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Stratigraphy and Tectonics of the Húsavík–Western Tjörnes Area
October 2006

Útdráttur á íslensku

Í skýrslunni er sett fram mat á jarðfræði og uppbyggingu jarðlaga innan fyrirhugaðrar álverslóðar norðan Húsavíkur. Langstærsti hluti ummerkja um jarðskorpuhreyfingar sem er að finna norðan Húsavíkur- Flateyjarmisgengisins eru frá míósen. Á plíósen færðust hreyfingarnar hins vegar yfir á Húsavíkur- Flateyjarmisgengið. Eftir því sem nær dregur í tíma verða ummerki jarðskorpuhreyfinga í jarðlagastaflanum mun minna áberandi, bæði hvað varðar þéttleika þeirra og stærðargráðu.

Sérstök áhersla var lögð á að beita öllum mögulegum aðferðum til að finna og rannsaka hugsanleg ummerki jarðskorpuhreyfinga innan rannsóknarsvæðisins. Sérstaklega var reynt að greina á milli eldri og yngri (mögulegra virkra) misgengja. Þrátt fyrir að í gegnum tíðina hafi verið gerð mörg kort sem sýna mismunandi útbreiðslu misgengja á svæðinu, leiddi sú ýtarlega rannsókn sem unnin var vegna þessa verkefnis í ljós að mörg þeirra misgengja sem þar eru sýnd, m.a. þau sem stefna á fyrirhugaða lóð, eiga sér stoð í raunveruleikanum. Húsavíkur- Flateyjarmisgengið (Skjólbrekka og Laugardalur) eru greinileg og umfangsmikil ummerki jarðskjálftahættu. Óreglur sem fram komu í könnunarskurðum benda til að stórir jarðskjálftar hafi gengið nokkrum sinnum yfir svæðið. Sá stærsti átti sér stað í upphafi nútíma, eða fyrir um 2500 árum (löngu eftir að aska úr Heklu-3 féll fyrir um 3100 árum). Síðustu tveir atburðir jarðskjálfta og jarðskorpuhreyfinga sem urðu árin 1755 og 1872 virðast hins vegar aðeins hafa skilið eftir sig minniháttar ummerki í jarðveginum.

Report
Project no.: 500-005

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Abstract

The report presents an assessment of the geology and structure of a proposed building site for an aluminium smelter north of the town of Húsavík. Most deformation of the basement rocks in the area north of the Húsavík Faults occurred in the Miocene. During the Pliocene, transform faulting became focused on the Húsavík Faults. Deformation structures (exclusive of the Húsavík Faults) become much less intense in both density and magnitude upward in the local geologic section. Special effort was made to critically examine the evidence for proposed faults in the area from all available sources. In particular, an attempt was made to distinguish between older structures and younger (and possibly active) structures. Although many different maps have been published with many different fault interpretations, our detailed, ground-based investigations indicate that many of the faults shown there, including those which trend towards the proposed building area, are without basis. The Húsavík Faults (Skjólbrekka and Laugardalur) are an obvious major seismic risk. Disturbance seen in trenches cut across them indicate several faulting events. The largest occurred in early Holocene and about 2500 years ago (long after fall out of 3100 years old Hekla-3 ash). The last two seismic and faulting events on record (1755 and 1872 A.D.) seem to have left only minor disturbances in the soil.

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1 Overview

The Húsavík–Western Tjörnes area is underlain by a complex succession of Late Miocene to Pliocene basaltic lavas and sedimentary rocks partially overlain in the south by a sheet of Late Quaternary lavas and breccias. Glacial deposits and thick soils cover the bedrock extensively. The Húsavík–Western Tjörnes area has been tectonically active for at least the past 7–8 m.y. Intense faulting of the oldest rock unit diminishes sharply upward into the younger units. Faulting has been focused on the Húsavík Faults, a major oblique-slip fault system since at least 5 m.y. This fault system bounds the Tjörnes block on the south. It extends offshore to the NW and landward to the SE where it merges with the westernmost fissure swarm of the active Northern Rift Zone. Seismogenic faulting has occurred on these faults at Húsavík in historic time (last millenium). Field evidence from the area near Húsavík suggests that faulting and related processes have affected even the youngest (Late Quaternary) bedrock unit in an area that is substantially wider than that suggested by the major faults alone. This applies in particular to the area south of them. Regional onshore and offshore fault patterns suggest focused deformation on the major faults linked to more diffuse faulting in the areas adjacent to them.

2 Geology of the Húsavík–Western Tjörnes Area

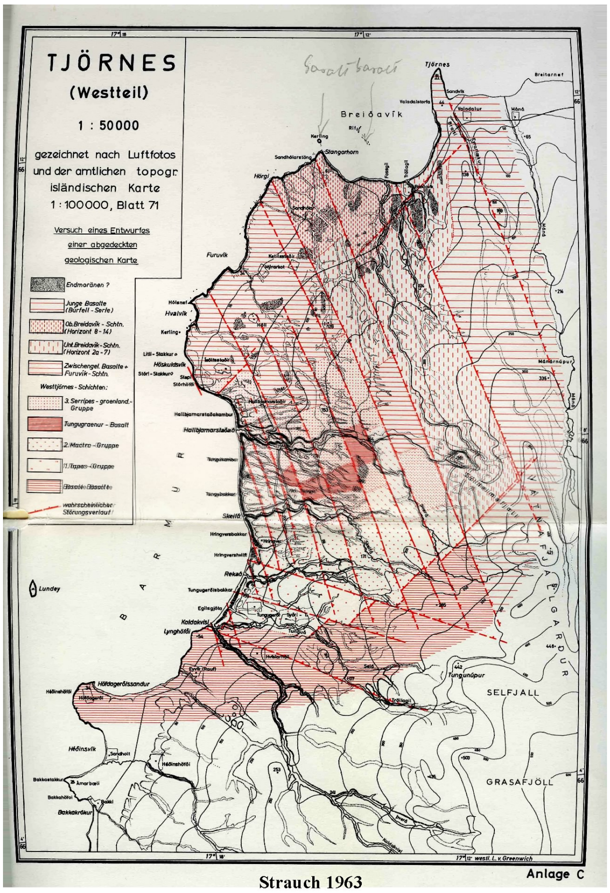
2.1 Introduction

The goal of this study is to provide an objective assessment of the geology and structure north of the town of Húsavík, an area presently under consideration as a building site for an aluminium smelter. Tjörnes and its surrounding offshore area has been included in many previous reports dating back to the early 20th century. The main focus of these studies has been: 1) the stratigraphy of Pliocene to Early Quaternary sediments and lavas, 2) offshore investigations of sedimentation and faulting, and 3) regional studies of faulting and seismicity related to the Tjörnes Transform Fault System. The area has long been known for its faulting and active seismicity (Ward 1971, Sæmundsson, 1974; Zverev et al., 1978; Einarsson and Björnsson, 1979), and yet detailed structural studies on land have not addressed the details of faulting in this area.

A search of available literature turned up at least 10 maps of the general onshore area, most of them showing faults cutting or trending toward the proposed building site (Figure 1 a-k). It is clear that some of these have simply copied or extended faults from the earlier maps. Others include faults that are perfectly straight lines, which contrast with the curvilinear traces of the faults that have been traced carefully on the ground. In fact, most previous maps showing faults at or near the site seem to be based on rather meagre field work and are probably based solely on interpretations of air photos and satellite images. The map of Egilsson, et al. (2004) shown as Figure 1i was specifically made with regard to the Bakki Site.

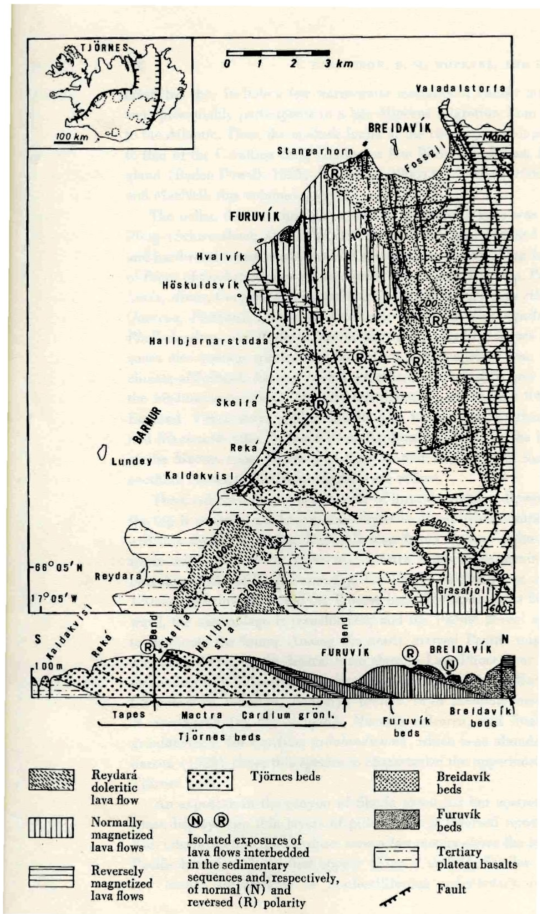
Our purpose was to evaluate all the previous reports of the geology of the area with special attention to proposed faults. Steep terrain, stream cuts and coastal cliffs provided excellent exposures of bedrock units. Gravel pits, quarries, river banks and irrigation ditches also provided some information on surficial deposits. Several trenches were also dug in order to evaluate known and proposed faults in critical areas. We made a special effort to critically examine the evidence for proposed faults in the area from all available sources. In particular, we attempted as possible to distinguish between older structures and younger (and possibly active) structures. Our study does not evaluate seismic risk other than what could be defined from trenching, as has been done in similar settings elsewhere (Weldon el al., 2004; Hartleb et al., 2006). We also briefly address effects from ground-shaking that might be found in appropriate unconsolidated sediments and discuss the general patterns and distribution of faulting as it has developed through time.

Figure 1 a–k. *Geological maps of western Tjörnes and the peninsula as a whole that were published over the last 40 years show the main features of the geology. Some of these maps focused on faulting of the area. The map by Egilsson et al. (2004) was specifically made with regard to the Bakki building site. We checked the straight lines shown there as possible faults. Some of them are exposed in stream cuts, others are covered. None of them were found to be faults. We had trenches dug across two of the covered and rather prominent ones without finding evidence of faults in the Late Glacial and Holocene sections. Those two are marked by arrows.*



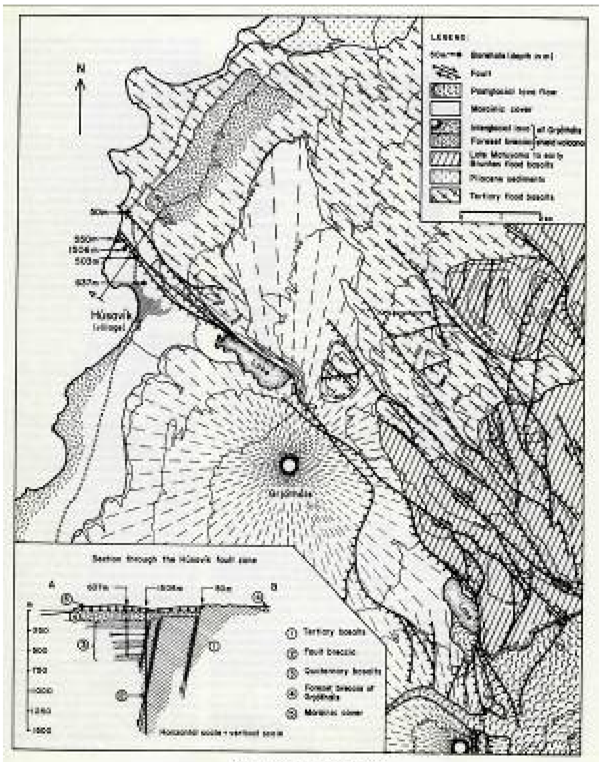
Strauch 1963

a



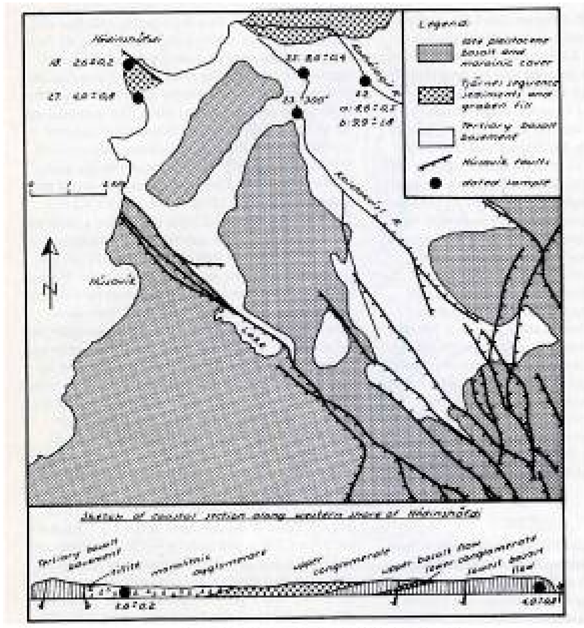
Einarsson et al. 1967

b



Sæmundsson 1974

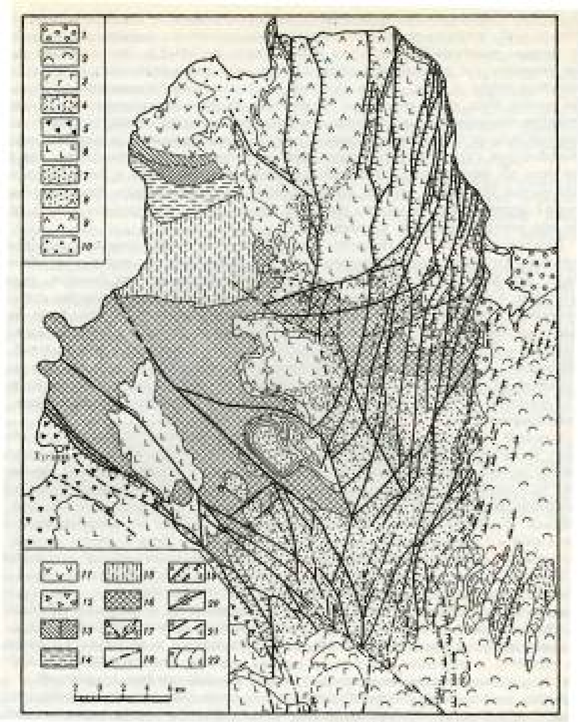
c



Aronson and Sæmundsson 1975

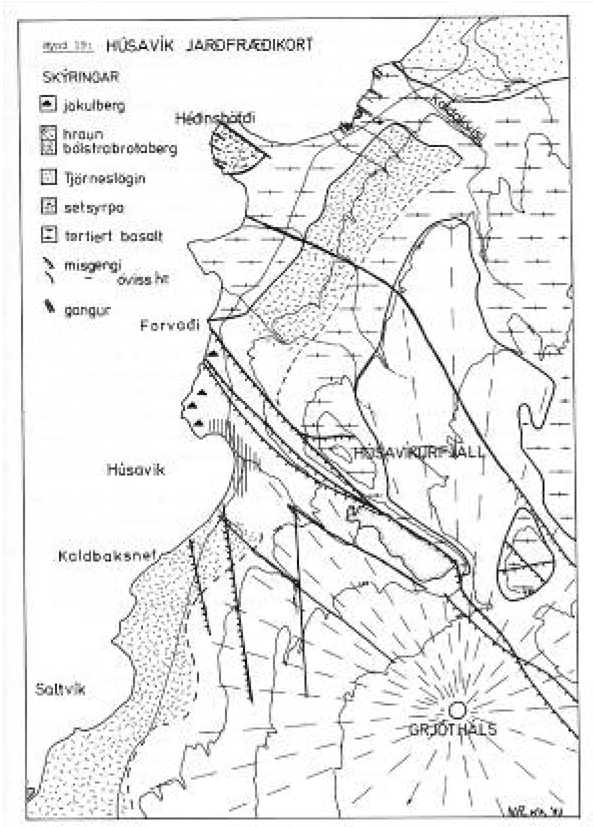
d

Figure 1 a–d.



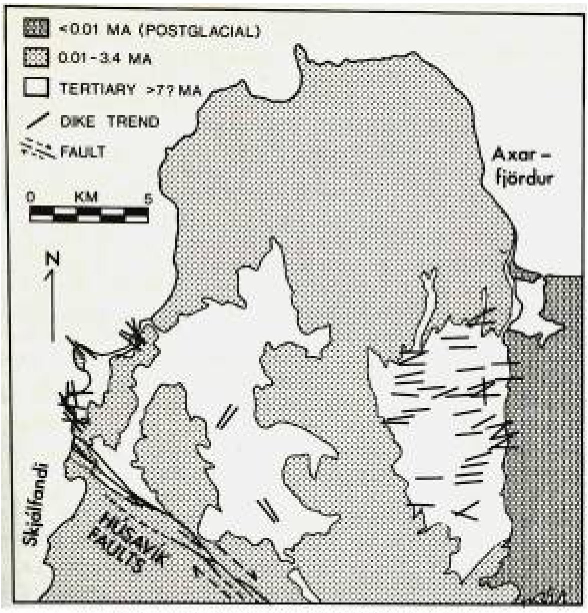
Gladenkov 1978

e



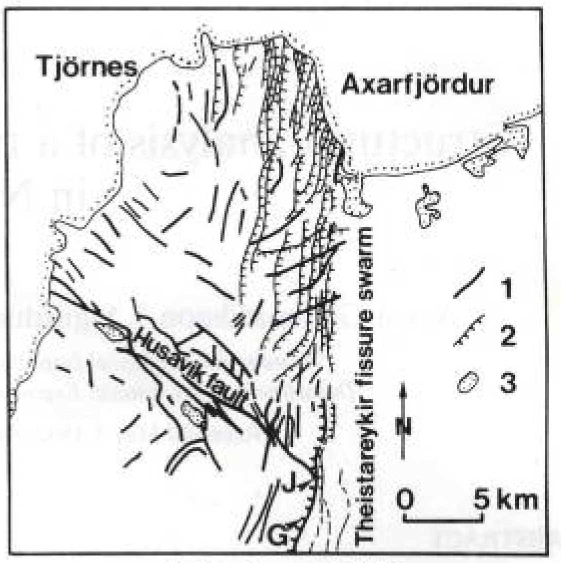
Þóroddsson et al. 1984

f



Young et al. 1985. Dike orientations.

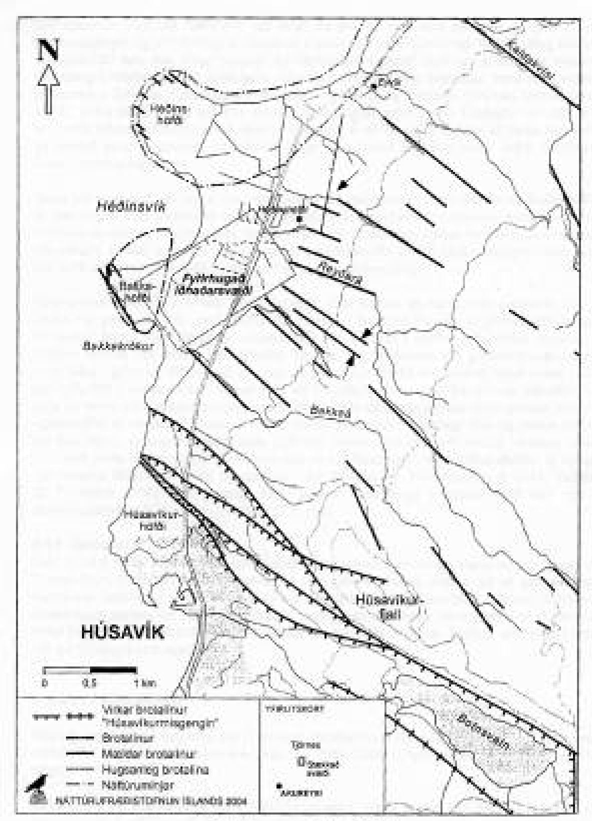
g



Gudmundsson et al. 1993

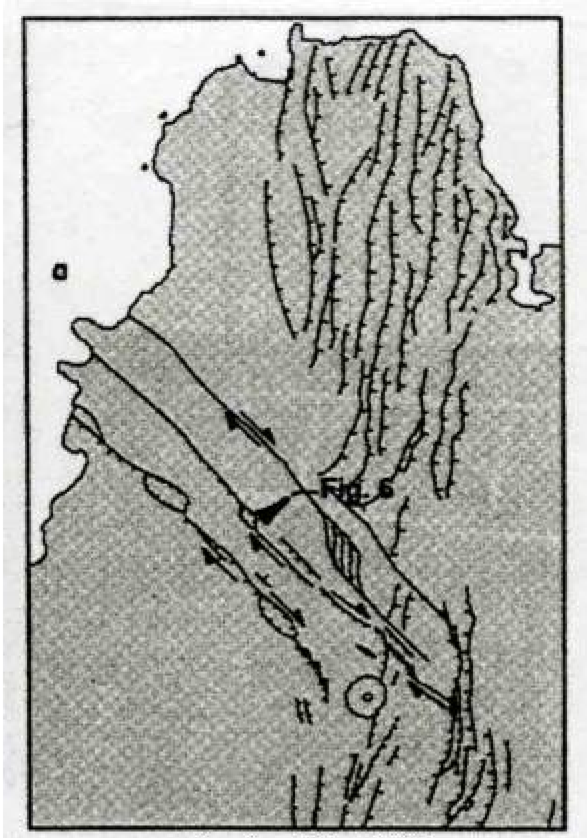
h

Figure 1 e–h.



Egilsson et al. 2004

i



Garcia and Dhont 2005

k

Figure 1 i–k.

Figure 1 i: *Arrows point at two overgrown NW-SE furrows which were trenched. Faults were not seen in them. A suggested fault trending NNE-SSW is also marked by arrow farther north. No indication of a fault was found there either.*

2.2 Local Geology

In the following sections we describe the geologic structure of the study area (see accompanying geological map). We draw on previous reports as well as our own field observations in which we have made a critical evaluation of the geologic units and tectonic structures. In part following previous workers, we subdivide the rocks into a series of 7 mappable units. We group these under broader headings of Basaltic Lavas and Sedimentary Rocks, Glacial and Post-Glacial Units, Subsoil and Soil, and Offshore Geology. For each unit we provide a basic geological desciption, a summary of major structures and a brief interpretation. The Húsavík Faults are treated under a separate heading.

2.3 Basaltic Lavas & Sedimentary Rocks

Unit 1-Miocene Lavas

Unit 1 consists of basaltic lavas dated at about 10 m.y. (Aronson and Saemundsson, 1975). The unit extends from the shore north of Húsavík towards SE, rising in altitude to the topographically highest outcrops at over 700 m above sea level (m a.s.l.) in the south central part of the Tjörnes Block. Towards south the Unit 1 basalts are abruptly cut off by the NW-SE trending Húsavík Faults. The basalts are not known to occur south of the faults. These lavas include mainly grey to brown massive lava flows up to about 15 m thick including flow-top breccias. Red sandstone to siltstone interbeds are common. Secondary minerals in the basalts include scolecite, mordenite, stilbite, laumontite, chabazite and thomsonite. Laumontite occurs sporadically near sea level indicating that the laumontite zeolite facies is about to be reached (Walker 1960). The presence of laumontite would require a temperature of about 120°C at the time of secondary mineralization which is expected at a depth of about 1500 meters of rock. Dikes cutting the lavas are common. They trend mostly NW-SE or E-W. The dike rock is primarily of two types, a coarse-grained, rather fresh olivine basalt and finer-grained more altered basalt. The proposed building site is located on Unit 1 basalts.

Coherent blocks of basalt and red sedimentary interbeds are heavily fractured and jointed. They are bounded by discrete fault zones and tilted up to 40° towards the north (dips of flows vary from northwest to northeast) (Figure 2). Tilting occurs as a result of slip on north- to northeast-trending normal and oblique-slip faults, commonly with sinistral strike-slip components. Prominent northwest-trending, strike-slip faults occur in some places. Inconsistent cross-cutting relations among the normal and strike-slip faults suggest that they slipped concurrently. Many faults have rather pervasive damage zones up to more than 1 m wide with the fractures lined mostly with scolecite. Relatively few faults have well developed clay gouge. Fault breccias and cataclasites are lined mainly with scolecite, and subordinate stilbite and laumontite and gouge fillings are also commonly impregnated with zeolites (Figures 3 and 4). It has been suggested that the strongly faulted and tilted Miocene basalts including most of the dikes which cut them suffered clockwise shear rotation along the southern margin of the Tjörnes Fracture Zone (Orkan et al. 1984). The distributed style of faulting over a 5 km wide area between Húsavík and Kaldakvísl might be related to aseismic deformation rather than focused seismic slip.

Exhumation of Unit 1 basalts involved removal of nearly 1500 m of rock and a corresponding isostatic uplift. Building up of a 1500 m thick lava pile may have taken some 2 m.y. About 3 m.y. are left for its subsequent uplift, erosion and intense faulting as an age gap of about 5 m.y. separates Unit 1 basalts from the much less faulted overlying unit.

Figure 2. *Miocene basalts (Unit 1) dipping about 30° NW. Debris filled fault dipping SE in right of picture.*

Figure 3. *Faults are very common in the Miocene basalts (Unit 1). Some of them are filled with cataclastite.*

Figure 4. *Miocene basalt (Unit 1). The basalt of Unit 1 as a rule is strongly fractured and infilled with zeolites. Striations are very common and well preserved.*

Unit 2-Pliocene Lavas & Interlayered sedimentary rocks

Unit 2 consists of interlayerd basaltic lavas and sedimentary rocks. They are exposed over a stretch of 1 km in the sea cliff at Kaldakvísl and upstream beyond the bridge and are conformable with the overlying Tjörnes Beds (Bárðarson 1925; Harðarson et al. 1978) (Figure 5). Radiometric ages on the basalts indicate an age of about 4.3 m.y. (Albertsson 1976) in accord with their position conformably beneath the Tjörnes Beds (Unit 3). Some previous authors included this unit with the strongly tilted and fractured Miocene basalts described here as Unit 1. Unit 2 lithologies are separated from Unit 1 by an angular and erosional unconformity. This unconformity is distinct but rather poorly exposed in deeply weathered rocks.

The unit consists of three flows which are thick, coarse-grained and aphyric. Thick red and brown interbeds of clay- or siltstone (up to 10–12 m) separate the flows. Unit 2 basalts are poor in secondary minerals (chabazite and calcite were found). A characteristic feature is a very pronounced spheroidal weathering. Dikes were not found in Unit 2.

Unit 2 lava flows have a northerly dip of about 8–10°. They are less faulted than Unit 1 basalts and single members are mappable for several hundred meters in the coastal cliff, in contrast to the underlying flows of Unit 1 which are rarely tracable more than a few tens of meters. However, at Kaldakvísl the fairly regular sequence of Unit 2 is broken up by NW-SE and NE-SW faults with vertical separations of a few meters to about 10 m. Poor exposures and deep weathering prevented detailed obsevations of the fault rocks in this unit.

Figure 5. *Tjörnes Beds (Unit 3) conformably overlying spheroidally weathered basalt flow (Unit 2) at Kaldakvísl.*

Unit 3-Pliocene Tjörnes Beds

Unit 3 consists of the Pliocene, fossiliferous Tjörnes Beds including mainly coastal to shallow marine sandstones, siltstones and shales but also thin lignite seams in the lower half. They range in age from at least 4 to 2.5 m.y. (Einarsson et al. 1967, Albertsson 1978). They are exposed in sea cliffs from Kaldakvísl for about 5 km to the north and upstream along river courses. They have northwesterly dips of about 5–8°. The total thickness of the unit amounts to a few hundred meters. Interlayered basalts are of Plio-Pleistocene age (Albertsson 1978). There is an isolated outcrop of Unit 3 in the map area on the shore at Eyvík, about 1.5 km south of Kaldakvísl. It extends for about 100 m along the shore and eastward along a stream course to the mainroad. The sediment consists of poorly consolidated mudstone intercalated with streaks of lignite. It occupies a depression in Unit 1 basalts, Unit 2 being absent. It has been correlated with the lowest part of the Tjörnes Beds (Hardarson et al. 1978).

The Tjörnes Beds are cut by faults but much less so than Unit 1. This was noted by both Bardarson (1928) and Strauch (1963). We looked into one of Strauch´s best exposed sections at Hallbjarnarstaðaá and generally confirmed his findings. Contrary to his mapping, we find that the faults vary in trend from N-S to NE-SW, rather than trending consitently NNW-SSE. They are primarily normal faults with vertical separations of as much as 10 m, but NW-trending, strike-slip faults are also present. The faults create no relief on the top of the Tjörnes Beds (Unit 3). This also applies to the basalts which overlie the sediments in the northwest of Tjörnes. Of faults exposed in the sea cliffs the first which have a topographic expression, in these basalts appear 3–4 km east of the coast. Dikes are conspicupusly absent in Unit 3.

Unit 4-Local Lavas & Conglomerates

Unit 4 is confined to a depression created by faulting and/or erosion into Unit 1 basalts (Aronson and Saemundsson 1975). It is filled by basaltic lava flows and conglomerates which are exposed in the cliffs of Héðinshöfði. The contact of Unit 4 with the Miocene basalts of Unit 1 is not exposed. The better constrained of two radiometric dates from the upper flows yielded an age of 2.6 m.y. (Aronson and Saemundsson, 1975).

There are three flows. The lower ones are coarse-grained and distinctly porphyritic (plagioclase). The flows are up to 25 m thick with two-tiered columnar jointing and very thick entablatures created as a result of water flowing over them while still hot. The two upper flows are separated by a ~5 m thick layer of brown sandstone and conglomerate. The topmost flow is overlain by a thick sandstone and mainly boulder conglomerate of up to 12 m. Cross-bedding of the finer-grained sediments and textural maturity of the conglomerates indicates fluvial transport.

The flows dip 5-15° to the northeast and are cut by both normal and strike-slip faults mostly trending N35-45°E and N10W-N10°E, respectively. Most of the faults have vertical separations with down-to-the-NW displacements (Figure 6). Faults with displacements of less than a few tens of centimenters are marked by damage zones with high fracture density but little grain-size reduction. Consequently, these appear to be rather permeable structures as is indicated by seepages. Faults with larger displacements have well-defined gouge zones and are probably impermeable. Consistent tilting of lava flows and bedding indicate planar, domino-style normal faulting. Fault surfaces are in some cases lined with amorphous silica (opal). A major NW-trending, dextral strike-slip fault marks the northern limit of this unit. The amount of diplacement on this fault could not be determined because of a lack of appropriate offset markers.

The flow tops of Unit 4 basalts are vesicular with abundant chabazite as the main amygdale mineral. The degree of zeolitization, although poor in species (levyne, thomsonite and calcite also occur), indicates a position of the lavas in the upper 100–200 meters of the chabazite-thomsonite zone. This zeolite zone begins to develop some 200 m deep in other Icelandic lava piles (Walker 1960). In total the original thickness of Unit 4 group may have amounted to at least 300 meters. Unit 4 has been correlated with the so called Furuvík basalt group which overlies the Tjörnes Beds in the NW of the Tjörnes Peninsula (Aronson and Saemundsson 1975). The rock type (entablature flows occur) and the degree of weathering is similar. Unit 4 thus may have formed a protective cover of the Tjörnes Beds during most of the Pleistocene, but suffered erosion, such that the Héðinshöfði outcrop was left as a remnant detached from the main outcrop farther north.

Figure 6. *Sea cliff in the SW of Héðinshöfði (Unit 4). Sediment overlying entablature flow. The faults trend N30-40°E.*

2.4 Glacial and Post-Glacial Units

The next units are much younger than the ones previously described. They are not visibly tilted, but they are significantly eroded and affected by brittle deformation associated with the Húsavík Fault System. The oldest members may date from the second- or third-last interglacial, about 0.2–0.3 m.y.

Unit 5- Sandstone & Siltstone

Unit 5 is a sedimentary unit found in a few localities underlying Unit 6 (Grjótháls Lava Shield). The lowest outcrop of this unit at 60 m a.s.l. at Reyðará is slightly indurated shell bearing sandstone and siltstone of marine origin. The main outcrop of gray sandstone at 210-220 m altitude at Bakkaá is at least 10 m thick. Fossils were not found there. However, marine fossils do occur in sediment at the base of the Grjótháls unit (Unit 6) at sea level 5 km south of Húsavík (Einarsson, 1965). The sediment probably dates from the second or third-last interglacial as the Grjótháls Shield (Unit 6). Fractures in the sediment (sandstone and conglomerate at Bakkaá) trend NE-SW and NW-SE.

Unit 6- Grjótháls Lava Shield

Unit 6 consists of the products of the Grjótháls Lava Shield including both relatively fresh, gray-green lavas at higher elevations and gold and brown hyaloclastites of a lava delta (Einarsson, 1965) closer to sea level. The main outcrop of the Grjótháls Shield is south of the Húsavík Faults. This unit has largely buried and smoothed-out the topography created by the faults and a veneer of its lavas covers a large area on the footwall north of and adjacent to the main fault. The transition zone from lavas to foresets of the hylaoclastite delta is at about 100 m.a.s.l. north of the Húsavík Faults and at about 35–

40 m to the south of them. The difference indicates the accumulated throw of the faults since the formation of the shield. The thickness of the unit is variable, but probably reaches over 200 m around the apex of the shield south of the faults but may exeed 50 m in erosive channels to the north of them. The Grjótháls Shield lava flowed into the sea as is evident from silty sedimentary beds containing shells underlying the breccia as mentioned above. The age of the Grjótháls Shield was estimated as last or second-last interglacial by Saemundsson (1974).

Special attention was paid to fracturing of Unit 6 hyaloclastite breccia north of the Húsavík Faults as it covers the lowest part of the slope east of the proposed plant site. This made it possible to observe to what degree faulting affected Late Pleistocene rocks in this specific area. The breccia is cut by dominantly N-S and fractures and faults, most of them showing centimeter-scale displacements. NW-SE trending fractures occur also. The small number of these is probably due to the exposures which follow this trend (Figure 7). Dip-slip and oblique-slip displacements were observed. Exposures are mostly limited to three stream cuts, all of them shown as faults on a recent map (Egilsson et al. 2004) and trending towards the plant site. Significant faults were not found in any of these. Instead, fractures and minor faults up to 1–2 cm wide and trending in a northerly direction are common. Most of them are plugged with indurated clayey fill or fault gouge.

Larger faults cutting Unit 6 were also documented. These occur south of the Húsavík Faults and north of them in the far eastern part of the outcrop area.

Figure 7. *Type of fracturing observed in Unit 6 breccia (right of spade). The fractures are seldom more than 2 cm wide, with a filling of compact sand- or siltstone. Most of them have a northerly trend.*

To the south of the Húsavík Faults, the largest fault cutting Unit 6 is exposed in coastal cliffs about 1 km south of the Húsavík harbor. This is a steeply dipping, strike-slip fault that strikes N50°W and has both a well-developed damage zone and a core of clay fault gouge. Fresh exposures in the rock quarry to the southeast of town also expose a fault zone about 20 m wide made up of several discrete faults, each with (normal-dextral, oblique-slip) displacements of less than about 1 m. Other faults in the hanging wall of the Húsavík Faults include NE-trending splays that link the main NW-tending strike-slip faults. These bound pull-apart basins (e.g., Botnsvatn) and other extensional relay zones (Saemundsson, 1974; Gudmundsson et al., 1993; Garcia et al., 2006) (Fig. 1 b, g and k).

Just north of the Húsavík Faults the Grjóthàls Shield Lavas are cut by at least one NW-SE-trending normal fault in the easternmost part of the outcrop area. The topographic expression (throw?) of this fault diminishes from about 15 m to about 2 m from SE to NW over a distance of 1.5 km and is lost as a topographic feature farther to the NW.

Generally it can be stated that the intensity of faulting changes markedly from north-west to southeast adjacent to the Húsavík Faults, with more and larger faults towards the southeast.

Unit 7-Tillite

Unit 7 is a sequence of tillite and related sedimentary rocks exposed in low hills north and east of Húsavík (Húsavíkurhöfði) in the area of the Húsavík Faults and banking up against them. A tillite sequence is also exposed as an erosional remnant in Lundey, an island 5 km to the north (Pjeturss, 1910). This material consists of well indurated to friable light brown, buff, to brownish gray sandstone, siltstone, shale and conglomerate including tillite like boulder-clays (Figure 8). Complex cross-bedding and trough structures are common. The thickness of the sequence is about 50 m and the whole of it is thought to have been deposited during the last glaciation.

The tillite sequence is cut by the large NW-SE trending Húsavík Faults just north of the town. The vertical separation on the two main faults amounts to at least 12 m in the tillite. In addition, there are numerous N-S trending, dip-slip to oblique-slip (normal-dextral) faults throughout most of the exposures. Displacements on those are typically on the order of a few centimeters. Hot water (over 60°C) issues from NW-SE faults at sea level south of the main faults and also (30–36°C) from the N-S ones at the harbour. The faults in Unit 7 look very fresh and some of the larger ones are gaping by several centimeters. Others have been partially filled with laminated clay deposits. They differ in this respect from faults in Units 1 to 6 north of the Húsavík Faults.

Figure 8. *Húsavíkurhöfði is made up of alternating, several meters thick layers of siltstone, sandstone and conglomerate, including tillite like boulder clays. The rock is well indurated to friable. Height of section about 10 meters.*

2.5 Subsoil and Soil

Gravel terraces occur locally on the lower slopes between Húsavík and Kaldakvísl at an altitude of 20–40 m. They are more extensive at a similar altitude south and south-east of Húsavík. Part of the town is built on them at a lower terrace level. The terraces formed at a time of marine trangression during rapid ice melting in Finiglacial to Early Holocene time. The gravel has been exploited and the pits have been left partly open.

Lower down to the west, in the area of the proposed building site, the ground is boggy, underlain by silt, probably of marine origin too.

We looked for evidence of liquefaction or disturbance in the silty sediment that might have resulted from earthquake shocks. The only exposure of that kind which we found was at the mouth of Reyðará at Héðinsvík. Two irregularities were seen in a 30 m long section. These include injections of sandy to gravelly material into overlying clayey layers of the subsoil and lower part of the soil which contains peat and diatomite. Higher up the soil is composed largely of loess with volcanic ash layers, not very suitable for preserving these kinds of features.

Another instance was seen in a gravel pit on the terrace south of Eyvík. Here, moderately indurated gravel is cut by small NE-trending faults marked by pink clay seams. Two small (2–15 cm wide) clastic sediment dikes intrude upward into the late glacial gravel.

The Bakki Site was the specific focus of a recent study (Egilsson et al., 2004). This includes a map with several proposed faults crossing the proposed building site (Figure 1 i). We checked most of these proposed faults (shown as straight lines on the map of Egilsson et al., 2004). Some follow the main trend of streams, others are overgrown stream beds in an area of fluted moraines and glacial outwash dating from the end of the last glaciation.

We had trenches dug across two of the most prominent lineaments down to hardened conglomerate or moraine. These two are marked by arrows on Figure 1 i. Near its base, the soil above contains a nearly continuous, yellowish, rhyolitic ash (so called S-layer, from Askja volcano, here about 5 cm thick). It is 11,200 years old, i.e. earliest Holocene (the Holocene began 11,450 yr ago). Several other, more or less continuous, centimeter-scale, ash layers are also present in the walls of the trenches. No disturbance attributable to faulting was seen. We are confident that the same applies to other grooves and lineaments in the area that have been proposed as faults on the various maps.

2.6 Springs and geothermal activity

Springs are sometimes a useful guide to subsurface fracturing so particular attention was paid to springs around the proposed plant area. Springs rarely occur in the fractured Miocene basalts (Unit 1) and none were found in the Bakkahöfði promontory. Small seepages occur in the entablature flows of Héðinshöfði, mostly from joints but in one case also from a NE-SW-fracture. Numerous springs were found to occur near the base of the Grjótháls Shield Lava unit, generally following topographic contours. The springs there do not occur along a lineament and therefore do not appear to be related to a fault. Late Pleistocene lavas of this type, being unaltered and retaining much of their original vesicularity, are known to be permeable and good aquifers. Very copious cold springs issue from the Grjótháls lava southeast of Húsavík, some of them yielding over 100 l/s (Hjartarson 1984).

A hot spring occurs in fractures in Unit 7 tillite on the narrow wave cut platform about 100 m south of the Laugardalur Fault (Figure 9), not far from a 1500 m deep borehole in the tillite above. Warm springs also issue from fractures in the tillite at the Húsavík harbour.

Figure 9. *Fissures trending N50°W south og Laugardalur. This is part of a 40 m broad fissure zone from which hot springs well forth (60°C max.).*

Geothermal gradient boreholes have been drilled in Tjörnes at Kaldakvísl and Hallbjarnarstaðir 4.5 km north of the stream. At Kaldakvísl a gradient of ~8°C/100 m was found, a value close to the regional average found in near impermeable basalts in North Iceland (6–7°C/100 m) unaffected by geothermal or cold ground water systems. At Hallbjarnarstaðir high gradients of 18° and 26°C/100 m (there are two boreholes) most likely indicate proximity to a fracture-related geothermal system.

The result from the Kaldakvísl boreholes excludes the presence of a geothermal or cold ground water system (i.e. good fracture permeability of the bedrock) within about 800 m distance. Drilling of three additional shallow (50–60 m deep) wells within and near the proposed building site would help to locate/exclude such anomalies if present.

2.7 Holocene displacement on the Húsavík Faults

The Húsavík Faults are the obvious major seismic risk for the building site at Bakki. There are two main faults, Skjólbrekka and Laugardalur Faults. The distance between them is 500 m. We tried to define the displacement that occurred on them during the Holocene. They are exposed only in the sea cliff north of Húsavík. The coastal exposures reveal a vertical displacement of the Skjólbrekka Fault of about 4.5 m in semi-indurated loess from early Holocene. The displacement of the Laugardalur Fault could not be determined as an early Holocene reference layer was not preserved on both sides of it in the cliff (Figure 10). However, a similar throw is indicated by the size of the fault step as seen there. In addition trenches were cut by backhoe excavator and dug by hand across both faults near the shore and about 1 km east of the shore. Ash layers in the soil provide dated reference markers which make it possible to define a few disturbances in time.

Figure 10. *Laugardalur Fault (southern Húsavík Fault). The fault is about 80 cm wide filled with chaotic debris. The higher wall consists entirely of tillite (Unit 7) with 6 m of coarse gravel (Late glacial outwash) banking up against it on the lower wall.*

The Skjólbrekka Fault shows two distinctive faulting events (Figure 11). At least one event occurred in early Holocene, some time after deposition of the Saksunar-ash layer about 10,000 years ago. The other event occurred after deposition of the Hekla-3 ash about 3100 years ago. The total Holocene displacement on this fault is just over 4 m of which about 1 m occurred after Hekla-3. Two faulting events are on record after deposition of basaltic ash layers in 1477 and 1717 A.D., one of them in 1755, the other in 1872. The 1477 ash is disturbed, but it could not be ascertained whether this was caused by soil creep or fault slip.

Three trenches were dug across the Laugardalur Fault. They were difficult to interpret because of slides which, however, are suggestive of earthquakes and fault movement.

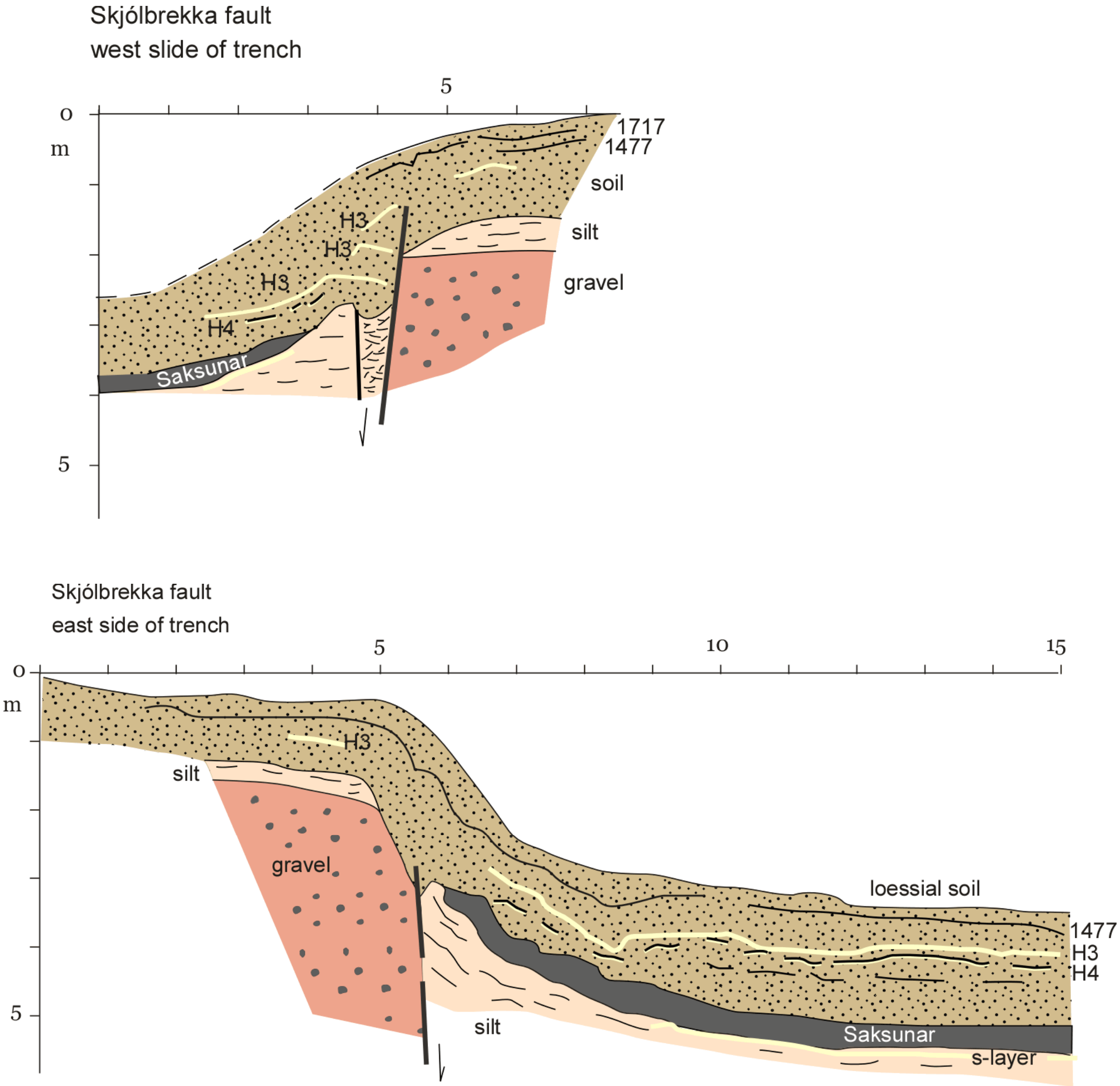


Figure 11. *Section across Skjólbrekka Fault. Both sides of trench. Two faulting events stand out. One after fall out of the Saksunar ash (less than 10.000 years ago) and another after Hekla 3 ash (less than 3100 years ago). The base of the silt layer is about 2 m below the Saksunar ash on the hanging (lower) wall of the fault.*

The easternmost trench across the Laugardalur Fault did not reveal ashes older than Hekla-3 other than traces of Hekla-4 (4500 years old). The main disturbance in the section occurs after deposition of Hekla-3 where silty gravel has slid down into a depression filled with more or less structureless sandy silt and peat intruded by a wedge of silt. The 1477 ash is torn, offset and folded locally, possibly as a result of later fault movement.

Two trenches 15 m apart across this fault at the sea cliff revealed three slides of gravelly rubble mixed with soil (Figure 12). The lowest one underlies Hekla-4 forming a slide mound close the fault escarpment. The second overlies Hekla-3. Closest to the fault wall it has partly tumbled into a fissure and beyond bending and disrupting soil which includes both Hekla-4 and Hekla-3 ashes (Figure 13) in front. The third occurs well below the 1477 ash. The 1477 and 1717 ashes are only slightly disturbed, probably due to later ground movement (1755 and/or 1872).

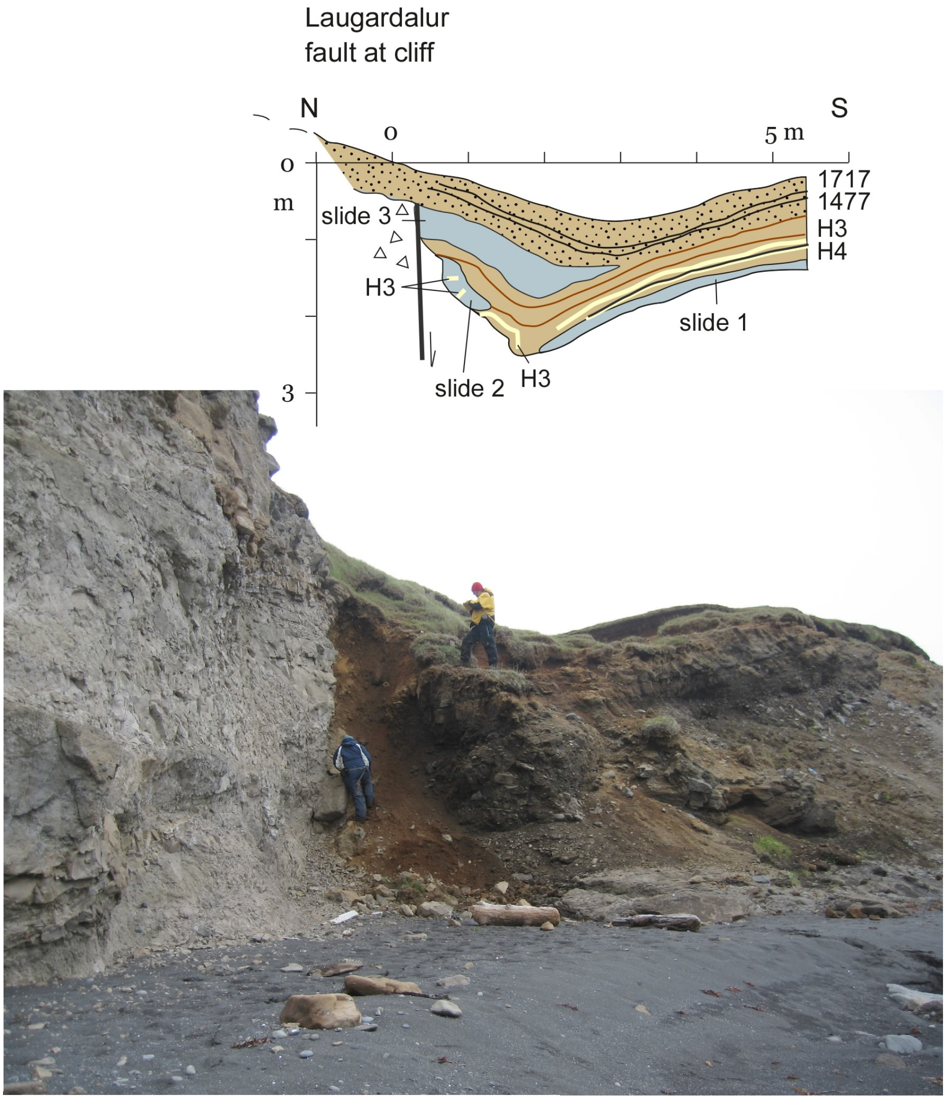


Figure 12. *Close up of Laugardalur Fault. A soil section shown above was dug through the grass covered soil above tillite and gravel. The small mound behind the person is a slide.*

Figure 13. *Laugardalur fault showing disruption and bending over of ash layers Hekla-4 (yellow and black, 4500 years old) and Hekla-3 a little above (3100 years old). A debris slide has distorted both.*

It was not possible to recognize a temporal recurrence pattern from those observations, but Table 1 shows what was observed. It should not be taken as a complete record of faulting events. It seems that there have been a few large displacement events probably due to closeness of the epicenters and smaller ones also, varying in intensity depending on distance and/or magnitude.

The last significant displacement on both faults occurred some time after Hekla-3, approximately 2000–2500 years ago. It may have amounted to about 1 m on each fault. There were fault displacements on the Skjólbrekka Fault shortly after fall out of the Saksunar ash about 10,000 years ago and on the Laugardalur fault well before fall out of the Hekla-4 ash, probably about 6000 years ago. A slide on the Laugardalur Fault may indicate a faulting event some time between 1000-800 years ago. The latest recorded movements of 1755 and 1872 did not show up as large displacement events.

Table 1. *Movement on Húsavík Faults in relation to volcanic ash layers of known source and age. A few faulting events were noted but a temporal recurrence could not be defined.*

Years B.P.	Volcanic ashes	Húsavík faults: Skjólbrekka	Húsavík faults: Laugardalur	*Type of disturbance*
0				
1717	—		:	> minor discontinuities and folds 1755 and /or 1872
1477	—			debris slide
		✶	✶	debris slide, fault opening, liquefaction of mud and down faulting
H3	·····			
H4	·····			
5000				
			✶	debris slide
		↕ ✶		fault opening and down faulting, debris slide, liquefaction of mud (after Saksunar)
10.000				
Saksunar	—			
S-layer	·····			
11.450		*Beginning of Holocene*		

3 Offshore data

Figure 14 shows seismic activity of the Tjörnes Fracture Zone from 1974-2001. The activity is concentrated along discrete NW-SE trending fault zones. Activity of the Krafla volcanic system of the Northern Rift Zone in 1975-1984 stands out prominently.

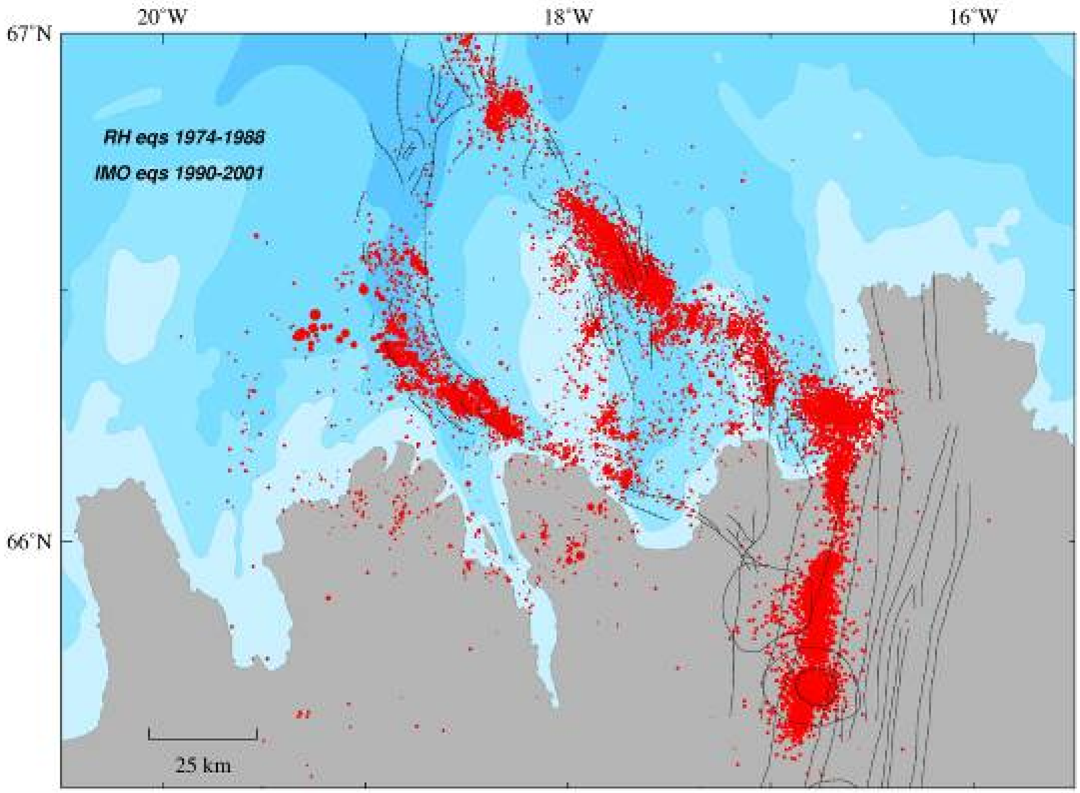


Figure 14. *Tjörnes Fracture Zone. Seismic activity 1974-2001. Earthquakes of the Krafla rifting episode 1975-1984 in the SE of the map are included.*

Figure 15 shows microearthquake activity of the area nearest to Húsavík from 1998–2006, after installation of additional seismometers. Here the Húsavík Faults show minor activity, i.e. the Langidalur Fault whereas the Skjólbrekka fault is quiet. A more concentrated activity of the Húsavík Faults was obtained in a microearthquake study of the Húsavík area in the summers of 1972–1973 (Zverev et al. 1978). The onshore part of the Húsavík Faults has been very quiet during this over 30 years period in contrast to the offshore part west of Skjálfandi. This might indicate that they are locked or perhaps are controlled by activity of the Theistareykir volcanic system to the east which cuts through eastern Tjörnes with faults branching off from it towards NW (Saemundsson 1974 Gudmundsson et al. 1993). There are two rifting episodes of this volcanic system on record. They occurred in 1618 and 1885. The latter episode may have been a prolonged one, beginning with an eruption at Mánáreyjar 10 km north of central Tjörnes in 1868. For comparison the “Krafla Fires”-episode lasted 10 years (1975–1984).

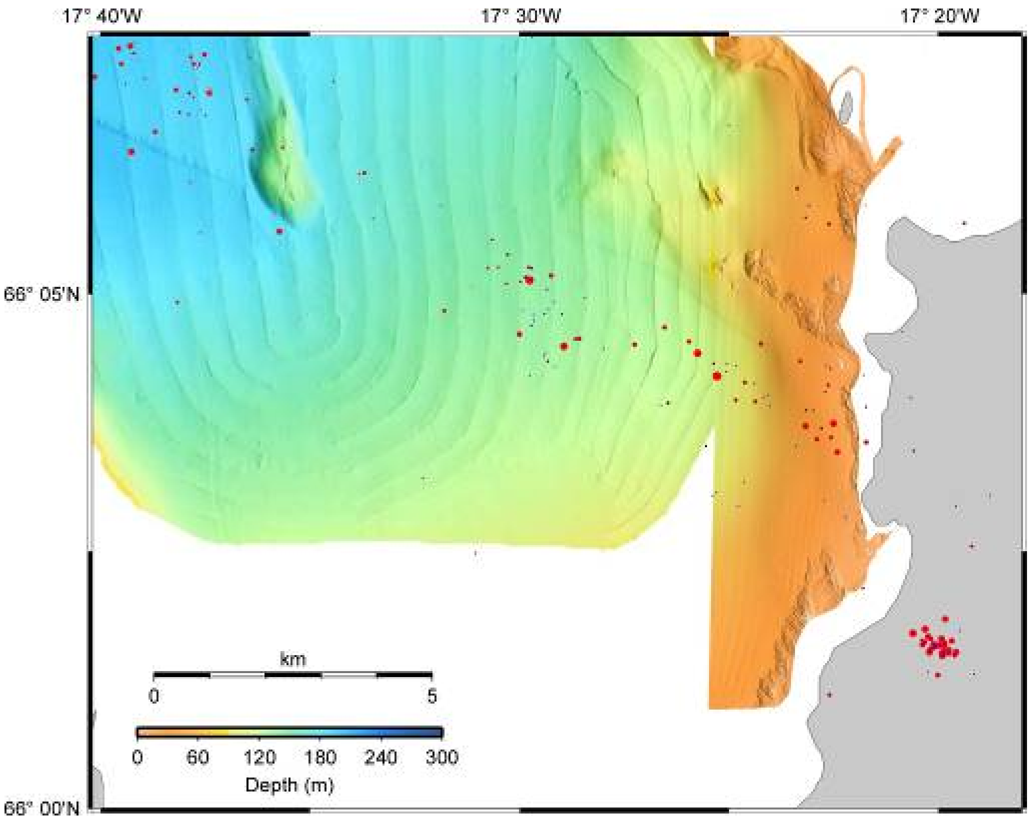


Figure 15. *Húsavík Faults. Seismic activity 1998–2006. The cluster SE of Húsavík is due to blasting in a rock quarry. The main activity occurs on the offshore continuation of the Laugardalur fault.*

Recently acquired multibeam bathymetry and CHIRP reflection data from Skjálfandi, offshore to the west of Tjörnes and the building site, show a regional pattern of NW-trending continuous, strike-slip faults that bound shorter, but more closely spaced NS-trending faults (Brandsdottir et al., 2003; 2004; Detrick et al., 2003; Fenwick et al., 2006). This fault geometry is most evident north of Flateyjarskagi 30 km NW of Húsavík (Figure 14) where sedimentation rates have been somewhat lower than farther east. This pattern matches that of faults mapped on land nearby (Young et al., 1985; Gudmundsson et al., 1993; Karson et al., 2004). The seafloor faults have well-defined bathymetric expressions and displace very young, post-glacial sedimentary units. Thus, they must be regarded as active tectonic features.

Sediment accumulation is heavy immediately west of Húsavík but nevertheless, the NW-trending Húsavík-Flatey Fault can be traced to within about 2.5 km of the shoreline just N of the town (Figure 16), probably linking to the historically seismically active Húsavík Faults. In addition, seafloor projections of coastal promontories north of Húsavík are cut by NS-trending lineaments that also appear to be active structures. Subsurface CHIRP reflection records show many more faults in the Skjálfandi area, though their orientations have not been determined.

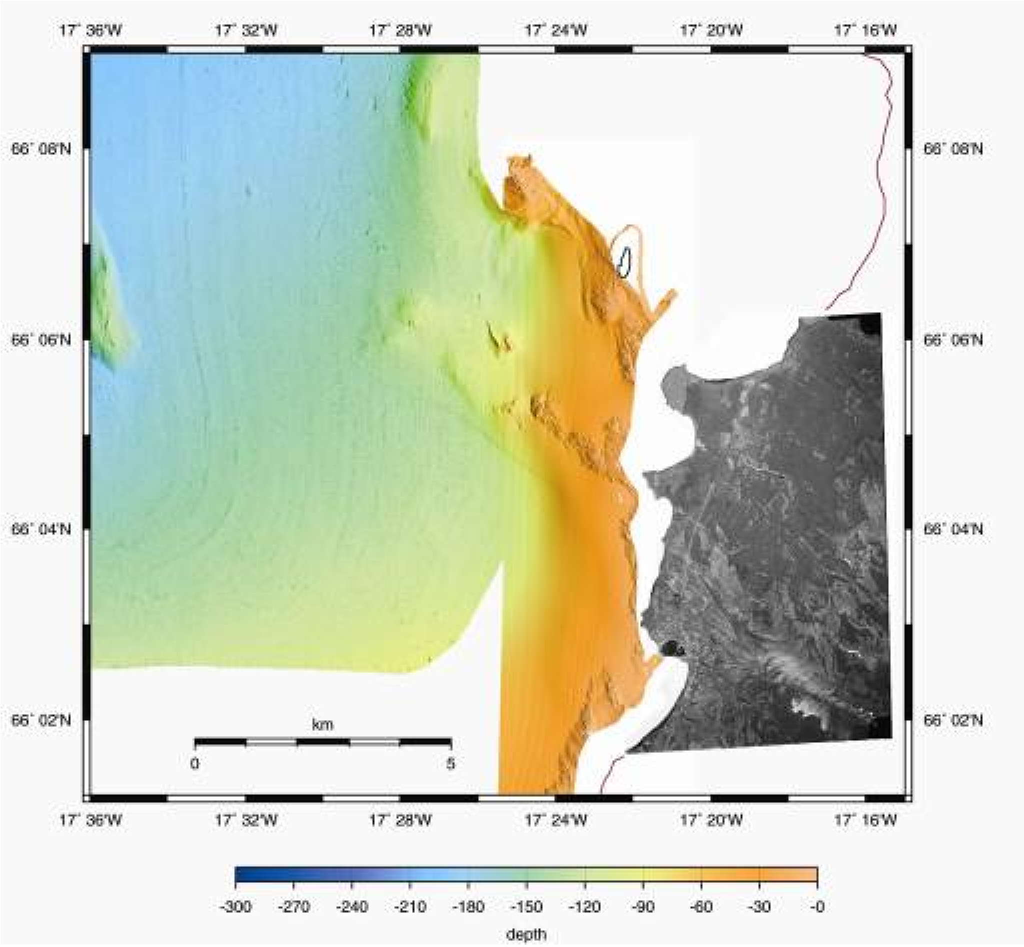


Figure 16. *Bathymetry and CHIRP reflection map of Skjálfandi, offshore to the west of the building site north of Húsavík. A fault lining up with probably the Skjólbrekka fault is visible to within 25 km off the shoreline. The two NW-trending topographic features nortwest of Bakkahöfði and Héðinshöfði are most likely fault bounded on the south. A landward continuation suggesting active faults southeast of the two promontories was not found.*

4 Structural and Tectonic Interpretation

Prior to the eruption of Unit 2 much of the faulting and fracturing of Unit 1 basalts took place. Deformation probably began about 8 m.y. ago. At this time an older rift zone in western North Iceland died and jumped from there to the present location in Northeast-Iceland. As a consequence a NW-SE trending, right-lateral transform fault zone became active, linking from south of the Tjörnes Block to the Kolbeinsey Ridge which at that time terminated near the mouth of Eyjafjörður (Saemundsson, 1974). With time movement seems to have become progressively more concentrated on the Húsavík Faults.

Collectively, the previous geological reports and publications on the area provide a very complex and in some cases contradictory view of the area. Some of this clearly stems from inadequate ground data. We were able to discount proposed faults in key parts of the study area and to modify fault interpretations in others. Although major lineaments to the east of the area may link rifting to faults seen in coastal exposures and in offshore data, it was not possible to locate or confirm that faults proposed to cut across the proposed building site are active.

Based on field relations in the study area, offshore, and to the west in the Tjörnes Transform Fault System, we interpret this pattern of deformation in terms of a book-shelf style of faulting (Einarsson and Eiriksson, 1983; Mandl, 1987). This includes NW-trending, dextral strike-slip faults bounding volumes of rock cut by relatively closely spaced, NS- to NE-trending, normal (to sinistral, oblique-slip) faults. In the study area, the same fault geometry and kinematic patterns persist upward into younger rock units. Therefore, it appears that reactivation of older faults, probably Miocene in age, has affected all overlying units to a diminishing degree upwards. Considering the regional pattern of active faulting to the west, active tectonics along the Tjörnes Transform Fault System would be expected to include displacements on both NW-trending, seismically active faults as well as NS- to NE-trending normal faults.

In addition, we note that faulting in some of the younger units is unevenly distributed with respect to the Húsavík Faults. There are more faults and larger faults in Unit 6 (Pleistocene Grjóthráls Shield Lavas and hyaloclastites) to the south of the Húsavík Faults. Some of these have topographic expressions and may be active structures. To the north of the Húsavík Faults, however, there are only minor faults and fractures in Unit 6. Trenching along lineaments in the central part of the area shows no evidence of active faulting. A few faults occur in the immediate vicinity of the Húsavík Faults where several separate fault strands branch from the main fault. In the eastern part of the area, one such fault which runs parallel to the Húsavík Faults has a topographic expression in Unit 6 lavas. The vertical separation on that fault increases towards southeast from less than 2 m to 15 m. A few faults with vertical separations of a few centimeters to about 2 m occur in Unit 7 tillites at Húsavík, within a distance of about 1 km south of the Húsavík Faults.

5 Summary of Tectonic Features

General fault pattern and its development through time

1. The large, seismically active Húsavík Faults mark the southwestern limit of the Tjörnes Block. They separate Miocene flood basalts to the northeast from Quaternary rocks to the southwest. The Húsavík Faults are part of the Tjörnes Transform Fault System with tens of kilometers of right-lateral offset.
2. Transform faulting decreased during the Quaternary as a result of rift propagation of the North Iceland spreading zone into Axarfjörður east of Tjörnes. Normal rift related faulting has since dominated in the north and east of Tjörnes affecting Quaternary units.
3. Most deformation of the basement rocks in the area north of the Húsavík Faults occurred in the Miocene. During the Pliocene, transform faulting became focused on the Húsavík Faults.
4. Deformation structures (exclusive of the Húsavík Faults) become much less intense in both density and magnitude upward in the local geologic section.
5. Although in the geologic record, NW-trending strike-slip faults appear to be the most significant structures (largest displacements, seismicity, major geologic boundaries), movement on NS- or even NE-trending strike slip and normal faults in crustal blocks between the major strike-slip strands are also significant and peristent.
6. Fault orientations and kinematics in the youngest units are similar to those in the older units, suggesting that old faults may be reactivated at least locally.
7. Seismic activity on the Tjörnes Transform Fault System has been activated during rift-related volcanic and dike intrusion events centered far to the S and E. Similar events in the Northern Rift Zone may re-activate faults in various orientations (NW but also NE trends) in the Húsavík-Western Tjörnes area.
8. Distributed deformation in some fault zones may indicate that aseismic slip is a significant mechanism in this area.
9. Offshore data along the Tjörnes Transform Fault System and in areas near the site mimic the fault patterns mapped on land. Faults in offshore areas cut surficial sediments and must be regarded as active tectonic structures. The only major offshore lineament in the immediate area that emerges from the heavy sediment cover is the Húsavík-Flatey Fault that intersects the coastline just north of Húsavík town.

Recent movement on the Húsavík Faults and effects of ground shaking:

10. Although many different maps have been published with many different fault interpretations, our detailed, ground-based investigations indicate that many of the faults shown there, including those which trend towards the proposed building area, are without basis.

11. Holocene offset on the Húsavík Faults has been oblique-slip, with the dip-slip component prevailing.
12. The Húsavík Faults (Skjólbrekka and Laugardalur) are an obvious major seismic risk. Disturbance seen in trenches cut across them indicate several faulting events. The largest occurred in early Holocene and about 2500 years ago (long after fall out of 3100 years old Hekla-3 ash). The latter event caused about a meter-scale vertical offset on the two faults. The last two seismic and faulting events on record (1755 and 1872 A.D.) seem to have left only minor disturbances in the soil.

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