1963) indicate that the sediment source at that time was to the south of Tjörnes, and the same is true for the Breidavík Group rocks (Eiríksson 1979).

The purpose of this paper is to describe and interpret some of the sedimentary rocks of the Breidavík Group on Tjörnes. The results are based on field investigations that began in 1975 while I was studying at the University of East Anglia, Norwich (Eiríksson 1979), and on later research at the Science Institute of the University of Iceland, Reykjavík. Lithostratigraphy and research history of the Tjörnes sequence were discussed in recent review papers (Eiríksson 1981a, 1981b). The Breidavík Group is an over 600 m thick sequence of mainly sedimentary rocks. Apart from the youngest member unit, all the rocks are lithified and crop out in coastal cliffs and along brook gullies. In central Tjörnes there are good outcrops in mountainous valleys. Some of the more resistant units, such as lava flows, can be traced on flat terrain, especially where soil erosion has been severe.

The main objectives of the field work were to establish the regional stratigraphy, describe rock units in terms of sedimentary facies, and to analyze vertical and lateral facies relationships. Facies definitions were entirely descriptive and based on field observations of textural and structural properties. Photographs of steep coastal cliffs were used to analyze inaccessible and indistinct coarse grained bedding structures.

In the following account it is attempted to unravel the glacial history of Tjörnes by means of both lithological and stratigraphical lines of research. A genetic classification of the sedimentary rocks is presented. Some units, especially the marine mudrocks and sandstones, have been classified more broadly than the glacially derived rocks. The genetic classification of the rocks forms the basis of a hypothetical reconstruction of palaeoenvironments in terms of a few simple facies models. The application of these models may be tested further by detailed sedimentological and palaeontological studies of selected Member units of the Breidavík Group.

A vertical section through the Breidavík Group rocks exhibits a distinct repetitive pattern of alternating sedimentary and volcanic rocks (Fig. 3). The latter component consists mainly of basaltic lava flows and a few tuff layers. Several lava flows usually occur together in a succession, followed by sedimentary associations. The Furugerdi Member, which is the lowest Member unit, begins with a diamictite bed, followed at first by conglomerates, sandstones and siltstones, and then by sandstones and conglomerates, capped by lava flows. Younger units, although they vary in their completeness, do conform to the same pattern of vertical facies sequence.

FACIES MODELS FOR GLACIAL SEDIMENTATION

A simple model for glacial conditions where ice reaches the sea during glacial maxima is presented as a framework for discussing the geological evidence. The model produces an ideal sequence and covers a cycle in the recurrent change from interglacial through glacial back to interglacial conditions, a change that is a major and well established feature of the Quaternary ice age. Three geographically adjacent zones are defined within the model, zone A which is constantly below sea level, a transitional zone B, which is subjected to alternating emergences and submergences, and zone C, which is terrestrial and constantly above sea level. Zone B is invaded by depositional or erosive processes typical for zones A or C whenever relative sea level changes. Possible courses of events through an interglacial–glacial–interglacial cycle are illustrated in Figs. 4 and 5, and may be briefly summarized as follows: Interglacial conditions (1) are interrupted by a eustatic drop of sea level (2) due to increased ice volumes on land outside the area, and the lower part of zone B emerges. Eventually, a glacier advances over the area (3) and isostatic depression of the crust begins. Glacial conditions (4) take over until the glacier retreats from the area (5). A concurrent reduction of ice volumes elsewhere leads to a eustatic rise of sea level and submergence of zone B (5, Fig. 4), the crust being still depressed by ice. On the other hand, a relative rise of sea level may

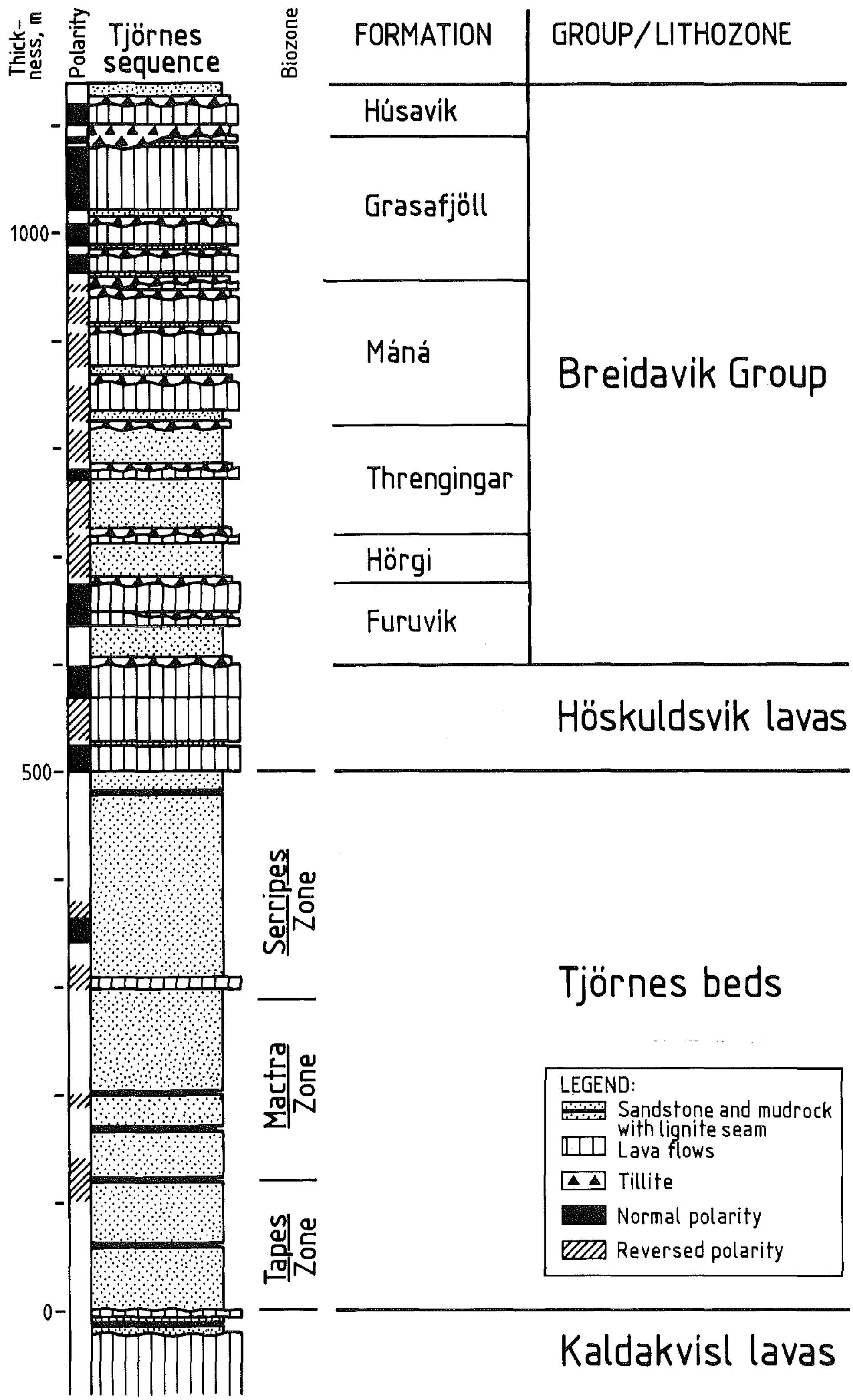

Fig. 3. Composite stratigraphical column of Breidavík Group strata.

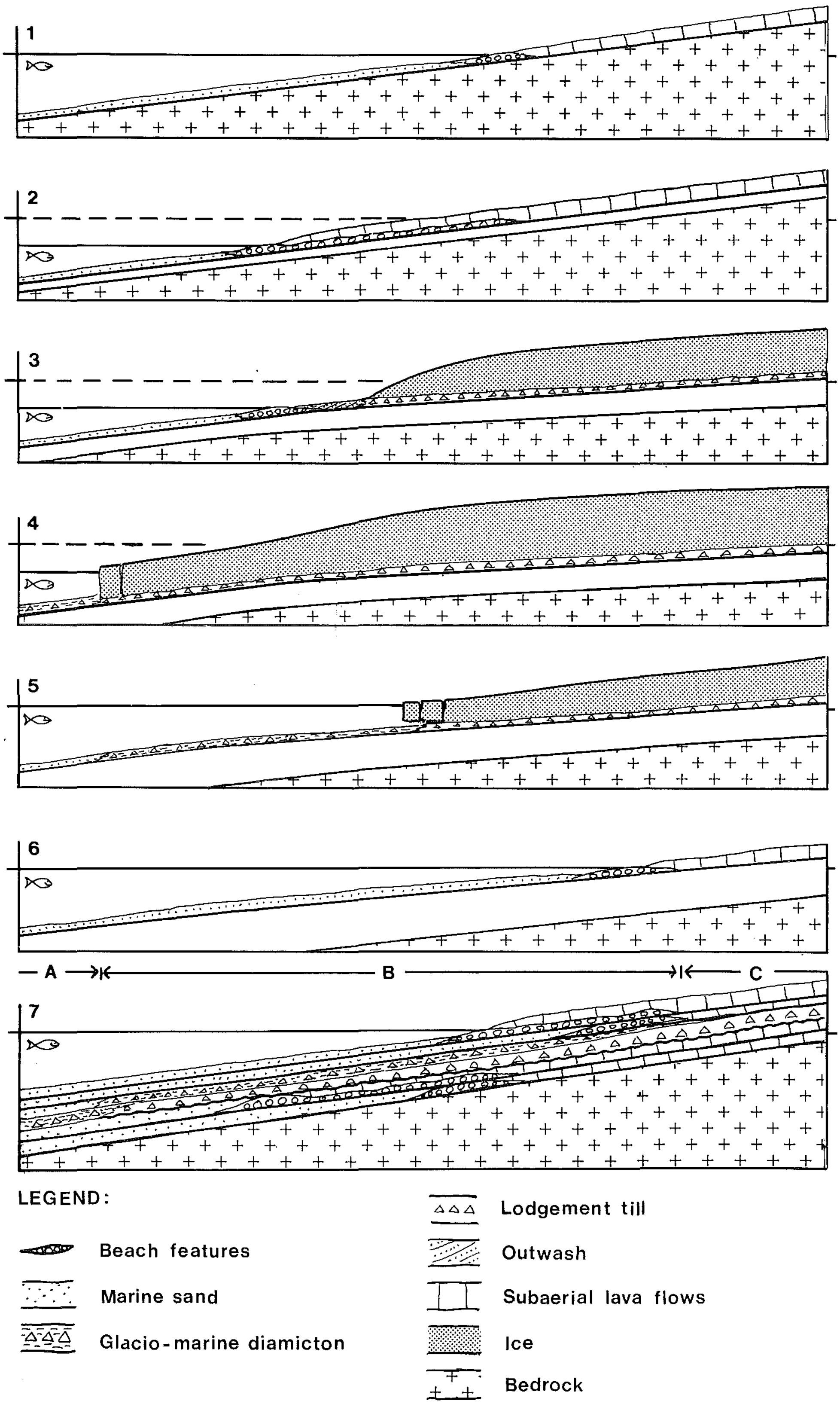

Fig. 4. Model (a) for accumulation of lithofacies in Zones A, B and C. See discussion in text.

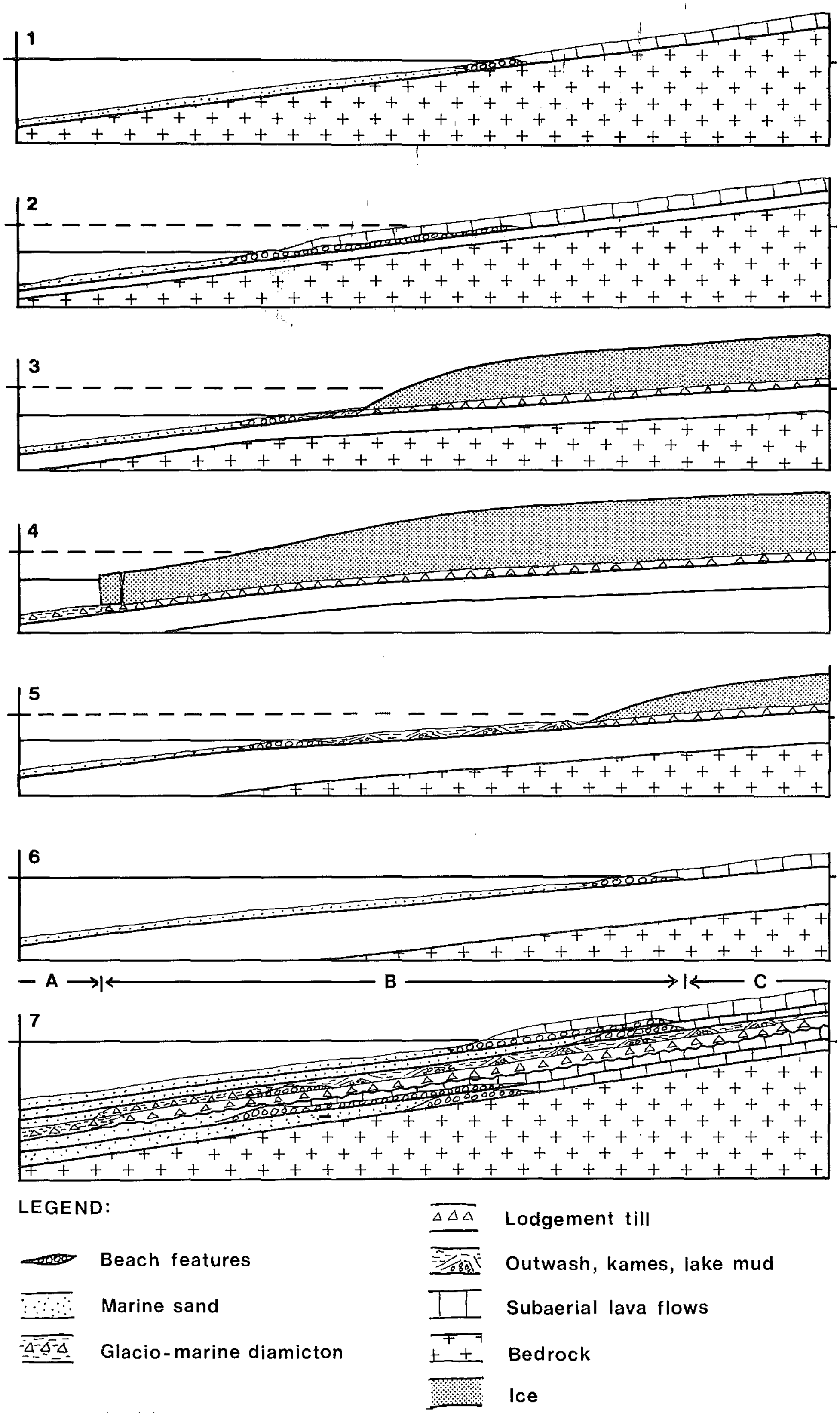

Fig. 5. Model (b) for accumulation of lithofacies in Zones A, B and C. See discussion in text.

be delayed either by rapid isostatic rebound of the area or by a delayed eustatic rise of sea level, in which cases the glacier would retreat on "dry" land (5, Fig. 5). Highest relative sea level is reached during late-glacial conditions (6, Figs. 4 and 5). Isostatic rebound has begun, and the conditions revert back to interglacial (1).

Many problems face anyone who attempts to interpret ancient sequences of diamictites and related rocks. During the past two decades, however, considerable progress has been made in the study of processes at present-day glaciers, which is a key factor in genetic classification of old glacial sediments and understanding of facies types and relationships. Nevertheless, there are relatively few features that are unique to glacial sediments, and some of the classification criteria require laboratory techniques that are not applicable to lithified sediments. Conclusions about the origin of these sediments are commonly based on a wide range of observations that cannot be standardized because of outcrop limitations and heterogeneity of sediments in the glacial environment. In addition to criteria which point to a particular mode of deposition, the vertical sequence of sedimentary facies can be strongly diagnostic of the origin.

Present-day glaciers fall into three broad categories defined by topographic and climatic factors. The first type consists of valley glaciers terminating within the valley system. The second type features glaciers or an ice sheet terminating on flat lowlands or broad, flat valleys, and in the third type the ice reaches the sea to form an ice shelf or an ice cliff. Boulton and Deynoux (1981) have summarized criteria, which allow recognition of genetic varieties of till, and reviewed definitions of sediment associations and land systems in the glacial environment. Two main types of glacial environments are identified, a glacioterrestrial environment and a glaciomarine one. Boulton and Deynoux differentiated between four types of associations on land. A glaciated valley land system and sediment association is characterized by coarse grained supratill in close association with lateral kame terraces, scree and solifluction material, as well as fluviatile sediments. A glaciolacustrine valley land system was coined for conditions which arise when a valley glacier retreats and the whole valley floor beyond the glacier margin is drowned by a lake. Rhythmites are deposited distally over proximal ice-marginal fans. Major deltaic deposition is likely to take place at the mouths of lateral streams producing upwards coarsening sequences or alternating coarse/fine units. A distinction based on the thermal regimes of glaciers was made between a subglacial/proglacial land system and a supraglacial land system. Temperate glaciers produce a subglacial/proglacial land system, where the sediment association consists of lodgement till associated with outwash sediments. Subpolar or polar glaciers, on the other hand, lead to a supraglacial land system, where the sediments are mainly lodgement till, flowtills, and meltout till, associated with kamiform outwash and proglacial outwash sediments. Glaciomarine sediment associations were subdivided into proximal and distal ones. The proximal glaciomarine sediment association may resemble the deposits of the glaciolacustrine valley environment strongly in fjords and coastal areas. Coarse grained submarine fans are deposited at the glacier margins by freshwater currents, and the fines settle rapidly as the freshwater plumes mix with the saline sea water. Turbidity currents and slumping are also important processes in this environment. Melting ice-bergs may release coarse debris which forms erratics in the fine grained bottom mud close to the ice margin, but may produce pebbly diamicton further away. The distal glaciomarine environment enjoys much slower sedimentation rates than the proximal one, and a slow accumulation of suspended sediment and iceberg-dropped detritus produces a fairly massive glaciomarine diamicton.

In the general model developed for the Breidavík Group, the area delineated by the upper and lower limits of relative sea level is particularly important for evaluating the implications of the geological record, because a section through a wholly terrestrial cycle or a wholly marine one can only be expected to serve as an on/off gauge for glacier advance-retreat cycles in lithological terms. An access to the transitional zone is more likely to yield information about sea level changes, which are clearly very important when the implications of changes of the extent of glaciers or ice sheets are to be evaluated. Only major, world-wide climatic fluctuations and resulting growth or reduction of ice volumes, can be expected to be accompanied by major eustatic changes. Conversely, minor climatic changes, although capable of causing glacier advances and deposition of till within the terrestrial zone, are unlikely to cause major changes in either absolute or relative sea level.

SEDIMENTOLOGICAL CHARACTERISTICS OF THE BREIDAVÍK GROUP

Very refined classification schemes exist for tills and related sediments of the glacial environments (Boulton 1972, 1976a, Dreimanis 1976, Boulton and Deynoux 1981).

More and more tools are becoming available for the study of Quaternary environments and their products. Many of these tools and the methodology are based on the study of either active glacial environments, deposits of the last glaciation where morphological data are often available, or on theoretical grounds. The student of old Quaternary sections does not always have access to some of the information neccessary for advanced classification, and the methodology for the study of hard rocks such as the Breidavík Group rocks differs from that of easily dispersed aggregates (cf. discussion in Eyles et al. 1983).

In the study of the Breidavík Group glacial sediments, the main emphasis was on establishing the local stratigraphy and on field descriptions of textural properties, sedimentary structures and fossils, as well as vertical and lateral facies relationships. The terminology by Boulton and Deynoux (1981) is adhered to in classifying the glacial sediments.

Tillites

The term diamictite was used in the field to describe rocks which "do not have an intact framework of gravel clasts but display, instead, a dominant matrix of fine grained materials in which the larger clasts are imbedded or "float"" (Pettijohn 1975). The term was introduced by Flint et al. (1960) as a lithified equivalent of diamicton, which the same authors defined as a nongenetic term for "any nonsorted or poorly sorted terrigenous sediment that consists of sand and/or larger particles in a muddy matrix". The terms diamicton and diamictite are thus defined to cover sediments and rocks which display certain grain size characteristics.

The main criteria used for the subdivision of the Breidavík Group diamictites were the size and shape of the diamictite beds, grain size characteristics, petrography of the clasts, and structures.

The combined effects of the landscape on Tjörnes Peninsula and the tectonic dip of the lower part of the Breidavík Group rocks limit the exposures of individual diamictite (and other) beds to a few hundred metres to a few kilometres. This poses a limit to the scale on which the overall shape and size of diamictite bodies can be assessed. Where bed thickness does not vary systematically within outcrops, it is assumed that the diamictite is sheet shaped. Irregularities in substratum topography may sometimes cause a local thinning or disappearance of diamictite beds without affecting such an assumption. The thickness of lodgement till is extremely variable in general, and may perhaps be related to topography (Flint 1971). Diamictite sheets in the Breidavík Group vary in thickness from a few tens of centimetres to tens of metres.

A bimodal or polymodal grain size distribution in a diamicton where one of the major modes is in the silt range strongly suggests glacial origin. Smalley (1966) suggested that glacial crushing of sand grains would produce a bimodal distribution with a major silt component. Dreimanis and Vagners (1971) concluded from studies of till in Ontario, Canada, that crushing and abrasion during glacial transport was responsible for an increase in the silt mode of tills away from source areas. Post-depositional crushing due to subglacial shearing and dilatation was suggested as an alternative possibility for silt enrichment by Boulton et al. (1974).

Because of the petrological uniformity of Iceland, the petrography of the diamictites on Tjörnes would seem unlikely to hold important clues about their origin. Nevertheless it is well known that the bedrock piled up since the onset of widespread glaciations within volcanic zones in Iceland is characterized by hyaloclastites, breccias and pillow lavas. This change in volcanic rock facies should be reflected in sediments derived from erosion of bedrock. The composition of clasts was noted in the field in order to assess bedrock composition in source areas. In practice, the composition of some of the diamictites was found to be intimately related to local bedrock composition.

The form of clasts was not studied systematically. Pebble and boulder roundness was assessed visually in the field, and striations were noted whenever observed. Their genetic significance is somewhat restricted, however, as the striae may be inherited from an earlier phase of sedimentation if the clast has been recycled. The same is probably true of clast form.

The structural properties of the diamictites proved to be an important diagnostic feature. It was possible to identify different types of diamictites on the basis of variations in sedimentary structures. Bands (sedimentary or shear), folds and faults were used to differentiate between lodgement till, meltout till and flow till by Boulton (1976a) and Boulton and Deynoux (1981). According to Boulton, flow tills may show both sedimentary and shear banding. The folds are asymmetric overturned or flat-lying isoclinal folds with synclinal and anticlinal fold noses preserved. Gentle folding and high angle folds are common in sediments beneath flow tills. Meltout tills tend to be massive but may incorporate englacial ice tunnel deposits. They are probably difficult to distinguish from flow tills in some cases (Haldorsen and Shaw 1981). Lodgement tills contain no sedimentary banding or stratification of any kind unless subtill sediments have been tectonically incorporated in the till. Shearing of recently deposited till or subtill sediment may lead to streaked out lenses or shear bands. Lodgement till folding reflects subglacial shearing and is characterized by isoclinal folds with flat lying axial planes. Anticlinal fold noses are, according to Boulton (1976a), rarely preserved. Synclines facing up-glacier are common, but fold noses are often streaked out.

The diamictites of the Breidavík Group are classified here as lodgement tillite, flow tillite, glaciomarine diamictite, and glaciolacustrine diamictite. The genetic classification is based on the examination of textural and structural properties, and on stratigraphical relationships. These factors are discussed below under separate headings for each diamictite variety.

Lodgement tillite

Extensive sheet shaped diamictites in the Breidavík Group vary in thickness from a few tens of centimetres to tens of metres, and are generally interpreted as lodgement tillites.

Distinct glacial striae have been found at four localities underlying such sheets (Hörgi Formation, Svarthamar Member, Raudsgjá Member, and Skeidsöxl Member), and they are widespread beneath sediments of the youngest Member of the Breidavík Group. In addition, large scale planing of underlying strata indicates glacial erosion even though striations are missing or cannot be observed because of exposure relations. These erosional features represent an important facies.

When beds immediately above a diamictite sheet are identified as flow tillites, kame and outwash conglomerates, or glaciomarine or glaciolacustrine diamictites, the stratigraphical relationship strongly suggests a lodgement tillite interpretation for the diamictite bed. A meltout tillite could occupy a parallel stratigraphical position, and a differentiation of the two genetic varieties may be problematic. The meltout process does not, however, lead to any structures within the till (Boulton et al. 1974, cf. also Boulton 1976a).

Grain size distribution was originally used to classify conglomerates as diamictites. Although a high silt content in the matrix does not in itself constitute a proof of a particular mode of deposition, it does indicate a glacial origin. However, a lodgement till which becomes recycled by a nonsorting process, e.g. a mass flow, would still retain a high silt content. Generally, lodgement till is expected to be richer in silt than supraglacially derived till. There is no evidence of a crushing process during supraglacial transport, and supraglacial debris is therefore likely to retain the grain size distribution produced by weathering, mechanical or other, in source areas and during transport. A depletion of fines may locally take place through sorting by meltwater. The deposits classified as flow tillites were generally found to have a silty matrix, similar to that of the lodgement tillites, although internal variations and occasional sorting were observed in the flow tillites.

The lithology of clasts in some diamictites was seen to follow the lithology of the substratum closely. For example, a lateral change in clast composition occurs within a distance of a few hundred metres in the lowest diamictite of the Breidavík Group (Furugerdi Member, Fig. 6). Clasts of sedimentary origin only make up a

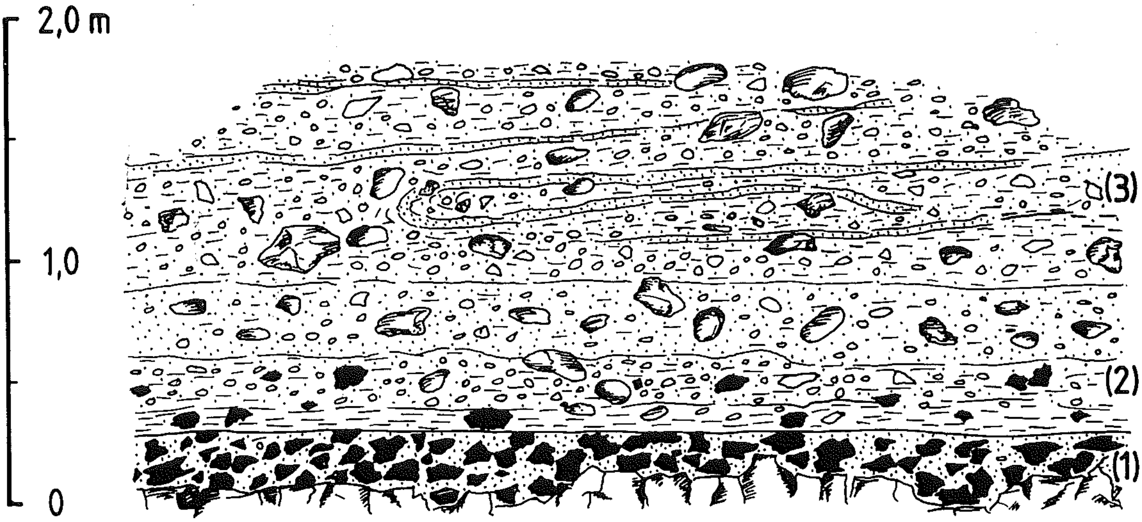

Fig. 6. Tillite (2) immediately above scoriaceous lava (1) is enriched in scoriae. Upper part of tillite (3) reveals folds and sorted lenses.

significant proportion of diamictites where they overlie erosional surfaces cutting across sedimentary rocks. Subglacial erosion (shearing and plucking) of jointed sedimentary rocks and lava flows is considered to explain this close relationship, which is compatible with a lodgement tillite interpretation of such diamictites.

The fabric of the diamictites was generally not studied. Although its genetic significance has been illustrated repeatedly (Flint 1971, Boulton 1971), the availability of other evidence was considered to render a substantial fabric sampling programme unneccessary.

Two types of structures in some Breidavík Group diamictites support an identification as lodgement tillite. Basal grooves were observed on the sole of the Torfhóll Member diamictite (Fig. 7), and grooved planes were observed within the Húsavík Formation diamictites. The grooves are identified as flute molds. The problem of flute genesis was recently examined by Boulton (1976b), who noted that flutes are almost omnipresent on the surface of modern lodgement tills. Boulton's general conclusion was that flutes are formed by the squeezing up of deformable subglacial sediment into low pressure areas in the ice in lee of rigid obstructions such as boulders. This is in line with a hypothesis of flute genesis put forward by Schytt (1959). Fluting of the substratum of the Torfhóll diamictite indicates that the underlying marine sandstone was overridden by glacier ice before lithification took place. Some 30 cm beneath the grooved plane there is another plane within the marine sandstone. The latter grooves are on a much smaller scale, the amplitude of the grooves and ridges is only 1–2 cm. The grooves are parallel to the larger grooves (flutes) above. This lower plane of grooves is interpreted as resulting from shear movement within the topmost part of the sands caused by the overriding glacier ice (Fig. 8).

The fluting process envisaged by Boulton is obviously not confined to particular planes in a lodgement till, but is likely to be initiated whenever a boulder or any protruding obstacle becomes lodged or is overridden by moving ice. The lodgement of boulders is expected to happen at random in a vertical sense as lodgement till accumulates. This random distribution may be altered during deposition by the condition that the lodgement of one boulder may form an obstacle to the path of the next one, and a boulder cluster will result. Such clusters should also be randomly distributed. The splitting up of diamictites along nearly horizontal planes as in the case of the Breidavík Group diamictites is therefore not predicted from the fluting process. It is suggested that the internal groove planes were either caused by subglacial shearing within recently deposited till, or that the lodgement was intermittent so as to allow fluting at certain levels during non-deposition.

The second type of structures in the Breidavík Group diamictites consists of bands of silt-enriched diamictite, which give the sediment a

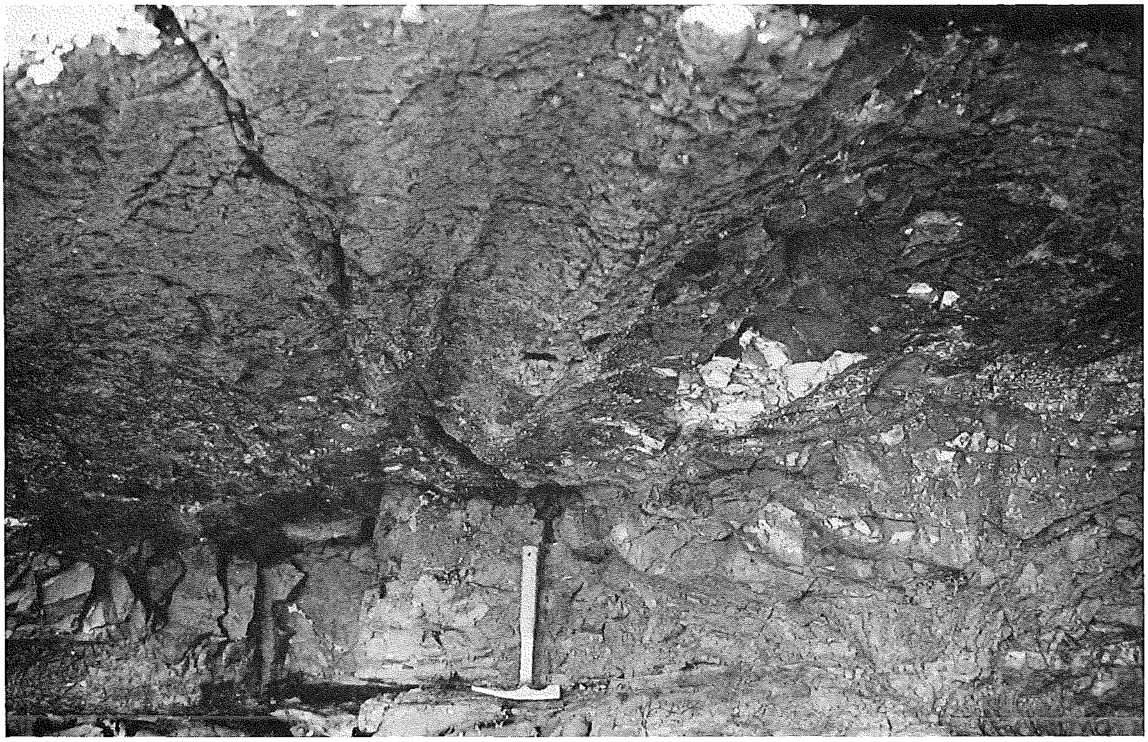

Fig. 7. Flute molds on the sole of a tillite bed in Stapavík. Geological hammer beneath a topographic low on the till-substratum contact.

Fig. 8. Grooved shear plane in sub-tillite sediment (Stapavík). 15 cm long biro points to plane.

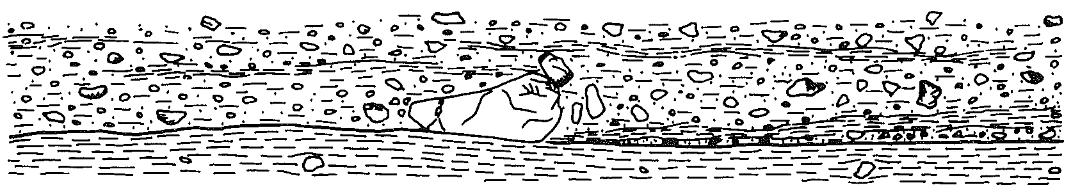

Fig. 9. Faceted boulder (1.8 m long) in lodgement tillite in Fossgil.

streaked look, especially in matrix dominated diamictites. The bands are generally lighter coloured than the adjacent rock, and sometimes have a weaker resistance to weathering. The lateral extent of these bands varies from a few tens of centimetres to a few metres or more. They tend to be undulating rather than flat, particularly in stony diamictites. The absence of primary sedimentary structures suggests that the bands were formed by post-depositional deformation. Boulton (1976a) listed shear banding as a feature of lodgement till, or, if interdigitation with stratified sediments occurs, flow till. Shear banding results when at least two materials are deformed together so that folds develop and become sheared into bands. Subglacial shearing was discussed by Boulton et al. (1974) who described an upper zone of sheared till within a lodgement till horizon at the margin of Breidamerkurjökull in Southeast Iceland. Presumably, a gradual buildup of lodgement till means that every part of it has undergone shearing. Boulton et al. concluded that a considerable amount of crushing takes place in the shearing zone. This leads to a silt enriched matrix. It is noteworthy that some of the silt bands observed in the Breidavík Group diamictites were seen to originate at large boulders. It is suggested that banding can result, when boulders become lodged beneath glaciers and are then subjected to shearing of material against them. This would involve crushing of material for a period of time at a certain level in the lodgement till, which finds expression in silty bands extending downglacier from the boulder. Faceting and even striation of the up-glacier side and the top of the boulder may result (Fig. 9). Boulders have been observed in horizontal clusters in the Breidavík Group diamictites, e.g. in the Fossgil Member (Fig. 10). Such boulder clusters are characteristic of lodgement tills (Boulton and Paul 1976).

Flow tillite

The diamictites of the Breidavík Group rarely occur in multiple sequences without erosional breaks. The lowest part of the Furugerdi Member is an exception. Here a number of diamictite bodies are interbedded with sorted material ranging from siltstone to conglomerates above a diamictite which is interpreted as a lodgement tillite. The stratification is often distinct, and the diamictite beds alter-

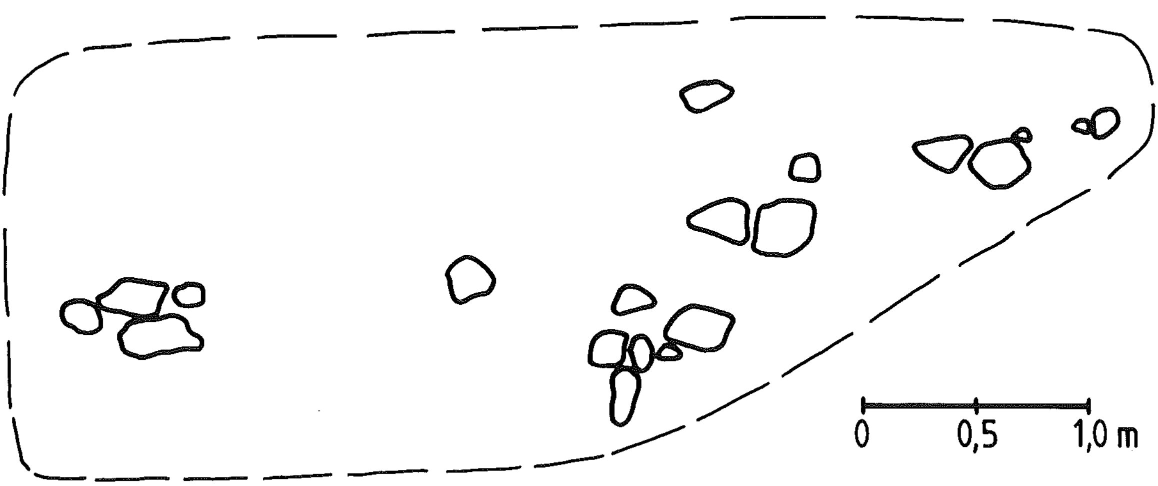

Fig. 10. Boulder clusters in Fossgil lodgement tillite.

nate with sandstone and siltstone lenses of a limited lateral extent (up to a few tens of metres). Internal structures are common and vary from thin, poorly sorted silt bands to distinct folds. The banding and folding of the upper, stratified part of the Furugerdi Member diamictite sequence is thought to result from post-depositional deformation. Recumbent folds and low angle faults are interpreted as evidence of slumping within soft sediments originally deposited in a supraglacial position. Boulton (1968, 1972) has described sedimentation processes at the snouts of present day glaciers in Spitzbergen, where ablation of ice releases englacial debris which is deposited in a fluid state upon the glacier surface. Differential melting of underlying ice leads to a downslope flow of the debris. Meltwater streams cause local sorting of material and short lived ponds are common. Sections through flow till formed in this way revealed isoclinal folds. Flow till is typically deposited on top of lodgement till or meltout till although other sediments may well intervene. Stratified conglomerates and sandstones interpreted as ice-contact sediments were for instance observed between lodgement tillite and flow tillite in the Hörgi Member. The Furugerdi Member flow till, however, rests directly upon lodgement tillite. The structural and textural properties appear to fit the criteria for distinguishing flow till deposition.

Kame conglomerates

Review of kame genesis

The research history of kames and ideas about their origin were reviewed by Holmes (1947), who defined kames in the following way: "A kame is a mound composed chiefly of gravel or sand, whose form has resulted from original deposition modified by any slumping incident to later melting of glacial ice against or upon which the deposit accumulated".

Goldthwait (1959) listed two conditions for present day development of areas of ice-contact washed deposits: rapid melting and thinning of glacier ice so that ice flow slows down or stops; and presence of hilly topography to cut off flow. Presumably the melting slowed down after the ice stagnated, and slow melting is generally assumed during kame genesis (Embleton and King 1975). Goldthwait deduced from studies in Ohio, U.S.A., that the last ice sheet in that area began to disappear by rapid melting. Hills gradually protruded near the edges as the ice sheet became thinner, and thin ice became covered with dirt which had been near the base. Goldthwait went on to describe kames: "The outstanding deposit of such areas is the glacial *kame*. It is an irregular hummocky mound of layered sand and gravel, – some coarse, some fine. Some layers are dirty (i. e. silty), but most layers have silt and clay washed out. Huge boulders may be sprinkled through the deposit like raisins in rice pudding, and not uncommonly there are irregular blobs of till" (Goldthwait 1959).

According to Flint (1971), kames are formed in two principal ways. One type of kame is deposited "in or on the surface of stagnant or nearly stagnant ice ...". Another type consists of deltas built outward from ice or inward against ice (kame deltas). According to Flint kames may grade into kame terraces, collapsed masses, ablation drift, and some types of eskers. Flint's classification scheme was not based on the location of deposition relative to ice. He suggested supraglacial and englacial origin for kames, but discussed "collapsed sediments" separately, these being deposited supraglacially but becoming deformed as they are let down onto the ground as the ice melts away. In Flint's scheme, eskers are typically deposited in subglacial tunnels.

Boulton (1972) distinguished between deposition of ice-contact stratified sediments upon (supraglacial), within (englacial), and beneath (subglacial) stagnant and ablating ice, and based a genetic classification on this position of deposition relative to the ice. The supraglacial and englacial models were based on observation at the margins of modern glaciers in Spitzbergen, and the subglacial one is partly predicted with reference to the englacial one. Boulton's classification also included ice-walled deposits as defined in Clayton and Freers (1967). Ice-walled deposits resemble supraglacial ones but generally retain a flat top.

Karczewski (1971,1974) presented a genetic classification of kames based on structural and lithological studies of kames in Western Pomerania, Poland. He put forward a theoretical reconstruction of kame forming conditions and identified four types of kame macrostructures: horizontal, isoclinal, anticlinal, and synclinal. Original deposition of kame material was envisaged by Karczewski in supraglacial, englacial, and intraglacial position, in all cases with an original horizontal bedding. Subsequent slumping and faulting of the margins and irregular melting of ice in the supraglacial case would cause the development of anticlinal or synclinal forms, while lateral deposition relative to the ice would lead to an isoclinal macrostructure. Squeezing up of clay and glaciofluvial material may cause an updoming of kames in the intraglacial case. Karczewski noted, that "boulder clay and ablation sediments" are intimately associated with the kame sediments.

Embleton and King (1975) discussed various hypotheses as to the origin of kames and reviewed kame distribution. They noted that eskers and kames were formed of stratified deposits laid down in contact with slow-moving or stagnant ice by glacial meltwater. They distinguished between kame terraces formed along walley side margins of glaciers, and kames deposited at glacier margins in proglacial lakes or accumulating as lone kames in hollows on or in the decaying ice.

Distribution of kames in the Breidavík Group

Four of the Breidavík Group Formations contain spectacular conglomerate bodies, whose thickness is measured in tens of metres. Three of the conglomerate horizons are interpreted as kame complexes. Stratigraphically they all belong immediately above lodgement tillites or a glacially striated substratum. The conglomerates are characterized by an irregular outer form and a limited lateral extent. Internal bedding structures are highly variable, and deformation structures are common. Grain size and sorting are extremely variable. Many of the conglomerate bodies are intimately associated with mudrocks. Ice-contact conditions are suggested by their stratigraphical position above lodgement tillites, and by their form, texture and structure. Their whole appearance brings to the mind a quotation from Flint (1971), when he discussed processes in the immediate proximity of stagnant ice: "In such a place anything can happen, and it often does". A panorama view of one of the kame complexes is exposed in the western side of the bay of Breidavík, where individual kames tower up to 40 m above the coastline in vertical cliffs which jut out from the adjacent mudrocks because of the greater resistance of the conglomerates to weathering.

The contacts between lodgement tillite and the overlying kame complexes are sharp with no evidence of an erosional interval preceding the deposition of the gravels (Fig. 11). A continuity in sedimentation, if by a different process, is evident. It is an inherent feature of the Ice Age concept that processes associated with an ice sheet and lodgement till deposition will eventually be naturally succeeded by processes associated with the melting of that ice sheet. Consequently it is not surprising to find ice-contact sediments above tillite sheets.

Although deglaciation processes generate kames it does not follow that they will be conserved. Even after a modification of their depositional form and structure during the kame genesis, further changes are likely to occur. Kames are probably short-lived phenomena in many cases. Their mound form will generally make them accessible to erosion, and a low conservation potential is therefore predicted. The kame is likely to become modified or destroyed by erosion during ice free periods. This factor may account for the fact that kames are only found in those Breidavík Group Members (Formation in the case of the Hörgi unit) where there is evidence of submergence below sea level soon after the ice retreat phase. Deposition of lacustrine and marine mud tends to level out the kame topography and increase their conservation probability. A further point worth bearing in mind is that not all ice margins retreat by stagnation of ice. Kame formation is hardly expected where glaciers calve into the sea or lakes during retreat.

Size and shape of the Breidavík Group kames

The external form of kames is related to at least three factors. In the first instance their form is controlled by channel or local basin form during the original deposition. Secondly, the post-depositional removal of lateral and/or basal support (ice) will lead to a modification of the overall shape of kames. Thirdly, an adjustment of shape may take place as kames are lowered onto the substratum topography.

As kames are essentially fluvial deposits (Holmes 1947), their depositional form must be controlled by the runoff pattern within the stagnant ice area. This is related to the distribution

Fig. 11. Conformable kame conglomerate/lodgement tillite contact in Stapavík.

of debris in the ice which affects the ablation rates, and to crevasses in the ice which are likely to form natural runoff channels. It is well known from modern glacier margins that englacial dirt tends to be concentrated along planes which are either sub-horizontal or dip up-glacier in the snout areas. Release of englacial debris from these planes by melting of ice will lead to an accumulation of supraglacial debris ridges striking parallel to the ice margin (Boulton 1972). Other debris ridges may consist of supraglacially transported debris, and these would be arranged parallel to ice flow (medial moraines), or lodgement till squeezed up into crevasses (Hoppe 1953). Any debris ridges on the surface will reduce ablation of ice if they are thick enough, and the meltwater will be channelled along elongate depressions, most commonly parallel to the ice margin. This pattern is likely to be interrupted by crevasses in the ice, which in a stagnant ice may either be controlled by weaknesses inherited since the ice was active or be uncontrolled (Embleton and King 1975). In the absence of a three dimensional view of the kame complex and with only a limited knowledge of the topography beneath the stagnant dead ice, – as in the case of the Breidavík Group kames, – it is difficult to establish whether the crevasse pattern was controlled or not. In any case, a very indiscriminate runoff pattern may develop on the stagnated ice. In addition, all channels are likely to be highly unstable because of the easily penetrated ice, and frequent avulsions are to be expected. Generally speaking the depositional form of ice floored kames will be that of elongate channel fills. Deposition may stop when the meltwater stream is cut off by either an avulsion, a moulin, or a decreased rate of melting (seasonal control). More stable channels may develop if the meltwater penetrates through the ice down to the substratum.

Subsequent to the deposition of kame gravels, their form begins to be affected by a slow melting of ice at the margins of and beneath the channels. The ice melts away faster along the flanks than beneath the channel fills because of the insulation effect of the sediments, and the steep depositional contacts with the ice in the confined channel spaces will collapse through slumping and faulting at the margins when the lateral support disappears. Due to irregularities in sediment thickness along the channels, and possibly also due to inhomogeneities in the ice below, melting beneath the kames may not be uniform. Therefore, slumping may also take place along the axes of channels into hollows created by locally rapid melting. An originally continuous elongate kame may thus disintegrate into a string of mounds. Only the former, marginal type of deformation is expected, where channels have penetrated down to the substratum of the ice.

At the margins of some modern glaciers (Embleton and King 1975) fluvioglacial material is not only deposited in channels, but also as outwash fans spreading over relatively flat dead ice surfaces. It appears that a complete transition from channel deposition to outwash plain deposition exists in supraglacial position at modern glaciers. The fate of such outwash sheets is naturally controlled by the melting of ice below. If the melting is uniform, no kames will be formed. Minor variations in the thickness of ice may lead to the development of kettle holes and a pitted outwash plain.

Finally, the shape of kames may be affected by topographical features of the substratum (Boulton 1972). If the substratum is flat and horizontal no deformation will take place apart from that resulting from the melting of adjacent ice. If the kame is lowered onto a sloping surface it will be tilted and deformed until equilibrium with the slope has been reached. The amount of deformation is related to the slope angle and to the shear strength of the kame material. Internal structures of the kame are likely to become asymmetrical or folded, if not completely destroyed as a result of this deformation.

Field conditions do not allow a detailed three dimensional analysis of the form of the Breidavík Group conglomerate bodies. At best, a two dimensional picture can be obtained, but the sole is rarely exposed, and the top has often been modified by erosion.

Internal structure and genesis of the Breidavík Group kames

All the Breidavík Group kames are stratified. Vertical changes in bedding and lithology are commonly often abrupt. Depositional structures vary from massive, poorly sorted conglomerate beds (sometimes a few metres thick) to laminated sandstone and siltstone beds. Tabular sets of cross beds occur locally. Graded bedding is fairly common. The primary structures are considered consistent with supraglacial fluvial deposition and slumping. Cross bedded and flat bedded conglomerates and sandstones are interpreted as fluvial deposits, and the laminated facies as suspension sediments. Very poorly sorted beds and graded beds probably indicate occasional slumping of supraglacial debris into the channels. Some of the unsorted lenses are interpreted as flow till lobes.

Many of the conglomerate bodies in question display severely deformed bedding. Only the elongate kame at Svarthamar has retained the original bedding intact. The nature of the deformation enables a reconstruction of the genesis of individual kames and kame complexes. A model explaining common deformation structures in kames was presented by Boulton (1972). According to the model, melting of ice concurrent with supraglacial channel deposition will affect the internal structure of the resulting kame. A loss of lateral support during deposition will lead to lateral slumping and an

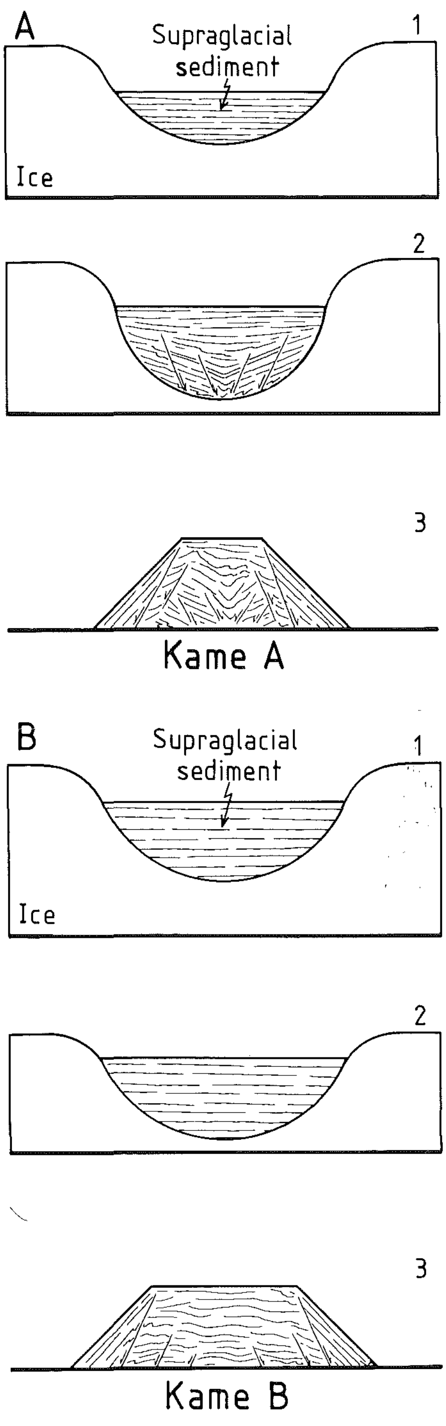

Fig. 12. Hypothetical reconstruction of the genesis of two kames of the Hörgi Formation. Kame A was deposited on ice (1) and deformed because of basal melting during accumulation (2). Resultant kame (3) shows synclinal structure. Kame B was deposited on ice (1) and lowered onto the substratum (2) without sub-channel melting, producing an essentially flat bedded kame (3).

anticlinal structure with dips decreasing upwards. Subchannel melting during deposition will, on the other hand, produce a syncline, again with dips decreasing upwards. When no appreciable melting accompanies deposition, the resulting kame will be flat bedded, but with secondary dips and faults due to slumping at the kame margins. In all cases, substratum irregularities may cause further deformation and faulting.

Exposed kames of the Breidavík Group are most numerous in the Hörgi Formation. Several structural varieties present themselves. Fig. 12 shows two kames and a reconstruction of their genesis. Kame A is over 35 m thick (the lower contact is not exposed). Its central part reveals a steep syncline with parallel bedding on the limbs. The axial plane is nearly vertical, which indicates that the kame landed on a flat substratum. The synclinal structure is thought to reflect foundering of the channel bed during deposition due to simultaneous melting of basal ice. Higher up the bedding is irregularly folded (compression in the knee of the syncline), and the top section is essentially flat bedded, and no deformation was observed there. The flanks of kame A are characterized by outward dips which are explained as a result of slumping when the lateral support was removed. The kame has a flat top, but this may not be an original feature.

Kame B in Fig. 12 has an exposed thickness of 30 m, but its base is not seen. The kame is mound shaped in the coastal outcrop where it is flanked by a smaller kame remnant. The central part of kame B is essentially flat bedded, but deformation folds occur at a central fault. The central deformation is considered to result from minor irregularities of the substratum. On the western flank there is a marginal fault, beyond which the bedding planes dip outward, presumably because of slumping. On the eastern flank there are also faults, but the bedding is folded. This is explained as abortive slumping against the juxtaposed kame, the top of which has later been eroded away. There is no evidence of basal melting during the deposition of kame B, which indicates that the channel was a short lived one or that the sediment was dumped rapidly into a depression in the ice.

A more complicated genesis is proposed for the evolution of the kame complex in Fig. 13. It consists of three separate kame bodies, the two

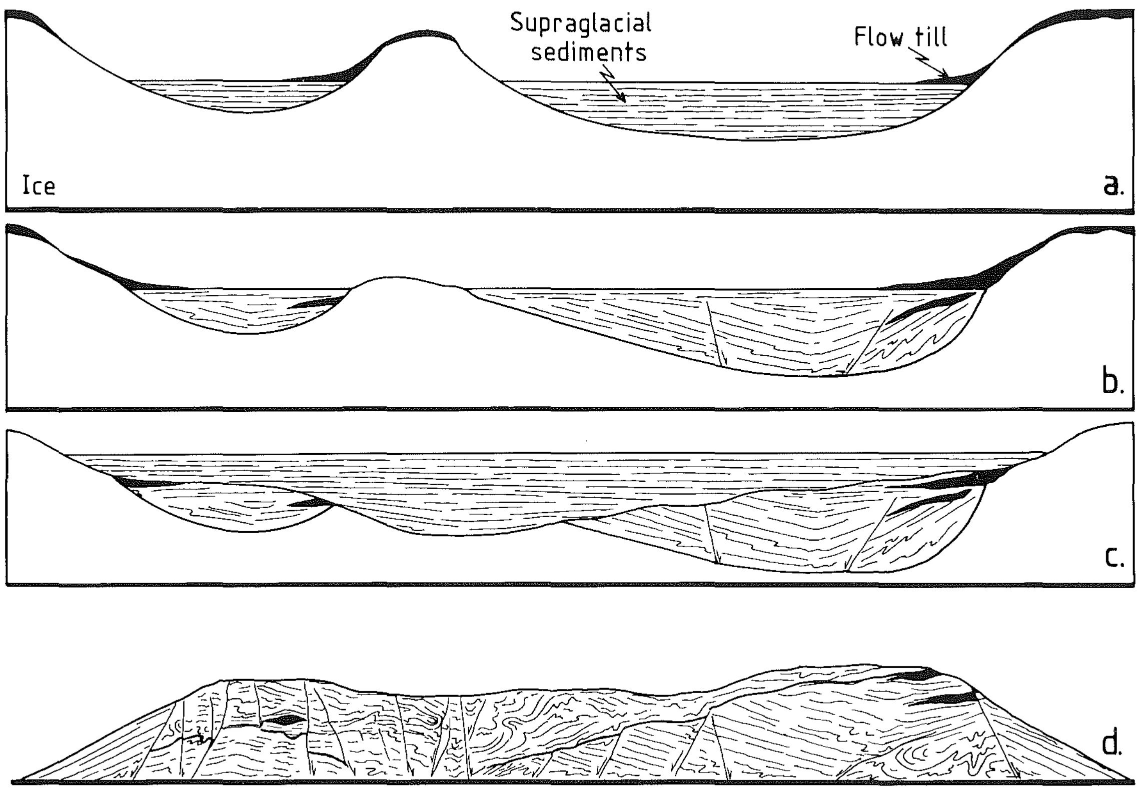

Fig. 13. Hypothetical reconstruction of the genesis of a kame complex in the Hörgi Formation. For explanation see discussion in text.

lower ones have affected the deformation of the third one. The inferred genesis of these kames may be summed up as follows. Gravel begins to accumulate in two closely spaced channels flanked by debris covered ridges. One of the channels is fairly short lived (on the left in Fig. 13a), but the other one is more stable. Subchannel melting concurrent with fluvial deposition leads to synclinal deformation. Flow till lobes from the adjacent ridges interdigitate with the gravel. Eventually the topography between the two channels becomes reversed and a new channel is cut into the ice, and partly into the already deformed older gravels. Flat bedded gravels are deposited in the new channel, and an angular unconformity at the interface between separate channel fills is created (c). Deposition is now halted in the area and slow melting of the adjacent ice begins to affect the depositional form. Lateral slumping and faulting takes place. Deformation is most severe in the central kame, the bedding planes of which become severely folded in the process of adjusting to the irregular substratum, which in this case consists of the first generation of kames. Detail sketches of portions of the kame complex in Fig. 13 are presented in Fig. 14, and a photograph of deformation folds in Fig. 15.

Bedrock slope may have played a part in the deformation of structures in a 20 m high kame in the Torfhóll Member exposed in Stapavík. The bedding is most severely disturbed where the slope of the tillite bed beneath is steep, and the deformation decreases and is characterized by lateral slumping where the tillite flattens out towards north.

Outwash and lacustrine mudrocks and conglomerates

Many of the Member units of Breidavík Group contain a vertical sequence where stratified ice-contact sediments are succeeded by mudrocks. In the absence of ice-contact conglomerates, lodgement tillite beds are often

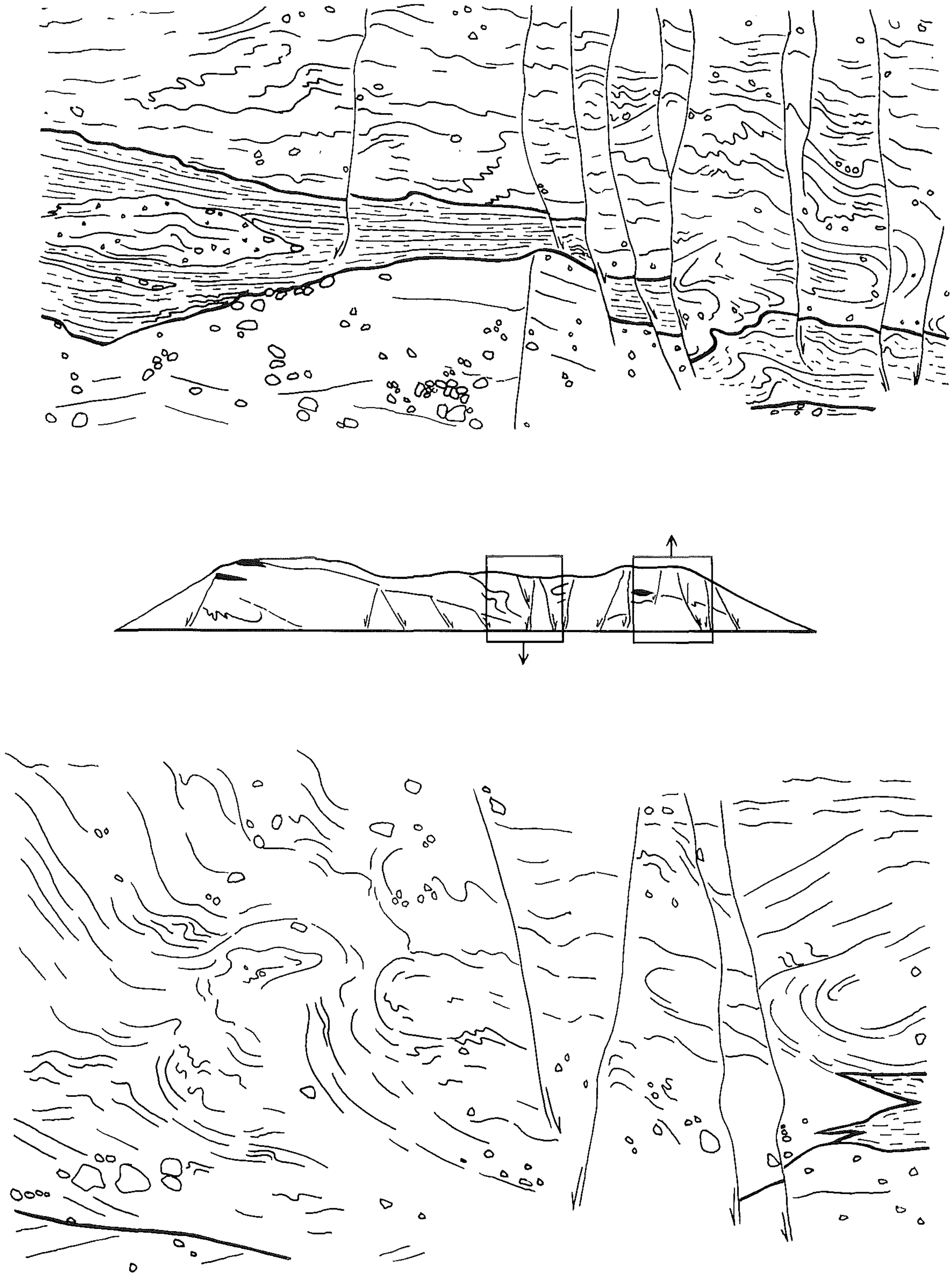

Fig. 14. Detail sketches of deformation structures in a Hörgi Formation kame complex (centre, cf. Fig. 13). Vertical height of blow-ups ca 20 m.

Fig. 15. Deformation fold in a Hörgi Formation kame. Height of exposure 7 m.

directly overlain by mudrocks. Sedimentary structures in the mudrocks hold clues to the depositional relationship between the mudrocks and the adjacent sedimentary bodies.

The Fossgil Member contains a good example of a case where mudrocks overlie lodgement tillite. Bedding and lamination planes in the siltstone are conformable with the surface of the tillite, which is irregular. The attitude of the bedding is interpreted as evidence of sedimentation from suspension in water. The laminae indicate variations in the concentration and grain size of the suspended material (sediment influx). Erratic pebbles and lenses of diamictite in the siltstone at Fossgil indicate that ice bergs drifted across the basin and melted there. No fossils are found in this lowest, laminated siltstone facies, and a glacio-lacustrine environment is inferred.

A more complicated relationship exists where mudrocks overlie or are adjacent to kame complexes. The mudrocks, which are mostly siltstones, are generally thickly laminated to thinly bedded (on a scale proposed by Ingram 1954). The bedding may either represent proximal varves or reflect intermittent input of turbid

Fig. 16. Folds and faults in mudrock adjacent to a kame (Hörgi Formation).

meltwater on a smaller time scale. Stray pebbles and sand grains are very common, and the general texture of the rocks is very similar to that of mudrocks overlying lodgement tillite.

The internal structure of the siltstone units is characterized by deformed bedding on three different scales. Slump structures are common on a small scale involving only convolutions of one or a few laminae. These structures are probably synsedimentary, as laminae beneath and above are not affected, and indicate that the sedimentary basin was not flat.

The second type of deformation manifests itself on a scale of several metres as intense folding and faulting (Fig. 16). This kind of deformation occurs at steep lateral contacts with kames. The contacts are locally very intricate, and slumping of gravels into muds is indicated. The structures in Fig. 14 are interpreted as a result of a deformation of an unstable lateral contact leading to wall rock crowding within the silt body. The deformation is thus apparently caused by the kames, a stratigraphically lower unit than the mudrock (low-relief kames are submerged by the very silts that are deformed by the high-relief ones). The distribution of the silts in pockets shows that the kames must have had a mound form when mud deposition began. It is considered likely that the original contact of the silts/gravels had a slope approaching the angle of repose for the kame material. A model explaining a postdepositional increase of the silt/gravel contact is presented in Fig. 17. Initial deposition of the gravel and sand takes place in a relatively steep sided channel, and the kame sediment is built up to a certain level, which is controlled by the drainage conditions in the decaying ice (Fig. 17a). After the deposition of the kame, lateral ice melts away, the topography becomes reversed, and ponds and lakes are formed on the ice between kames (Fig. 17b). Meltwater streams may carry mud into these depressions, which settles out of suspension. The depositional mud/gravel contact has an initial slope equal to the subaqueous angle of repose for the kame sediment. The accumulation of such a blanket of sediments composed of mud and gravel upon the ice retards surface melting, but slow subglacial melting continues. At this stage the gravel bodies (kames) may form wedges with ice below and mud above, especially if the drainage deteriorates or the water table of the area is

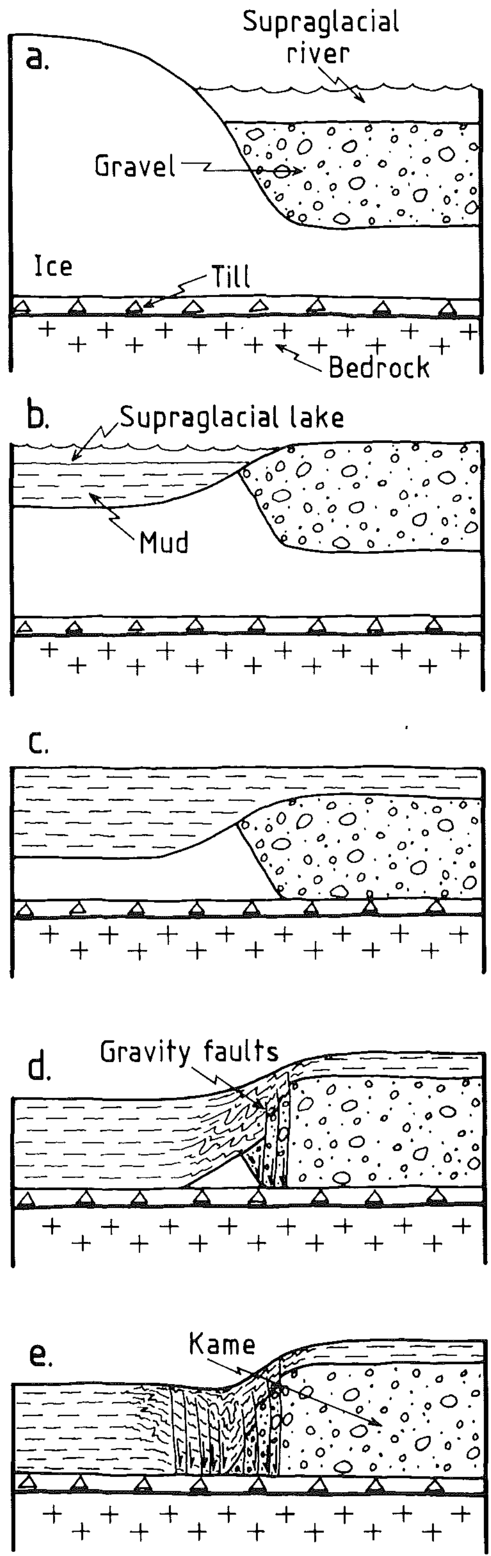

Fig. 17. A model of kame genesis involving a post-depositional increase of the dip of mud/gravel contacts. For explanation see discussion in text.

raised by external factors (Fig. 17c). If the ice beneath the sediments is thickest where the kame gravel wedges out, which would be natural in the model above, the continued subglacial melting leads to deformation of the sediments through a series of gravity faults, which are more likely to be conserved as planes in the more cohesive muds (Fig. 17d). The resulting fault escarpments involve loss of lateral support, and mass movement of soft sediments is predicted near the surface. One of the effects of such gravity faults is an increase in the steepness of the mud/gravel contact and possibly the formation of a graben adjacent to the kame (Fig. 17e). Successive slope failures near the surface may also cause further steepening of contacts if the kame sediments are affected by the failures. A third type of deformation observed in the mudrocks associated with kame complexes affects entire silt pockets. The large scale structure is that of a syncline with bedding planes dipping away from the kames. This down-warping of the siltstones, which is much too steep to represent a depositional slope (Fig. 18), is accompanied by normal faults with downthrows away from the silt pocket margins. Coarser sediments immediately above the siltstones are also affected by the deformation, although decreasingly so, as one goes higher up in the section. The deformation of the mudrocks on this large scale is considered to result from postdepositional compaction coupled with loss of pore water. Rapid deposition and a high original water content of the sediments is inferred. The kame gravels, having been deposited in running water and thereby acquiring a much denser depositional packing than the mudrocks, did not suffer a corresponding compaction, and slippage at the contacts has locally taken place.

An altogether different contact between the mudrocks and the kames is observed adjacent to the uppermost regions of the kame bodies, where reworking of gravels is indicated by conglomerate lenses stretching laterally outwards and thinning away from the parent kame bodies. This kind of interfingering relationship is concurrent with an upwards coarsening of the mudrocks. In the Hörgi Formation the siltstones change from bedded to massive structure where the gravel lenses begin to appear at the

Fig. 18. Steeply dipping bedding planes in intra-kame mudrocks. Height of exposure 25 m. Dark kame remnant to the left.

same level as marine fossils. It is inferred from the presence of siltstone beds between and above ice-contact conglomerates and tillites that ponds and lakes did form during and after glacier retreat on repeated occasions during the accumulation of the Breidavík Group rocks. Meltwater streams carried suspended glacially derived silt into standing water bodies.

Sedimentary processes in active proglacial lakes in Iceland were recently studied by Harris (1977, cf. also Boulton et al. (1983), Evensen et al. (1977), and a review of ice-marginal lake deposits in Embleton and King (1975)). Analyses of glacial lake sediments show that they consist largely of silt, but diamicton, gravel and sand lenses are fairly common. Bedding characteristics and internal structures may represent varves, or deposition may be dominated by frequent turbidity currents and slumps from the adjacent lake slopes into a central basin (Harris 1977). Floating and stranded ice-bergs melt to yield diamicton lenses within the lake sedimets. Near the ice margin jets of meltwater deposit delta fans which interfinger with the silts.

Such features were all present in the mud facies under consideration, and a glacio-lacustrine environment is inferred. An example of a diamictite lens within a silt facies is present in the Furugerdi Member. The siltstone facies is generally followed by an upwards coarsening sandstone and conglomerate facies. The sandstones are nearly flat bedded in the Hörgi Formation, and the conglomerate lenses can generally be traced to kame mounds. Observed dips of bedding planes in this facies constitute low angle synclines which probably result from compaction. Locally, channels have been cut into the Hörgi Formation sandstone facies and have subsequently been refilled with sandstone.

Lodgement tillite and kame conglomerates of the Torfhóll Member are cut off laterally by an erosional unconformity upon which a cross bedded conglomerate facies has been deposited. The unconformity defines a broad (ca. 1 km) channel, and the conglomerate above contains upwards fining sequences. The channel strikes approximately perpendicular to the direction of ice flow as indicated by grooves and flutes in the lodgement tillite at the base of the Torfhóll Member. The conglomerate is locally deformed into folds (Fig. 19), perhaps due to slumping. Beds below and above the folded conglomerate

Fig. 19. Folded conglomerate (Torfhóll Member).

Fig. 20. Outwash conglomerate west of Stangarhorn.

are undeformed. A similar conglomerate facies is present at the base of the Furugerdi Member, but the channel there is narrower (ca. 50 m). A thick conglomerate facies with sandstone lenses occupies an analogous position at the base of the Hörgi Formation at Stangarhorn (Fig. 20. The conglomerate rests directly on a striated lava flow, and the lodgement tillite observed at Hörgi is missing. In all three places the conglomerate facies is replaced vertically by a poorly sorted siltstone facies. These two sedimentary facies probably formed in a proglacial environment where outwash sediments and channels were subsequently submerged by standing water. The sporadic occurrence of tillite beneath the Hörgi conglomerate west of Stangarhorn indicates that the outwash was partly deposited upon stagnant ice. Irregular dips and folds are locally observed in these conglomerates.

Marine mudrocks and sandstones

Many of the fine grained sedimentary rocks of the Breidavík Group abound with marine fossils. Molluscs (bivalves and gastropods) are particularly common, but annelid casts and vertebrate bones have also been found. Marine fossils have been found in five of the six Breidavík Group Formations. A marine environment is inferred from the study of lithology, sedimentary structures, and fossil assemblages.

Starting with the finest grained rocks, it was already noted in the description of outwash and glacio–lacustrine sediments that marine fossils appear in the sections during silt deposition. Siltstones with marine fossils directly above glacio–lacustrine and outwash sediments are present within the Furugerdi Member, the Hörgi Formation, and the Fossgil, Svarthamar, and Torfhóll Members. This facies consists of poorly sorted siltstone with stray sand grains and sand lenses, pebbles, and boulders. Lamination is notably absent, but sand lenses are commonly contorted. Laterally, a gradational relationship is observed in the Svarthamar Member, where the siltstone facies passes into thinly bedded convoluted sandy siltstone facies. Fossils do not appear to be concentrated in lenses or horizons in the siltstones, and are generally unbroken. In Svarthamar two thin tuff layers are interbedded in the siltstone facies. The lower one contains marine fossils. The undulating attitude of these tuff layers indicates a development of considerable topography within the silts concurrently with their deposition. In the Fossgil Member, a thick sequence of basaltic tuff layers is also interbedded in a fossiliferous siltstone facies.

The second facies is sandy with abundant marine fossils. Individual beds appear to be sheet shaped. The sandstone facies ranges from fine to coarse grained, and is fairly well sorted. Some of the fossils occur in living position, but in other cases they have been transported and appear as lenticular shell horizons, mostly with unbroken shells. Trough cross bedding, although faint, is fairly common. The Hörgi Formation and the Svarthamar and Torfhóll Members contain this sandstone facies, which overlies a siltstone facies everywhere. The contact is distinct, but only locally in the Svarthamar is it marked by a conglomerate facies, which is lenticular in shape and consists of well sorted basaltic pebbles with abundant shell fragments and whole shells. Intraformational pebbles of sedimentary rock are rare, which is unusual for conglomerates within the Breidavík Group. Well rounded pebbles of gabbroic and gneissic composition have been found in this lens. The upper contact, where the conglomerate is replaced by the fossiliferous sandstone facies, is gradational.

In the Svarthamar Member, it has already been noted that the siltstone facies is closely related to a thinly bedded sandstone facies. The latter passes laterally into a large scale cross bedded conglomerate facies just east of Fossgil. Internal bedding planes within the conglomerate dip 330°/15°E. The sandstone facies clearly interfingers with this conglomerate, and eventually climbs towards southwest over the northeast dipping interfingering contact in the coastal section. Penecontemporaneous deformation structures characterize the sandstone facies, which grades into siltstone facies laterally as well as vertically away from the conglomerate. East of Breiduvíkurlaekur there are marine fossils in the sandy facies. The conglomerate is basally very coarse and there are very large boulders at the foot of many of the cross beds. Some of these are derived from a series of thick tuff layers immediately below the conglomerate. Sedimentary pebbles containing marine fossils have also been found.

Shoreline sedimentary environments have been studied extensively both in the modern environment and in ancient sedimentary sequences (Selley 1970, Pettijohn 1975). The nature of shoreline deposits is a reflection of the interplay between sediment influx and marine redistribution. Shoreline environments are (somewhat arbitrarily) divided into deltaic and linear ones, the former being typically regressional with a high rate of sediment influx, the latter may be either regressional or transgressional. Within the deltaic model, three elements occur: A delta platform characterized by subaerial and subaqueous channel sedimentation (gravel, sand, mud, peat), a delta slope, where most of the suspended mud settles out and may slump down to the foot of the delta slope, and a prodelta, where clays are deposited from suspension in quiet water. Sedimentary environments associated with clastic linear shorelines were listed by Selley (1970). From land to sea, in a static shoreline, four major environments can be recognized: Fluviatile, coastal plain, lagoonal and tidal flat complex, barrier island, and offshore marine shelf. Each one produces distinguishable facies. During regression with high sediment influx, all four facies build above one another seawards, and and upwards coarsening sequence, similar to a prograding delta sequence results. On the other hand, a transgression with high sediment influx will produce a fining upwards sequence. The actual sequence deposited is a function of both the sediment availability and of the rate of relative sea level changes.

It is a well established feature of the Late Cainozoic cold periods that drastic changes of sea level took place repeatedly. The regressions and transgressions involved have probably been much more rapid than those of more "quiet" times of geological history. Another feature of the cold periods is a high availability of sediments. Alternating periods of abrasion and rapid deposition are borne out by erosional unconformities and penecontemporaneous deformation structures in the Breidavík Group sediments. The fining upwards sequences observed in the lower regions of the Breidavík Group cycles are compatible with a transgressional shoreline environment.

Nonfossiliferous sandstones and conglomerates

The uppermost parts of the Furugerdi Member, the Hörgi Formation, and the Fossgil, Svarthamar, and Torfhóll Members of the Breidavík Group consist of upwards coarsening seqquences, where marine fossils disappear, either vertically or laterally.

The contacts between fossiliferous sandstone facies and medium to fine grained cross bedded sandstone facies are generally distinct but with no record of a major break. Such contacts were observed in the Furugerdi Member and the Hörgi Formation. In the Fossgil, Svarthamar, and Torfhóll Members, fossiliferous sandstone facies pass laterally (towards south) into coarse grained nonfossiliferous sandstones.

The barren sandstone facies is generally followed by a conglomerate facies, which is locally characterized by upwards fining sequences. In the Fossgil and Furugerdi Members, a siltstone facies is present, at least locally, beneath the conglomerate facies. The barren sandstone facies is up to at least 20 m thick in the Hörgi Formation. It contains carbonized twigs and pollen (Schwarzbach and Pflug 1957). In the sedimentary sequence in Búrfell, the predominant facies are cross bedded sandstones and conglomerates, in addition to diamictites. One of the sandstone beds has been found to contain plant remains and pollen (Th. Einarsson 1977). The vertical and lateral changes from shell bearing sandstones to nonfossiliferous or plant-bearing sandstones and conglomerates seem to reflect a regressional shoreline environment and a lateral change from marine to fluvial coastal plain environment.

Volcanic tuffs and lava flows of the Breidavík Group

Three horizons of basaltic tuff are present in the Breidavík Group sequence. The lowest of these is located above a nonfossiliferous conglomerate facies at a high level in the Hörgi Formation. It is exposed in two outcrops near Hörgi in the coastal section. The tuff bed is up to 3 m thick, but it has a lenticular form. Sand sized basaltic glass is the main constituent, but rounded rock fragments and pebbles indicate, along with the bedding, that the tuff has been reworked and mixed with fluviatile sediments.

A second tuff horizon forms a conspicuous part of the Fossgil Member (Geptner 1973). It is exposed in the coastal section at and near the Fossgil waterfall, and along Tröllagil and Fossgil gullies (Fig. 21). It can be traced southwards to Ytriklofi, and probably corresponds to a tuff layer exposed in Búrfell. The tuff is predominantly made up of silt to sand sized basaltic glass. Characteristically it consists of multiple tuff layers interbedded with a silty sand facies. Load casts and ball and pillow structures are very common. The multiple tuff layers reach a total thickness of some 25 m in Fossgil. The attitude of individual tuff layers is affected by the topography of the substratum. The tuff layers encroach upon underlying hills and then submerge them. At the level at which the topography has been levelled out, the tuff layers dip 2–3° towards NNE. There is no detectable break in deposition immediately prior to the deposition of the tuffs, and the boundary is gradational. Thin tuff layers occur in the underlying siltstone, and siltstone beds alternate with the tuff layers throughout. Horizon 4 is thicker further inland than in the coastal section, and contains marine fossils there. Near the coast the top of the tuff layers is marked by an erosional unconformity, and the observed thickness is probably a minimum value. Further

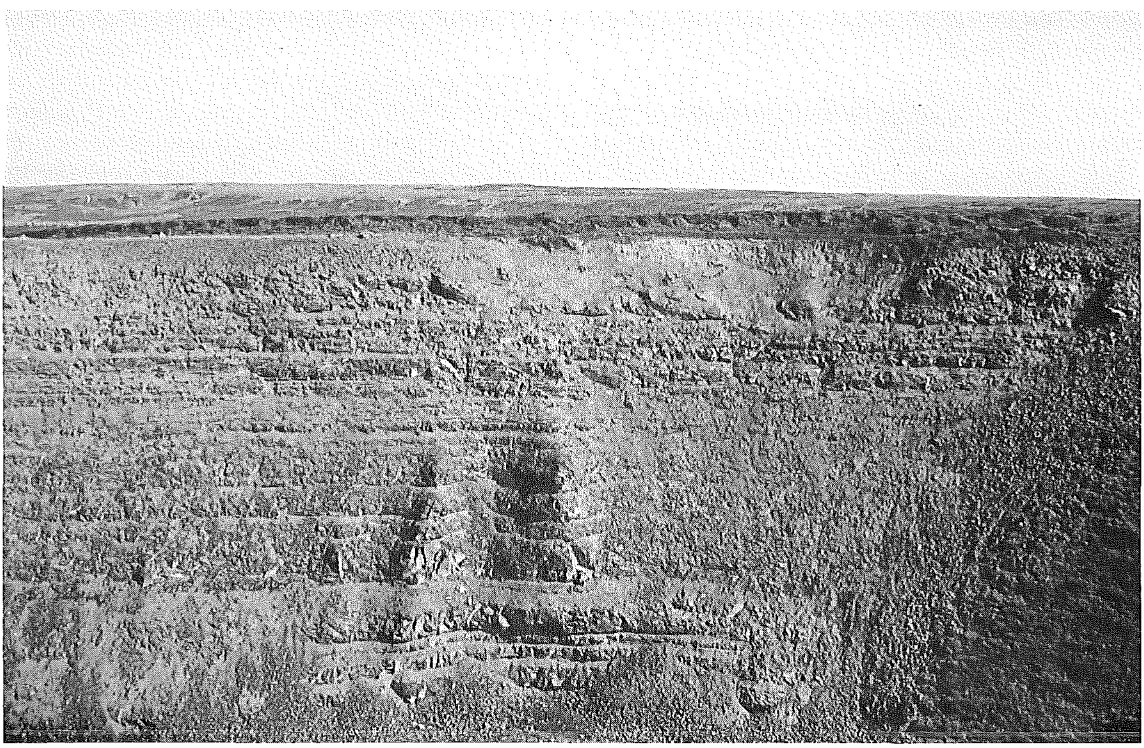

Fig. 21. 15 m thick series of tuffs in Tröllagil. Lenticular conglomerate (channel fill) at top of section.

south along Fossgil (at an altitude of ca. 250 m), the tuff/siltstone ratio decreases upwards in vertical sections. Locally, the tuff layers have been reworked and contain marine fossils (Tröllagil, altitude of 160– 170 m).

The third tuff horizon corresponds to Bárdarson's horizon 9 (Bárdarson 1925) and consists of one to five tuff layers separated by a siltstone facies. Locally, it reaches a thickness of 2 m. It is composed of silt sized basaltic glass, and locally contains abundant marine fossils. A few metres above it there is a thin, discontinuous tuff layer of similar composition.

The two latter tuff horizons (horizons 5 and 9) both occupy a position within marine mudrocks, which indicates that they were deposited in a subaqueous environment. Rapid, intermittent influx of the tuff material is indicated by load structures and the interbedded silts in both cases. The variations in sediment supply were probably controlled by pulsations in the ash producing volcano and/or fluctuating water currents, tidal or other. The origin of the tuffs has not been studied thoroughly. It may be tentatively suggested, that the ash was produced by explosive volcanism during shallow water submarine eruptions. The grain size of the tuffs is remarkably uniform. The semiconformable relation of horizon 5 to the substratum topography is thought to reflect a distribution of the ash by weak currents.

The Breidavík Group contains numerous lava flows. Most of these are clearly subaerial, being crystalline throughout. There are four exceptions. A reversely magnetized lava flow at the top of the Hörgi Formation appears to be locally affected by rapid cooling, e.g. at Tröllagil, where a pillow structure was observed. In the coastal section, however, this flow is quite regularly jointed. The two lava flows of the Fossgil Member are irregularly jointed and somewhat brecciated. They have flowed across fluviatile sediments at the site of the outcrop, which may indicate presence of water and rapid cooling. The lowest part of the Torfhóll Member lavas (Máná basalts), as exposed in the coastal section at Voladalstorfa and up to an altitude of 120 m, reveals pillowy and brecciated structure. It seems likely that this lava flow actually entered the sea as a lava delta to cover marine sediments. At an altitude of 120 m in the Threngingar area, the fossiliferous sandstone passes into nonfossiliferous sandstones, and this may reflect the location of the shoreline at that time. The lava flow becomes regularly jointed at the same level.

The final exception is the table mountain Búrfell. The volcanics at the top of the mountain were interpreted as a subglacial volcano by Th. Einarsson et al. (1967).

INTERPRETATION OF THE BREIDAVÍK GROUP

A local environment is defined by a set of physical, chemical, and biological processes (Selley 1970, Pettijohn 1975). The net effect of an environment may be either erosion, nondeposition, or deposition of sedimentary facies. In the Tjörnes area, constructive volcanic processes must be added to the sedimentary ones. Local environments are reflected by geologically significant geomorphic units. The analysis of these was mainly carried out in the field by means of detailed geological mapping in order to determine the macroscopic features of sedimentary and volcanic units (Eiríksson 1979). 120 sections were measured and analyzed. The combined stratigraphical column was then analyzed, and a distinct repetitive character in the vertical sense is obvious. &l

Palaeoenvironmental reconstructions for the Breidavík Group rocks are presented below in six sections with schematic illustrations of paleoenvironments within each stratigraphic member or formation. Any attempt to decipher past environments of the Tjörnes sequence must depend on a reliable genetic classification of the various rock facies types preserved in the Tjörnes sequence. Such a classification for the Breidavík Group rocks is attempted in Table 1. The table summarizes distinguishing criteria and matches facies types with depositing processes. This constitutes the basis of the genetic classification of the rocks. Sets of processes then add up to an aproximation of palaeoenvironments. In addition to rock facies, erosional and angular unconformities, and fossils, offer important evidence pertinent to the approximation.

Some of the features of Table 1 are clearly more relevant than others. Particularly important is the interpretation of some diamictites as lodgement tillites. That conclusion explicitly implies that the Peninsula was repeatedly covered by glacier ice in the past. Less critical but nevertheless important in determining the evolution of environments is the recognition of delta sediments, flow tillites, and kame conglomerates. The presence of marine fossils in sediments is important, particularly when they occur in living positions, when it comes to evaluating the wider significance of events recorded in the Tjörnes sequence. A manifest demonstration of sea level changes is recorded in the Breidavík Group rocks and ties in with evidence of glaciations to form a picture consistent with the ice age concept.

It was noted by Th. Einarsson et al. (1967), that the lava flows in the Tjörnes area generally originate from eruption sites outside Tjörnes Peninsula. Among exceptions are the table mountain Búrfell, and a lava flow from the Grjótháls shield volcano. The average frequency of lava flows in a typical section through the Icelandic lava pile has been estimated at 1 lava flow per 11,150 yr. (McDougall et al. 1977). Watkins and Walker (1977) concluded that the eastern part of Iceland was built up by virtually continuous volcanism from 13.5 to about 2 Ma, producing on average 1 lava flow every 16,000 yrs.

The distance between the Tjörnes sequence and the presently active volcanic zone in Eastern Iceland is only a few kilometres. In spite of differences in the tectonic history of the Tjörnes area and the area studied by McDougall et al. (1977), it is probable that a similar order of availability of volcanic products prevailed during the formation of the Breidavík Group. It follows that a surface left exposed for a few thousand years is likely to have been covered by lava flows. Sediments in the sequence are therefore unlikely to have suffered much subaerial erosion. The probability of a lava flow occurring in a given section is related to several palaeogeographical factors. Amongst these are palaeoslope and distance from active volcanic centres, both of which have allowed lava flows to reach the Tjörnes area during the period under investigation. In addition, land–sea relationships do affect the areal extent of lava flows. Contact of hot lava with water leads to rapid cooling and the flow is diverted, slowed down or confined. As a result the sea in most cases forms a natural barrier to flowing lava. An extensive glacier ice cover will similarly reduce the spread of volcanic products during eruptions and also alter the physical character of the solidified rocks. The probability of a lava flow

Table 1. Genetic classification of the Breidavik Group rocks

FACIES	DISTINGUISHING FEATURES	PROCESSES	GENETIC CLASSIFICATION	ENVIRONMENT
Diamictite. (1)	Large clasts embedded in a matrix of fine grained (silty) materials. Sheet shape. Striations and polshing of substratum. Flutes. Intimate relation of petrological composition to local bedrock composition. Silty shear bands.	Subgacial erosion. Till lodgement. Subglacial shear. Fluting.	Lodgement tillite.	Subglacial.
Diamictite. (2)	Large clasts embedded in a matrix of fine grained (silty) materials. Limited lateral extent. Folds and thrust faults.	Ice melting. Slumping.	Flow tillite.	Supraglacial.
Conglomerate. (3)	Poorly sorted gravel with boulders and sand lenses. Irregular mounds. Steep contacts intricately associated with (5). Bedding deformed into anticlines or irregulary. Interfingering tongues of (2).	Fluvial. Ice melting. Sagging. Slumping.	Kame conglomerate.	Supraglacial.
Conglomerate. (4)	Cross bedded gravel and sand with fining upwards sequences. Lenticular shape in cross section.	Fluvial channel erosion and depostion.	Outwash conglomerate.	Proglacial.
Siltstone. (5)	Thickly laminated poorly sorted silt with stray sand grains, pebbles and till lenses. Bedding conformable with substratum, locally intricate relationship with (3). Local sand lenses.	Suspension sedimentation. Slumping. Iceberg melting. Channel deposition.	Lacustrine mudrock.	Glaciolacustrine.
Conglomerate. (6)	Large scale cross bedded moderately sorted gravel with sand lenses. Wedge shape. Grades into (7) laterally and vertically. Basally abundant angular intraformational tuff fragments.	Fluvial channels. Floods?	Delta platform/foreset conglomerate.	Delta platform.

(continued)

Table 1 (*continued*)

FACIES	DISTINGUISHING FEATURES	PROCESSES	GENETIC CLASSIFICATION	ENVIRONMENT
Sandy siltstone. (7)	Laminated sandy siltstone, locally thinly bedded. Penecontemporaneous deformation structures. Interfingering contact with (6). Wedge shape. Marine fossils.	Suspension sedimentation. Slumping.	Delta slope mudrock.	Delta slope.
Siltstone. (8)	Massive, moderately sorted siltstone with erratics. Sheet shape, but slump scars affect topography during deposition. Marine fossils, often in living position.	Supension sedimentation. Iceberg melting. Slumping.	Prodelta/lagoon mudrock.	Prodelta (lagoon).
Sandstone. (9)	Cross bedded to massive, moderately to well sorted sandstone. Sheet shape. Marine fossils, locally in living position, also in shell banks.	Waves. Tidal currents.	Bar sandstone.	Offshore bar.
Conglomerate. (10)	Well sorted gravel with abundant shells. Lenticular shape. Grades upwards into fossiliferous sandstone (9).	Waves.	Beach conglomerate.	Shoreline beach.
Sandstone and conglomerate. (11)	Cross beddeld and flat bedded sandstone and conglomerate. Lag gravels and upwards fining sequences. Sheet or channel shape.	Fluvial.	Alluvial sandstone and conglomerate.	Alluvial plain.
Tuff. (12)	Silty-sandy basaltic glass composition. Sheet shape, conformable with substratum. Load structures.	Volcanic eruption. Suspension sedimentation. Tidal currents.	Glassy tuff.	Prodelta (lagoon).

occurring in a sequence located in the vicinity of active volcanism is thus high in dry, ice free areas where the volcanics enjoy free flow, but much lower in one that accumulated during subaqueous and/or subglacial conditions. In the latter two cases the physical character of the rocks will readily suggest contact with water and exclude ambiguity (e. g. pillow structure, brecciation, etc.).

It is suggested that lava flows within the Breidavík Group that do not show water contact structures are indicators of subaerial conditions. Furthermore, a general statement can be made about the sequence when it is considered, that most erosional activity tends to be subaerial. As subaerial conditions in the Tjörnes area or any area near or within a volcanic zone lead to accumulation of lava flows, subaerial erosion is not expected to have removed large parts of the marine sequence exposed at Tjörnes to leave significant gaps in the record.

The extrusion of lava flows to cover the sedimentary record during ice free periods has in many cases probably contributed towards conserving the sediments by providing an armour against subsequent erosion. This feature of the Tjörnes sequence was already emphasized by Pjetursson (Pjetursson 1905). It is a feature shared with many other Icelandic sections of Late Tertiary and Quaternary age, which are thereby set apart from glacial sequences in continental areas, where renewed erosion tended to destroy geological evidence about the immediate past.

Palaeoenvironmental reconstruction of glacial–interglacial cycles

The Furuvík Formation

The lowest part of the Breidavík Group is exposed in the Furuvík Creek, where the Furuvík Formation begins with an at least 45 m thick sequence of sedimentary rocks, followed by a 3 m thick lava flow, and a 2 m thick sedimentary bed. A series of lava flows then completes the Formation.

Previous research of the Furuvík sections (Bárdarson 1925, Áskelsson 1941, Líndal 1964, T. Einarsson 1958, Strauch 1963, Th. Einarsson et al. 1967) generally suffers from insufficiently detailed mapping and has given rise to controversy over the history of the Formation. Marine origin was suspected by Bárdarson, littoral deposition followed by a questionable till by Strauch, but Th. Einarsson et al. described the beds in Furuvik as a sequence of iceberg tillite, conglomerate, sandstone of probable marine origin, a lava flow, and another tillite layer.

Facies types and other important features of the Furuvík Formation as mapped in the present study are summarized in Table 2 below, number 1 being at the base of the Formation.

A reconstruction of palaeoenvironments based on an interpretation of the vertical sequence of Table 2 is presented in Fig. 22. It is emphasized that the drawings only show some steps in the evolution of environments during the accumulation of the sequence. They are schematic, and have not been drawn to scale. An outline of the geological history of the Furuvík Formation is presented below along with notes on the palaeoenvironmental reconstructions:

Table 2. Main facies types of the Furuvík Formation

12. Lava flows.
11. Diamictite facies.
10. Lava flow.
9. Laminated siltstone facies.
8. Coarse grained trough cross bedded sandstone facies.
7. Well sorted conglomerate facies, grades into 8.
6. Massive siltstone facies with marine fossils.
5. Coarse grained wedge shaped sandstones, occur within 4.
4. Poorly sorted laminated to massive siltstone facies with stray pebbles, deformation structures, and lenses of diamictite facies.
3. Moderately sorted cross bedded lenticular conglomerate facies and coarse grained flat bedded lenticular sandstone facies.
2. Diamictite facies.
1. Erosional unconformity.

1. *Glacial – proglacial.* A glacier advances over the Höskuldsvík zone lava plain. Glacial erosion leaves an erosional unconformity cut across the Höskuldsvík lavas. The glacier deposits lodgement till upon the unconformity (facies 2). During retreat, the glacier locally and repeatedly pushes the lodgement till surface into ridges (push moraines). Proglacial meltwater streams cut channels into and locally rework the lodgement till, depositing outwash gravels and sands (facies 3), which are widely found resting on the till.

2. *Glacio-lacustrine.* A proglacial lake now develops at the margin of the retreating glacier. Turbid meltwater jets carry mud into the lake, where it is distributed by mixing with the lake water and/or density currents (facies 4). Sandy delta fans (facies 5) are built out into the lake mud at rapidly shifting jet mouths. Locally, supraglacially derived till slumps into the lake at the glacier snout to form waterlaid flow till lenses interfingering with the lake mud. Stones and till melt out of ice bergs which calve off the glacier snout (ice cliff), these sediments are

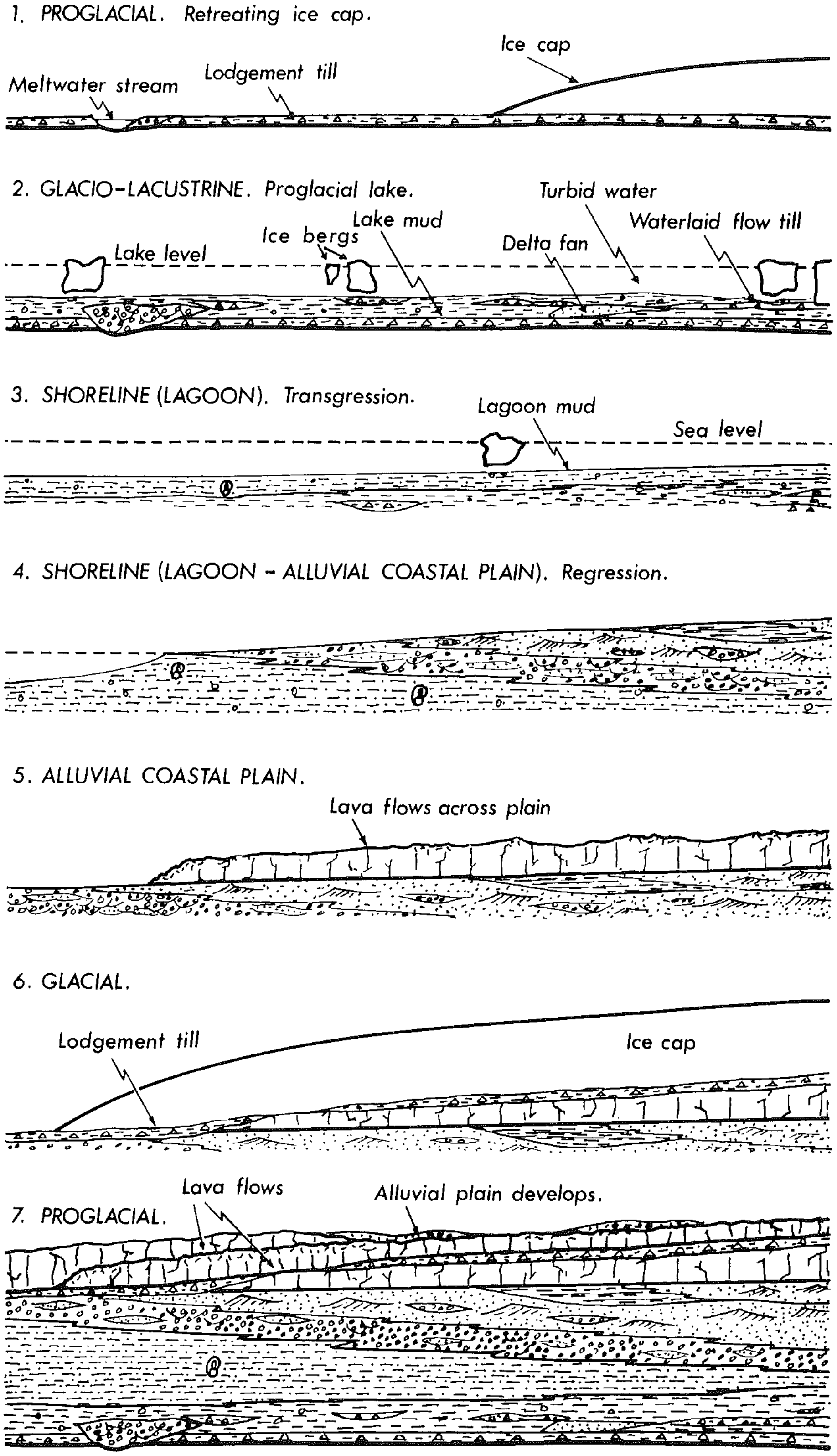

Fig. 22. Palaeoenvironmental reconstruction of the Furuvík Formation. See discussion in text.

found dispersed in the lake mud as dropstones and diamicton. The glacio-lacustrine environment evolves into a shoreline environment as the area becomes submerged beneath sea level by a eustatic transgression. The only remnants of life discovered in the sedimentary facies deposited in the lower part of the sequence are carbonized twigs of wood found in the delta fans. These are probably derived from older sediments (Tjörnes beds) and occur as pebbles.

As an alternative, one could possibly argue that the mud, sand, and diamicton lenses were deposited in the sea, and that sedimentation rates were high enough to render the environment lethal for organisms. However, there is no evidence of a redistribution of the sediments by the sea, and a sheltered fjord model would be required. There is nothing to suggest landscaping of that order at this time, and a glacio-lacustrine environment interpretation is favoured.

3. *Shoreline (lagoon)*. The sediments interpreted so far are all exposed in the western part of the Furuvík Creek. To the east of normal step faults at Midnef a massive siltstone facies replaces the lacustrine mudrocks to the west of the faults. The massive siltstone is younger than the lake mudrocks. Although there is no overlap at the faults, radiometric dating of lava flows below and above excludes ambiguity (Albertsson 1976). Nevertheless, some sedimentary or other facies may be missing due to these faults. In 1975 I found a cast of a closed bivalve in the massive siltstone facies. It was identified by L. A. Símonarson as cf. *Mya truncata*. Although only one individual was found (by chance), the fact that it was unbroken and found in a massive, fine grained sedimentery facies, is thought to indicate (but not prove) a marine environment. Deposition in quiet water is indicated by fine grain and massive structure. A lagoon environment, perhaps brackish (hence the apparent paucity of fossils) is inferred.

4. *Shoreline (lagoon – alluvial coastal plain)*. The next sedimentary facies is an upwards coarsening conglomerate, starting with sandstone (facies 7). In the eastern part of Furuvík where the sedimentary sequence disappears below sea level, the conglomerate grades into a trough cross bedded sandstone facies (8). At Stangarhorn, where the top of this sequence crops out again, a nonfossiliferous laminated siltstone facies, interpreted as lacustrine sediments, is seen below a conglomerate with sandstone lenses at the top of the sedimentary sequence. These sedimentary facies are taken to indicate first an intensification of currents, and the sedimentary structures and the presence of lacustrine sediments to indicate a regression, possibly due to an emergence of the area above sea level.

5. *Alluvial coastal / lava plain*. The upwards coarsening trend of the upper part of the sequence discussed above is thus thought to reflect a regressional environment, and the development of an alluvial coastal plain studded with lakes. The sediments are now covered by a lava flow which is seen in both the Furuvík and Stangarhorn sections. The lava flow is columnar jointed. Both in Furuvík and at Stangarhorn numerous vertical or nearly vertical up to 20 cm thick sedimentary dykes run up through the topmost conglomerate and along joints through the lava flow. Some of the dykes, which are composed of silt, sand, and granules, are seen to originate in the sediments below. T. Einarsson (1958) mentioned a sandstone dyke at Stangarhorn and Strauch (1966) has described sedimentary dykes in the Breidavík area. The presence of the dykes indicates that the lava flowed across soft sediments, which were thereby deformed and squeezed upwards by the suddenly increased load. The lava flow is the topmost stratum of the Furugerdi Member. It completes the first cycle of the Breidavík Group. The cycle started with a glaciation of the area followed by deglaciation, marine transgression, regression, and finally, development of an alluvial/lava plain during ice free conditions.

6. *Glacial*. The lowest bed of the Midnef Member is a diamictite above the Furugerdi lava. This diamictite (facies 11) is 2 m thick, has a low clast/matrix ratio, and contains striated pebbles. It was interpreted as a tillite bed by Th. Einarsson et al. (1967). The stratum has a rather limited lateral extent as far as can be judged from the coastal outcrops, being only exposed in the eastern half of the Furuvík Creek. The top of its substratum has clearly been smoothed and eroded (facies 1), but no glacial striae have been found. The origin of the diamictite is somewhat doubtful. It may represent a lodgement tillite. In that case, it would indicate a second glaciation of the area. Such an

interpretation will be assumed in the present study.

7. *Proglacial – lava plain.* The diamictite facies (11) is directly overlain by a series of thin lava flows in Furuvik, and there is no record of a transgression after the deposition of the diamictite. If the interpretation of the diamictite as a lodgement tillite is correct (this is assumed in Fig. 22), it is possible that the lava flows entered the proglacial area immediately after the glacier retreated (corresponding to the glacio-lacustrine environment in the Furugerdi Member). The lava flows probably represent a very short time span, being of the shield volcano type (they are probably all derived from one eruption). This timing is, however, rather speculative. Such an influx of lava flows into the proglacial area, one could hypothesize, would have created a topographic high, which might explain the lack of a sedimentary record. Further east along the coastal section towards Breidavík the thin lava flows wedge out and are covered by thicker flows with thin sandy and gravelly interbeds, indicating an alluvial environment associated with the lava plain. According to T. Einarsson (1958) and Th. Einarsson et al. (1967), all the lavas are normally magnetized.

Directional evidence within the Furuvík Formation is scant. A northeast trending exposure in Furuvík reveals a series of sections through ridges at the surface of lodgement tillite. These ridges were interpreted as push moraines, which normally strike perpendicular to ice flow. The nearly vertical sections make it impossible to determine the real strike of these ridges accurately, but it probably lies within a sector between 0–90°, indicating an ice flow direction either towards NW or towards SE. Cross beds in the lowest part of facies 7 near Midnef generally dip towards NNE, wheras cross beds in the sandstone at the top of the Furugerdi Member generally dip towards NE. Bedding planes in the sandstone dip 60°/11°W. The regional dip here is 45°/8°W. Strauch's (1963) analysis of the Tjörnes beds revealed a palaeoslope and sediment transport towards north to northwest throughout. The slender palaeodirectional data from the Furuvík Formation indicate that the palaeoslope remained similar to that of the Tjörnes beds, which are conformably overlain by the Höskuldsvík lava zone and the Furuvík Formation.

The Hörgi Formation

The surface of the top unit of the Midnef Member is erosional. In the coastal section east of Stangarhorn a shallow valley, of which only the western side is now exposed, has been eroded into the Midnef lava plain. The basal sediments of the Hörgi Formation rest on this unconformity.

Numerous authors have described the Hörgi Formation (Pjetursson 1905, Bárdarson 1925, Áskelsson 1941, Líndal 1964, T. Einarsson 1958, 1963, Schwarzbach & Pflug 1957, Strauch 1963, Th. Einarsson et al. 1967, Geptner 1973). Pjetursson gave the first description of the Breidavík sequence and presented two sections. Both contain a basal conglomerate unit which he interpreted as a fluvioglacial and glacial deposit which should be correlated across the bay. Pjetursson mentioned a tillite bed above the conglomerate. The next contribution came from Bárdarson, who published a profile of the coastal section in Breidavík. He assigned the number 1 to the topmost lava flow of the Midnef Member at Stangarhorn, and number 15 to the lava flow in Voladalstorfa. Later, Strauch introduced the notation H1–H15 for the same strata. Bárdarson argued against Pjetursson's conclusions about a glacial origin of the sediments in Breidavík, and subsequent workers have put forward several possible origins of the rocks.

Table 3. Main facies types of the Hörgi Formation

11. Lava flow.
10. Volcanic tuff.
9. Laminated siltstone facies.
8. Flat bedded sandstone facies with conglomerate lenses.
7. Sandstone facies with conglomerate lenses and marine fossils.
6. Massive siltstone facies with conglomerate lenses and marine fossils.
5. Poorly sorted laminated siltstone facies with deformation structures.
4. Mound to ridge shaped conglomerate facies.
3. Sheet shaped conglomerate facies.
2. Diamictite facies.
1. Erosional unconformity.

In the present work, particular attention has been paid to the relationship between the basal diamictite at Hörgi (it is also sporadically exposed in the Bay of Breidavík), the irregularly surfaced conglomerates, and to the mudrocks and sandstones.

This problem has already been discussed in connection with the origin of the various types of sedimentary facies. The diamictite facies is interpreted as a lodgement tillite. It rests on a glacially striated lava flow which belongs to the Furuvík Formation. The conglomerate bodies represent kames, and are juxtaposed by lacustrine mudrocks, which are followed by marine fossiliferous mudrocks and sandstones. The main sedimentary facies types and other features of the Hörgi Formation are listed in Table 3.

Fig. 23 shows reconstructions of steps in the evolution of environments during the accumulation of the rocks of the Hörgi Formation. The reconstructions are mainly built on the interpretation of the sedimentary facies exposed in the coastal section. Fig. 23 shows a cross section through the western side of a valley carved into the Midnef lava plain. Exposures are also found in the Fossgil and Tröllagil gullies and in Búrfell, which is useful in determining the shape and extent of the Formation. An outline of the geological history of the Hörgi Formation is presented below. Steps in the palaeoenvironmental evolution refer to Fig. 23.

1. *Glacial.* A glacier advances across the Midnef lava plain, initiating valley erosion and leaving glacial striae and lodgement till (facies 2) on the erosional unconformity at the base of the Hörgi Formation. As the glacier retreats, masses of ice stagnate and supraglacial outwash sediments (facies 4) accumulate in meltwater channels and pools. Lobes of flow till slump down the snout of the glacier and to and fro on the dead ice topography. Mud (facies 5) is locally and intermittently deposited adjacent to or along with the outwash sediments in pools of standing water. Melting of ice beneath the supraglacial sediments and removal of lateral support leads to sagging, faulting, and deformation of the sedimentary bodies.

2. *Glacio-lacustrine.* The glacier recedes further back and the buried ice gradually melts away. Kettle holes and depressions in the kame topography form traps for mud carried by meltwater streams (facies 5). The deformation of kames continues, and intricate and frequently collapsed contacts develop between the kame gravels and the lake mud. On the western side of the valley, meltwater streams locally sweep the lodgement till away, and an outwash plain (facies 3) with lakes (facies 9) develops.

3. *Shoreline (lagoon – alluvial coastal plain).* A transgression now submerges the area in the wake of the retreating glacier. The reworking of kames is intensified. Deposition of silt (facies 6) continues, however, and the conditions appear to be relatively quiet. A saline lagoon environment is inferred from the sedimentary facies and marine fossils.

4. *Shoreline (bar – alluvial coastal/lava plain).* The lagoon mud is covered by a sandstone (facies 7) with conglomerate lenses and marine fossils. Reworking of the upper regions of kames is intensified and the contact with the marine mud beneath is erosional. The coarse grain, cross beds and fossils of the sandstone are compatible with a bar environment, initially transgressing over the lagoon mud, but later receding again. The bar sediments form a wedge shaped body. The lagoon mud, however, is not found again above the bar sands, perhaps because the regression was rapid and the alluvial plain prograded directly over the bar sands. Landwards of the shoreline the alluvial coastal plain is characterized by fluvial gravels and lacustrine sediments. A tuff horizon (facies 10) is conserved in the lacustrine sediments but is not found elsewhere. It may have been swept away by fluvial erosion and redistributed by the sea. A regressional sequence is reflected in the coastal outcrops in Breidavík by the disappearance of marine fossils and deposition of flatbedded sandstones with channels and lag gravels (facies 8). A lava now flows across the plain. It is at present found exposed at Hörgi, in the Fossgil and Tröllagil gullies, and in Búrfell.

Glacial grooves on the Stangarhorn lava strike N40°E, and this coincides with the approximate trend of the valley at the base of the Hörgi Formation, as far as its direction can be deduced from exposures in the coastal cliffs. The strike of the flow lines of the glacier was therefore northeasterly, at least in the vicinity of the valley, and the palaeoslope probably remained similar to the one inferred in Furuvík. Southwest dipping cross beds were observed in the bar sands. The erosional unconformity at

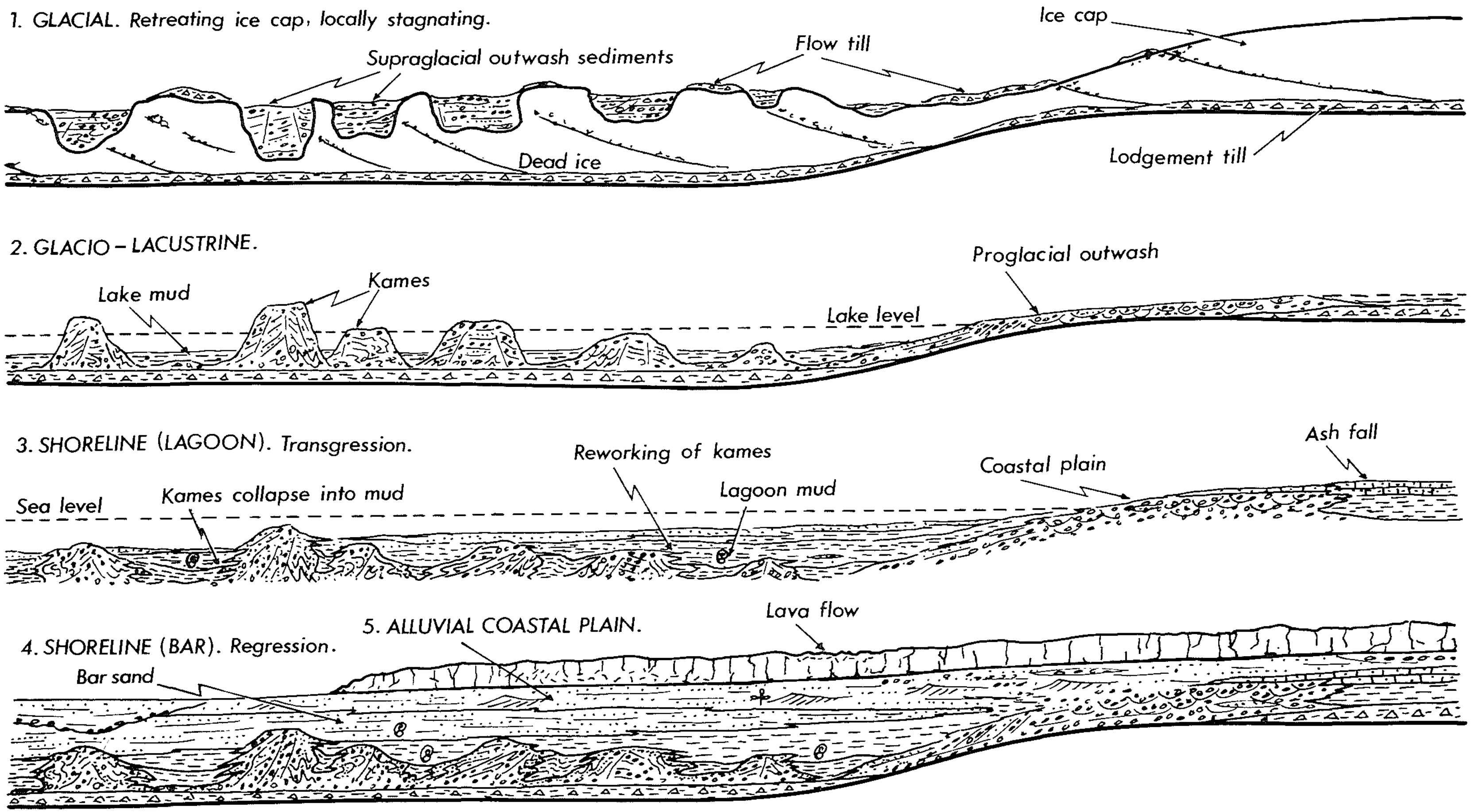

Fig. 23. Palaeoenvironmental reconstruction of the Hörgi Formation. See discussion in text.

the base of the Hörgi Formation is also an angular one. A gap may exist in the sequence at that level.

To summarize, the interpretation of the Hörgi sequence indicates a new cycle of glaciation, deglaciation and transgression. A prograding alluvial plain environment with lava flows during interglacial conditions then completes the cycle.

The Fossgil Member

The lower unit of the Threngingar Formation, the Fossgil Member, is exposed in the coastal area near the Fossgil waterfall, in the Tröllagil and Fossgil gullies, and has been mapped all the way to Búrfell Mountain. The tuff layers of the Member represent an excellent marker key horizon.

Several workers have studied the rocks of the Fossgil Member (Bárdarson 1925, Líndal 1964, T. Einarsson 1958, Strauch 1963, Th. Einarsson et al. 1967, and Geptner 1973), and their ideas about the origin of the sediments are contradictory. For ease of reference to earlier literature, the numbers assigned to the Breidavík horizons are adhered to (Bárdarson 1925).

The present mapping of the Fossgil Member in Breidavík and inland on Tjörnes Peninsula added considerably to the knowledge of the extent and nature of these beds. Marine fossils have been found at two new localities in the H4 horizon. The position of the normally magnetized Fossgil lava flows cannot be fixed with absolute certainty, but their isolated occurrence within a graben flanked by Fossgil Member strata seems to justify their assignment to the top of the Member. In the present interpretation, H3 represents a lodgement tillite displaying banded structure, boulder clusters, striated and faceted boulders, sheet shape, and an irregular surface. H4 begins as a lacustrine sediment with erratic boulders, but grades upwards into a massive poorly sorted marine siltstone with fossils. It is interrrupted by the multiple tuff layers of H5, which have locally been reworked. Marine sedimentation continued as the fossiliferous sandstones at the Tröllagil bifurcation were deposited. The section including the normally magnetized Fossgil lava flows indicates terrestrial conditions. The main sedimentary facies types of the Fossgil Member are presented in Table 4 below, number 1 (an erosional unconformity) being at the base.

Table 4. Main facies types of the Fossgil Member

10. Lava flows.
9. Well sorted conglomerate facies with sandstone lanses.
8. Thinly bedded siltstone facies with sandstone lenses.
7. Nonfossiliferous flat bedded sandstone facies.
6. Coarse sandstone facies with marine fossils.
5. Thickly bedded tuffs with siltstone interbeds and load structures.
4. Thinly bedded to massive mudrock facies with marine fossils. Grades upwards into 5 by an increase in the number and thickness of tuff beds.
3. Laminated siltstone facies with stray boulders and till lenses.
2. Diamictite facies.
1. Erosional unconformity.

The coastal section in the Bay of Breidavík shows that the erosional unconformity (1) forms a fairly steep slope dipping towards east. An eastward migration of the valley initiated and partly refilled during the accumulation of the Hörgi Formation seems to have taken place. The unconformity cuts off the Hörgi Formation laterally. A reconstruction of the evolution of the palaeoenvironments of the Fossgil Member is attempted in Fig. 24. The cross sections are not drawn to scale.

1. *Glacial – glacio lacustrine.* A renewed glaciation of the Tjörnes area, coupled with a lowering of sea level, continues the valley erosion begun during the Hörgi glaciation. A new erosional unconformity (1) is created and subsequently covered by lodgement till (facies 2). The till is discontinuous and thin on the slope exposed in the coastal section. Upon retreat of the glacier, an extensive proglacial lake is formed, where laminated to thinly bedded mud with erratics (facies 3) is conformably deposited on the uneven substratum.

2. *Shoreline (lagoon).* The glacier retreats further and sea level rises gradually. The lake becomes saline and marine molluscs colonize the mud which continues to accumulate (facies 4). A lagoon environment is inferred from the

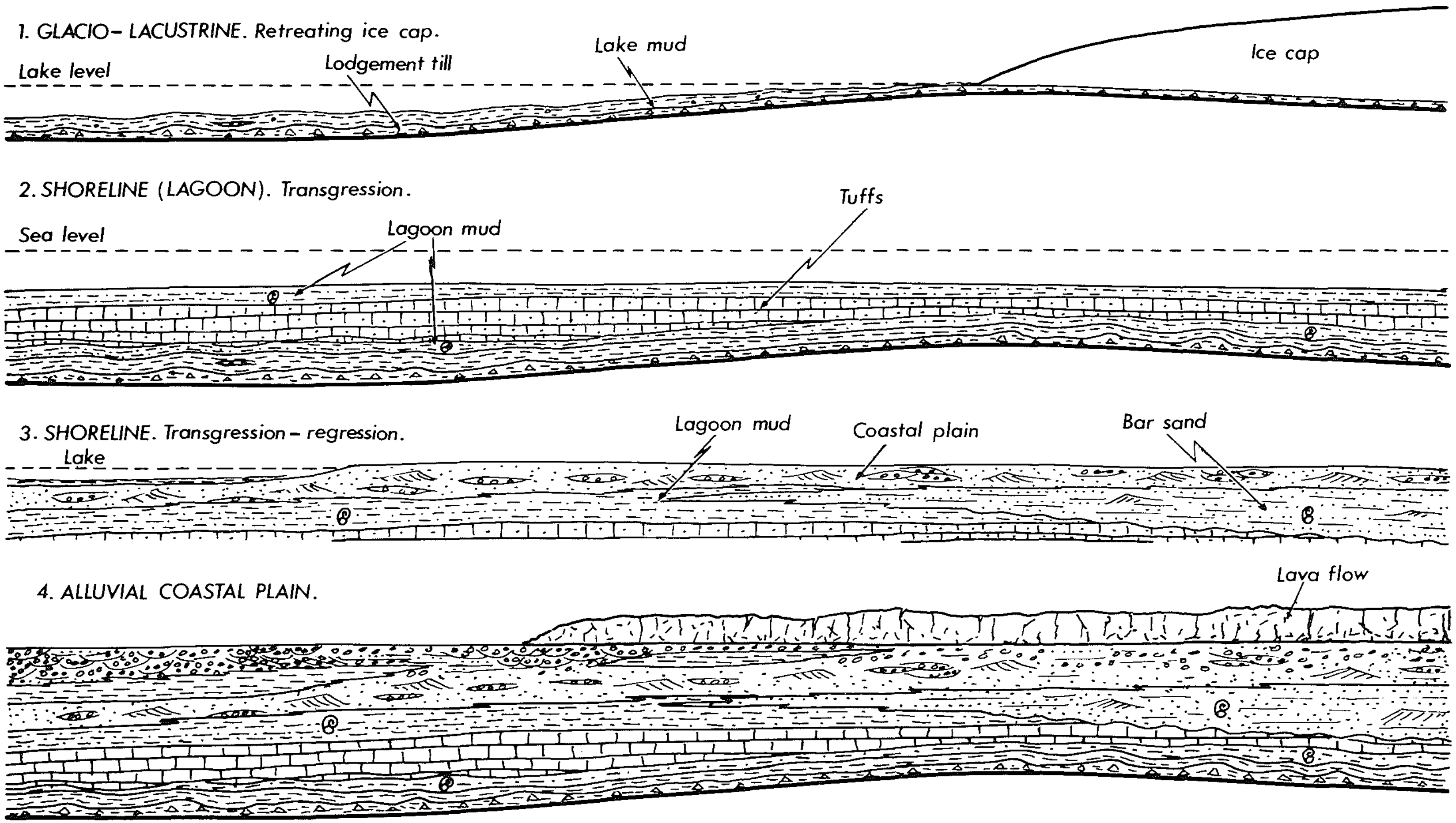

Fig. 24. Palaeoenvironmental reconstruction of the Fossgil Member. See discussion in text.

character of these sediments. Volcanic eruptions (submarine?) now take place in the vicinity of the area, and the undulating surface topography of the till surface, having persisted throughout the mud deposition, is gradually levelled by tuff beds (facies 5). The lowest tuff beds are thin (5–10 cm), but gradually the silt interbeds become thinner and individual tuff beds reach a thickness of 5 m. The sandy tuffs were clearly deposited rapidly upon the fresh, porous muddy sediments, as the contacts display load casts, flame structures and ball and pillow structures. Gradually, the silty interbeds increase in thickness again at the expense of the tuff layers. Lagoon mud continues to accumulate.

3. *Shoreline (bar – alluvial coastal plain).* The lagoon mud is followed by a sand facies (facies 6). The contact is gradational, but locally there is evidence of reworking, which has penetrated into the tuff beds. An increase in current velocity or a change of water depth is inferred. A transgressing bar environment is reflected by coarse sand with marine fossils, which encroaches upon the lagoon mud as sea level continues to rise.

4. *Alluvial coastal/lava plain.* The sea level rise eventually comes to a halt and the situation becomes reversed. An alluvial coastal plain environment progrades over the bar sands (facies 7, 8, and 9). Lake sediments, flat bedded sands and channel sequences involving gravels and sands characterize the environment at the top of the Fossgil Member. Two lava flows now reach the area and cover the sediments at Fossgil.

The long axes of pebbles in H3 were measured at two localities (in Fossgil and Tröllagil). A strong unimodal distribution is centred around N15°E on a rose diagram over the Fossgil data (53 measurements). A smaller sample (20 measurements) from Tröllagil has a unimodal distribution centred around 0° on a rose diagram. A 2 m long boulder in the H3 lodgement tillite at Fossgil is oriented with the long axis parallel to N20°E. Striae on top of that boulder strike N40°E. These data are considered to show the approximate direction of ice flow, which is in agreement with the apparent trend of the valley. Similar palaeogeographical conditions to those of the Hörgi Formation are inferred. After the Hörgi interglacial sea level drops, a new glacier advances across the area, and a new cycle begins. Soon after the retreat phase of the cycle a transgression takes place and volcanic activity produces abundant ash carried into the area. During the following interglacial the shoreline environment progrades and lava flows are poured over the alluvial coastal plain.

The Svarthamar Member

The stratigraphical relationships and origin of the sedimentary rocks of the Svarthamar Member have been a matter of debate in the literature (Pjetursson 1905, Bárdarson 1925, Áskelsson 1941, Strauch 1963, T. Einarsson 1958, 1963, Geptner 1973). Because of the various conflicting views on the origin of the rocks of the Svarthamar Member, and because of the conflicting opinions of stratigraphical relationships within the Breidavík sequence, all exposures were remapped in 1975 and 1976. Particular attention was paid to the extent of Bárdarson's (1925) H8 horizon, its physical character, and the relation to H6 and H7. The irregular and discontinuous position of H9 was also studied closely, and evidence of slumping emerged. Glacial striae on the substratum of H6 and the texture of the lowest bed of that horizon confirm Geptner's (1973) conclusion about the origin of what he called H6a, it represents a lodgement tillite. It is followed by an upwards fining sequence interpreted as a delta, H6 and H7 corre sponding to the delta platform and H8 to the delta slope. H10 corresponds to the distal slope or prodelta mud. The facies types of the Svarthamar Member are listed in Table 5 with other important aspects of the sequence, number 1 being at the base of the Member.

The reconstruction of palaeoenvironments presented in Fig. 25 is based on the facies types and on field relationships. It is schematic and has not been drawn to scale.

1. *Glacial – proglacial.* An erosional surface with glacial striae (facies 1), lodgement till (facies 2), and kames (facies 3) are products of a glacier which advanced over the Tjörnes area and receded again, leaving stagnant ice on a valley floor. Supraglacial outwash sediments are preserved as kames at Svarthamar and to the east of Svarthamar.

2. *Shoreline (delta).* The proglacial environment is now submerged by a eustatic rise of sea level. Sedimentation rates are high due to an

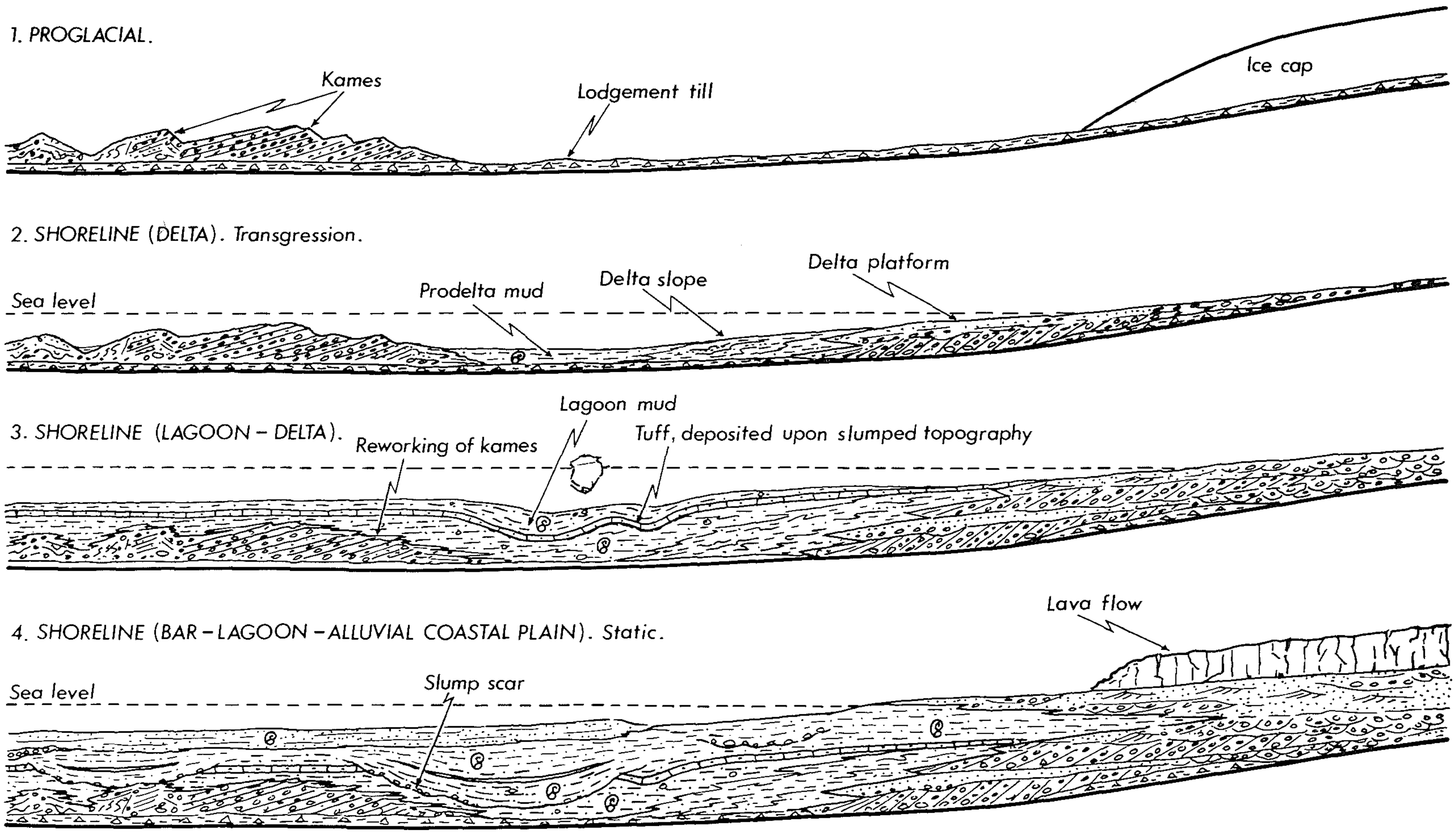

Fig. 25. Palaeoenvironmental reconstruction of the Svarthamar Member. See discussion in text.

Table 5. Main facies types of the Svarthamar Member

13. Lava flow.
12. Nonfossiliferous sandstone facies with conglomerate lenses.
11. Coarse sandstone facies with marine fossils.
10. Conglomerate facies with marine fossils.
9. Local erosional unconformity.
8. Volcanic tuff with marine fossils.
7. Local erosional unconformity.
6. Mudrock facies with marine fossilis and erratics.
5. Thinly bedded to laminated silty sandstone facies with deformation structures and marine fossils.
4. Cross bedded conglomerate facies.
3. Conglomerate facies.
2. Diamictite facies.
1. Erosional unconformity.

intensive runoff from the waning glacier. A delta sequence is built out from the shoreline (facies 4, 5, and 6), but as the rise of the sea level is relatively rapid, the typically regressional delta model is reversed here, leading to an upwards fining sequence. Marine fauna colonizes distal parts of the delta slope and the prodelta. The delta platform sediments are locally very coarse and contain abundant intraformational sedimentary pebbles and boulders. Some of these are fossiliferous, and are probably derived from the Tjörnes sedimentary zone (Bárdarson 1925). The extremely coarse grain and steep large scale cross beds, which occur locally in the platform sediments, and the presence of intraformational angular boulders may indicate that sheet floods took place during the development. This may reflect increased valley erosion in the interior, leading to the formation of ice dammed lakes as the ice cap thinned, and to occasional bursts.

3. *Shoreline (lagoon – delta)*. The delta environment continues to regrade as sea level rises further. In distal parts marine mud continues to accumulate rapidly in relatively quiet water, indi cating perhaps a lagoon environment at this time (it is later transgressed by fossiliferous sands interpreted as bar sands). The upper regions of kames are reworked considerably at this stage, and the kame topography is levelled out by mud deposition. The lagoon mud is, however, unstable, and large depressions (scars) form locally, either through slumps or erosion by turbidity currents initiated in the delta slope. Lag gravels are observed at some of these "channels". A tuff layer (facies 8) is now deposited on this locally erosional surface of the lagoon mud during submarine conditions. The tuff layer is colonized by marine fauna. Mud deposition continues unaffected by the ash fall. Large scale slumping also continues to occur, and the tuff layer (H9) is locally swept away. The scars created by the slumps (or turbidity currents) were yet again filled with marine mud and occasional thin tuff layers.

4. *Shoreline (bar – lagoon – alluvial coastal/ lava plain)*. A sheet of coarse fossiliferous sand is now deposited above the lagoon mud. A lens of gravel (facies 10), which is seen at the base of the sand sheet (facies 11), contains abundant marine shell fragments and complete shells. The gravel is composed of basaltic pebbles with a trace of rhyolitic, plutonic, and meta morphic pebbles. The gravel was deposited on an erosional surface of a soft substratum (9), the contact is locally intricate and bands of mud stretch upwards into the gravel. These facies are interpreted as a transgressing bar environment. The gravel may be partly derived from a protruding kame, and it represents the basal part of the bar environment. Vertically, the gravel grades into fossiliferous sands. Landwards of the shoreline, an alluvial plain develops. Fluvial channels are cut into the substratum (into H5 along the Tröllagil gully), elsewhere nonfossiliferous sands (facies 12) accumulate, e.g. in the Búrfell area. A lava flow enters the area and covers the alluvial plain.

Glacial striae were found beneath lodgement tillite (on the surface of H5) at the Fossgil waterfall. The striae are parallel and strike N18°E, which is similar to the direction obtained for the Fossgil glacier. The Svarthamar Member as interpreted here contains evidence of advance and retreat of a glacier followed by a transgression and a development of interglacial shoreline en vironments. Lava flows then enter the area. A valley continues to migrate eastwards during glacial erosion, but is subsequently filled with sediments during late-glacial and interglacial time.

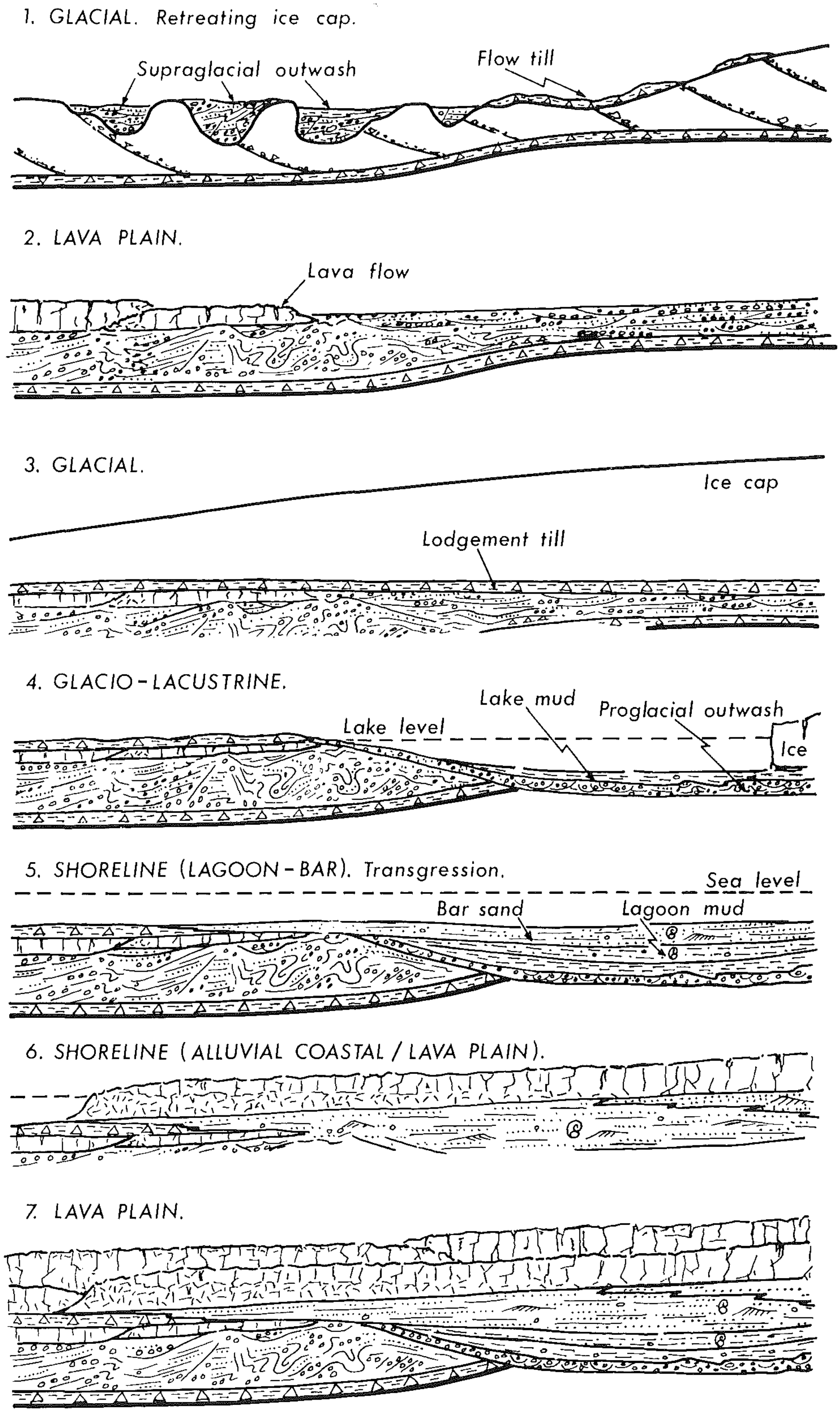

Fig. 26. Palaeoenvironmental reconstruction of the Máná Formation up to the Dimmidalur Member. See discussion in text.

The Máná Formation

In earlier stratigraphical nomenclature and classification (e.g. Th. Einarsson et al. 1967), the Breidavík beds were defined to reach up to reversely magnetized lava flows (H15) at Voladalstorfa. These lava flows are placed within the Máná Formation in the present study, and they constitute the top of the Torfhóll Member, which then contains Bárdarson's (1925) horizons H13–H15.

Líndal (1964) traced the lava at Voladalstorfa towards south. A more detailed account was later presented by T. Einarsson (1958), who traced this unit of reversely magnetized lava flows (the "Máná basalts") from Voladalstorfa to Búrfell. In Búrfell mountain he described a group of normally magnetized lava flows above the Máná basalts, separated from them by a conglomerate. T. Einarsson called the two lava units "the young basalts of Tjörnes" and supposed that they had originally covered the peninsula completely.

Recent mapping (Eiríksson 1981b, Gudmundsson and Sigfússon 1982, Eiríksson et al. 1982) has led to the definition of 4 member units within the Máná Formation, each containing a diamictite bed and one or more reversed polarity lavas. Two of the units, the Stapavík and Torfhóll Members are exposed in the coastal sections, but another two, the Dimmidalur and Búrfellsá Members crop out in Grasafjöll and Búrfell (Fig. 27).

Geptner (1973) described a ground moraine in the northeastern part of the Bay of Breidavík. The bed was numbered H13a by Geptner, who noted that it cuts across H12 and is overlain by a non-laminated gravel and sand deposit with large blocks (H13b). This was in turn overlain by a conglomerate (H13c) with a distinct erosional contact at the base. Geptner found fragments of ground moraine (a term used by him for lodgment till) in H13c where it cuts across H13a. He regarded the H13b conglomerate as a glacial burst deposit, the burst having been caused by subglacial volcanism. Geptner's section of the Voladalstorfa coastal cliffs is considerably more accurate than earlier versions. His interpretation of the origin of the sediments is, however, different from the one presented below. The lowest part of the H13 horizon in Stapavík had already been recognized as a tillite by Th. Einarsson et al. (1967). The basal flute molds, internal shear planes and silt bands, and the frequent striated boulders support the conclusion that the ed was deposited as a lodgement till. The contact between the beds indexed H13a (the lodgement tillite) and H13b by Geptner (1973) is not erosional, a feature hardly compatible with a glacial burst event. The internal structure of the conglomerate (severe deformation and irregular dip directions) leads to their interpretation as kames. The conglomerate H13c is interpreted here as a fluvial deposit (outwash). It is followed by lacustrine mud with erratics, and then by cross bedded sandstones.

The three units above (H13c, mudstone, sandstone) belong to the Torfhóll Member as well as the lava flow at the top of the section. On the northeast side of Tjörnes (200 m south of Skarfaflös, cf. Eiríksson 1981b), a lodgement tillite is found intercalated between an erosional unconformity and the Máná basalts. This tillite forms the lowest unit of the Torfhóll Member, the unconformity below it probably corresponds to the one beneath the conglomerate 13c in the Torfhóll section. The lodgement tillite 13a and the kame conglomerate 13b belong to the Stapavík Member, and two lava flows exposed at Knarrarbrekkutangi form the uppermost known units of that Member.

The reversed polarity Torfhóll Member lava unit in Voladalstorfa is correlated with unit GF–3 in Grasafjöll (Fig. 27). In that section there are two additional reversed polarity lava units (GF–5 and GF–7) separated by sediments. The lower unit, GF–5, can be traced in the valley sides of Búrfellsskardadalur and Dimmidalur and to the southeast slopes of Búrfell. It forms the top of a separate member unit, the Dimmidalur Member, which belongs to the Máná Formation and is younger than the Torfhóll Member. Unit GF–5 rests on a sedimentary horizon consisting of a 0.7 m thick conglomerate, followed by an up to 3 m thick diamictite, and then by an up to 2 m thick sandstone (unit BS–4, Fig. 27).

The upper lava unit, GF–7, is separated from the Dimmidalur lavas by a single up to 2 m thick diamictite bed, and this couplet forms the Búrfellsá Member, named after the brook that exits Búrfellsskardadalur at the foot of section GF (Björnsson 1977). The Búrfellsá Member forms the top of the Máná Formation.

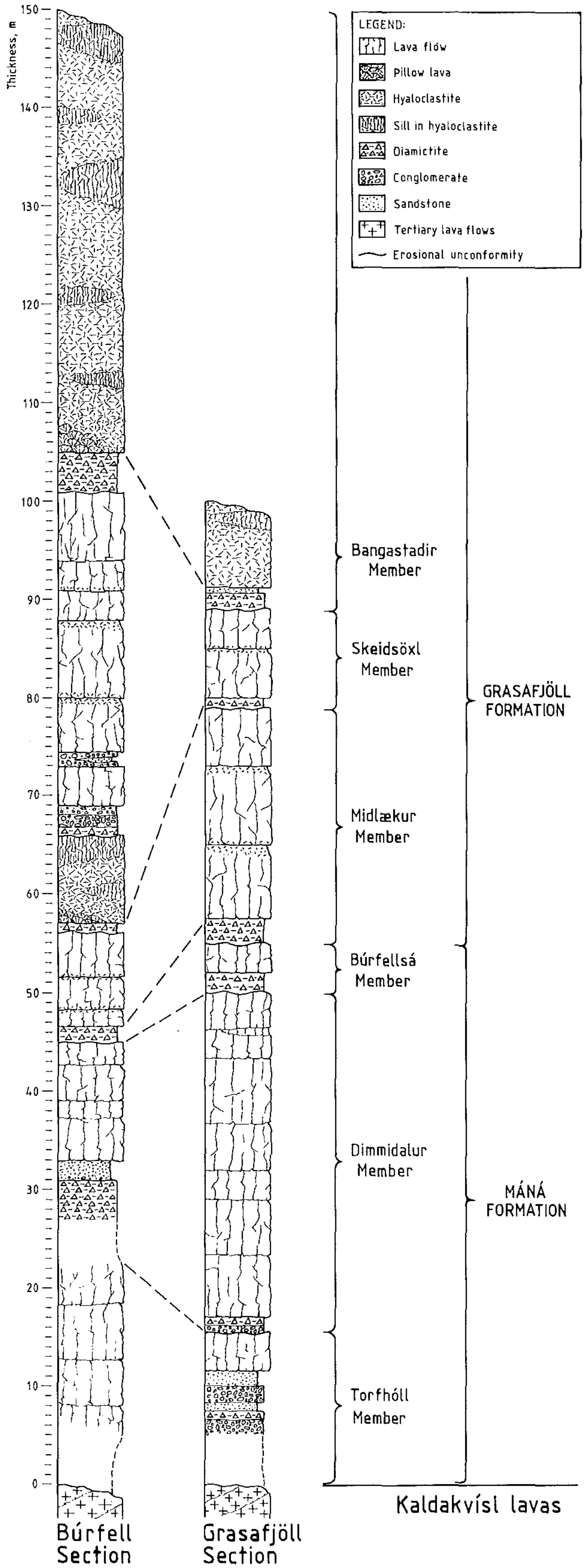

Fig. 27. Sections in Grasafjöll and Búrfell.

Table 6. Major facies types of the Máná Formation

18. Lava flow.
17. 2 m thick poorly sorted diamictite with silty matrix and angular to subangular pebbles and boulders, up to 0.5 m in diameter.
16. Multiple lava flows.
15. Up to 2 m thick reddish, medium grained poorly to moderately sorted pebbly sandstone with basal lenses of conglomerate.
14. Very poorly sorted diamictite with angular pebbles and boulders up to 0.5 m in diameter. Topmost part reddish with trace of rounded pebbles.
13. 0.7 m thick red-grey conglomerate with rounded pebbles, lower part well sorted, upper part poorly sorted with pebbly–sandy matrix.
12. Lava flows.
11. Nonfossiliferous sandstone and conglomerate facies.
10. Fine grained trough cross bedded sandstone facies with marine fossils and erratics.
9. Coarse gravelly sandstone facies with marine fossils.
8. Pebbly mudrock facies, laminated near base.
7. Cross bedded conglomerate facies with local deformation structures.
6. Diamictite facies.
5. Erosional surface.
4. Lava flows.
3. Conglomerate facies with deformation structures.
2. Diamictite facies.
1. Erosional unconformity.

The major sedimentary facies types and other features of the Máná Formation are presented in Table 6, number 1 being at the base.

A reconstruction of palaeoenvironments during the accumulation of the Stapavík and Torfhóll Members is presented in Fig. 26, which is schematic and has not been drawn to scale. The reconstruction of the Dimmidalur and Búrfellsá Members is shown in Fig. 28.

1. *Glacial.* A glacier covers the Tjörnes area and deposits lodgement till. Flute molds on the sole of the till indicate that the underlying sediment was still soft and deformable at the time of glaciation (facies 1). The flutes strike N2°E, and grooves on an internal plane within the till (facies 2) strike N8°W. During retreat the glacier stagnates in places and supraglacial outwash sediments accumulate (facies 3). The supraglacial outwash sediments are lowered onto the sloping till surface due to the melting of stagnant ice beneath. In the process, intense folding and faulting takes place within the materializing kames. Proglacial meltwater streams rework and erode the kame deposits locally.

2. *Lava-plain.* Lavas flow across the area during ice free conditions (facies 4).

3. *Glacial.* A glacier covers the area once again and deposits lodgement till (facies 6) upon an erosional surface.

4. *Glacio-lacustrine.* The glacier retreats and a proglacial outwash plane (facies 7) is now submerged by a proglacial lake, in which poorly sorted mud accumulates (facies 8) along with erratics dropped from ice bergs calved off the glacier margin. Local deformation of the cross bedded outwash gravels is taken to indicate a temporary readvance of the glacier front (perhaps as the lake was formed). Possibly, it might have been caused by scouring ice bergs.

5. *Shoreline (lagoon – bar).* The appearance of marine fauna in the mud facies (facies 8) coincides with a marine transgression in the wake of glacier retreat, and a lagoon environment develops. A transgressing bar environment with increased wave action and current velocities then brings cross bedded sands with marine shells across the lagoon mud (facies 8). Reworking of the kames leads to an admixture of gravels (facies 9) in the basal part of the bar sands (facies 10) in the vicinity of the kame mounds.

6. *Shoreline (alluvial coastal/lava plain).* Alluvial sands and gravels (facies 11) are deposited landwards of the shoreline, only to be covered by numerous lava flows.

7. *Lava plain.* The glacier has now retreated, and alluvial sedimentation and volcanic activity now characterize the environment.

Steps 3–7 are recorded in the rocks of the Torfhóll Member. These rocks crop out in several sections on the east coast of Tjörnes, and these sections have recently been analyzed and interpreted by Birgisdóttir (1984). She identified a sedimentary horizon intercalated

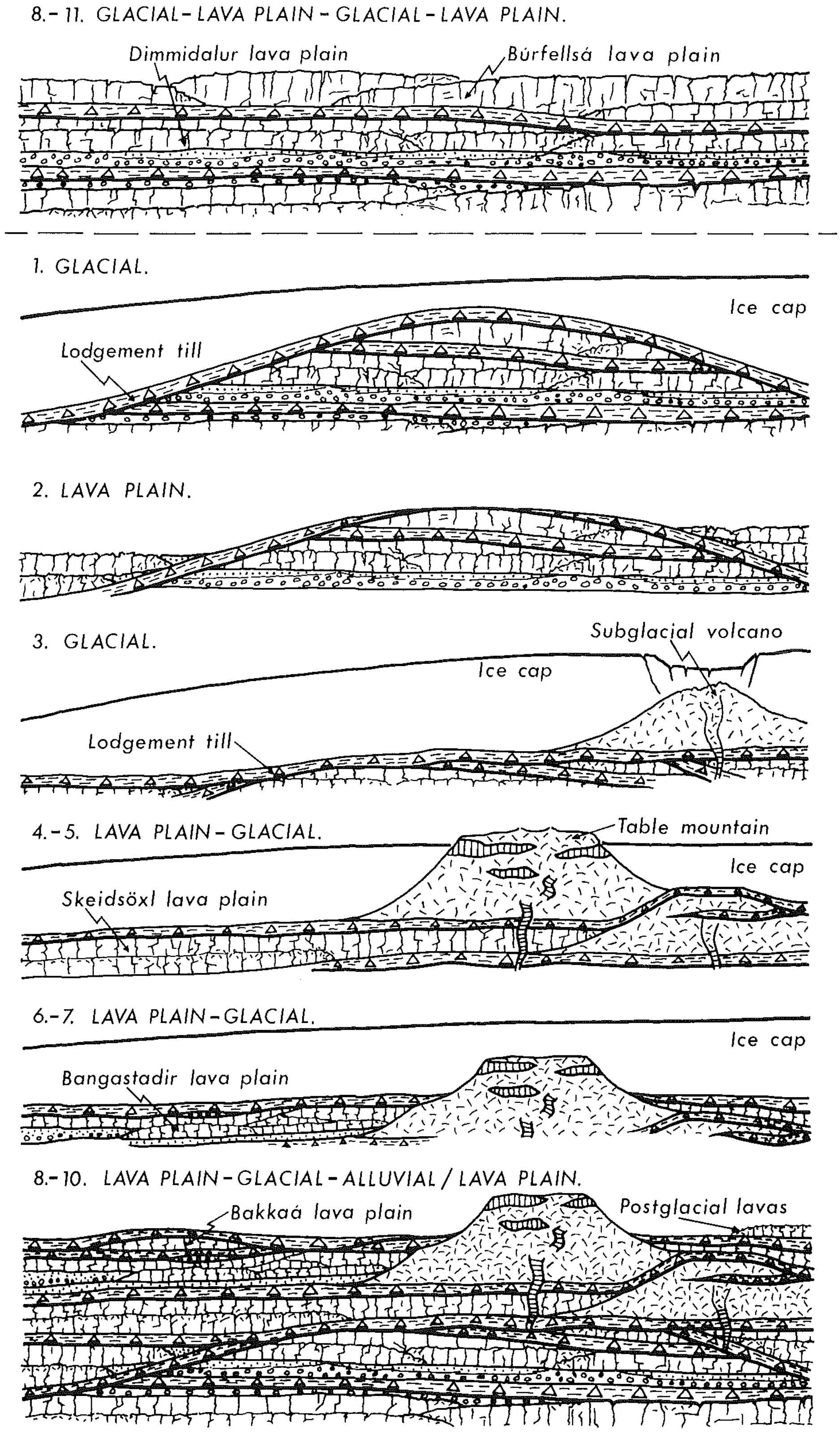

Fig. 28. Palaeoenvironmental reconstruction of the Grasafjöll and Húsavík Formations (including the Dimmidalur and Búrfellsá Members of the Máná Formations).

between the lavas of the Stapavík and Torfhóll Members ("Sedimentschicht I") as a lodgement tillite, ice-contact and glaciofluvial deposits and fluvial deposits.

8. *Glacial.* Renewed glaciation and deposition of facies 14. Facies 13 may represent proglacial fluvial sedimentation during ice sheet advance. The ice then melts away and a pebbly sandstone facies is deposited on the till plain.

9. *Lava plain.* Subaerial volcanism produces lava flows (facies 16).

10. *Glacial.* Renewed glaciation.

11. *Lava plain.* Ice free conditions allow lavas to flow across the till plain left by the retreat of ice.

The Grasafjöll and Húsavík Formations

Rocks of the Grasafjöll Formation are widespread on eastern and central Tjörnes, and have recently been mapped in detail (Eiríksson 1981b, Gudmundsson and Sigfússon 1982). The work of Líndal (1964), T. Einarsson (1958) and Th. Einarsson et al. (1967) clarified the main stratigraphic succession, but several new units have been added. The interpretation of the stratigraphy takes into account rock facies exposed along the coast and in Grasafjöll and Búrfell mountains. The Grasafjöll Formation contains 3 member units, the Midlaekur Member, the Skeidsöxl Member, and the Bangastadir Member.

The Húsavík Formation is the youngest formation of the Breidavík Group, and contains two distinct subunits. The lavas of the interglacial shield volcano Grjóthâls represent a key horizon. At Bakkaá, Reydará and Botnsvatn the lavas overlie a diamictite, and at the former two localities they reveal vertical gradation from breccia to solid lava, which is also true of exposures south of Húsavík and in Aervík. According to T. Einarsson (1965) and Birgisdóttir (1984) the Grjóthâls lava in Aervík rests on sediments containing marine fossils.

At the top of the section in Höfdaskard in Breidavík there are local remnants of sedimentary horizons that discordantly overlie sediments of the Torfhóll Member. The sediments were described by Gudfinnsson et al. (1983), and they occupy a similar position to that of the Húsavík tillite. According to Gudfinnsson et al. the sequence above the unconformity begins with a diamictite with shear planes. Fossils of the burrowing molluscs *Mya truncata* and *Hiatella arctica* are found in living positions in the top of the diamictite, which is covered by a sandy conglomerate in which a granite pebble was found.

At Botnsvatn the lava is solid and rests directly on a diamictite, which is in turn underlain by olivine porphyritic lava. The sequence of exposed strata in Húsavík begins with a normal polarity olivine porphyritic lava flow followed by a very thick diamictite with internal shear planes in Húsavíkurhöfdi. This diamictite thins out and disappears towards south because of an erosional unconformity. In the southern part of Húsavík the basal lava appears to be overlain by the Grjóthâls pillow breccia, but the contact is not exposed. At the top of the section there is another diamictite, which should probably be correlated with a diamictite above the erosional unconformity in the northern part of Húsavík. The uppermost part of this diamictite is loosely cemented, and it probably represents till deposited by the Weichselian ice cap, which has left numerous features on or at the surface of Tjörnes, among them glacial striae on the top of the Grjóthâls lavas. Till, lateglacial marine deposits, soil and postglacial lava flows form the uppermost part of the Húsavík Formation.

The main rock facies and other features of the Grasafjöll and Húsavík Formations are presented in Table 7, number 1 being at the base.

A reconstruction of a few steps in the evolution of environments during the accumulation of the rocks of the Dimmidalur and Búrfellsá Members of the Máná Formation and those of the Grasafjöll and Húsavík Formations is presented in Fig. 28, and an attempt to interpret the record is as follows.

1. *Glacial.* Approximately at the time of the geomagnetic polarity reversal from Matuyama to Brunhes, a glacier covered Tjörnes Peninsula, eroded the substratum and deposited a lodgement till (facies 2). It is now found between reversed and normal polarity lava flows at Engidalsgjá.

2. *Lava plain.* When the glacier had retreated, a lava plain environment developed (facies 3). There is no information about sea level during this cycle, which belongs to the Midlaekur Member.

3. *Glacial.* The lava plain of the Midlaekur Member is now covered by a new glacier. A volcanic eruption now takes place. Hyaloclas-

Table 7. Facies sequence of the Grasafjöll and Búrfell Formations

22. Soil with ash layers, and lava flows.
21. Sand with marine fossils.
20. Nonfossiliferous gravels and sands.
19. Diamicton with fluted surface.
18. Erosional surface.
17. Normal polarity lava flows, basally brecciated in coastal sections.
16. Marine fossiliferous siltstone.
15. Diamictite with grooved internal planes.
14. Erosional unconformity.
13. Multiple flows of normal polarity lavas.
12. Up to 4 m thick cross bedded conglomerate with sandstone lenses.
11. Hyaloclastites, pillow breccias and lava flows of the table mountain Búrfell.
10. Discontinuous laminated siltstone with deformation structures.
9. Up to 5 m thick diamictite with silty matrix, bouldery near base.
8. Erosional unconformity.
7. Normal polarity lava flow.
6. Hyaloclastites with lenses of diamictite.
5. 2.5 m thick platy and banded diamictite with grooved internal planes.
4. Erosional unconformity.
3. Normal polarity lava flows.
2. 5 m thick diamictite.
1. Erosional unconformity.

tites (facies 6) are piled up in a cavity which is melted into the glacier. The volcanism is intermittent and local lenses of diamictite become intercalated in the volcanic pile, which is finally eroded considerably and locally covered by diamictite.

4. *Lava plain.* Upon retreat of the glacier, subaerial lava flows (facies 7) cover the till surface and the topography is levelled to some extent. These are the lavas of the Skeidsöxl Member.

5. *Glacial.* The Skeidsöxl Member lavas are now covered by an advancing glacier, depositing diamicton (facies 9). A subglacial eruption now takes place and the top of Búrfell mountain is piled up. Explosive volcanism continues until the pile exceeds the thickness of the ice, and subaerial lava covers the fragmental pile of volcanics. Upon ice retreat, local lakes and ponds silt up to level a dead ice topography on the lowlands (facies 9 and 11).

6. *Lava plain.* After a retreat of the Bangastadir Member glacier, subaerial lava flows cover the till/outwash plain and the topography is levelled to some extent. The table mountain Búrfell towers over the surroundings.

The most conspicuous Bangastadir Member lavas on the east coast of Tjörnes are multiple flows of highly plagioclase porphyritic basalt, which serve as a useful marker unit. A local outcrop of olivine porphyritic basalt is separated form the plagioclase rich lavas underneath by a sedimentary horizon (mainly sandstone) north of Hringsbjarg.

7. *Glacial.* Tjörnes is once again covered by a glacier which deposits an exceptionally thick diamictite, which at present juts out as sea cliffs in Húsavíurhöfdi, Lundey and at the top of the Engidalsgjá section. A bed of large rounded boulders is intercalated in the basal part of this diamictite in the Engidalsgjá section. Marine sediments in Aervík may have been deposited during a transgression in the wake of the retreating glacier, and the same is true of the fossiliferous sediments at the top of the section in Höfdaskard in Breidavík.

8. *Lava plain.* After a retreat of the glacier the Grjótháls shield volcano poured lavas over the southern part of the area. The lavas probably entered the sea as they are extremely brecciated at the base. Elsewhere, they covered the till plain of the Bakkaá Member.

9. *Glacial.* The last glaciation of the Tjörnes area sets in and the oldest sediments are till deposited by the glacier. This glacier has also left glacial striae and grooves at numerous localities on Tjörnes Peninsula. Fluted and drumlinized till plains are observed in the Kaldakvísl area. The strike of these linear features is northwesterly.

10. *Shoreline – alluvial coastal plain.* A notch roughly parallel to the present coastline marks an abrupt end of the fluted surface on the Kaldakvísl area till (facies 19). It is tentatively suggested that a marine transgression at the end of the last glaciation reached this lineation. Sediments near the top of the costal cliffs near the farm Ytri Tunga contain marine fossils and are not lithified (Gladenkov 1974). They might have been deposited during the same transgression. After an isostatic rebound, the present

environments evolved with soil formation and coastal and fluvial processes. Recent lava flows have not reached the northern part of Tjörnes Peninsula, but are to be found to the southwest, south, and southeast.

CONCLUSIONS

The Breidavík Group documents a remarkably detailed history of Quaternary glaciations. The unusual tectonic setting and volcanic activity are critical conservation factors. The ideas about the origin of the Breidavík Group rocks and the interpretation of the lithological cycles presented in this paper may be summed up as follows:

1. Lodgement tillite beds in the sequence were deposited by ice caps which are assumed to have covered most of Iceland and the surrounding shelf.
2. Kame conglomerates and glaciolacustrine mudrocks were formed during the retreat of ice caps.
3. Marine transgressions in the wake of retreating ice are evident by the presence of marine sediments with fossils in close association with deglaciation sediments. The fauna is arctic in the sediments immediately above glacial sediments.
4. Marine sediments with interglacial fauna cover the tillites and deglaciation sediments in Breidavík. These sediments interfinger with and are followed in the vertical sense by fluvial sediments and lava flows indicating regression and ice free conditions.

Such a sequence of facies (1–4) constitutes an ideal Breidavík Group cycle, and is considered to have accumulated during a climatic glacial–interglacial cycle.

5. The frequency of the cyclicity of the Breidavík Group is similar to that of the oxygen isotope stages defined for the Quaternary deep sea sediments. According to palaeomagnetic and K/Ar data, the first seven of the lodgement tillites were deposited between ca. 2 Ma and ca. 1.25 Ma. The upper part of the Breidavík Group was formed during reduced rate of subsidence and later during uplift on Tjörnes, which to-day represents a horst structure. The apparently lower frequency of glacial events may thus not reflect overall changes in the rate of climatic cyclicity, but instead a reduced conservation potential of the rocks on Tjörnes.

The results presented here need to be supported by mapping, lithostratigraphical classification and facies analysis of Quaternary sections elsewhere in Iceland, where volcanism has been active. Correlations between different parts of the country may solve questions about the extent of individual glaciations. After this task has been completed, correlation with Quaternary sections elsewhere and a comparison with the deep sea record will probably add to our knowledge of the history of glaciations and climatic changes in the North Atlantic area.

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