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Fissure-fill and tunnel-fill sediments: expressions of permafrost and increased hydrostatic pressure

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ABSTRACT: A spectacular network of fissure fillings and pipes (tunnels) cuts Quaternary gravelly delta deposits northeast of Myvatn, precisely on the spreading axis of the North Icelandic rift zone. The delta was formed in an ice-contact lake during deglaciation towards the end of the last glaciation. Subsequently the lake was drained and permafrost conditions developed in these poorly sorted gravel deposits. Hydrostatic pressure was transmitted from the adjacent glacier to the non-frozen core of the delta beneath the discontinuous permafrost crust and the seasonally frozen active layer. Owing to increased hydrostatic pressure, a network of subhorizontal to vertical fissures was opened along the taliks. In these fissures free ground-water flow and sediment transport were established. Tunnel erosion and probably also seepage erosion were associated with these fissures. Subsequently, the fissures and tunnels were filled by laminated fine sediments interbedded with poorly sorted material resulting in the formation of fissure-fill sediments and tunnel-fill sediments.

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KEYWORDS: Fissure-fill sediments, tunnel-fill sediments, permafrost, hydrostatic pressure, Iceland.

Introduction

Various post-depositional sedimentary structures occur in sedimentary successions. Some of these are tabular, wedge-like or cylindrical structures that are bed-parallel or cut the previous structures. A number of post-depositional sedimentary structures of different geometry and origin are described in the literature, and are presented briefly below. Fissure-fill sediments have been discovered recently in northern Iceland. They are similar to some of the structures described in the literature, but appear to be dissimilar in origin. These structures are described later in this paper and their origin discussed.

Tabular structures

Fissure fillings are tabular structures that are known in the literature under various names, e.g. clastic dykes (Dzulynski and Radomski, 1956; Potter and Pettijohn, 1977; Marschalko, 1978), sandstone dykes (Diller, 1890), intrusive clastic or sedimentary dykes (Allen, 1984), ptygmatic dykes (Allen, 1984), or sandstone sills (Potter and Pettijohn, 1977; Bates and Jackson, 1987). Some authors restrict the term clastic dyke to those tabular structures that are formed by intrusions that cut across the possible previous structures (Dzulynski and Walton, 1965; Potter and Pettijohn, 1977; Marschalko, 1978; Bates and Jackson, 1987). Other authors also allow the term clastic dykes to refer to structures formed by passive sedimentation in an already open fissure under the influence of gravity (see Aspler and Donaldson, 1985).

Intrusive dykes and sills are generally formed while the fissure is being opened. The resulting structures are mostly massive with possible wall-parallel lamination along the edges (Hayashi, 1966; Winslow, 1983; Dreimanis, 1992). In some cases lamination is observed to be oblique to the walls (Hesse and Reading, 1978; Aspler and Donaldson, 1985). In another case the material was interpreted as being intruded horizontally into vertical fissures (Aspler and Donaldson, 1985). Some dykes display grading, with larger clasts being concentrated in the centre of the dyke (Young, 1968; Eisbacher, 1970; Winslow, 1983). In a subglacial environment, laminated dykes have been interpreted as the result of repeated intrusions taking place in a fracture or a system of fractures (Mangerud *et al.* 1981; Larsen and Mangerud, 1992).

Those tabular fissures that are filled by passive sedimentation may be formed in the following ways.

1. Opening of fissures may be due to *physical processes* such as faulting or folding in sedimentary or crystalline rocks, slope processes in solid or semi-consolidated sediments (Strauch, 1966; Potter and Pettijohn, 1977;

Winslow, 1983; Allen, 1984; Winterer *et al.*, 1991), frost action such as frost cracking (see Washburn, 1979; Williams and Smith, 1989) or glacier tectonics (Kälin, 1971; Sjörring, 1977; Stephan *et al.*, 1983; Croot, 1988).
2. *Chemical processes*, e.g. karstification, may result in the development of tabular cavities (see Dzulynski *et al.*, 1988). The resulting fissures, except those formed in the subsurface, generally have high angles to the local land surface. The fissure fillings may be massive and/or laminated and the lamination may be horizontal or vertical.
3. Along glacier margins, *hydrostatic pressure* from the glacier waters may, according to some authors (Carlsson, 1979; Pusch *et al.*, 1990), lift slabs of crystalline rocks beneath the ice, opening pre-existing, subhorizontal fissures in the bedrock. Subsequently, these open fissures will be loci of clastic deposition.

Tubular structures

Intrusive structures may be tubular as well as tabular. Tubular structures may contain an infill of sand, conglomerate, breccia or limestone, etc. Many authors consider these structures as typically vertical; they are known in the literature as clastic pipes, sandstone pipes, breccia pipes, etc (Kugel, 1978; Bates and Jackson, 1987). No clear distinction has been made between instrusive pipes and those filled passively by sedimentation. In the latter case the open spaces may be formed in at least two different ways:

1. *Sub-surface erosion* (i.e. seepage erosion and tunnel erosion), in which ground-water flow moves sediment particles through the porous host sediment. The process and structures have been described mostly in silty to fine sandy deposits (e.g. loess or other fine-grained deposits, Prinz, 1969; Hughes, 1972; Bryan and Campbell, 1986; Higgins *et al.*, 1988). Pipes (tunnels) are the resulting structures and they may change their attitude from vertical to horizontal. Lamination is a characteristic sedimentary structure in the infilling material.
2. *Subrosion*, a dissolution process related to karstification, in which cavities and caves are formed and widened (Bates and Jackson, 1987; Dzulynski *et al.*, 1988). The filling material may be massive or display horizontal lamination. In German literature *subrosion* also includes subsurface erosion.

New work

Recent research in the Myvatn area of northeast Iceland (this paper) adds two additional, remarkable features:

1. Subhorizontal, open, tabular fissures may be formed, not only in crystalline rocks, but also in frozen gravels, apparently also in settings that are sheltered from ice push or are not covered by glacier ice. The fissures are subsequently filled by stratified material. Fissure-fill sediments are defined here as deposits composed of (i) stratified sediments, settled from traction currents or suspension, and (ii) possible interlayering massive units collapsed from the fissure walls or ceiling. These beds are deposited in subhorizontal to vertical open fissures and are sandwiched between pre-existing units of non-lithified sediments, sedimentary or crystalline rocks.
2. Piping (see Higgins *et al.*, 1988) may take place, not only in fine-grained deposits, but also in poorly sorted gravels.

The Myvatn area

Glaciogenic gravels (Thorarinsson, 1951; Sæmundsson, 1991) accumulated, over a period of several hundred years, on the southern outer rim of the Krafla caldera northeast of Myvatn in the North Icelandic rift zone (Fig. 1). They are thought to constitute a delta deposited in an ice-contact lake and possibly influenced by jökulhlaup sedimentation (Kumpulainen, unpublished.) The delta sediments are composed of poorly sorted gravels (mass flows), stratified gravels (traction currents), and minor sandy and silty deposits. On this south-facing caldera slope, the local spreading axis forms a volcanic ridge, Dalfjall–Námafjall, striking NNE–SSW. The ridge limits the delta to the east. At the time of deglaciation, the glacier ice supported the delta in the south and west. The ice made at least one advance to the north (Sæmundsson, 1991), causing some ice-push deformation in a narrow segment of the southern part of the delta. While the delta was still active the glacier meltwaters escaped northwards through the delta and the Krafla caldera. During further deglaciation the outlet northwards was abandoned and a new outlet was developed

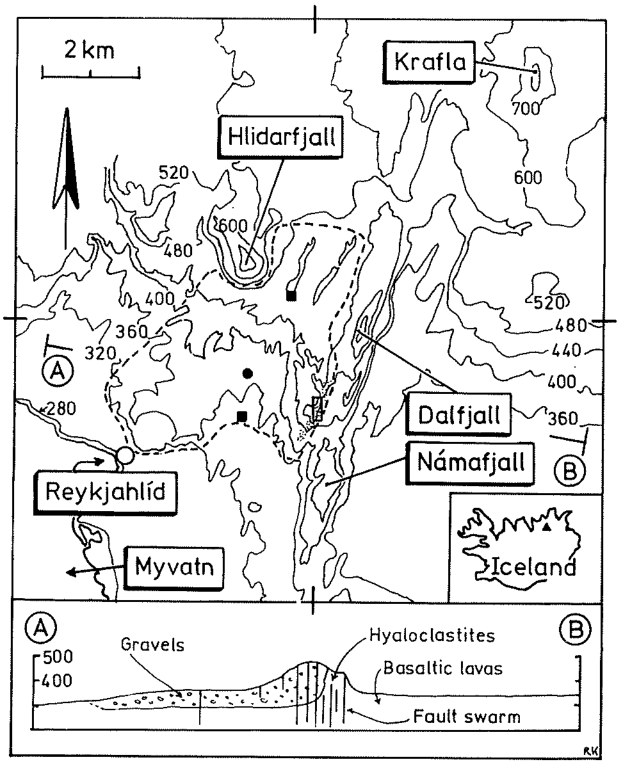


Figure 1 Map of the southern, outer slope of the Krafla caldera (a triangle on the insert map) rim at Myvatn showing the location of the late glacial gravel delta (broken line) west of Dalfjall–Námafjall. Topographic contours are in metres. Above 520 m a.s.l. the contours are at every 100 m. Longitude 16° 50′ W and latitude 65° 40′ N are shown along the figure margins. Location of sections in Fig. 2 is shown with a rectangle south of the figure centre. Profile A–B shows diagramatically the relationships between topography, delta gravels, spreading ridge and basaltic lavas. Key: stippled, location of fissure-fill sediments on Dalfjall; filled square, occasional fissure-fill sediments; filled circle, tunnel-fill sediments (see Fig. 7b).

south of Hlídarfjall to the west. Parts of the proximal portion of the delta were removed by erosion, resulting in a landscape that is largely preserved to the present day. The original delta top is best preserved in the northeast. It drops ca.10–20 m from south to north over a distance of ca.4 km. The remnant delta reaches its highest point (ca. 490 m a.s.l.) just south of the rectangle in Fig. 1 (see also Fig. 11). Fissure-fill sediments occur frequently in the gravels on top of this ridge and on the eroded slopes of the delta.

The dominating rock types occurring as clasts (from silt to boulder) in the gravels are of basaltic composition and consist of pillow fragments, occasional whole pillows and volcanic glass. The lava rocks are dominantly grey, sometimes brownish grey. The volcanic glass of sand grade may be black to brownish grey, whereas the silt fraction is yellow. Rare clasts of hyaloclastites also occur.

Most of the exposures in the area are found along fault scarps of the rift fissure swarm, parallel to Dalfjall. Faults have been active in the area from prior to the deposition of the delta until the present day. Fissure-fill sediments cut some of the faults, whereas other faults cut the fissures. It is important to note that one of the faults liquified both the stratified delta sand and the fissure-fill sediments. This indicates that the sedimentary infill was deposited in fissures in non-lithified gravels. The gravels are today semi-lithified to lithified owing to rapid diagenetic processes within the rift. The degree of consolidation, which, at least partly, appears to depend on the percentage of silt in the sediments, does not allow systematic granulometric (sieve) studies of these deposits.

Description of the structures

The sediment-filled fissures in these gravels vary from less than 1 mm to more than 1 m in thickness, a common thickness being ca. 5–20 cm. The fissures, which are mostly bed-parallel, may be traced subhorizontally for more than 125 m and reach a depth of at least 15 m into the gravels (Fig. 2). On the other hand, laterally the fissure sediments may extend less than 1 m and could be described as very thin lenses. The fissures may change their attitude over a short distance, bifurcate and form minor beds. Subhorizontal fissures at two different levels may connect through a set of steep to vertical fissures (Fig. 2), although only one of the steep fissures was active at any particular time (Fig. 3). The sedimentary infill is dominated by horizontally to subhorizontally laminated silt to very coarse sand. The silt and sand are intercalated by subordinate, massive to poorly sorted gravel (Fig. 4a). In subhorizontal fissures, the individual silt–sand laminae extend laterally generally less than 1 m. In some locations the clastic infill displays cross-lamination. The infill in inclined fissures may display horizontal to inclined lamination (Fig. 4b), suggesting that the original open fissures were wide enough to allow formation of this structure. Wall-parallel lamination (Fig. 4c) is also present, where the fissure was very narrow. In other instances the steep fissure filling is dominated by massive, coarse sand and gravel and some stratified sand (Fig. 5); some folded pieces of silt–sand laminae may also occur. The fissure-fill sediments are generally separated from the host gravels by a silt envelope a couple of millimetres thick.

Sediment-filled fissures may locally widen up to sediment-filled tunnels, from centimetres to more than 1 m in cross-section (Fig. 6). Other tunnel fillings appear to be independent of the fissures. The tunnels (pipes) are observed to cut the delta gravels and sands, earlier fissure-fill sediments (Fig. 7a) or earlier tunnel fillings (Fig. 6a and 6c). The filling material is composed of various proportions of laminated silt to coarse-grained sand and unsorted gravel. The infill can be either finer grained than the host sediments (Fig. 6d–f), or coarser (Fig. 7b). In some tunnels, the sand is cross-bedded (Fig. 6e and 6f) or cross-laminated. In this case the infill may be well sorted to very well sorted and range from silt to medium sand (Fig. 8). In most cases, silt laminae or a thin unit, 1–2 cm, of fine-grained, sometimes cross-laminated, sand caps the core of the infill (Fig. 6b and 6c). Apart from the cap, fine-grained sediments also dominate the uppermost part in many tunnel fillings. Some tunnel fillings appear to be independent of the fissures, but are similar to deposits inside the fissure system.

The attitudes of the sediment-filled fissures and tunnels were measured on one of the exposures (Fig. 2, S-section). Tunnels strike approximately SE–NW, whereas poles to the fissures, plotted on a Schmidt net, establish a diffuse girdle ca. 90° from the tunnel orientation (Fig. 9). Together with the above descriptions, this suggests that the tunnels and fissures are genetically related to each other and that they together reflect a ground-water flow pattern in a general SE–NW direction perpendicular to the orientation of the gravel ridge in which they occur.

Discussion

Fissure-fill sediments in the Myvatn area appear to be different from other features described in the literature. Several possible interpretations will be discussed below. Some additional explanations may still remain.

The descriptions indicate that the fissure-fill sediments and tunnel-fill sediments were deposited in open fissures and cavities respectively, while the host gravels were still non-lithified. Most of the clastic infill displays a distinct subhorizontal lamination or wall-parallel lamination, in both cases intercalated by stratified to unsorted gravels. These characteristics are in clear contrast to those of intrusive clastic dykes that have been described in the literature. Intrusive dykes are mostly massive, displaying only minor lamination along the edges (see Introduction). Indeed, some of the classical neptunian dykes in the Alps and Apennines that contain a distinctly laminated infill, and have previously been interpreted as intrusive, have recently been reinterpreted as formed by passive sedimentation in fissures opened in solid rocks by tectonic movements (Winterer *et al.*, 1991).

The delta gravels at Myvatn that host the fissure-fill sediments and tunnel-fill sediments were formed in an ice-margin environment and subjected to a very cold climate with the probable development of a discontinuous permafrost crust and possibly frost polygons. At first glance, some of the steep fissures are similar to fossil ice-wedges and soil wedges, but those structures (see e.g. Péwé, 1966; Washburn, 1979) are not observed to change from vertical to horizontal and then continue subhorizontally for several tens of metres (Fig. 2).

Laminated and cross-bedded sandy sediments deposited in subhorizontal fissures have been described from ice-margin gravels, e.g. in Denmark (Sjörring, 1983). The formation of these fissures has been related to glacier tectonics, i.e. direct

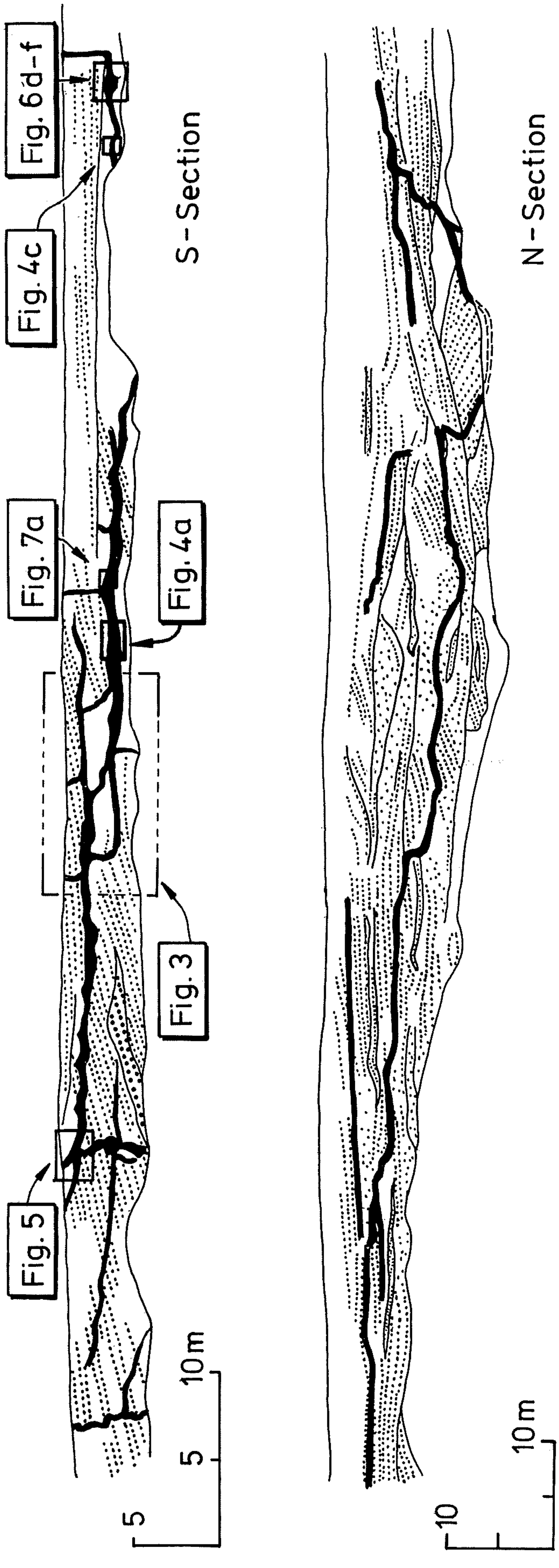


Figure 2 Two portions of the same fault scarp displaying details in the delta sediments and the fissure network (black). Separation between the sections is ca. 300 m. The thickness of the fissure is overemphasized in some parts of the diagram. Note that no apparent deformation structures, e.g. faults and folds, have been recognized in these sections.

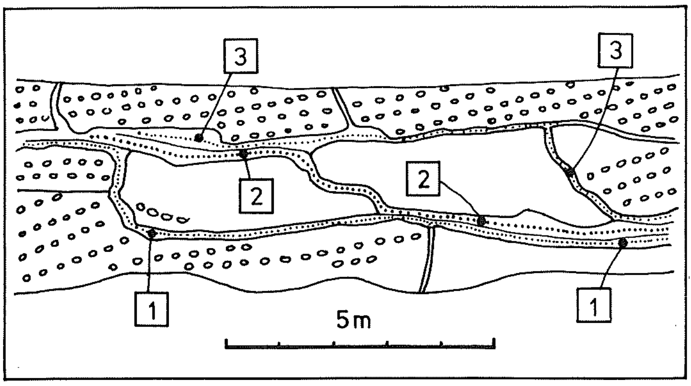


Figure 3 Three steep portions of fissure-fill sediments connecting two subhorizontal portions of the fissure network on Fig. 2. The sediments in the steep beds may be traced into the subhorizontal portions, where they appear in the same stratigraphical order at both the lower and upper levels. It is possible that the steep bed to the left (1) was formed first and the bed to the right (3) was formed last.

Figure 4 (a) A sedimentary infill composed of laminated, fine-grained sediments and intercalating poorly sorted gravelly layers was deposited in a subhorizontal open fissure. A block was attached to the base of the frozen delta gravels. The active open fissure was located directly below the gravel ceiling. Repeated opening and infilling of the thin fissure resulted in the arched layering below the block. Arrows indicate the base and the top of the sediment-filled fissure. The location is indicated in Fig. 2. (b) Detail of an inclined fissure with (large arrows, base and top) stepwise changing internal lamination (intermediate size arrow). Structures inside the bed suggest repeated episodes of opening and filling of the fissure (small arrows). Some of the material has also infiltrated the underlying gravels. The diameter of the coin is 28 mm. (c) This fissure fill displays a wall-parallel lamination. Similar geometry of the base and the top of the bed supports the interpretation that the gravels above the bed were subject to vertical uplift. The wall-parallel lamination is thought to indicate a slow, stepwise uplift, fissure opening and sediment infilling. Hand lens 43 mm. The location of this bed is shown in Fig. 2.

ice push and folding of frozen gravels adjacent to the glacier (Berthelsen, in Sjörring, 1977).

Formation of ice-push moraines may also include development of up-glacier dipping listric thrust faults. Subsequently a stack of inclined sheets of frozen moraine may result. The thrust surfaces develop readily to conduits of meltwater and may be filled later by sediment (Kälin, 1971). These sediments are likely to be deformed if the individual frozen sheets move in relation to each other (Stephan *et al.*, 1983).

In the present area, at Myvatn, the application of an ice-push interpretation may be plausible for the fissure-fill sediments. The following discussion summarises some published (Saemundsson, 1991) and unpublished field data (Kumpulainen, unpublished). Ice-push structures, such as folds and reverse faults, are very subordinate, being observed locally in a narrow segment, ca. 1 km wide, along the southern margin of the delta gravels. A minor advance to the north-northwest is indicated in this area. In other parts of the delta no obvious ice-push structures have been recognised. Ice-flow data (Sæmundsson, 1977) suggest that glacier ice was probably pushed up on the eastern slope of Dalfjall–Námafjall (Fig. 10), which apparently sheltered the gravel deposits from ice-push from the east. A minor gap in the present topography (Fig. 11) could be taken as evidence

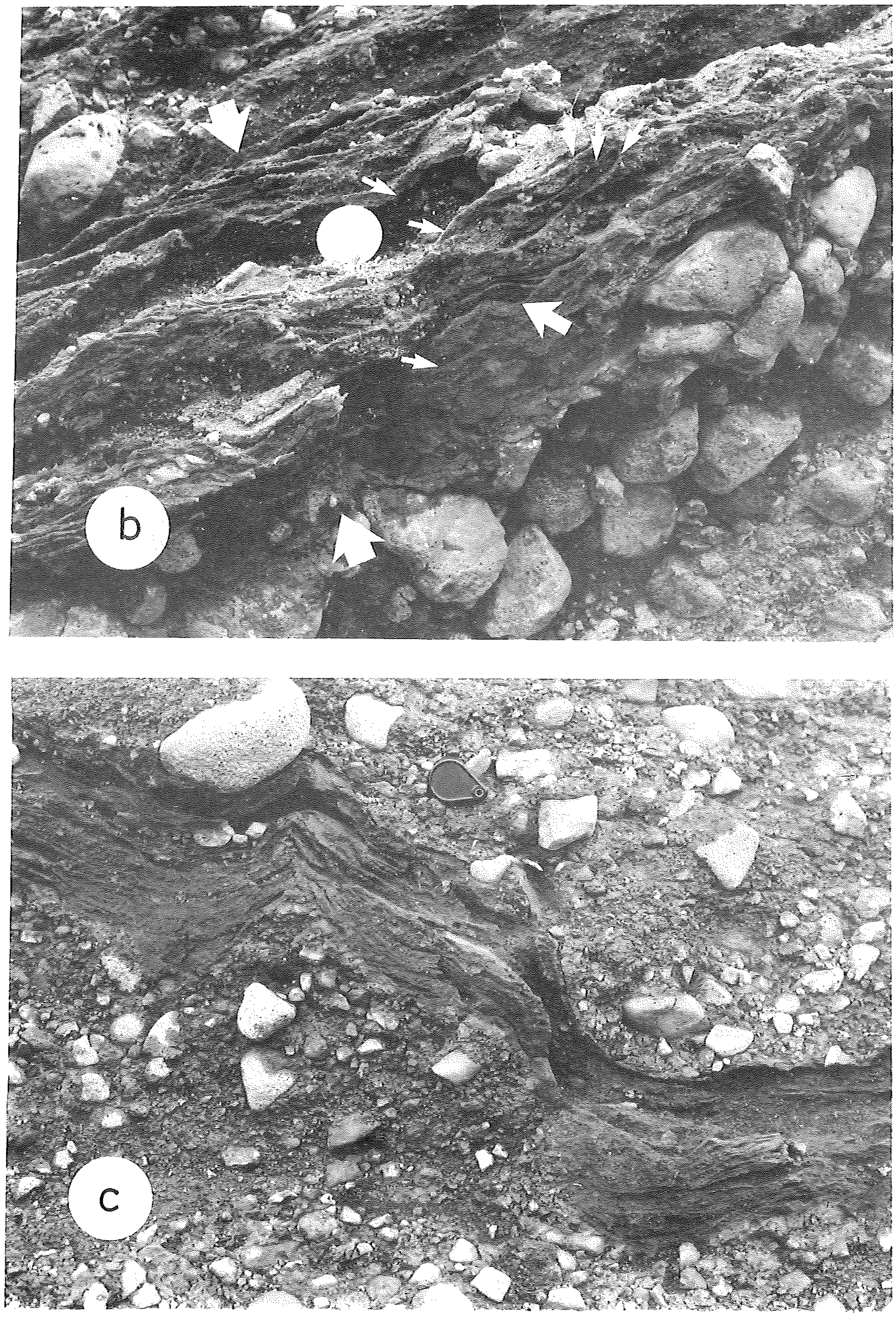


Figure 4 Continued.

that the ice advanced westwards and exerted a direct mechanical stress on the gravels around the cross-cutting valley. It is also possible that the valley is a late structure, which may not have existed while the glacier rested high on the eastern slope of Dalfjall–Námafjall.

If the fissure network on Dalfjall (Fig. 2) is interpreted as evidence of ice-push, then the compression from the glacier in the east was apparently weak, being just enough to open a fissure network in the frozen gravels but not strong enough to offset the primary structures in the host sediments, adjacent to the fissures, or to fold the sequence. It is possible that the frozen crust of gravels transmitted the weak compressional stress from the glacier to other areas (Fig. 1). This weak compressional stress may have contributed to the opening of a fissure system in those areas. Excessive hydrostatic pressure may, however, be a more important agent in this process. The role of compressional stress could perhaps be evaluated in further detail by laboratory experiments.

As mentioned above the area is cut by a swarm of normal faults due to tension across the rift. Certain blocks have subsided in relation to adjacent blocks. Faults were active also at the time of deglaciation while permafrost conditions

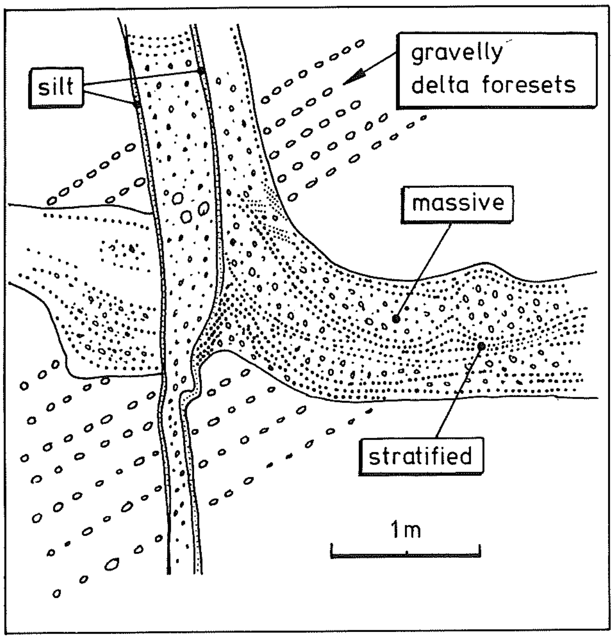


Figure 5 A detailed sketch of a thick subhorizontal sedimentary infill, which branches out into a vertical bed that may have reached the original land surface. Note the massive and stratified character of the bed. A subsequent, poorly sorted, vertical fissure cuts the subhorizontal bed. The later fissure filling is separated from the earlier by a thin layer of yellow silt. The location of this diagram is shown in Fig. 2.

prevailed in the top of these gravel deposits. The following scenario may have existed. Faults cut the frozen gravel, including the possible taliks (meltwater conduits), into polygons. Some of the frozen sheets may have hung across a certain fault or supported by adjacent blocks. Depending on the strength of the frozen gravel, narrow fissures may have been opened below the hanging slabs. In addition, a range of deformation structures would result from movements, small or large, between the different units of the permafrost crust.

Because the faults strike ca. N–S, a ground-water flow pattern and potential tunnels in that direction would have dominated. This interpretation would not require excessive hydrostatic pressure in the ground-water system. However, no N–S striking tunnels have been observed on Dalfjall (which may be due to limited exposures). Instead, the available data indicate a general SE–NW ground-water flow pattern in the gravels (Fig. 9). No faults in that direction have been observed to support the establishment of the SE–NW flow direction and, consequently, the fault hypothesis is perhaps a less probable explanation for the formation of the fissure system.

Because we are dealing with a glacier margin environment, one could also argue that the subhorizontal fissure fillings are intrusive sills or dykes caused by increased hydraulic pressure associated with formation of pingos (see Leffingwell, 1919; Müller, 1959; Mackay, 1962; Cruickshank and Colhoun, 1965; Bostrom 1967). Pingos are generally divided into two different categories, open-system pingos and closed-system pingos. The former are found on valley floors or at the toes of an adjacent slope, the latter are formed in large flat areas, commonly below a very shallow lake. A pingo explanation introduces two problems, however: (i) as with other intrusive dykes, pingo-related fissure fillings would be massive rather than laminated, and (ii) the top of a gravel ridge is a less probable location for pingos. Pingos may have been present, but in a location closer to the present Reykjahlíd village.

Mangerud *et al.* (1981) and Larsen and Mangerud (1992) described laminated clastic dykes from western Norway which according to the interpretation of the authors, were formed in non-frozen Quaternary deposits. Åmark (1986) described some similar structures (dykes and sills) from the Quaternary of southernmost Sweden. According to Åmark, these structures were formed in frozen, and later unfrozen, glacier substratum by deposition from glacier melt waters. The requirement in both of these cases, however, is that the dykes and sills were formed beneath the snout of an active glacier. The data from the Myvatn area suggest that the delta gravels west of Dalfjall were not covered by a glacier, at least not at the time the fissure-fill sediments were formed (see Introduction). Consequently, the above interpretations can be applied only with difficulty in the present case.

To explain the formation of the subhorizontal open fissures, in the Myvatn area, two additional hypotheses are presented in the following discussion.

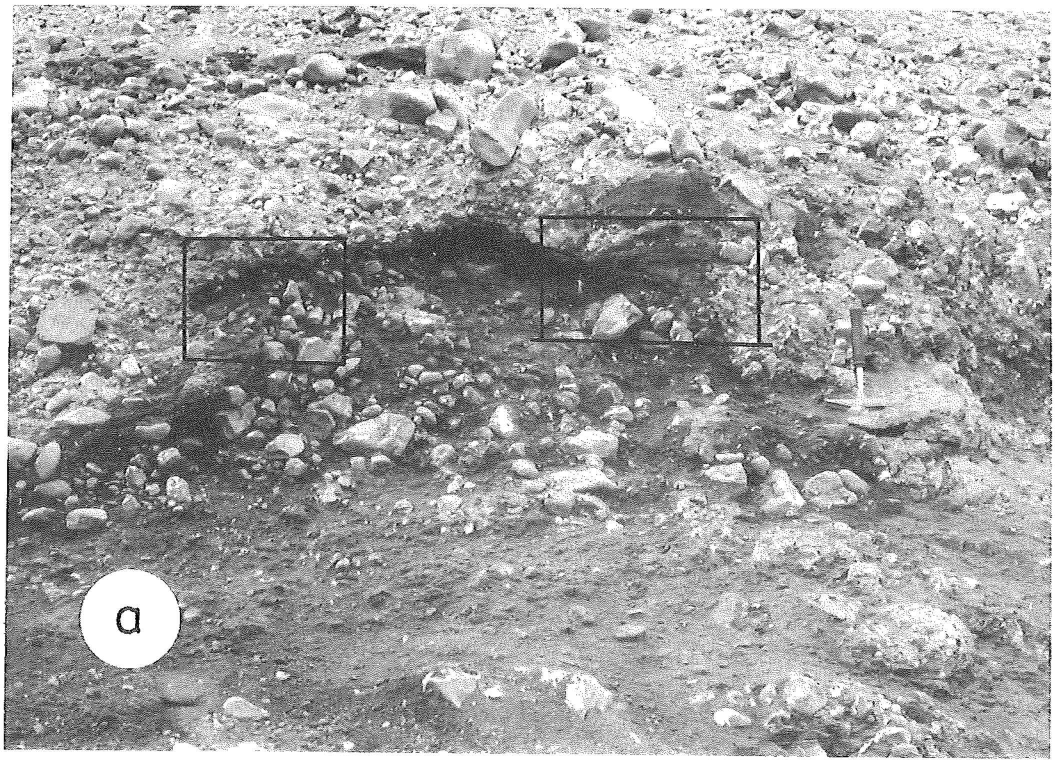
1. Between periods of eruption along this spreading ridge, the heat flow was low enough to allow permafrost conditions to develop on the eroded slopes of the gravel delta. Permafrost that included lenses and sheets of non-frozen soil (taliks) as well as frozen soil (Stearns, 1966; Brown, 1970; Washburn, 1979; Sloan and van Everdingen, 1988; Williams and Smith, 1989). The taliks operate as conduits for ground-water flow.
2. Increased hydrostatic pressure in the delta core would eventually lift some parts of the permafrost crust and open subhorizontal fissures, in which ground-water flow would be established (see Carlsson (1979) and Pusch *et al.* (1990) for application of the hypothesis elsewhere).

Hydrostatic pressure would primarily require a water reservoir, which in this area should be located higher than the delta top. As discussed above, glacier ice was probably pushed up on the eastern slope of Námafjall–Dalfjall. Also, thin sheets (<1 m) of debrites interdigitate the stratified delta gravels along the western slope of Dalfjall (Fig. 11). In contrast to the adjacent stratified gravels, these debrites display an abundance of striated stones of hyaloclastites, without a preferred long-axis orientation. The debrites are therefore interpreted as flow-tills, which flowed down the western slope of Dalfjall from the adjacent melting glacier. The glacier apparently rested high up on Dalfjall and could easily have been the required aquifer.

Meltwaters leaked through the glacier sole into the non-frozen ground, flowing slowly through the porous hyaloclastite ridge (i.e. Dalfjall) and the poorly sorted delta gravels (see Fig. 12) downslope in the direction of present Reykjahlíd. During the summer, some of this ground-water probably reached the slope surface and was collected there into small rivers.

Increased hydrostatic pressure would require that very little or no ground-water seeped up to the slope surface. It is highly probable that low winter temperatures in this glacier-margin environment resulted in a frozen crust (permafrost and the frozen active layer) with effectively reduced permeability. Aufeis (icings), if present, would have reduced the permeability additionally.

It seems likely that these conditions together resulted in increased hydrostatic pressure below the frozen ground, lifting locally the frozen lid of the overlying gravel and opening a network of subhorizontal to vertical fissures. The fissures enhanced the ground-water flow through the delta.



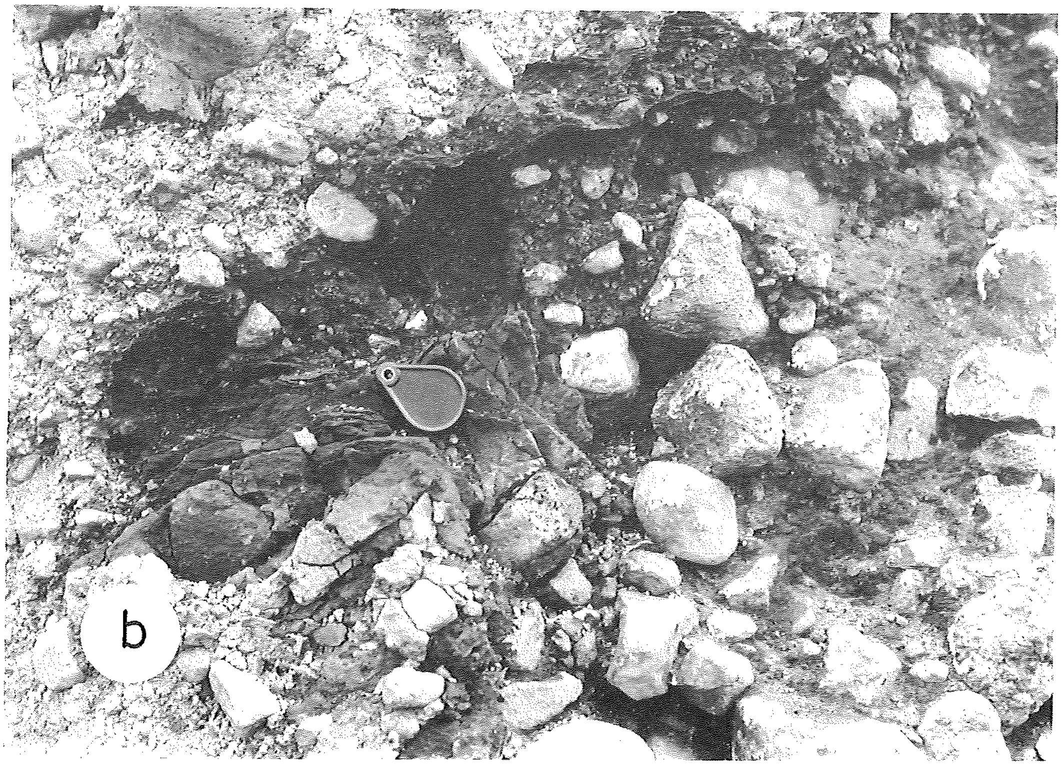
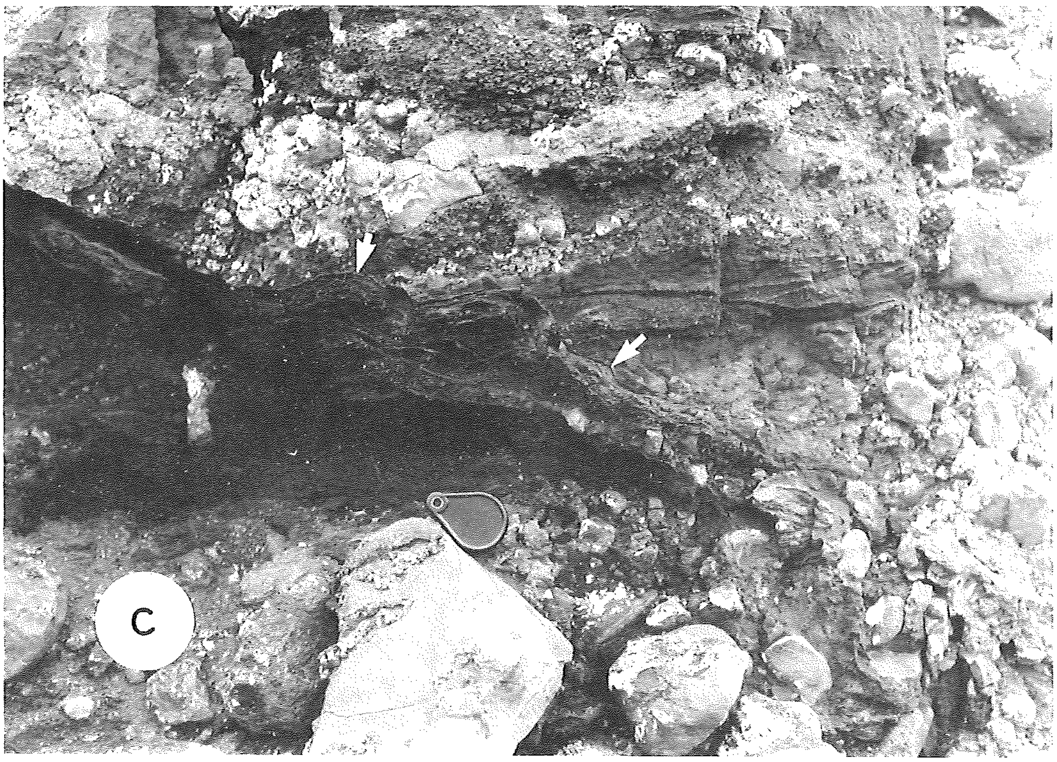
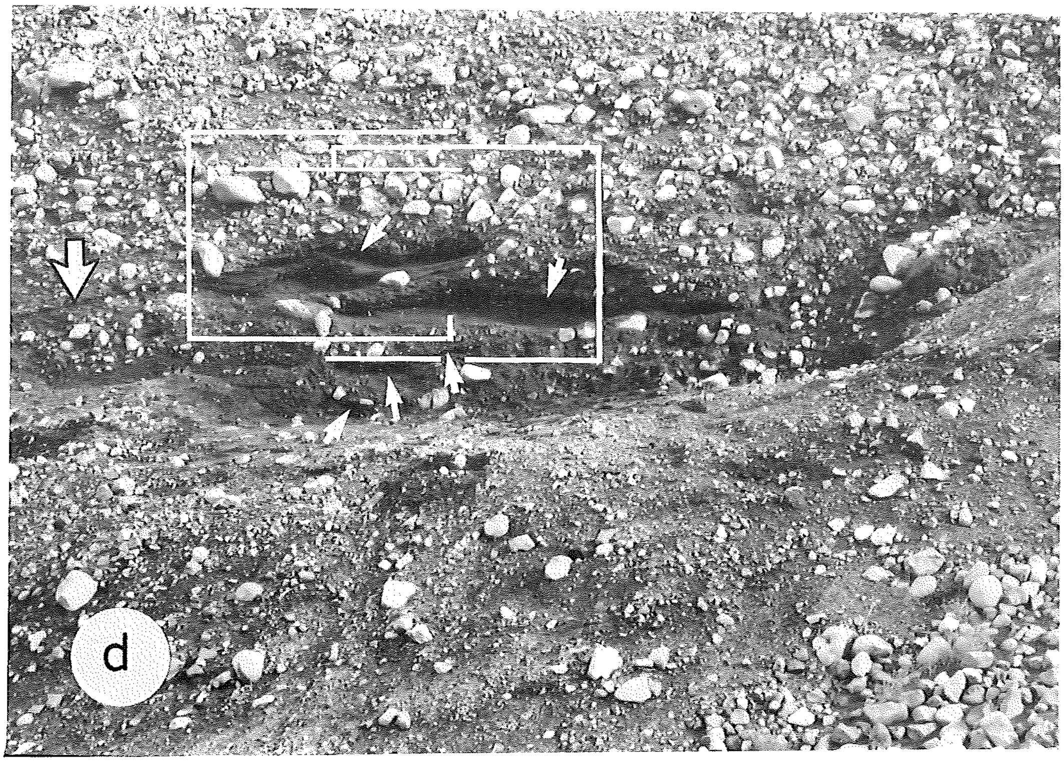


Figure 6 (a) Cross-section of a tunnel-fill dominated by a poorly sorted gravel core with sand layers in the middle and the top, both of them being capped by a thin veneer of wavy-laminated and cross-laminated black sand of volcanic glass. A close examination of the exposure reveals that this tunnel thins laterally into a very thin fissure bed, in the lower left and lower right. (b) A close-up shows the irregular lamination in the tunnel rim, which probably also contains a number of minor pipes. (c) The tunnel ceiling cuts the lower left part of an earlier tunnel with a similar laminated and poorly sorted infill. Note the distinct very thin layer (arrows) dividing these two tunnel fillings. (d) Isolated tunnel fillings (small arrows) surrounded by gravels. Also these tunnels thin laterally into very thin filled fissures (large arrow). The scale bar is 1 m. (e and f) Details in the two larger tunnel fillings of unconsolidated sand, which displays large-scale cross-bedding (small arrows). The upper tunnel (e) apparently also shows a cross-section of a longitudinal dune. The location is indicated in Fig. 2. Sample sites for grain-size analyses are encircled.





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A similar process, which has been documented in the literature, is the formation of frost blisters, which may contain a minor water reservoir between a seasonally frozen ground surface and the underlying permafrost (Williams and Smith, 1989). It is possible that sediment transport and deposition takes place inside the conduits and the blister reservoir. In the Myvatn case, some of the open subhorizontal fissures were formed and later filled by laminated sediments at a depth of at least 15 m (Fig. 2), which is too deep for seasonal frost and subsequent blister formation. Permafrost, however, will readily penetrate to that depth. Such a thick permafrost layer would be quite strong, and hydrostatic pressure would be applied to a larger area and would not result in blister formation. Instead, it is likely that narrow, subhorizontal fissures would be opened locally in the delta slope, as suggested above.

When a ground-water flow through the fissures had been established, fine particles were transported by the running water and were accumulated subsequently in the fissures as well-sorted deposits. The coarser material was left behind. While sedimentation took place at the base, ice in the frozen ceiling or wall gravels was melted gradually by the ground-

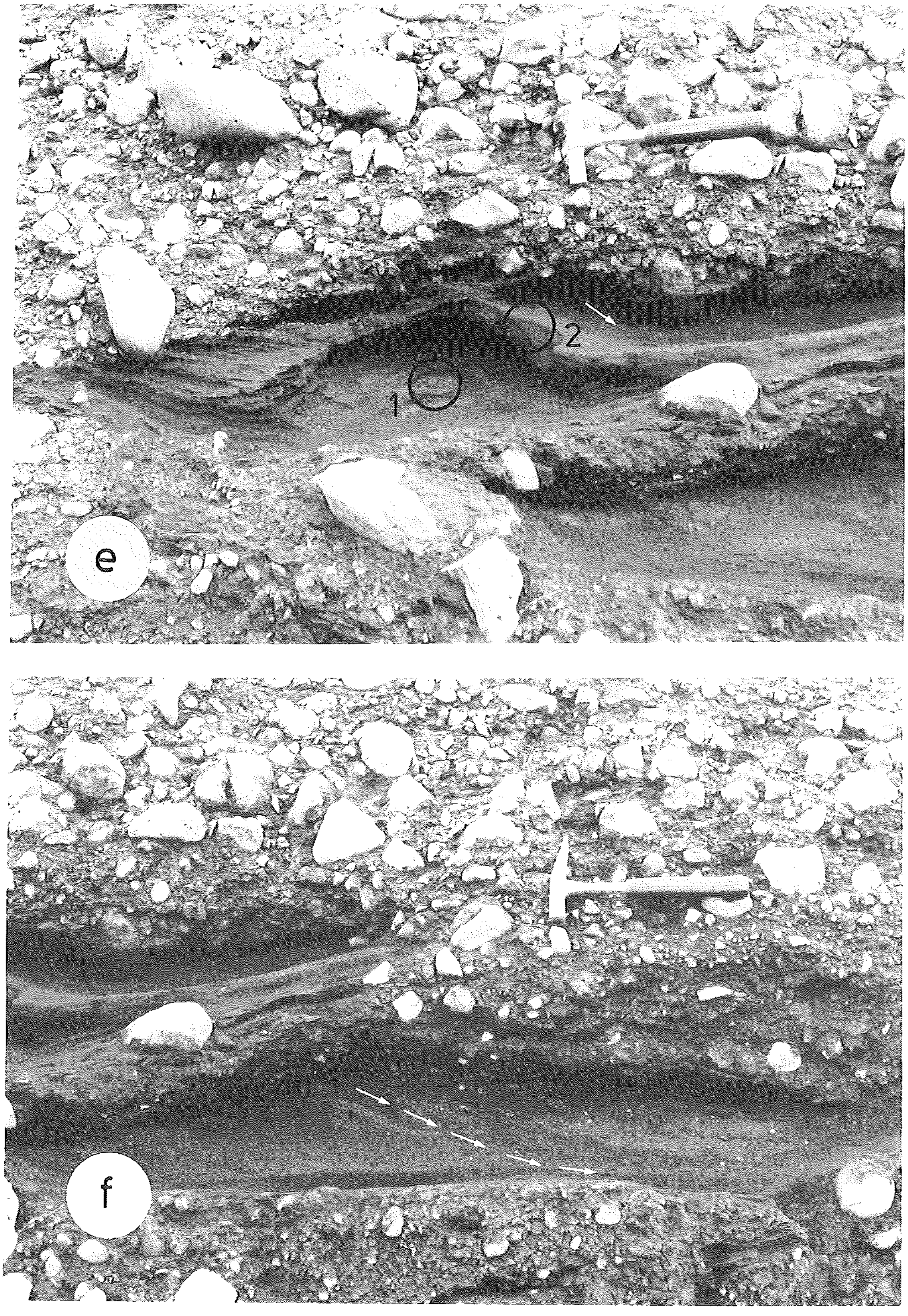

Figure 6 Continued.

water flow or due to seasonal temperature variations. Unsorted material was released and subjected to sorting and transport. Sometimes large parts of the ceiling may have collapsed resulting in very poorly sorted intercalations in the otherwise distinctly laminated deposits. In this way, the active parts of the fissures, which were possibly never wider than millimetres or centimetres, successively moved upwards, while more stratified deposits were accumulated below. In vertical to subvertical fissures, collapsed material may have originated from both walls.

Current velocity in different parts of this fissure system was probably changing continuously depending on factors such as the temperature of the ground-water current, hydrostatic pressure and permeability of the sediments in the ceiling or walls. In places a pipe (tunnel) was developed resulting in increased currents within it, which may have changed the current velocity in other parts of the fissure system. These velocity changes were probably responsible for the development of lamination in the fissure-fill sediments.

The isolated tunnel fillings are thought to be formed as a result of increased hydrostatic pressure enhancing an initial seepage erosion, which removed the fine particles and resulted in the subsequent formation of tunnels with continued erosion along the tunnel walls (tunnel erosion). Decreased

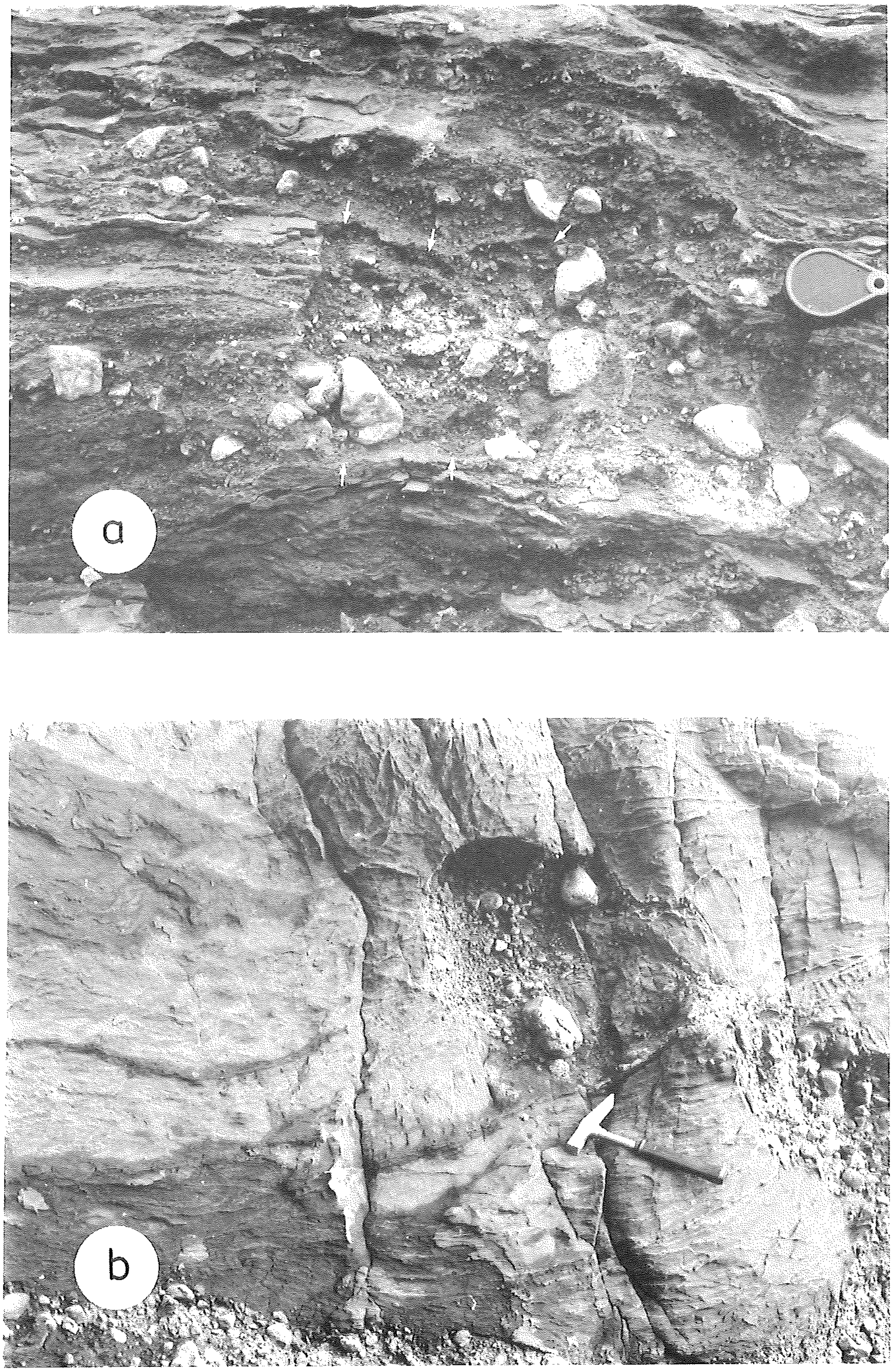

Figure 7 (a) Fissure-fill sediments with characteristic internal stratification are subsequently cut (arrows) by a tunnel, which later was filled with very poorly sorted material. The location is indicated in Fig. 2. (b) Coarse clastic tunnel fillings cut medium- to coarse-grained sandstones, which display an irregular network of veining and/or faults. These tunnels are thought to be related to the same system of tunnels as those described above. Location ca. 2 km south of Hlídarfjall (see Fig. 1).

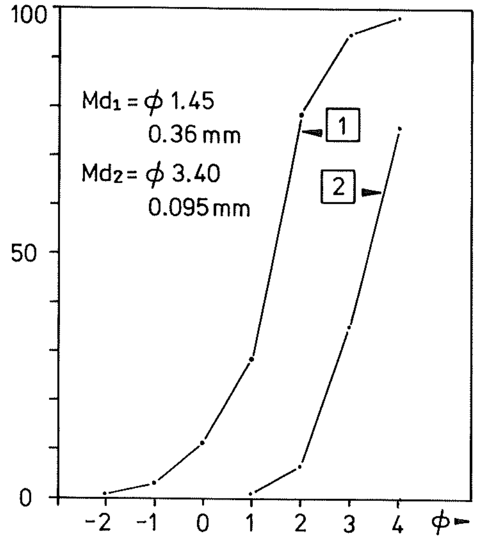

Figure 8 Grain-size distribution of samples from two well-sorted tunnel fillings. Sample sites are indicated in Fig. 7b.

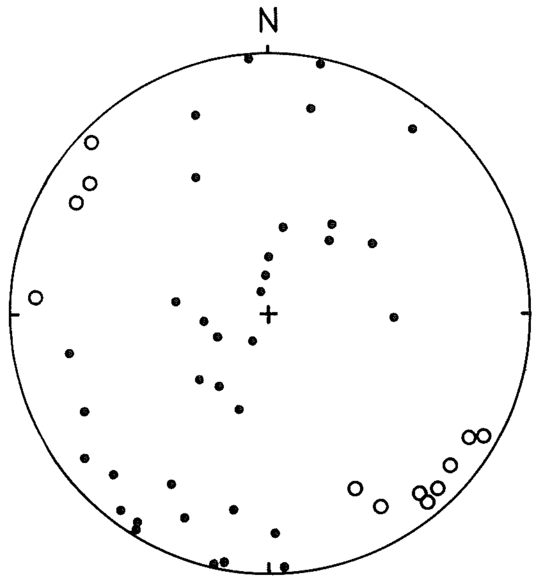

Figure 9 The attitude of the fissure-fill sediments (dots, i.e. poles to the fissures) and tunnels (circles) plotted on a Schmidt net. For further explanation see the text, and for location Fig. 11.

hydrostatic pressure led to lower current velocity in the tunnels allowing deposition of sedimentary particles.

Lenses of stratified sediments inside till-like deposits are generally considered as partial evidence for melt-out tills (Dreimanis, 1988). In those cases the stratified sediments are thought to be deposited either (i) inside the debris-rich glacier ice or (ii) in open spaces between the glacier base and the subglacial tills. The present study offers an additional mechanism for interpreting the origin of thin sheets of laminated clastic deposits inside various glacier margin accumulations, such as very poorly sorted gravels.

Conclusions

The evidence presented above indicates that the fissure-fill sediments and tunnel-fill sediments were formed in open

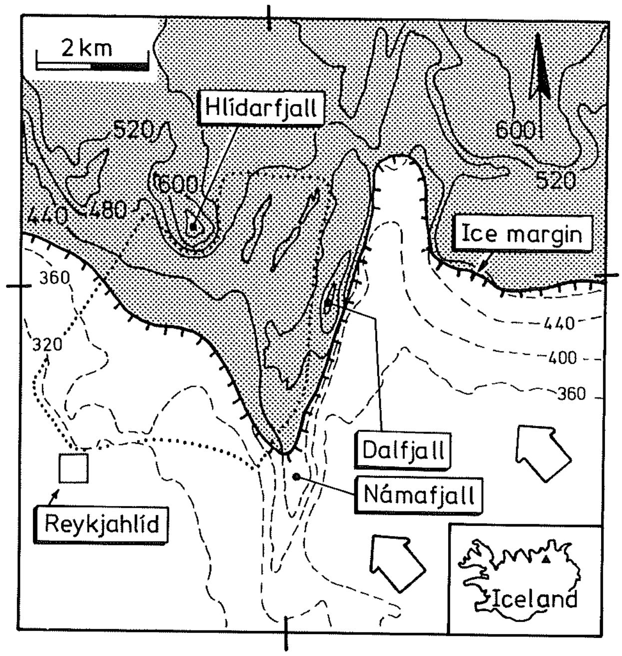

Figure 10 A probable location of the ice-margin during a stage of the deglaciation and the glacier retreat towards the south. Ice-free areas in the north are shown in grey. Some of the proximal part of the delta were removed and the delta top and eroded slopes subjected to subaerial conditions. The glacier ice still rested on the eastern slope of Dalfjall. The local ice-flow direction is given by arrows in the lower right of the figure.

fissures in the non-lithified gravel delta northeast of Myvatn. At the time of the formation of these structures, glacier-margin conditions with permafrost still prevailed in the area. To open the fissure system, a contribution of horizontal compressional stress applied by the glacier on the frozen gravels cannot be excluded. Because no obvious deformation structures have been observed, however, the author favours the interpretation that the fissures were opened primarily by excessive hydrostatic pressure below a frozen crust of fluvial gravel. The fissures were later filled by traction deposits and gravity deposits. Excessive hydrostatic pressure probably also formed the tunnels in these gravels.

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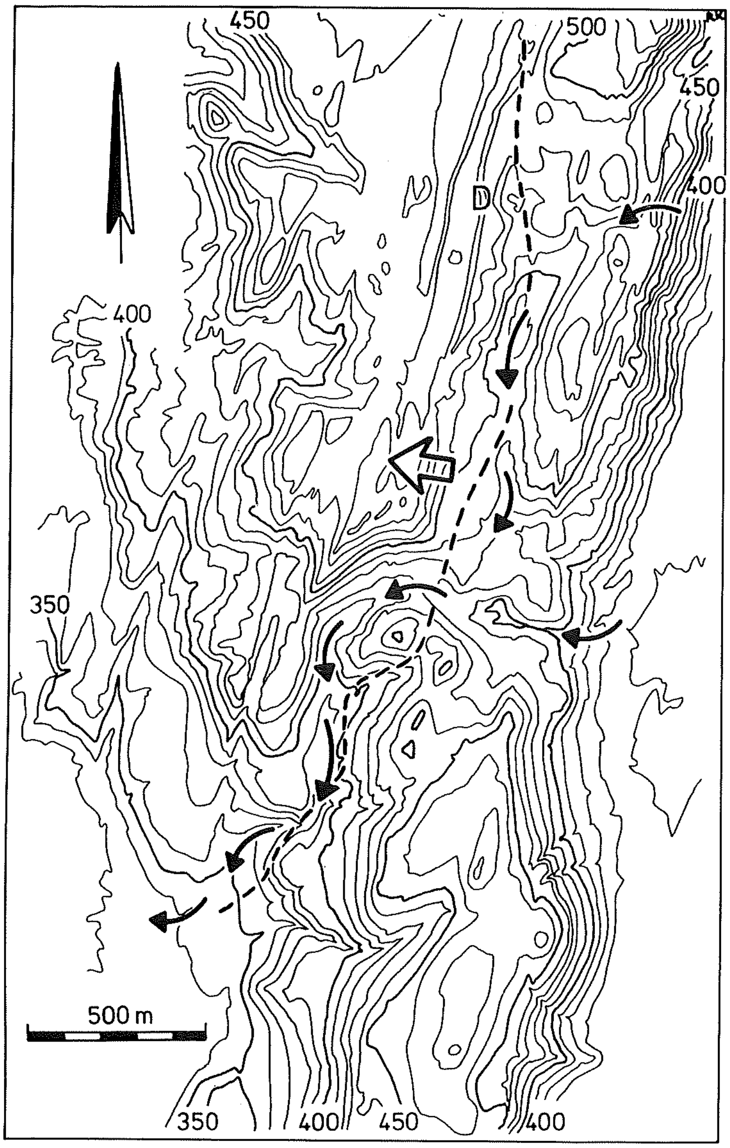

Figure 11 Topographic contours (m a.s.l.) over the central parts of Dalfjall–Námafjall. The broken curve shows the boundary between hyaloclastites in the east and gravels in the west. A minor occurrence of flow tills is indicated by D on the map. The cross-cutting valley, Námaskard, over the ridge was formed by glacier meltwaters. Another meltwater flow may have joined this channel from the north. The open arrow indicates the locality where the data for Fig. 9 were collected.

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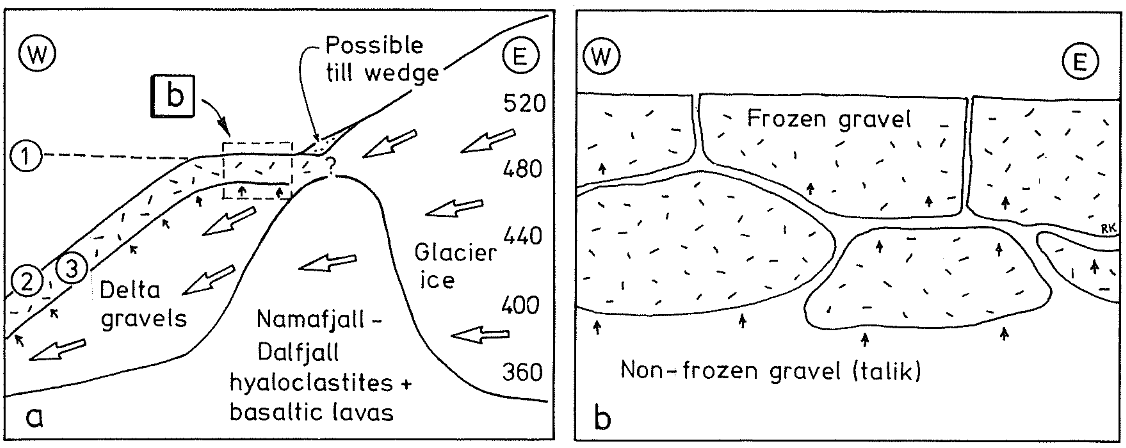

Figure 12 (a) A schematic diagram, essentially an E–W profile across Dalfjall, illustrating the interpretation of the environment in which the fissure-fill sediments and the tunnel fillings were formed. 1. The original delta surface. 2. The eroded delta surface. 3. Frozen crust of discontinuous permafrost and overlying active layer. Ground-water flow (large arrows) through the sole of the glacier, the volcanic ridge and the delta gravels was trapped below the frozen crust. Direction of the hydrostatic pressure exerted on the base of the frozen layer is indicated by small arrows. (b) A hypothetical cross-section through the permafrost layer on the top of Dalfjall. Note that fissure-fill sediments also occur down on the slope, e.g. east of Hlídarfjall and the other two localities west of Dalfjall in Fig. 1.

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