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Overview of landslide hazard and possible mitigation measures in the settlement southeast of Fjarðará River in Seyðisfjörður

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Report

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Report

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Abstract

Evaluation and interpretation of existing studies of the landslide hazard in Seyðisfjörður shows that parts of the settlement below the Þófi shelf are threatened by fast-moving debris flows from high elevations in Strandartindur as well as from slower-moving debris flows and debris slides from the shelf itself. The danger from the higher starting areas may partly arise from permafrost areas that can pose an increasing danger in the future due to warming climate. There is geological evidence for three or four large, prehistoric landslides reaching the Fjarðará river or the sea below Botnabrún during the last several thousand years that demonstrates that danger due to large landslides extends to essentially all the current settlement south of Fjarðará. The main source areas for landslides that threaten the settlement below Botnabrún are the depressions in Neðri-Botnar, above Nautaklauf and Klauf. Landslides from these areas in Neðri-Botnar are likely to travel more slowly than landslides from high elevations in Strandartindur and are therefore less hazardous for the affected settlement. Parts of the settlement between Þófi and Nautaklauf, close to the main paths for debris flows and torrents from the mountain, in particular the settlement near Stöðvarlækur and Búðará, may also be threatened by fast-moving debris flows from high elevations in Strandartindur that can be affected by permafrost. There is high hazard, corresponding to the C-zone in the Icelandic hazard zoning regulation, within the main debris flow paths below Þófi and the eastern part of Botnabrún to Nautaklauf and in the uppermost rows of houses below Botnabrún. The most effective mitigation options to improve the landslide hazard situation in southern Seyðisfjörður is draining of the main source areas in Neðri-Botnar in the lower part of the mountainside as well as a construction of a moderately high catching dam above the top row of houses below Botnabrún, and debris retention basins and guiding dams at the lateral sides of the main debris flow paths. Point protection of individual buildings, in particular some of the more important industrial buildings below Þófi, should also be considered.

Contents

1 Introduction

The settlement in Seyðisfjörður is endangered by snow avalanches and landslides that have caused accidents and extensive material damage through the centuries since the settlement of Iceland 1100 years ago. The most devastating accidents have been caused by snow avalanches but landslides have also killed people and caused widespread damage and disruption to society. A catastrophic snow avalanche from the mountain Bjólfur in 1885 hit the northern part of the town, killing 24 people and causing extensive damage to living houses and other buildings. A debris slide from Þófalækur in Standartindur killed 5 persons in 1950. Both these accidents occurred within the current limits of the town of Seyðisfjörður but snow avalanches and landslides have also caused several fatal accidents around the Seyðisfjörður fjord and in the Seyðisfjörður valley as further described in the snow avalanche and landslide chronicles for the area (Halldór G. Pétursson & Þorsteinn Sæmundsson, 1998; Kristján Ágústsson, 2002) and in section 3.

Snow avalanche and landslide hazard in the town of Seyðisfjörður has been investigated in several reports and the current hazard zoning (Þorsteinn Arnalds and others, 2002) was attested by the Minister for the Environment in 2003. Snow avalanche and landslide protection measures for Seyðisfjörður have also been considered in several reports, the most extensive of which are the studies by VA and NGI (1998, 2003) about snow avalanche protection measures for the main Bjólfur avalanche path. An overview of existing studies of protection measures for Seyðisfjörður has been compiled by Sigurjón Hauksson (2015). The focus of earlier studies have mainly been on the snow avalanche hazard in the northern part of the town, below the mountain Bjólfur, but landslide hazard in the southern part has more recently attracted attention as further described in following sections. Protection measures for the southern part of Seyðisfjörður were not explicitly considered in the overview study of avalanche and landslide protection measures in Iceland that was carried out in 1996 (Tómas Jóhannesson and others, 1996). Landslide hazard in the southern part of Seyðisfjörður was the subject of several studies in the period 2002–2014, as summarised by Sigurjón Hauksson (2014), and the discussion of landslide hazard in this report is to a large degree based on the results of these studies, in particular the studies by Ágúst Guðmundsson and others (2003) and Óskar Knudsen and Guðrún Larsen (2013). The list of references at the end of this report lists several reports about hazard zoning and protection measures for Seyðisfjörður as background for the investigations presented here.

The settlement of Seyðisfjörður was until the last century concentrated in the Aldan area on the northern side of the fjord, below the mountain Bjólfur, where the oldest part of the settlement is located, and on the southern side, below Strandartindur, see map 1. The currently settled area between river Fjarðará and the mountainside Botnabrún was developed during the 20th century. The photograph in Figure 1 from the turn of the 20th century shows the undisturbed debris fan below Botnabrún, built up by rockfall, debris flows and other landslides over thousands of years. The current settlement is built on terrain partly excavated into this debris fan and for this reason obviously endangered by landslides. The geological history, as revealed by exploratory pits into the sediments on which the current settlement is built, indicates that several of the past landslides, that have descended from the mountainside into the lowland, are very large and have reached all the way into the fjord. The industrial area below Þófi is similarly built on land that was claimed by the excavation of a debris fan extending from mountainside below the Þófi shelf into the ocean.

Figure 1. View from the opposite side of the fjord over Botnahlíð and Neðri-Botnar around 1900, before the development of the settlement into the area south of Fjarðará below Botnahlíð. Photograph: The Seyðisfjörður historical photo collection.

This report presents an evaluation of possible landslide protection measures for the southern part of Seyðisfjörður, mainly the part of the settlement below the shelves of Þófi and Neðri-Botnar. First, the geographical setting and landslide history are described in sections 2 and 3. Potential starting areas for landslides and debris flows are discussed in section 4 and the hazard potential due to landslides from these areas is assessed in section 5. Analog hazard situations in the Austrian Alps are discussed in section 6 as well as implemented or planed mitigation measures for settlements in these situations. Finally, possible mitigation measures are investigated in section 7 and further investigations needed to shed light on the hazard situation and on the different mitigation options are suggested in section 8. Hazard due to snow avalanches in the area was not considered in this work but will be considered in a forthcoming formal reassessment by IMO of the snow avalanche and landslide hazard in the southern part of Seyðisfjörður.

This work is carried out for the municipality of Seyðisfjörður, as represented by major Vilhjálmur Jónsson, in a collaboration between the Austrian engineering company Ingenieurbüro Illmer Daniel e.U. (DI), Efla consulting engineers and the Icelandic Meteorological Office (IMO). Daniel Illmer carried out the analysis of landslide protection measures, Jón Kristinn Helgason, Tómas Jóhannesson and Eiríkur Gíslason wrote sections about the geographical setting, the landslide history and the assessment of landslide hazard. The geologist Árni Hjartarson, from ÍSOR – Iceland GeoSurvey, furthermore, carried out an investigation of the geology of loose materials and starting areas for landslides in the mountainside to the south of the settlement of Seyðisfjörður. Sigurjón Hauksson, from Efla, participated in the assessment with the aim of continuing the study as a formal appraisal and an explicit proposal for landslide protection measures for the southern part of Seyðisfjörður.

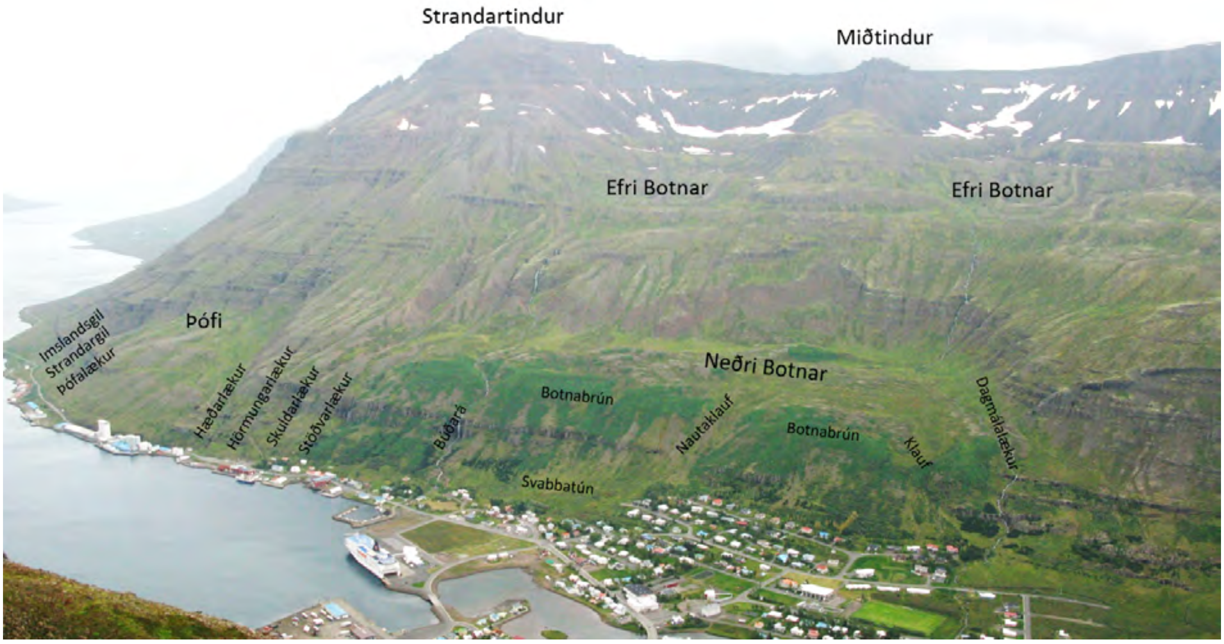


Figure 2. The southern part of the town of Seyðisfjörður and the mountainside to the south and east of the settlement with the names of locations and landscape features discussed in the text.

2 Site description and geological setting

The village of Seyðisfjörður is located at the head of the fjord Seyðisfjörður, see Map 1 and Figure 2. The general direction of the fjord is mainly ESE–WSW but the innermost part has a NNE–SSW direction. By local convention, the opposite sides of the fjord are referred to as the south and north side irrespective of the actual compass direction. This report adopts this local convention.

The mountainside south of Seyðisfjörður is characterised by diverse terrain that includes three summits, shelves and terraces, large cirques, gullies and cliffs. The following description of the geological setting is based on Ágúst Guðmundsson and others (2003) and Árni Hjartarson (2015), see their geological maps (Map 3 and Figure 3), as well as on the landslide hazard study by Þorsteinn Sæmundsson and Halldór G. Pétursson (1999). The outermost summit is Strandartindur (1010 m a.s.l.), sometimes also called Fjarðartindur. Next to Strandartindur is Miðtindur (also referred to as Dagmálatindur, 896 m a.s.l.) and the third summit is Innri-Strandartindur (1015 m a.s.l.). The north and west facing hillside of Strandartindur is rather steep and interrupted by gullies of varying size with small brooks.

Above the industrial area on the narrow coast by Strandartindur there is a $\sim$400 m wide and $\sim$1000 m long shelf called Þófi, terminating at 80–100 m a.s.l., see Map 4. The inclination of the shelf is $\sim 15^\circ$ on average. The surface of Þófi is covered with unconsolidated glacial till and landslide deposits and marked with five gullies. The brook called Þófalækur near the middle of the shelf divides it into an inner and outer part. On the outermost part of the shelf, there is a small gorge called Imslandsgil and a small gully between Þófalækur and Imslandsgil is named Strandargil. The rim of the outer part of the shelf is characterised by steep cliffs with unconsolidated

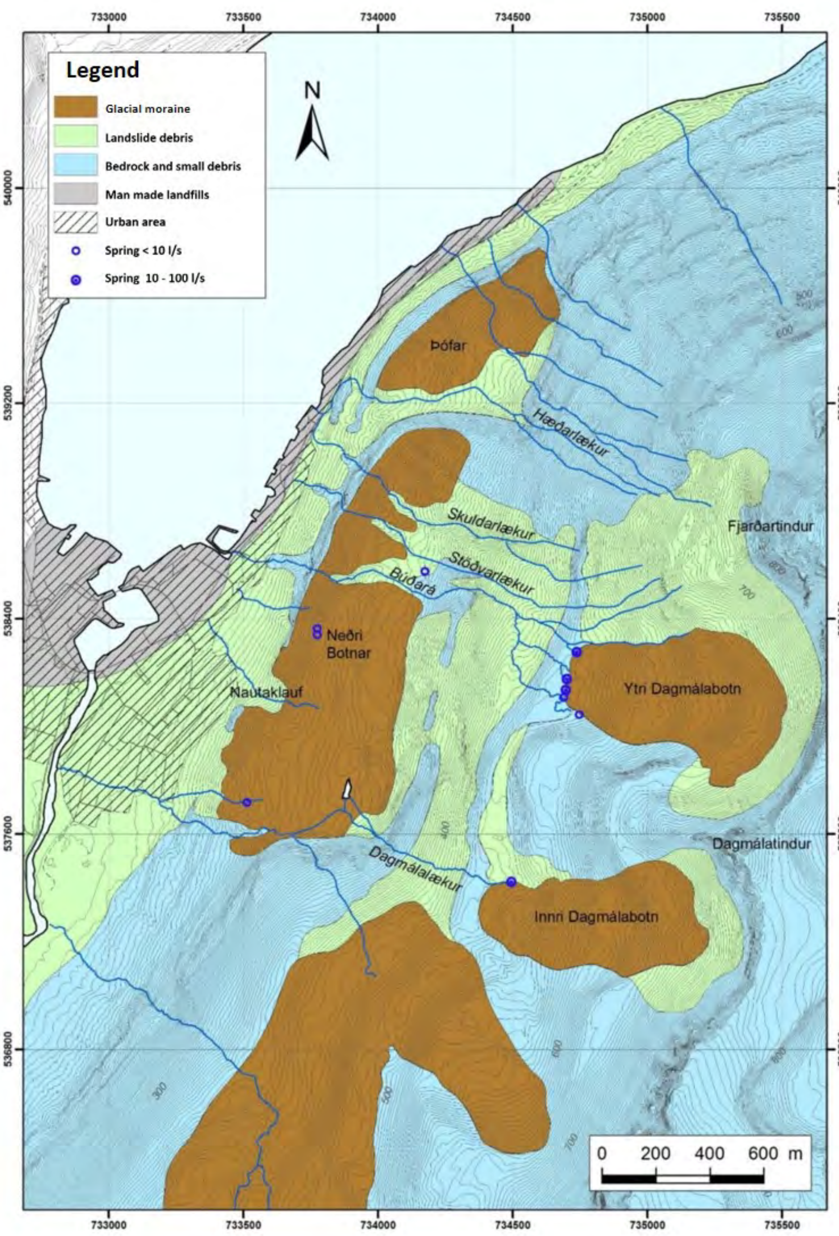


*Figure 3. Geological map of loose materials, springs and brooks in the mountainside south of Seyðisfjörður, between Þófi and Botnahlíð. Reproduced from Árni Hjartarson (2015). Note that the areas classified as "glacier moraine" (*Icel. *"jökulruðningur") by Árni are described as "diamicton" (*Icel. *"urðarset") by Ágúst Guðmundsson and others (2003).*

glacial till on top. The cliffs disappear under the unconsolidated till on the inner part of the shelf. The inner shelf is relatively flat and the surface layers are often saturated with water near the rim of the shelf where the vegetation is marsh-like. The drainage on top of the inner shelf is not confined to gullies as in the outer part, except for Hæðarlækur and Hörmungarlækur brooks near the inner shelf margin which capture most of the surface runoff from the mountainside above the inner part of Þófi. The edge of the inner part of Þófi is interrupted by several gaps (Þorsteinn Sæmundsson & Halldór G. Pétursson, 1999).

Figure 4. Efri-Botnar seen from northeast. The debris piles in the foreground are at the bottom of the inner cirque. Photograph: Árni Hjartarson.

Two cirques called Efri-Botnar (also called Dagmálabotnar) are situated at an elevation 400–500 m a.s.l. to the southwest of Strandartindur. The outer cirque is located between Strandartindur and Miðtindur while the inner one is between Miðtindur and Innri-Strandartindur. Most of the bedrock within outer Efri-Botnar is covered with loose unconsolidated material that forms several large piles of debris, see Map 3 and Figure 4. The thickness of the piles at the mouth of the cirque is around 4–8 m. Ridges and drumlins are not prominent but can be seen within the area. Although piles of debris cover most of the cirque, the shape of the underlying bedrock is nevertheless noticeable. These debris piles have many of the features that characterise rock glaciers formed by landslides on small glaciers that have transported the deposits into the cirque. The bedrock forms a small plateau at the rim of the cirque in front of the debris piles. There is neither evidence for recent movement of these piles nor for landslides from them reaching down into the Neðri-Botnar area. The piles are vegetated with moss, grass and other low vegetation. Snow melt within the cirque disappears into the ground and flows through the debris piles. The water resurfaces in small springs at the lower edge of the piles. The springs form three brooks from the rim of the cirque that join at lower elevation to form the river Búðará. On 8 of September 2015, the temperature of the springs was 0.1–0.2 °C and the flow was 40–50 l/s (Árni Hjartarson, 2015).

The inner Efri-Botnar area is similar to the outer cirque, but the thickness of the debris appears to be somewhat greater. There are ridges and lateral glacier moraines within the cirque and the thickness of the piles of loose materials near the mouth of the cirque is around 6–8 m. Glacier striations from the end of the last ice age can be seen on a bedrock plateau at the edge of the cirque in front of the debris piles. The debris piles are covered with thin vegetation, mostly moss, grass and other low growing vegetation. As for the outer cirque, there is no evidence for recent movement of these piles nor that a large landslide from them has reached into Neðri-Botnar during the Holocene. Snow melt disappears into the debris piles and resurfaces in small springs below the northwest corner of the cirque to form the brook Dagmálalækur. The temperature of the spring water was 0.1–0.2 °C and the flow was 60–80 l/s on the 8 September 2015 (Árni Hjartarson, 2015).

Flow measurements in the springs of Búðará and Dagmálalækur show high discharge fluctuations from more than 100 l/s down to almost nothing (Árni Hjartarson and others, 1981), indicating small groundwater storage capacity of the loose materials in the cirques. These fluctuations along with water temperature of close to 0 °C during the summertime, indicate that there is permafrost in the debris piles in both cirques. The landscape features of the debris piles suggest past deformations due to an ice core. However, there is no evidence suggesting that these piles are still deforming. Risk of large landslides originating from the loose materials in the Efri-Botnar cirques and reaching into Neðri-Botnar farther downslope appears vanishingly small (Árni Hjartarson, 2015).

Below the summit of Strandartindur there is a coarse talus slope marked with small gullies, similar to the slopes above the bottom of the inner and the outer Efri-Botnar cirques. A part of the slope, in the northwest face of the mountain is different, where several small depressions are noticeable between ridges that run parallel to the direction of the slope. The depressions narrow into the gullies in the cliffs below the talus slope.

Below the Efri-Botnar cirques, directly above the settlement, there is a large flat shelf called Neðri-Botnar (Fig. 2), covered with loose sediments of glacial origin, see Map 5 and Figure 3. The inner part of Neðri-Botnar, west of Búðará, is characterised by many small ridges, cracks, small basins with marsh like vegetation and two large depressions. Transverse ridges on the uppermost part of the shelf are interpreted as glacial moraines formed near the edge of an advancing glacier near the end of the last ice age. Landslides on the slope between Efri- and Neðri-Botnar do not appear to have travelled farther than to the glacial moraines, except in the path of Búðará river. There is no evidence that a landslide, with a source area in the slope above Neðri-Botnar, has traversed the inner Neðri-Botnar shelf.

A small, partially man-made pond that drains into the brook Dagmálalækur is located near the top of the shelf. The pond receives water from the previously mentioned springs at the northwest corner of the inner Efri-Botnar cirque. Dagmálalækur runs down along the inner margin of the Neðri-Botnar shelf and joins the river Fjarðará at the bottom of the valley. Below the pond and the glacial moraines there is a large flat area covered with marsh-like vegetation where the surface layers often become highly saturated with water during periods of rain or snow melt. The surface geometry is in places characterised by long arcuate, step-like features that are likely to be due to past, deep-seated creeping in the loose materials. Evidence for recent movement related to these features is not apparent.

The outer part of Neðri-Botnar is more uniform with wide gullies separated by ridges. The loose materials seem to be thicker on this side of the shelf and less disturbed. The brooks Skuldarlækur and Stöðvarlækur run along the two of the largest outermost gullies and the river Búðará through the third one and off the rim of Neðri-Botnar as a water fall.

The rim of the Neðri-Botnar shelf is called Botnabrún and is largely covered with lupine (Lupi-

Figure 5. The Nautaklauf gully in Botnabrún at the lower edge of the shelf Neðri-Botnar. Photograph: Árni Hjartarson.

nus nootkatensis). The average inclination of the slope below the rim varies between 25–33°. The settlement below Botnabrún reaches the foot of the slope more or less uninterrupted along a distance of ca. 1500 m. Cliffs rise continuously above the settlement below the outer part of Neðri-Botnar to a large gap in the cliffs called Nautaklauf (Figs. 2 and 5), which is situated below one of the two large, previously mentioned depressions in Neðri-Botnar. There is a narrow gap in the settlement below Nautaklauf that is covered with boulders and debris from past rockfall and landslides. The cliffs below the inner part of Neðri-Botnar are partly covered with loose materials and some trees stand near the foot of the slope. There is a smaller gap in the rim of Botnabrún, called Klauf, between Nautaklauf and Dagmálalækur and the second depression in Neðri-Botnar is located above this gap.

3 Landslide history

Several reports have been written during the past two decades about historical landslides in Seyðisfjörður, the two most significant ones being the landslide history of Seyðisfjörður by Halldór G. Pétursson and Þorsteinn Sæmundsson (1998) and the landslide hazard assessment by Þorsteinn Sæmundsson and Halldór G. Pétursson (1999). The former report covers the landslide history from 1882–1997 and the latter describes in detail the main source areas and areas that are prone to landslides near the settlement. One does not expect all landslides since 1882 to have been recorded as only the significant ones, for example landslides that caused accidents or damage to property, were documented in the early part of the 20th century. In the last decades, most landslides that have occurred near the settlement have been recorded. The location of at least 100 landslides within the settlement or in close proximity to it are known and it may be estimated that the total number of landslides in area since 1882 is at least 3–4 times that. All the recorded landslides are stored in the database of the Icelandic Meteorological Office (IMO) and the Icelandic Institute of Natural History (IINH). An estimate of the outlines of historical slides that can be localised based of contemporaneous descriptions, photographs and other evidence is shown on Map 2. Landslides have caused the death of 5 people in Seyðisfjörður, destroyed several residential houses and caused extensive of damage to infrastructure since the end of the 19th century. Damages to buildings, industrial properties and local infrastructure has been severe throughout the centuries.

Landslides in Seyðisfjörður can be divided into the following categories (Þorsteinn Sæmundsson & Halldór G. Pétursson, 1999):

A Debris flows that are confined to gullies and form a debris cone in the run-out zone. The source of the material is either within in the channel or in the talus slope above the channel. Most of the landslides that occur in Strandartindur are debris flows of this type.

B Debris slides that are not confined to gullies and occur near a concave break of slope. The main type of material is debris mixed with fine-grained material. Most of the landslides that occur in Botnabrún or at the rim of Þófinn are debris slides. The size of the slides varies depending on the source area.

C Mudslides or mudflows occur where there is an abundance of soils. They normally occur in areas where the vegetation cover has been breached. Common occurrences in Seyðisfjörður are in the mountain Bjólfur and in the valley west of the settlement.

D Rockfalls are a common occurrence in Seyðisfjörður and occur in steep cliffs or where rock have been exposed by surface erosion of thick sediments. Common occurrences in the area are the slopes below Þófi and Neðri-Botnar.

3.1 Historical landslides

At least eight severe landslide cycles have occurred in the past 134 years in Seyðisfjörður that have caused extensive damage to the southern part of village (Map 2). These cycles are all related to periods of heavy precipitation during the fall and some of the cycles are also related to snow melt. The three most destructive cycles were all due to heavy precipitation and occurred in August 1950, September 1958 and August 1989.

At least 40 landslides fell in the Seyðisfjörður area during the landslide cycle of 1950 and most of the damages occurred on the south coast below Þófi. At least six houses were hit by fast-moving debris flows that originated in the talus slope below the summit of Strandartindur and two of the houses were completely destroyed. Debris flows traversed down all the major gullies in Þófi, with the two largest ones coming down along Þófalækur and Hæðarlækur. The slide from Þófalækur completely destroyed a residential house located near the brook killing five people, four of them children. The slide from Hæðarlækur caused great damage to the fish factory and almost destroyed a residential house that was attached to the factory.

The cycle in 1958 was not as violent as in 1950 but it also caused extensive damage. At least 20 landslides fell near the settlement in Seyðisfjörður with most of the damage on the south coast. Two large debris flows from Hæðarlækur in Þófi filled the area between the slope and the buildings with debris but did not cause much damage to the buildings. Fast-moving debris flows from Hörmungarlækur, Skuldarlækur and Stöðvarlækur completely destroyed the residential house Hörmung, damaged the residential house Skuld and the house that holds the offices of the municipality.

The landslide cycle in 1989 also caused extensive damage. Two large, fast-moving debris flows from Hæðarlækur and Þófalækur originated in the talus slope below the summit of Strandartindur. The debris flow from Hæðarlækur hit the fish factory but did not cause much damage. The debris flow from Þófalækur caused damage to a house belonging to the fish factory. Debris flows also came down Stöðvarlækur and Búðará. The whole village west of Búðará was covered in mud and water.

Fresh surface cracks were found in soil near the rim of the Þófi shelf and in Botnabrún in the year 2000 (Esther H. Jensen, 2001). These tension cracks were evidence of creeping of the loose material that was particularly active in then inner part of Þófi. The uppermost crack in middle of Þófi, above the fish factory, was >200-m long, with maximum width of 15–20 cm and a maximum vertical displacement of the lower with respect to the upper edge of ~10 cm. After a long wet period in August–October 2001, with several heavy rainstorms, additional cracks, the largest of which ca. 100 m long, were discovered close to the rim of Þófi near Hæðarlækur. The movement of the surface slowed down and essentially stopped without a catastrophic failure but several small slides were released from rim of the slope. Fixed points were installed on boulders after 2001 to detect future surface movements and these points have been remeasured regularly with a GPS with a 1–2 year interval (Esther H. Jensen, 2002) (see Maps 6 and 7). The movements were particularly rapid for a couple of years after 2001 but have been slower during the last decade. Total horizontal displacement of the most active part of Þófi since the start of the measurements is mostly in the range 10–35 cm (maximum 69 cm), whereas the movement in Neðri-Botnar is slower, with the more active points having total displacement mostly in the range 5–10 cm (maximum 46 cm). The maximum measured velocity of the horizontal movement in the Þófi area was 92 cm/a over a two-month period in late 2002, and 16 cm/a over a ca. 12 month period in the Neðri-Botnar area in 2002–2003. The areas are still actively creeping and the rate of movement appears to be related to water pressure in the sediments that becomes higher after periods of precipitation or snow melt (Esther H. Jensen, 2001).

During the same rainstorms in 2001, a ca. 30-m long crack formed in Nautaklauf in Botnabrún. The movements there also stopped before they led to a slope failure. A year later, in November

2002, multiple tension cracks formed in Botnabrún during a heavy rainstorm after a long wet period. Most of the cracks that formed during the rainstorm occurred in the upper part of Botnabrún, between Skuldarlækur and Nautaklauf. These movements led to the release of two debris slides, just west of Búðará that luckily caused little damage. According to local sources, this is not the first time that cracks form in Botnabrún. Several cracks formed in 1925 at the same location as the slope failure in 2002. Photographs from the beginning of the 20th century (cf. Fig. 1) indicate that debris flows have been a common occurrence above the current settlement under the inner part of Neðri-Botnar. These slides occurred when the area was not settled and therefore caused no damage.

3.2 Prehistoric landslides

Evidence for large prehistoric landslides reaching the sea below Botnabrún was discovered in a recent geological survey of loose materials within the settlement and in Neðri-Botnar by Óskar Knudsen and Guðrún Larsen (2013). The main conclusion of this study was that layers of debris from three separate landslides were found in 6 exploratory pits within the settlement. The age of the landslides, hereafter denoted by A, B and C, was estimated with ^{14}C dating and the use of dated tephra layers in the area, see table 1. Map 8 shows the location of the pits that are all situated within the settlement and Table 2 shows the thickness of each layer in the pits. The source areas of the landslides were not determined in this study but it was suggested that they might come from the large debris piles in the Efri-Botnar area.

Table 1. Age of the landslides according to ^{14}C dating and observations of dated tephra layers (Óskar Knudsen & Guðrún Larsen, 2014).

Landslide	Uncorrected age (BP)	Corrected age (AD, 1 σ)	Corrected age (AD, 2 σ)
A	1286±38	670–770	650–820
B	1386±37	620–665	580–690
C	4500	–	–

Table 2. Thickness of the landslide debris (m) in exploratory pits (Árni Hjartarson, 2015).

Pit name	Landslide A	Landslide B	Landslide C
SG-21	0	0	>2.0
SG-22	0.9	1.5	–
SG-23	0.5	1.0	–
SG-24	0.6	0.8	>0.5
SG-25	–	–	–
SG-29	0.52	0	>1.6
Average	0.65	1.1	>1.4

Árni Hjartarson (2015) from ÍSOR investigated possible source areas for these large prehistoric landslides in the fall of 2015. He concluded that the landslides did not originate from the debris piles in Efri-Botnar, since there is no evidence to suggest that material from Efri-Botnar has traversed down to Neðri-Botnar during the Holocene. No signs of landslide movement were found in the Efri-Botnar area, the surface of which appears old and undisturbed, only glacial striations were found on the surface of bedrock at the edge of Efri-Botnar, no debris derived from Efri-Botnar was found in the upper part of Neðri-Botnar and the area between Efri-Botnar and Neðri-Botnar shows no signs of large slides travelling down the slope (Árni Hjartarson, 2015).

Árni Hjartarson suggests that the source of the landslides is loose material in Neðri-Botnar. The potential source areas and the likely extent of the slides are displayed on Map 8. The source areas for landslides A and B are most likely the large depression above Nautaklauf at the edge of the Neðri-Botnar shelf. Landslide C is by Hjartarson interpreted to have two separate source areas and may thus be considered as two independent slides of similar age, which we denote by C_W and C_E for the western and eastern lobes of the slide, respectively, see Map 8. The source area for the western part of this slide is above Klauf at the edge of Neðri-Botnar, just east of Dagmálalækur, where there is a large depression similar to the one above Nautaklauf. There are more than one potential source areas for the eastern part of the slide, which might come from Nautaklauf, but Hjartarson considers it more likely that it originated from the path of Búðará farther east.

A large slide may also have originated from the inner part of the shelf Þófi. Sediments on top of the inner part of Þófi are considerably thinner than on the outer part of the shelf and the landscape is completely different as described in the preceding section. Bathymetric data show a cone on the bottom of the fjord stretching at least 250 m from shore and down to 40 m depth just offshore from the mouth of Hæðarlækur. This might be the debris from a large landslide that originated on the inner part of shelf and slid into the ocean (Árni Hjartarson, 2015).

Neither Óskar Knudsen and Guðrún Larsen (2013) nor Árni Hjartarson (2015) make an attempt to estimate the volume of the prehistoric landslides. The areas of the four tongues are roughly similar, 20–30 ha each. Based on the thickness values in Table 2, the volume of slide A may be crudely estimated as $\sim 100 \cdot 10^3\,\mathrm{m}^3$, slide B may have been $\sim 200 \cdot 10^3\,\mathrm{m}^3$, and each of the lobes of slide C may have been $\sim 300 \cdot 10^3\,\mathrm{m}^3$ or even more. These numbers are quite uncertain as they are based on thickness measurements in only 3 to 4 exploratory pits for each slide and the areas are also only crudely known. Thus, they only give an estimate within a factor of two or three or even more but these volume estimates clearly show that slides of this size cannot be confined within debris flow containment measures that can be fitted in the available space above the settlement.

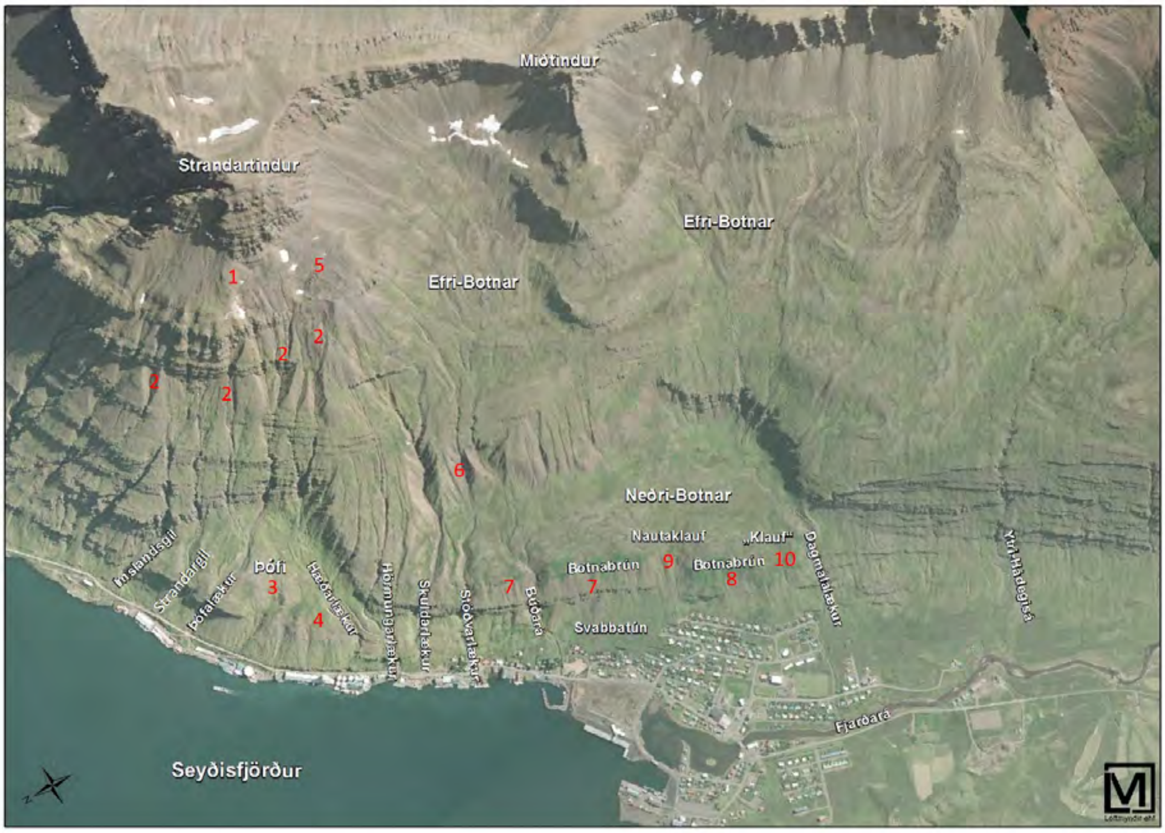


Figure 6. Main potential starting zones for landslides in the mountainside south of Seyðisfjörður between Þófi and Botnahlíð. Numbers denote starting areas that are described in separate subsections in the text and shown on Map 2.

4 Potential starting areas for landslides and debris flows

This chapter provides a summary of several previous studies that deal with landslide hazard in Seyðisfjörður. General geological investigations of loose materials and landslide conditions have been described in section 2 about the geological setting, and historical and prehistoric landslides in section 3 about the landslide history. These studies indicate that landslide source areas in Strandartindur, including Þófi, and in Neðri-Botnar are the main threat to the settlement in the southern part of Seyðisfjörður. Loose materials in the Efri-Botnar cirques do not currently appear to pose a threat to the settlement as there are no indications of past slides from this area of the mountain down to the lower hillside or lowland nor indications of impending slides in the surface morphology of the cirques.

Based on this overall assessment of the landslide conditions, ten areas in Strandartindur and Neðri-Botnar have been identified as possible primary starting zones for landslides. Their selection is based on geological, historical and geomorphological evidence for landslides in the area and earlier hazard assessments. The selected areas are displayed with numbers on figure 6 and on Map 2 and the situation in each area is briefly described below.

Landslides in the investigated area can be divided into four main categories (Þorsteinn Sæmundsson and Halldór G. Pétursson, 1999), as described in section 3 about landslide history, and these are of different relative importance in the individual starting areas depending on the local conditions as further described below.

4.1 Area 1 and 2: Talus slope below the summit of NW-Strandartindur

Two primary starting zones for debris flows have been identified at different elevations below the western part of the summit of Strandartindur. The upper zone is a talus slope at elevation 650–750 m a.s.l. The lower zone is an eroded talus slope with large gullies, between cliffs at elevation 450–600 m a.s.l. These areas were the main source areas for the devastating debris flows in 1950 and 1989 from Þófalækur and Hæðarlækur (Þorsteinn Sæmundsson & Halldór G. Pétursson, 1999). Landslide scars in these areas are visible on aerial photographs and photos. Based on the landslide chronology, the return period for sizeable debris flows in Þófalækur since the beginning of the 20th century is around 25 years, while the return period in Hæðarlækur appears longer, maybe around 60 years. Today, there is only one residential house below these two gullies and a few industrial buildings. Debris flows that originate in the upper part of Strandartindur can also travel down the brooks and the gullies on the outer/eastern side of the Þófi shelf. They are, however, less common and have been less destructive in the past.

4.2 Area 3: Upper part of Þófi

The Þófi shelf is flat and the thick surface sediments drain slowly after periods of rain or snow melt. The loose materials are often saturated with water up to the surface and creeping motion is related to the water content of the material near the surface (Esther H. Jensen, 2001). At least a 100-m wide area on the inner part of the Þófi shelf started creeping in 2000 or 2001 and further signs of movement were noticed after a period of heavy precipitation in the fall of 2002 (see Map 2 for the location of surface cracks caused by this movement). There is evidence suggesting that this is not the first time that this areas has moved as a prehistoric slide or slides into the ocean may have been released from there (Árni Hjartarson, 2015). A first step in the implementation of mitigation measures for the settlement below Þófi was carried out in 2002, when a 100-m long and 3–4-m deep drainage ditch was dug above the fish factory near the western margin of Þófi in order to drain a part of the shelf into Hæðarlækur (Figure 7). The draining is believed to have been successful in reducing the saturation level of the lower part of the slope and the risk of debris slides from the shelf edge. However, it can only be considered a partial measure as it affects a small part of the shelf that may be considered a potential starting area for slides. There are several important industrial buildings below the inner part of Þófi and substantial industrial activity with many people working in the area at times.

4.3 Area 4: The edge of Þófi

Evidence for small debris slides and flows can be seen at and below the edge of the Þófi shelf and the landslide history contains many descriptions of slides from the edge, particularly from the inner Þófi area. Small landslide scars from 2001 are still visible in the upper part of the slope, just below the convex break of the slope, where the water flow from above has a tendency to lead to saturation of loose materials near the surface. Rock falls from the cliffs on the outer side of Þófi area are very common and the steepest part of the inner edge is also a potential source for rockfall.

A small ledge above the guesthouse Norðursíld, that becomes saturated with water during pe-

Figure 7. Drainage ditch near the western edge of the Þófi shelf, dug in 2002. Photograph: Sigurjón Hauksson 26.8.2002.

riods of snow melt and heavy precipitation, is a potential starting area for slides. Just below the ledge, there is an old landslide scar that leads down to the road. Two minor slope failure have occurred there in the past two decades that have damaged the road. One of them reached the Norðursíld Guesthouse, but did not cause significant damage. There is enough remaining material on the slope in this area for much bigger slope failures with a potential for damage of buildings.

4.4 Area 5 and 6: Talus slope below the summit of W-Strandartindur and the gullies below

A ca. 250 m wide starting zone for debris flows can be identified at 650–750 m a.s.l. elevation in the western part of Strandartindur. This part of the slope is characterised by large boulders, small depressions, ridges that are parallel to the slope and small step-like features. The morphological evidence of creep and slope failure suggests that there might be permafrost hidden under the talus. The brooks Skuldarlækur, Hörmungarlækur and Stöðvarlækur become visible on surface, just below the talus slope. Several debris flows are recorded in these brooks since the beginning of the 20^{th} century. It is not clear whether the main source for these debris flows is this talus slope or loose materials at 100–300 m a.s.l. elevation in the gullies below the talus or both.

The return time for sizeable debris flows in these brooks is around 20 years and they tend to be released in two or even all three of them during the same rainstorm.

The main source of landslides in Búðará River is loose materials within the gully itself. The erosion caused by high discharge of water from the large catchment during heavy rainfall causes debris flows to be released into river channel. The source areas are located at two elevations; the gully below the Efri-Botnar cirque at an elevation of 200–300 m a.s.l. and the gully below the Neðri-Botnar shelf at an elevation of 100–140 m a.s.l. Several debris flows are recorded in Búðará since the beginning of the 20th century. It is not clear whether the upper or lower area is the main source for these debris flows.

The return time for sizeable debris flows in Búðará is around 20 years. It appears that the landslide activity has been more frequent in the last 30 years than earlier in the 20th century.

4.5 Areas 7 and 8: Botnabrún

There are several small gaps and cracks on the edge of the Neðri-Botnar shelf, Botnabrún, that indicate movement of the loose materials. The gaps are similar to landslide scars that were formed in Þófi and Botnabrún during the rainstorms in 2001 and 2002. The size of the gaps suggest that the volume of each corresponding landslide is not large. Since a part of the settlement is located very near the foot of the slope, even a small slide could cause damage to houses and potentially accidents to people, particularly in the area between Nautaklauf and Dagmálalækur, and between Búðará and Stöðvarlækur.

4.6 Areas 9 and 10: Nautaklauf and Klauf

The two depressions above Nautaklauf and Klauf in Botnabrún are likely to be formed by the large prehistoric landslides from this area that are described in subsection 3.2, see Tables 1 and 2. The soil in the two depressions tends to be more saturated during periods of rain or heavy snow melt than elsewhere in Neðri-Botnar and the vegetation is also more marsh-like, suggesting higher groundwater level than elsewhere on the shelf where grass, scrubs and lupine are more dominant. This is because the water table in the depressions is closer to the surface than in the surrounding area because of the lower elevation. The area between the two depressions, therefore, appears to be more stable, although small slides appear to have occurred there also in the past (Árni Hjartarson, 2015). According to the geological evidence, the return time of large landslides of similar magnitude as the prehistoric slides is several thousand years. It is difficult to assess the current danger of landslides of a similar magnitude. There appear to be sufficient loose materials in the starting areas for the release of further slides as only a small proportion of the available material was release by the past slides.

5 Assessment of the hazard potential

According to Icelandic legislation, hazard zoning in areas endangered by snow- and landslides in Iceland is primarily based on individual risk (The Ministry for the Environment, 2000). The methodology for risk zoning has been mainly developed for snow avalanches (Kristján Jónasson and others, 1999; Þorsteinn Arnalds and others, 2004) and it has not been explicitly extended to landslides. The regulation nevertheless stipulates that considerations of individual risk should be made in hazard zoning where other processes than snow avalanches are important.

Landslide hazard has been considered for several areas in towns and villages in Iceland that are threatened by both snow avalanches and landslides but the snow avalanches are in most cases the most important danger and landslide risk zoning has rarely been explicitly carried out. An exception is the Kjalarnes area under the mountain Esja in SW-Iceland that is threatened by large rock avalanches from bedrock, debris slides and flows of varying sizes, and by debris torrents (Tómas Jóhannesson and others, 2010; Jón Kristinn Helgason and others, 2014). The analysis of this area was based on a classification of the potential endangering landslides and an estimate of return period and vulnerability was made for each class of slides.

A similar methodology for the southern part of Seyðisfjörður will be applied here. Five classes or types of landslides are proposed in an analysis of the landslide hazard. The classification will not be used to develop a formal hazard assessment for Seyðisfjörður, which will be carried out in a separate study, but it will be used as a framework for discussing landslide hazard and landslide risk for the purpose of the study of feasible mitigation options presented here.

- Firstly, there are *very large and rapid landslides* due to an extensive and deep-seated failure of sediments from a mountainside, similar to landslides that have recently been reported at Stuðlar in Reyðarfjörður, E-Iceland, in November 2002 and in Fagridalur, by Vopnafjörður, E-Iceland in August 2011. Such landslides fall from a comparatively high elevation, cause extensive disruption and upheaval of loose materials and soils in their way, and can travel considerable distances uphill against opposing slopes.

- Secondly, there are *medium-sized or large, rapid debris flows* that are released from comparatively high elevations and are confined to gullies as they travel down the mountainside, similar to the debris flow in Þófalækur in 1950 that killed five persons below Þófi. The potential source areas for such landslides high up in Strandartindur may be affected by permafrost as further discussed below.

- Thirdly, we will consider *large debris flows and debris slides* that travel much slower than the rapid landslides of the first and second types. They are to a higher degree dependent on the mobility provided by water mixed with the sediments than the large and rapid landslides described above, and they may leave 0.5–1-m thick deposits with sizeable boulders below the foot of the slope in their run-out zones. We consider the prehistoric landslide A, B and C that have been identified in exploratory pits within the settlement in Seyðisfjörður, as described in section 3.2, to be of this type. Prehistoric landslides of this type left 0.5–1-m thick debris layers identified in sediments in exploratory pits in Kjalarnes rather similar to the layers A, B and C in Seyðisfjörður.

- A fourth type is considerably *smaller debris flows and debris slides* that travel still slower.

They may have an even larger relative proportion of water mixed with the moving sediments, and often spread laterally under the influence of gravity over wide areas when they reach the lowland. When confined to gullies, many such slides may be called torrents. Except directly in the path of brooks that carries such slides down a gully in the mountainside, this type of landslides often leaves little or only thin debris layers in sediments below the foot of the slope in their run-out zones. There are very many examples of such debris flows reaching settlements in towns and villages in Iceland, such as in Bíldudalur, Siglufjörður, Ólafsfjörður and Seyðisfjörður, and the well known landslides at Kjalarnes in 1886, that left little geological evidence in the soils in their run-out zones, were of this type.

- *Rockfalls* represent the final category that will be proposed here. In terms of danger to human lives and damage to property, they are not as important in Seyðisfjörður as the other classes listed above, but as they need to be considered in the context of mitigation measures, they are included as the fifth and final class.

The vulnerability of people and settlements to landslides is not easy to quantify and any analysis will have to be based on some subjective judgements. We will, in the spirit of the Icelandic hazard zoning regulation, base the following discussion on the probability of a deadly accident when a person is caught in a landslide, starting from the least dangerous class, the rockfalls, and proceeding to the most dangerous large and rapid landslides.

Tómas Jóhannesson and Kristján Ágústsson (2002) argue that the vulnerability of people to rockfalls under typical conditions in endangered Icelandic settlements is rather small so that rockfall hazard zones should in general not reach far from the foot of the slope. Typically, the end of the A-zone should be located at the lower end of the area reached by rocks released from the mountainside during the last ca. 50–100 years. This area can often be delineated by field inspection or simple geological inspection of the surface geomorphology. C- or B-zones due to rockfalls are in general not required. Hazard zones due to rockfall in Seyðisfjörður would in this light be limited to the area below Þófi and the buildings closest to the slope under Botnabrún. The rockfall danger would in neither area be the deciding factor in the delineation of hazard zones but should, nevertheless, be considered in proposals for mitigation measures for these areas. More detailed vulnerability analysis in support of this conclusion is provided by Tómas Jóhannesson and Kristján Ágústsson (2002).

Experience from Iceland indicates that the vulnerability of people caught in comparatively slowly-moving debris slides and debris flows, corresponding to the fourth class of landslides described above, is much smaller than for snow avalanches, such as the avalanches that hit the villages of Súðavík and Flateyri in 1995. This even applies to very extensive debris flows that can cause widespread damage to properties and cultivated land such as in the debris flows and torrents at Kjalarnes in 1886 that devastated fields and farmland over an area of several km^2. This fact is apparent from the record of people killed in snow avalanches and landslides in Iceland. Since the beginning of the 20th century, snow avalanches have killed 109 persons in settlements in Iceland while 6 were killed by landslides, thereof 5 below Þófi in Seyðisfjörður where a fast-moving debris flow from high up in the mountainside in Strandartindur destroyed a house as previously described in this report. In this time period, numerous debris flows and other landslides fell into settlements in Iceland. The probability of death in landslides, other than rock avalanches and very fast-moving slides, which are not thicker than nor contain a greater concentration of large boulder than the 1886 debris flows in Kjalarnes, may on the basis of the available evidence be crudely estimated as one or two orders of magnitude smaller than for snow avalanches, i.e. on the order of 1%. This even applies to people in buildings that are hit by such landslides a considerable distance, such as 100 m, upstream from the stopping position of the front. If a living house is located where the return period of landslides of this type is on the order of 100–300 years, one may roughly estimate that the local risk to people (Þorsteinn Arnalds and others, 2004) is close to or slightly higher than the acceptable level according to the Icelandic hazard zoning regulation, $0.3 \cdot 10^{-4}$ per year. Such a building would be located in the A-zone according to the hazard zoning regulation.

Thicker debris slides and debris flows with a greater concentration of large boulders, corresponding to the third class of landslides described above and comparable to the thick landslides that have been identified in exploratory pits in Seyðisfjörður and Kjalarnes, must be considered much more dangerous. Here it will be assumed that the vulnerability of people caught in such landslides is an order of magnitude larger than for the fourth class, i.e. on the order of 10%. This assumption is obviously quite uncertain but it is among other things based on evidence from debris flows in Alpine countries that have entered dense settlements as a thick, water-saturated slurry causing substantial destruction of property but without casualties (see Figures 8 and 9 in the next section). The vulnerability due to this type of landslides is, according to this assumption, considerably smaller than for fast-moving snow avalanches where the probability of death may be on the order of 30% (Kristján Jónasson and others, 1999). If a living house it located where the return period of landslides of this type is on the order of 1000–3000 years, the inhabitants would be exposed to local risk close to or slightly higher than the acceptable level according to the Icelandic regulation, and the building would be located in the A-zone.

The vulnerability of people and settlements in the way of fast-moving landslides, corresponding to the first and second class of slides described above, some distance upstream of the location where they stop, must be considered as great or even greater than for fast-travelling snow avalanches, that is on the order of 30% or greater (Kristján Jónasson and others, 1999). Our conclusion that the release of landslides from Efri-Botnar are not likely, and that the most likely source areas threatening the settlement under Botnabrún east of Nautaklauf are the water-saturated depressions in Neðri-Botnar, implies that we consider it unlikely that these types of rapid landslides poses a threat to the settlement there. Part of the settlement below Þófi, and perhaps also the neighbourhood of Stöðvarlækur and Búðará that may be reached by slides from permafrost areas at 650–750 m a.s.l. elevation in the western part of Strandartindur (see section 4), may be endangered by fast-moving debris flows from Strandartindur corresponding to the second class of landslides described above. Such parts of the settlement would be located in the C-zone according to the hazard zoning regulation if the return period of this type landslides is estimated a few thousand years or shorter.

We will not present a detailed return period assessment for the settlement in Seyðisfjörður here. The landslide history and geomorphological conditions indicate that the area under Þófi and many of the buildings in the uppermost rows of houses below Botnabrún are endangered by rather frequent landslides, mostly corresponding to the fourth class of slides defined above, with a return period of a few decades to several hundred years depending on the local conditions. Parts of the settlement below the outer part of Þófi and areas directly below the main gullies of the mountainside are threatened by rapid landslides from high up in Strandartindur. The thick debris layers discovered in exploratory pits within the settlement, furthermore, indicate a return period on the order of a thousand or a few thousand years for thicker landslides corresponding to the third class of slides defined above. This situation indicates that much of the uppermost rows of houses under Þófi and Botnabrún are situated in the C-zone according to the hazard regulation. Additionally, extensive settled areas below the C hazard line would be located in the B- and A-zones that, according to this preliminary assessment, should be much larger than on the current hazard map of Seyðisfjörður from 2003. Parts of settlement between Þófi and Nautaklauf, below or close to the main gullies that provide paths for debris flows and torrents from the mountain, may also be expected to be in the C-zone. The conclusion, that the C-zone encompasses mainly (a part of) the uppermost rows of houses, hinges on the conclusion, or the assumption, that the main settlement is not threatened by fast-moving landslides corresponding to the first and second class of slides defined above. Further studies of the landslide conditions and preparatory investigations for mitigation measures should aim to shed more light on this question and provide further validation of this conclusion. Any indications that larger and more dangerous landslides from the hillside are possible or impending need to be taken very seriously as the implications for the hazard assessment and possible mitigation measures would be great.

6 Analog hazard situations in the Alps and implemented or planned mitigation measures

This section describes some situations in the Alps where similar conditions as in Seyðisfjörður may have been encountered and mitigation measures that have been studied there. We will start with a few of photographs from recent debris flows or torrents in Austria where a water saturated slurry flowed into settlements and caused extensive damages to buildings, see Figures 8 and 9. Luckily no one was hurt in these debris flows.

Figure 8. The village of See in the Paznaun Valley in Austria that was hit by a thick debris flow or torrent on 8 June 2015 that left up to several-m thick layer of debris over a large settled area. Photographs FTD, 2015.

6.1 Kerschbaumsettlement/Navis

The Kerschbaumsettlement and the area above the settlement is situated on loose materials that have been moving for centuries (Figs. 10 and 11). Several buildings within the settlement and infrastructure have been damaged to varying degree because of the continuing mass movement.

The first mitigation measures were installed in 2002 in order to reduce the rate of movement. The water within the active zone was reduced by means of catching the springs and by draining

Figure 9. A building hit by a thick debris flow on 8 June 2015 in the village of Sellrain, Tyrol, Austria. Photograph FTD, 2015.

wet areas. For this purpose, a number of drainage ditches, exhaust pipes and shafts (Figs. 12 and 13) were installed above the settlement. Unfortunately, these measures were not sufficient to stop the movement.

A system for monitoring the movements was installed in August 2013, with nearly 80 points situated in the area, on houses and infrastructure, recording hourly measurements. The results are summarised in weekly reports for interpretation by geotechnical experts.

In addition to the previously mentioned mitigation measures, further measures were planned. These included several hundred meters of drainage ditches, discharge pipes and a number of shafts. Half-shell parts of pipes were installed within the existing ditches in order to prevent the infiltration of water into the ground. Furthermore, it was found necessary to drill very deep holes to get more information about the depth of the water-bearing layers and also to install inclinometers as well as standpipes. In 2016, the drainage measures will be extended up to the uppermost part of the mass movement.

The following investigations were conducted:

- 10 to 15 holes for inclinometers.
- 20–30 core drillings.
- Monitoring system was installed in 2013.

The following mitigation measures were implemented:

- Several hundred meters of drainage ditches (waterproofing, drainpipes, loose gravel).

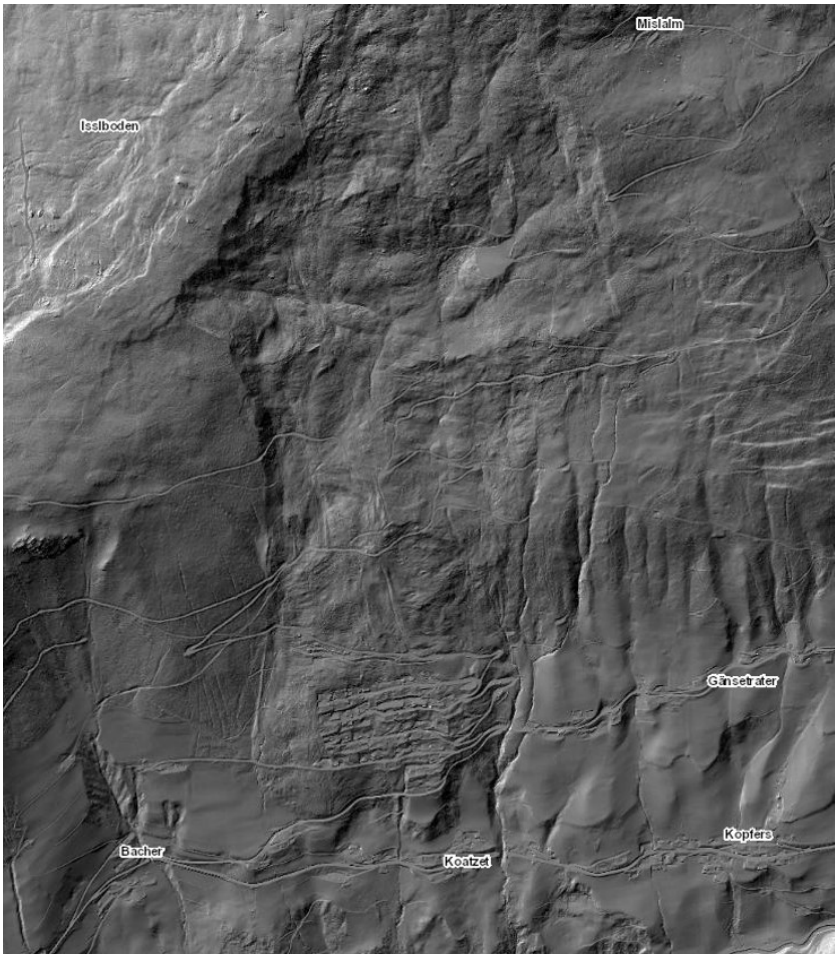


Figure 10. Hillshade of the mass movement at the Kerschbaum settlement.

- Several hundred meters of discharge pipes.
- Numerous shafts.
- Half-shell parts of pipes within the existing ditches to prevent the infiltration of water from the ditch into the ground,
- About 50 wells were drilled to pump water from deep layers to the surface,
- All the drained water is conveyed via two pressure pipes into a power station to produce the electricity for the pumping of water from the wells.

The estimated cost of the measures is approximately 11.0 million €.

The effect of these mitigation measures cannot yet be assessed.

6.2 Gschliefgraben

The mass movement at Gschliefgraben, southeast of Gmunden (Upper Austria), has been well known for centuries. Loamy, glacial, soil masses have crept and slipped with a regular interval of

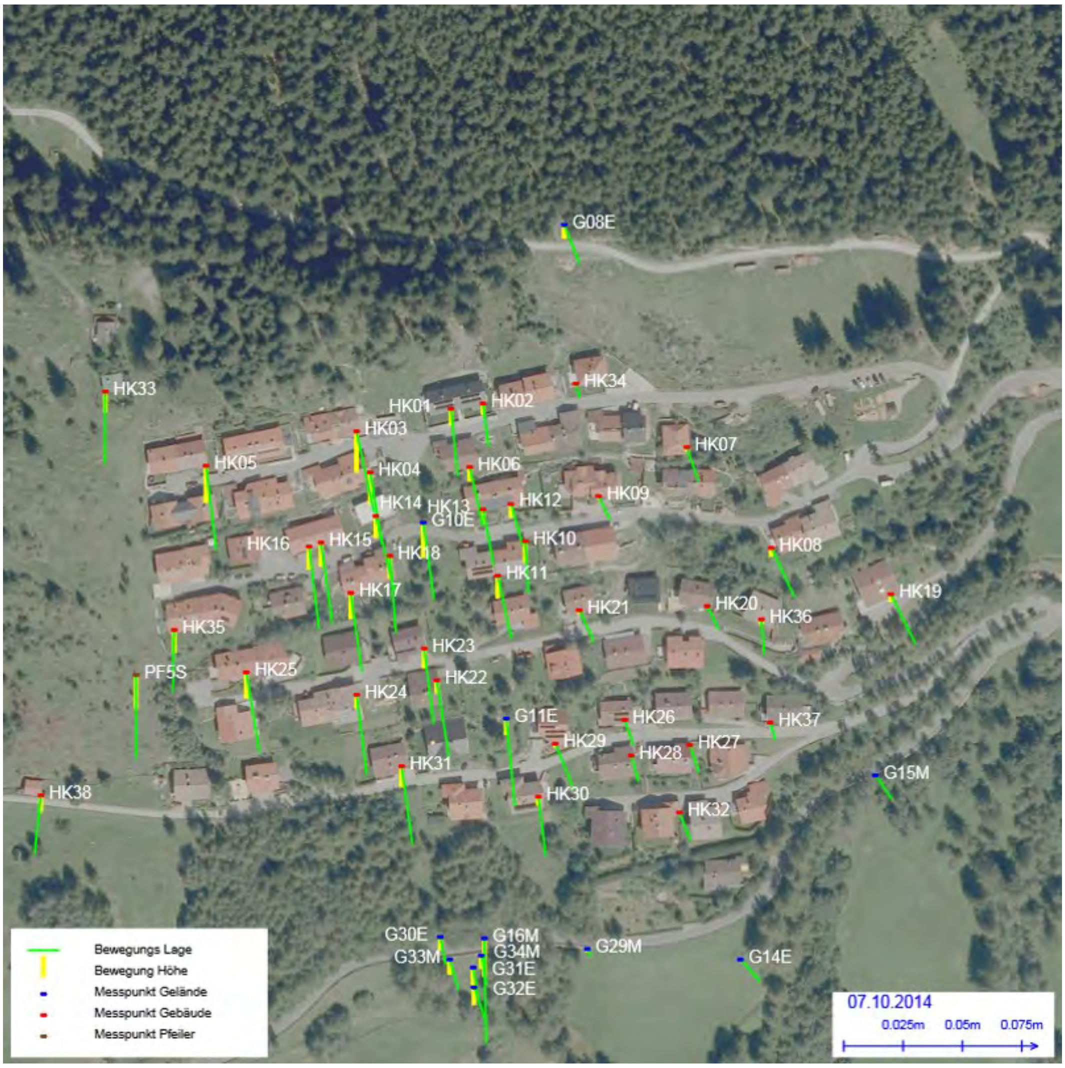


Figure 11. Monitoring system at Kerschbaum (green: magnitude and direction of horizontal movement; yellow: vertical movement; blue: measuring point terrain; red: measuring point building; brown: measuring point stilt).

about 100 years, in the 15th century, 1660, 1734, 1825 and, most recently, in 1910, to the settled areas on the eastern shore of Lake Traun. Several buildings were even moved to the lake. Since 1910, the earth and debris flows have in most cases terminated several hundred meters away from the inhabited area. In 1955 and 1987, however, the activity from Gschliefgraben reached the Traunsee shores. These slides had nothing to do with the glacial, loamy soil masses but were due to debris flows of the torrent.

Since the end of November 2007, the Gschliefgraben has again been brought to the attention of the local population and the media. Signs of ground movements were discovered on 28 November 2007 in the upper graben area. The movement spread gradually, then seemingly unstoppable, to areas situated farther down the slope.

Some weeks later, in an area of about 3 km^2, up to 4 million m^3 of soil were in motion at a rate of several meters per day. Thus, more and more material from the upper slope reached the region

Figure 12. Drainage pipe, discharge pipe, proofing, gravel.

Figure 13. Half-shell parts of drainage pipes.

near the settlement. It was found necessary to evacuate twelve inhabited houses for a period of eight months.

The area is highly sensitive to water and a prone to mass movements. An increase in groundwater pressure due to heavy precipitation and infiltration is one of the main factors driving the movement along with an increased load due to frequent rockfall from the surrounding mountainsides. The additional load over long period of time in connection with high groundwater pressure forces the mass to move down towards the Traunsee.

The following immediate mitigation measures were carried out:

- Discharge of 10,000 tons of water per day from the landslide area.
- Removal of 160,000 cubic meters of loose materials in the first seven months.
- Clearings on 22 hectares for the implementation of the mitigation measures.
- Construction of 220 drainage wells.
- Continuous evaluation of the introduced mitigation measures.

Subsequently, some additional mitigation measures were necessary to reduce the movements of Gschliefgraben. Several thousand m^3 of soil and debris material were removed from the Gschliefgraben to relieve the slope. Additional drainage ditches and drainage channels were furthermore constructed. The reforestation of Gschliefgraben is also considered to be an important part of the mitigation measures.

The aim of the implementation of an early warning and monitoring system is to evacuate the residents immediately in case of an emergency. This is ensured by refraction measurements, core drillings, ground surveys and a number of other geotechnical measures.

6.3 The Doren landslide

The Doren landslide is located primarily in steeply dipping rocks of the so-called Weißach layers. These layers consist of an alternation of competent, hard and brittle fine sandstone benches interbedded with layers of marl and incompetent, mutable solid layers and clay marl or siltstones. The movement in hard rock is transitional but is transformed into rotational sliding at the bottom of 60 m high quarry face where the hard rock is totally softened.

Material released from several locations in the quarry face continues as debris flow along a brook or a gully at the foot of the steep slope.

Measurements of the piezometer level in wells indicate that the water pressure of the mountain water body in the terrace and "im Liegenden" of the uppermost portion of the debris stream corresponds to a water level up to the surface or even higher as an artesian aquifer. That is seen as a probable cause of the recurrent major and minor landslides.

An outline of planned mitigation measures:

- Drainage measures in the upper area to reduce the high water pressures. High groundwater pressures were identified as a major trigger for the rock slides. This permits a rapid and effective stabilisation of the settlement area at Doren.

- In addition, drainage measures are also planned in the field of rock slope and the rotational slopes.
- The execution of the security measures should be done in steps from top to bottom in order to ensure the safety of the construction workers.
- All measures will be monitored by measurements (control of displacements / deformations using inclinometers and geodetic measurements, pore water pressure measurements etc.).

6.4 Landslide Rindberg, Sibratsgfäll

A long rainy season led to the development of a large landslide on Rindberg in the municipality Sibratsgfäll in Vorarlberg in the beginning of May 1999. The first signs of movement were tension cracks in the vegetation cover. Buildings were damaged on the lower slope just a day after the first signs of movement. The movement gradually accelerated, so that by mid-June displacement speeds of 30 to 40 cm per day were observed. The movements of the slope calmed down somewhat after that, but debris flows were released from some areas that continued to be quite active. Another episode of movement occurred on the lower part of the slope in August and this movement was only reduced in October of the same year.

An area of 1.4 km^2 with a volume of about 70 million m^3, corresponding to about 4.6 million truckloads, was affected by this mass movement. The mitigation measures included:

- Construction of 6.2 km access roads.
- 24.7 km of drainage ditches.
- Furthermore, 47,000 m^3 of material was transported away.
- 9,000 m^3 wood was cut before the slope was reforested with 11,000 plants.

Hazards due to landslides can be reduced mainly by constructing preventive structures and early warning systems.

Detailed knowledge about the relevant geological processes is required for implementing effective countermeasures and monitoring systems.

Since the year 2000, diverse monitoring and measuring systems have been installed at Rindberg as part of an extensive geomonitoring program. Geodetic, geophysical and hydrological data, as well as climatic data, are collected and made available online in real-time for long-term evaluation by experts.

6.5 Campo Vallemaggia landslide

The Campo Vallemaggia mass movement is a 0.8 km^3 landslide in the central Swiss Alps (Bonzanigo, 1999). It is composed of gneiss and metamorphic schists, with occurrence of amphibolitic and mafic series. Movement in the area has been reported for well over 200 years. The average rate of displacement is approximately 30 cm/year, varying between < 1 cm/year and a peak of 5 cm/day.

Surface and subsurface investigations, and seismic engineering campaigns have been carried out in the area (Bonzanigo (1999, 2007a,b). Geodetic displacement measurements have been collected for more than a century.

Several boreholes with downhole pressure transducers that were drilled within the unstable mass revealed artesian water pressures which could be correlated to deep inclinometer measurements of large deformations along preferential slip zones. The slope movements were attributed to the high pore water pressures, thus leading to a proposal for the following mitigation measures (Bonzanigo, 1999):

- Construct a 1800 m long drainage adit system to reduce the pore pressures and to stop or reduce the rate of movement.
- A series of drainage boreholes were drilled from the adit through the artesian aquifers to collect groundwater from a larger area.

The quick response of the slope to the drainage adit system shows that, although only a relatively small volume of waterflow was captured, pore water pressures were greatly reduced. Downslope movements have practically ceased. Surface lowering up to half meter, due to the drainage and consequent consolidation, have been observed (Bonzanigo, 1999).

6.6 Summary

The examples of mass movements in Austria and Switzerland described above have the several points in common concerning mitigation measures.

In every case, measures to drain water were implemented to reduce the groundwater pressure and to reduce the weight of the material in motion arising from the groundwater. These measures have been very successful in some cases or have yet to be evaluated in others. Additionally, measurements systems to monitor the mass movement and the effect of the mitigation measures have been installed in several cases.

7 Mitigation measures

The main mitigation measures proposed here to reduce the landslide hazard below Botnabrún and Þófi are (1) a network of drainage ditches in the two depression above Nautaklauf and Klauf and in Þófi, see Map 9, (2) catching dams and debris flow retention measures below the main gullies and brooks through Botnabrún, as well as by Hæðarlækur on Þófi, see Map 9, (3) point protection for a few buildings below Þófi, where workers are most frequently located, see Map 10, and (4) a deflecting dam on the outer side of Þófalækur, see Map 10.

Appendix I provides several photographs that illustrate the local conditions in the areas where the protection measures are proposed.

These proposals are intended more as a list of ideas to be further developed in the next stage of the preparations of protection measures for the south side of Seyðisfjörður rather than explicit proposals that can be designed and implemented as described here. The measures are thus only roughly described, in considerably less detail than is customary in formal appraisals of avalanche protection measures that are carried out for settlements with support of the Icelandic Snow- and Landslide Fund. Furthermore, only limited information is given about the expected cost of the measures, and no assessment is made of the value of buildings and other properties in the protected areas. We have not considered the legal, regulatory or practical framework for the construction of the proposed measures. Thus, the community of Seyðisfjörður, the Icelandic Snow- and Landslide Fund and the owners of the affected buildings will have to discuss the funding and practical arrangements that are required in each case.

No consideration is here given to snow avalanche protection measures. There is, however, considerable snow avalanche hazard below Þófi and snow avalanches do also pose a threat to parts of the settlement below Botnabrún (Þorsteinn Arnalds and others, 2002). The hazard zoning for the southern side of Seyðisfjörður is being reassessed by the Icelandic Meteorological Office, with the aim to present a revised hazard map in 2016. The need for snow avalanche protection measures for the settlement in this area will have to be assessed when the revised hazard zoning is ready.

7.1 Design assumptions

Snow avalanche protection measures are typically dimensioned with respect to design avalanches with explicit values for the velocity, thickness and total volume of the avalanching material. Such parameters are hard to determine for landslide protection measures. As described in subsection 3.2, there is evidence for more than one landslide with volume on the order of a hundred or several hundred thousand m^3 that have overrun the currently settled area below Botnabrún and reached Fjarðará River or the sea. It is imperative to reduce the likelihood of landslides of this magnitude and the main idea or concept of the measures proposed below is to do so by draining the most likely source areas for such slides.

Even if the groundwater level in the potential starting areas can be successfully lowered with drainage measures, and consequently saturation of the loose material during heavy rain and snow melt is less likely, some rest risk due to debris flows from undrained parts of the hillside and the slope below the edge of Botnabrún must be expected. We assume that drainage measures can reduce the volume of potential debris flows by an order of magnitude or more. Therefore, other measures, i.e. catching dams and debris retention basins, need to be dimensioned for debris flow volumes on the order of ten thousand m^3 in the main debris flow paths for the prehistorical slides identified in earlier studies below Klauf, Nautaklauf and Búðará. For dam height of 4–6 m this implies that the map area of debris retention basins and above catching dams affected by a single event needs to be several thousand m^2. These assumptions must be further discussed and evaluated in the further elaboration of the plans. Búðará, and possibly Stöðvarlækur, present a special problem because the possible source areas for slides in those paths cannot easily be drained and no drainage measures for them are therefore proposed there. We recommend further studies with exploratory pits in the lowland below the gully of Búðará to investigate whether one or more of the large prehistoric debris flows originated there as is suggested by Árni Hjartarson (2015). The risk posed by possible permafrost areas at 650–750 m a.s.l. elevation in the western part of Strandartindur (see section 4), that may release landslides into Skuldarlækur and Stöðvarlækur and perhaps also Búðará, also needs to be studied further. If such investigations confirm large prehistoric debris flows in Búðará and/or impending slides from the permafrost areas, the rest risk in the neighbourhood of the paths will be higher than for other areas considered here and this will have to be taken into account in the revision of the hazard zoning after protection measures are implemented.

Here it is assumed that rockfall danger in the investigated areas is in general less of a problem than the danger due to debris flows, see section 5. We propose a 4–6 m high debris flow catching dam along more or less the entire settlement below Botnabrún that may be expected to stop essentially all rocks that fall from the slope. Rockfalls are, therefore, not a dimensioning factor for the protection measures proposed here.

Floods in the main rivers and creeks through Botnabrún are among the design events that need to be taken into account in the design of the catching dams and debris retention basins. Design floods appropriate for each river and creek need to be estimated by statistical analysis and modelling. Appropriate by-pass structures through the debris retention basins as well as waterways through the settlement and into the ocean should be designed with sufficient capacity for extreme flood events with a return period of at least 100 years.

7.2 Drainage measures

Drainage measures can be pipes, tunnels or closed channels below the surface or open ditches or channels depending on the local conditions and/or the depth to the layer that should be drained (Figure 14). The depth and geometry depends mainly on whether only surface water needs to be captured or whether groundwater flowing through uppermost layers of loose materials should also be caught. The suitable volume or cross-sectional area of the pipe or ditch depends on quantity of water, the distance between the individual drainage channels, and the length of the ditches.

Open channels

The discharge capacity can be calculated with an appropriate calculation method (Parriaux and others, 2010). The inclination of the embankments must be rather low because of the danger of erosion. Narrow, rectangle-shaped ditches are typically filled with permeable material in order to limit maintenance. The minimum longitudinal inclination of open channels depends on the desired discharge capacity. The maximum longitudinal inclination, on the other hand, depends

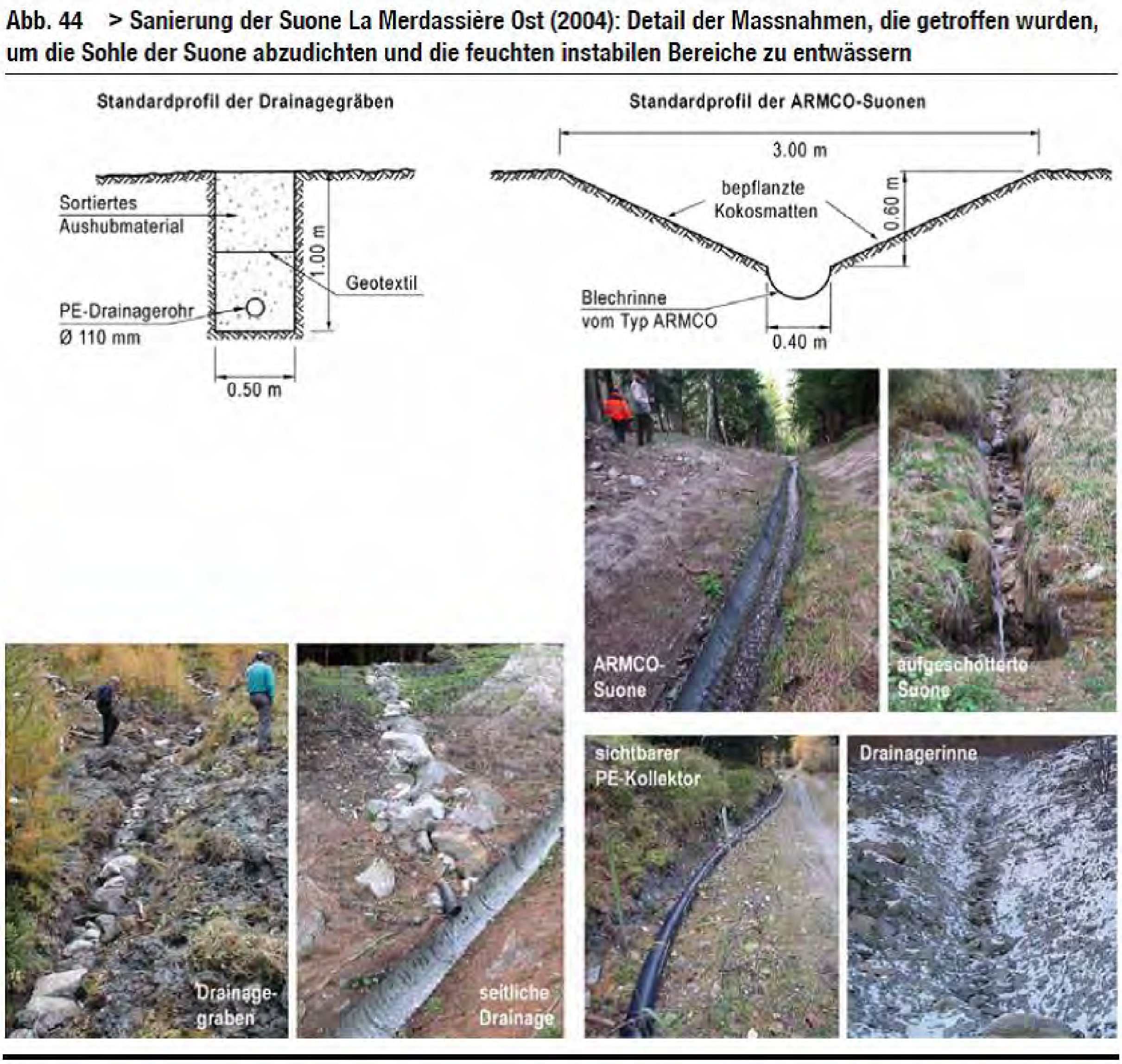


Figure 14. Examples of drainage channels. Top left: Standard profile of a drainage channel/ditch Top right: open hollow or open drainage ditch with a planted embankment and a metal channel at the base.

on the danger of erosion of the bottom of the channel. Channels with gravel at the bottom can be dug steeper than channels with more easily eroded bed material. The danger of erosion can be reduced by special construction methods, with suitable vegetation, or by stabilising the channel with mats or fabrics (Parriaux and others, 2010). In some cases, the water from open channels is collected into shafts so that the water can be diverted with a pipe into a waterway designed to rout it around or through a settled area.

Channels filled with gravel

A closed drainage channel/ditch will be filled with water-permeable material. The geometry depends mainly on the quantity of water that needs to be drained and the depth to the layer that has to be drained. Generally, the following dimensions are used:

- Depth: 0.5–1.5 m,
- Width: 0.5–1.5 m.

The discharge Q in a channel/ditch filled with water-permeable material (without a drainage pipe) can be calculated with the following formulas:

$$Q = A\,k_f\,i\ ,$$

where A is the cross-sectional area of the channel, k_f is the permeability of the fill material and i is hydraulic gradient/inclination (in principle the slope of the ditch). The inclination is given as:

$$i = \Delta h/\Delta l\ .$$

Some typical values of the permeability for different types of fill materials are given in the table in Figure 15.

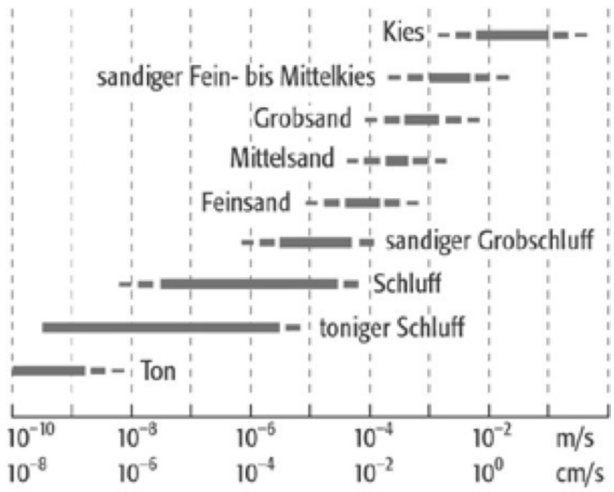


Figure 15. Table with values of the permeability of several types of loose materials (from Parriaux and others, 2010).

The maximum slope of a drainage channel/ditch filled with gravel depends on the friction angle of the material. The maximum allowable slope of coarse gravel is between 25 and 45%. The following points need to be considered concerning drainage channel/ditch filled with gravel:

- Whether a drainage pipe should be used.
- Waterproofing at the base and at the side of the embankment is needed if the subsurface material is permeable.

- It is necessary to line the channel walls with a mat or fabric if there is danger of illuviation of fine material from the sides into the fill material in the channel.

Figure 16 provides some examples of the technical layout of drainage channels/ditches of this type.

7.3 Protection measures for the settlement below Botnabrún

Drainage ditches in Neðri-Botnar

An important measure for reducing the landslide hazard below Neðri-Botnar is a network of drainage ditches in the two depression above Nautaklauf and Klauf, see Map 9. Figures 26–31 in the Appendix illustrate the local conditions in the areas where the ditches are proposed.

The following points should be noted about the layout and implementation of the ditches.

- The first ditch should be dug in the uppermost part of each area.
- The topmost drainage ditch above Klauf can discharge into Dagmálalækur.
- Due to terrain conditions, the next two drainage ditches should lead to a shaft and be discharged with pipes.
- The next three drainage ditches lead to a small channel; in order to prevent the water from disappearing into the underground it will be necessary, on the one hand, to discharge the water with pipes and, on the other hand, to prevent the percolation of the remaining water with proofing measures.
- In the lowest part of the area, where it is flat and completely wet (above the settlement), further drainage and discharge measures are proposed. These ditches lead to one ore more shafts and the water will be discharged with pipes.

In total, about 2.0 km of drainage ditches, about 400 m of discharge pipes, and about 80 m of waterproofing are proposed in the depressions above Klauf and Nautaklauf.

At this stage, we do not estimate the construction cost of the drainage measures as the plans are only preliminary and important design decisions that are fundamental for the involved cost have not been made.

Catching dams and debris retention basins below Botnabrún

Many of the buildings in the uppermost rows of houses below Botnabrún, both west and east of Nautaklauf, are endangered by rather frequent landslides, mostly corresponding to the fourth class of slides defined in section 3, as well as by small rockfalls. Furthermore, as mentioned above, there will be some remaining hazard due to landslides from the main starting areas above Klauf and Nautaklauf after the implementation of drainage measures. Therefore, the construction of a moderately high catching dam above the top row of houses below Botnabrún is proposed as an effective way to protect the settlement, see Figure 17 for a typical longitudinal profile and Map 9 for a rough layout. The height of the dam should vary between ca. 4–6 m depending

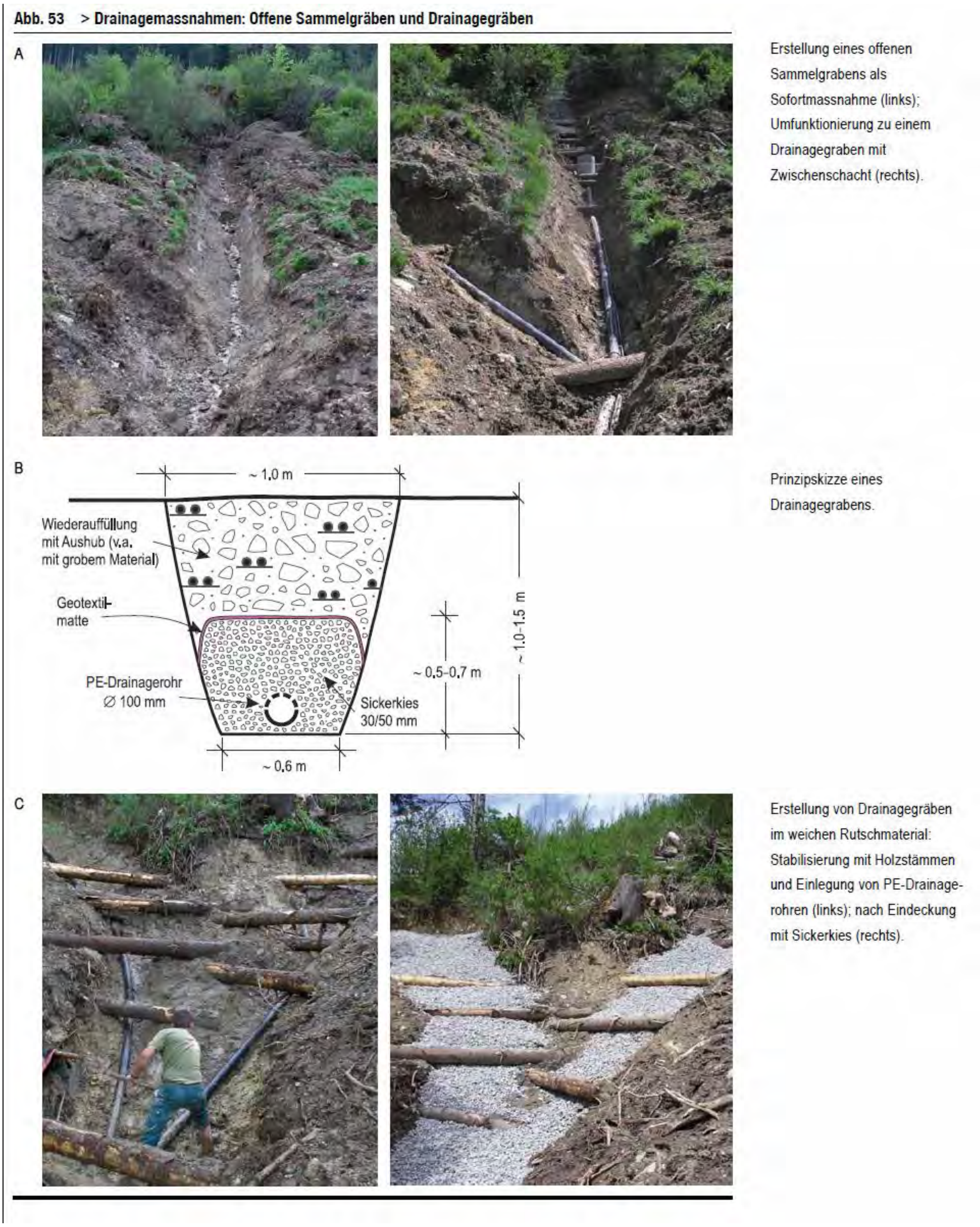


Figure 16. Further examples of drainage channels of different types. A, left: An open channel/ditch; A, right: An open drainage channel/ditch with a shaft B: Sketch of a drainage channel/ditch (drainage pipe, permeable gravel, fleece, filled with coarse material) C, left: drainage channel/ditch in soft material; Stabilisation with wooden trunks and using drainage pipes; C, right: channel is filled with gravel. (From Parriaux and others, 2010.)

on the local hazard situation. The uppermost ca. 2 m of the dams should be constructed with a steep slope >2:1 towards the mountain. There should be enough space for the dams between the uppermost houses and the foot of the slope and the material appears to be of sufficient quality to construct the dams in mass balance from the local material. It is important to consider proper drainage of water from the area above of the dams all the way through the settlement and into the sea.

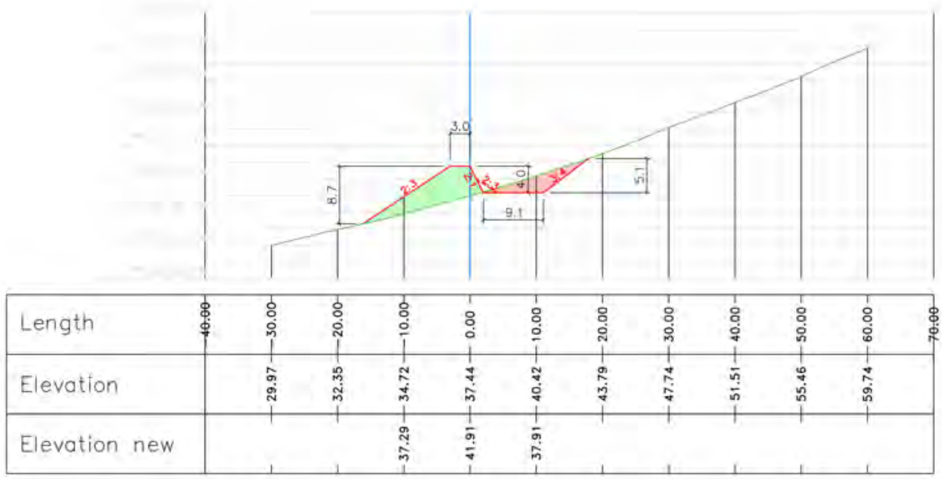


Figure 17. Typical cross-section of a 4–6 m high catching dam as proposed at the foot of the mountainside above the top row of houses below Botnabrún. The uppermost ca. 2 m of the upstream face of the dam is steep but the slope below this steep part is determined by the angle of repose of the loose materials.

Below Nautaklauf, Búðará and Stöðvarlækur it is proposed to construct debris flow and water retention basins directly above the uppermost houses in order to prevent debris flows and floods from reaching the settlement, see Map 9. There are existing drainage ditches above Svabbatún that divert rain water northeast to Búðará and southwest the brook from Nautaklauf. The ditches that drain water towards northeast, in particular, have become overgrown and are affected by erosion of the banks and do not seem to work effectively anymore due to lack of maintenance. The proposed catching dams and retention basins are intended as a reinforcement of these exiting drainage measures and need to be integrated into the surface water drainage network of the settlement farther downstream.

The debris flow retention basins should be constructed with by-pass openings with concrete or steel beams, see Figure 18, as is customary in Alpine countries. Erosion prevention measures may, furthermore, be needed where water flows into and out of the retention basins as indicated on Map 9. The lateral dam sides of the debris retention basins can be built with the angle of repose of the loose materials, but not less than 1:1.5, if this is suitable, but this will depend on the available space at each location. Due to lack of space to construct waterways of sufficient capacity downstream from the by-pass openings it may be necessary in some of the cases to build channels or a pipes to discharge the water into the fjord. The volume and the design of the retention basin has to be considered on the basis of the volume of debris that needs to be retained as well as with a hydrological model based on the size of the catchment area, an estimate of extreme precipitation intensity, and the runoff characteristics of the corresponding watershed. There is very little space for the construction of a retention basin by Stöðvarlækur. There may be need to relocate one of the current buildings by the brook (Hafnargata 42b) in order to gain space for the construction of a basin of suitable capacity. The retention basins must be designed with good access for construction vehicles that need to be used to empty debris from the basins so that they do not get filled with material from the retained landslides.

Figure 18. Bed-load samplers in Switzerland made of fill material (left) and concrete (right) with a by-pass structure made of concrete and steel bars (Margreth, 2015). The steel bars separate water from the bed-load. Such structures are often built in Alpine countries. Photographs: Stefan Margreth.

The total volume of fill material of the catching dams and retention basins is 60–70 thousand m^3, see Map 9. The storage capacity of the retention basins is ca. 8900 m^3 for Nautaklauf, 8000 m^3 for Búðará and 6400 m^3 for Stöðvarlækur. Based on information about the unit cost of dam projects in recent years in Iceland (3500 IKR/m^3 for fill, 40 kIKR/m^2 for steep reinforced dam sides), a rough cost estimate for the catching dams and the lateral sides of the retention basins proposed here for the area below Botnabrún is 300–400 million IKR. The cost of the by-pass openings through the retention basins cannot be estimated based on local information as no such measures have been constructed in Iceland. A rough estimate of the building cost of such a construction has been made in connection with plans for a slush flow retention basin in Patreksfjörður, indicating that a by-pass opening through a 6 m high dam could be 20–30 million IKR. The construction cost of planned debris retention basins at Rettenbach (storage capacity 9200 m^3) and Reastalbach (storage capacity 6600 m^3) in Austria has been estimated 1.2 and 0.5 million €, respectively, in both cases including the cost of the dams and by-pass opening. These cost estimates are only intended to give an idea about the involved construction cost. They does not include the cost of possible relocation of infrastructure such as electrical power lines, drainage pipes and channels which will be estimated as a later stage.

Real-time monitoring and warnings

The effectiveness and the impact of these measures, especially the drainage and discharge measures, should be monitored by inspections and by a geodetic measurements. The drainage ditches, shafts, discharge pipes and the area where the pipes empty into the channel must be monitored, and if necessary immediately repaired, to ensure proper functioning. This is especially important during and after heavy rainfall or snow melt.

7.4 Protection measures for the Þófi area

There are several important industrial buildings below the inner part of Þófi and substantial industrial activity with many people working in the area at times, see Figure 19. As already

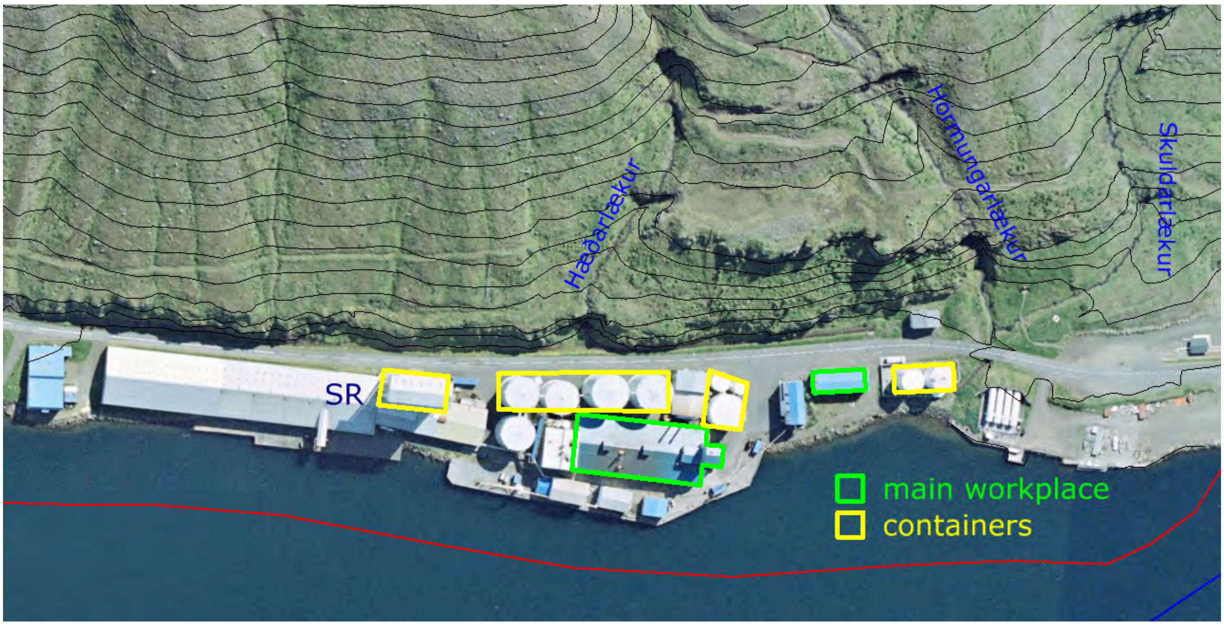


Figure 19. Buildings below Þófi where workers are most frequently located (green) and tanks that can contain large amounts of fish meal that may endanger other buildings if destabilised (yellow).

mentioned, a debris flow from Hæðarlækur caused extensive damage to the fish factory and almost destroyed a residential house that was attached to the factory in 1950. In 1989, a debris flow from Hæðarlækur hit the fish factory but did not cause much damage. A debris flow from Þófalækur in the same cycle caused damage to a house belonging to the fish factory. Figure 20 gives an overview of the settled area below Þófi and indicates the main protection measures suggested for this part of the settlement. We have not developed the ideas for protection measures for the Þófi area in sufficient detail to give meaningful cost estimates.

Drainage ditches, retention basin and discharge pipes on Þófi

As already mentioned in section 4, a 100-m long and 3–4-m deep drainage ditch was dug in the western part of Þófi above the fish factory in 2002 (Figure 7). It is proposed here to expand the existing drainage measures with additional drainage ditches in the uppermost part of Þófi. Near the drainage ditch from 2002, a debris flow and debris retention basin should be constructed,

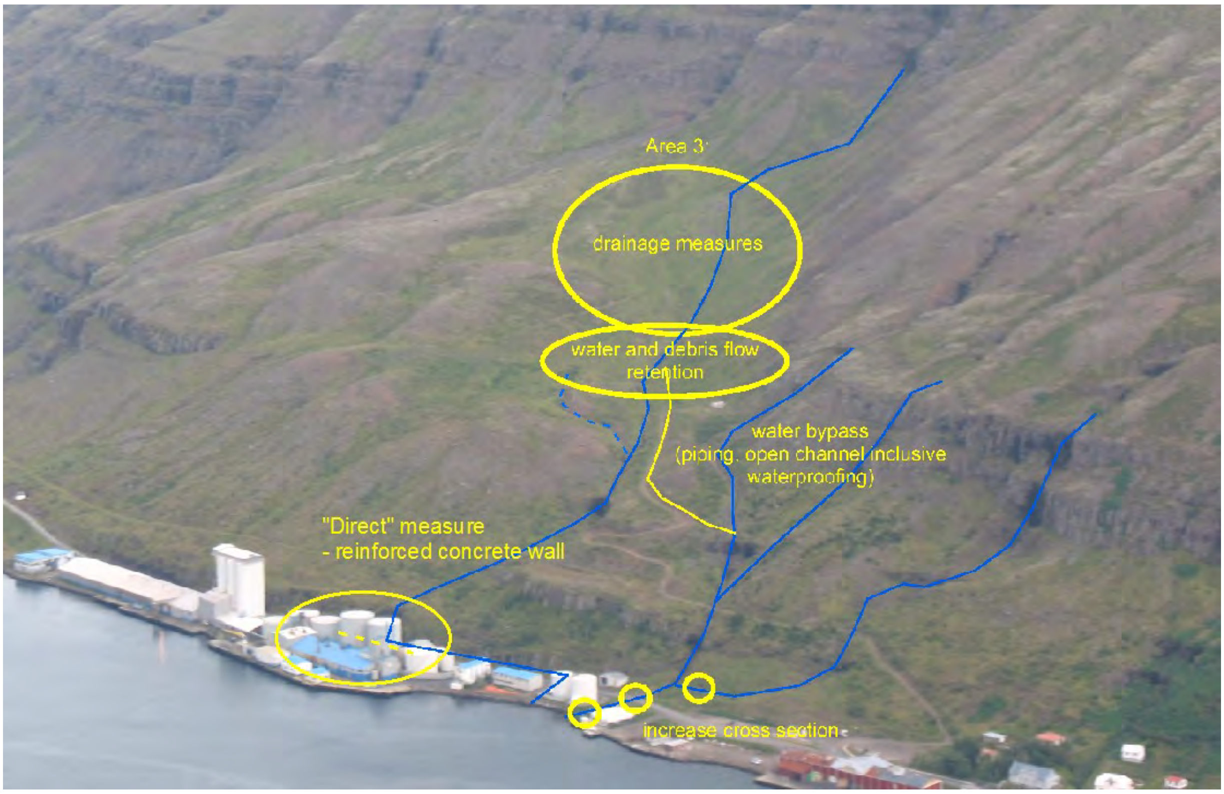


Figure 20. Overview of Þófi area and possible mitigation measures.

see Figure 21 and Map 10, as well as a low guiding dam, see Map 10, in order to prevent debris flows from Hæðarlækur from hitting the fish factory. The volume of fill material in the proposed guiding dam and retention basin is ca. 13 thousand m^3 and the storage capacity of the retention basin at Hæðarlækur is ca. 7800 m^3.

At the foot of the steep slopes of Strandartindur near the top of the shelf of Þófi, a low deflecting dam might be constructed in order prevent debris flows in Hæðarlækur from breaking out of the gully and into the depressions farther down, between Hæðarlækur and Þófalækur.

Furthermore, it is recommended to construct a by-pass for water from Hæðarlækur to the brook Hörmungarlækur, see Figures 22 and 23. This water by-pass can be constructed with a pipe or an open channel above the existing road. Waterproofing of the channel may have to be considered.

The design of the retention basin on Þófi has to be considered with a hydrological model based on the size of the catchment area, an estimate for extreme precipitation, and runoff characteristics of the watershed (the runoff coefficient and the roughness). The discharge capacity of the pipe or the open channel has to be estimated with a calculation model for pipes or with the Manning–Strickler formula for an open channel, respectively.

If these measures are carried out, it is necessary to carefully consider discharge conditions in the catchment area of the brook Hörmungarlækur, which would subsequently carry substantially greater discharge than under the current conditions. Therefore, the existing pipes under the road would have to be adapted and the cross-section of the waterway would have to be increased.

Figure 21. Inner part of Þófi where a debris flow and water retention basin is proposed.

Some of the cross-sections of the existing pipes under the road, as well as the size of the ditch above the road by Þófi, are clearly too small.

Point protection measures for buildings below Þófi

Point protection measures for individual buildings are an additional option for protecting the most sensitive buildings of the SR Mjöl fish factory, where people are most often located during working hours. An example is reinforced concrete walls against debris flows along the main tanks (see Figures 20 and 24). The wall must probably be situated nearby the towers, because there is too little space on the other side of the road for the deposition of debris flow material. The dimensioning of the reinforced concrete wall has to take a dynamical debris flow pressure and the pressure caused by the deposition into account. The main office building of SR Mjöl is not as endangered as the area where the tanks area located. As it is continuously occupied by people, it is, nevertheless, advisable to improve the safety of this building, possibly by a ca. 2-m high steel wall above the road, similar as employed by the Icelandic Public Road and Coastal Administration by roads below Súðavíkurhlíð and Ólafsfjarðarmúli (Figure 25).

Figure 22. Inner part of Þófi; where a water by-pass is suggested above the existing road.

7.5 Guiding dam by Þófalækur

The building Strandarvegur 27 (Físarhús) is endangered by debris flows and snow avalanches from Þófalækur. It will be hard to provide adequate protection against snow avalanches for this building as it is close to the mountain and Þófalækur must be considered one of the main avalanche paths of this mountainside. However, the geometry of the landscape is such that debris flows, which travel much slower than snow avalanches, are gently guided in a westward direction away from this building. A low guiding dam with height of ca. 5–6 m, fill volume of ca. 10 thousand m^3 and a deflecting angle of 20–25°, split in two by the road, see Map 10, would make this building much safer from debris flows. The dam could be built in mass balance from local loose materials with the slope of the dam sides determined by the angle of repose of the local loose materials. The dam should be combined with a widening of the western margin of the gully just above the road by the removal of the lowest part of the ridge that is located there. The dam must be split in two because of the road along the coast and the opening for the road must be carefully designed to prevent through-flow of tongue of debris towards the building to be protected. The access road to the building might need to be slightly adapted as a part of the design of this opening. A dam of this height would be able to deflect a 2-m thick debris flow travelling at >10 m/s (Costa, 1984; Prochaska and others, 2008) away from building according to design procedures for such dams (Tómas Jóhannesson and others, 2009). Such a dam might

Figure 23. The SR fish factory seen from Þófi; the brook Hörmungarlækur and existing pipe through the road.

make the building safe for summer use for various purposes, similar to the situation for buildings located on the north side of Seyðisfjörður whose use during wintertime is restricted due to snow avalanche danger.

Figure 24. The main tanks of the SR fish factory below Þófi where point protection by a concrete wall might improve the safety.

Figure 25. A steel wall above the road below Eyrarhlíð in NW-Iceland for reducing the frequency of snow avalanches reaching the road. Photograph: Jón Kristinn Helgason.

8 Further investigations

There are a number of studies that should be carried out to shed further light on the landslide problems of Þófi and Botnar and in preparation of mitigation measures for the settlement that might be implemented in the future.

8.1 Further studies of landslide conditions

A more extensive collection of basic information about the geological conditions needs to be carried out. Earlier studies of the geology of loose materials using repeated measurements of fixed points, boreholes, exploratory pits *etc*., that are summarised in this report, show the essential features of the situation. Such investigations and more detailed assessment of the hazard are an essential step in the preparations of mitigation measures. Further geological and hydrogeological investigations, as well as geotechnical investigations, may provide information about a possible connection between the mass movements and precipitation, snow melt and water level fluctuations. The following additional studies could improve our understanding of the problem.

Geodetic measurements of fixed points The programme of repeated measurements of fixed points that have been installed in Þófi and Neðri-Botnar (Maps 6 and 7) should be continued to investigate relative movements of the slope, which areas are stable and which unstable, whether the rate of movement changes with time and whether periods of precipitation and/or snow melt are associated with an increase in the rate of movement. In this connection, any new signs of movements in the form of cracks or other changes in surface morphology need to be described and mapped.

Water pressure measurements in boreholes A continuous measurement of water pressure / water level in one or more of the boreholes from 2002/2003 should be considered. This may be technically challenging as the pressure sensors may become clogged and the complicated hydrogeological situation may render the results hard to interpret (there may be multiple groundwater aquifers at different depths and it may not be clear which one the borehole represents). Results from one or two boreholes from a single year might be useful to decide whether to continue or expand such measurements after the first year. More intensive and more expensive monitoring programs may also include measurements of pore-water pressure and the widening of fissures with an extensiometer. The usefulness of such measurements should be considered at a later point in time.

Inclinometry and borehole photogrammetry The boreholes drilled in 2002/2003 should be logged to investigate whether any signs of slip or localised deformation at depth in the deep sediments can be detected from a deformation of the borehole casing.

Studies of prehistoric landslides from Búðará Further studies with exploratory pits in the lowland below the gully of Búðará are needed to investigate whether one or more of the large prehistoric debris flows originated there as is suggested by Árni Hjartarson (2015).

Studies of possible permafrost areas at high elevations in Strandartindur Possible permafrost areas at 650–750 m a.s.l. elevation in the western part of Strandartindur, that may release landslides into Skuldarlækur and Stöðvarlækur, and perhaps also Búðará, need to be studied further with a geological field investigation to throw light on the associated hazard for the settlement.

Detailed lidar mapping of the mountainside A high resolution lidar map with a resolution of 0.5–1 m of the hillside should be made. Such a map would make a more detailed analysis of surface fractures and deformations possible. Repeated mapping after a possible future period of slides and deformations would make it possible to analyse changes in surface geometry due to various movements and deformations within the sediments.

InSAR measurements of slope movements Further InSAR investigations, in addition to the study of Sigurjón Jónsson (2007), could be useful to see whether detailed fields of surface movements over several different time periods could be obtained.

Debris flow modelling It might be instructive to model debris flows in some of the main debris flow paths with a 2-D depth-integrated debris flow model.

8.2 Studies of mitigation measures

There are many open questions related to the mitigation measures outlined in this report that need to be studied further before the measures can be implemented. The following studies are needed in the next phase of preparations of the mitigation measures.

Drainage ditches in Þófi The drainage ditches from 2002 near Hæðarlækur in Þófi need to be expanded to drain a much larger area. Thus, a proposal for a network of drainage ditches in Þófi needs to be worked out. These need to provide further draining of the inner part of the shelf and also drain the small ledge near the shelf edge above the guesthouse Norðursíld mentioned in section 4.

Additional drainage ditches in the upper part of Neðri-Botnar The need or usefulness of further drainage ditches in Neðri-Botnar than suggested here (Map 9) should be investigated. A long drainage ditch near the top of the shelf could potentially divert surface water from the whole mountainside above the Neðri-Botnar shelf from east of the Nautaklauf depression to Dagmálalækur. However, the water level in boreholes in the upper part of the shelf (boreholes SB-9 and SB-10, see Ágúst Guðmundsson and others, 2003) show very deep water level in this area. Runoff from the upper slope, therefore, appears to seep deep into the ground and travel below the surface until it approaches the surface again farther down the mountainside. This indicates that it will be difficult to catch significant amounts of water with drainage ditches in this upper area. Nevertheless, this question needs further study.

Optimal configuration of drainage ditches The type of drainage ditches most appropriate for the lower depressions shown on Map 9 needs to be decided. Among the questions to be considered are whether the ditches should be open or closed, the appropriate or optimal longitudinal slope of ditches in case they are open, whether half-pipes or some kind of erosion protection is needed at the bottom of the ditches to prevent percolation of the flowing water into the substrate, and whether slides can be released from the sides of the ditches and what can be done to prevent this.

Modelling of debris flows against the guiding dam by Þófalækur The effectiveness of the proposed guiding dam by Þófalækur should be investigated with 2-D debris flow modelling with the proposed geometry of the dam included in the computational mesh.

Project organisation and management The investigations and mitigation measures proposed here require hydrogeotechnical preparations that can only be carried out by an expert group of geologists and engineers with experience in this field. As a next step, the community of Seyðisfjörður and the Icelandic Snow- and Landslide Fund need to decide how to appoint such a group and how to benefit from experience and know-how from similar situations in Alpine and other foreign countries (see for example Parriaux and others, 2010). We recommend to contact an international hydrogeotechnical expert to provide the necessary know-how and propose to appoint an engineer from an Icelandic engineering company to oversee this work locally. It seems likely that the draining of Neðri-Botnar is best carried out in multiple steps over a several-year period with an interaction between design, construction and monitoring of the effectiveness of already constructed measures.

9 Summary

Evaluation and interpretation of existing studies of the landslide hazard in Seyðisfjörður and further investigations carried out in the preparation of this report indicates that parts of the settlement below the Þófi shelf are threatened by fast-moving debris flows from high elevations in Strandartindur as well as from slower-moving debris flows and debris slides from the shelf itself. The danger from the higher starting areas may partly arise from permafrost areas that can pose an increasing danger in the future due to warming climate.

There is geological evidence for three or four large, prehistoric landslides reaching the Fjarðará river or the sea below Botnabrún during the last several thousand years that demonstrates that danger due to large landslides extends to essentially all the current settlement south of Fjarðará. The main source areas for landslides that threaten the settlement below Botnabrún are the depressions in Neðri-Botnar, above Nautaklauf and Klauf. Landslides from these areas in Neðri-Botnar are likely to travel more slowly than landslides from high elevations in Strandartindur and are therefore less hazardous for the affected settlement.

Parts of the settlement between Þófi and Nautaklauf, close to the main paths for debris flows and torrents from the mountain, in particular the settlement near Stöðvarlækur and Búðará, may also be threatened by fast-moving debris flows from high elevations in Strandartindur that can be affected by permafrost.

There is high hazard, corresponding to the C-zone in the Icelandic hazard zoning regulation, within the main debris flow paths below Þófi and the eastern part of Botnabrún to Nautaklauf and in the uppermost rows of houses below Botnabrún. Additionally, an extensive part of the settled area south of Fjarðará River may be expected to be located in B- and A-zones when the hazard zoning of Seyðisfjörður will be revised in light of the studies of landslide hazard summarised in this report.

The most effective mitigation options to improve the landslide hazard situation in southern Seyðisfjörður is draining of the main source areas in Neðri-Botnar in the lower part of the mountainside as well as a construction of a moderately high catching dam above the top row of houses below Botnabrún, and debris retention basins and guiding dams at the lateral sides of the main debris flow paths.

Point protection of individual buildings, in particular some of the more important industrial buildings below Þófi, should also be considered.

The implementation of the protection measures requires an extensive study of the landslide conditions and detailed planning of the layout of draining ditches, dams and other measures that needs to be carried out by an expert group of geologists, geotechnical and hydrogeotechnical engineers and engineers in the field of torrent and avalanche control.

10 Acknowledgements

This study is to a large degree based on the earlier geological investigations of Halldór G. Pétursson and Þorsteinn Sæmundsson (1998), Þorsteinn Sæmundsson and Halldór G. Pétursson, 1999), Ágúst Guðmundsson and others (2003), Óskar Knudsen and Guðrún Larsen (2013) and Árni Hjartarson (2015). Óskar Knudsen read a draft version of the report and contributed to the interpretation and conclusions presented here which is gratefully acknowledged.

11 Bibliography

Almenna verkfræðistofan (1998). *Snjóflóðavarnir á Seyðisfirði, Bjólfur, frumathugun. Athugun á lausum jarðlögum (Avalanche protection measures for Seyðisfjörður. Bjólfur, defence appraisal. Investigation of loose materials).* (Author Jón Skúlason).

Ágúst Guðmundsson, Óskar Knudsen & Haraldur Hallsteinsson (2003). *Seyðisfjörður – Athuganir á jarðgerð í Þófum og Botnum (Seyðisfjörður – Investigation of loose materials in Þófar and Botnar).* JJS – Geological Services, report dated October 2003.

Árni Hjartarson, Freysteinn Sigurðsson & Þórólfur Hafstað (1981). *Vatnsbúskapur Austurlands. III (Water balance of the Eastfjords. III).* National Energy Authority, report OS81006/VOD04, 198 pp.

Árni Hjartarson (2015). *Skriðurannsóknir á Seyðisfirði árið 2015 (Landslide investigations by Seyðisfjörður in 2015).* ÍSOR – Iceland GeoSurvey, report ÍSOR-2015/058.

Árni Stefánsson (after 1988 but before 1996). *Grjót og aurskriður í Seyðisfirði. Tekið saman af Árna Stefánssyni (Rockfall and debris flows in Seyðisfjörður. Compiled by Árni Stefánsson).*

Bonzanigo, L. (1999). *Lo slittamento di Campo Vallemaggia*. D.Sc. thesis, Engineering Geology, Swiss Federal Institute of Technology (ETH Zurich), Zurich, Switzerland. doi:10.3929/ethz-a-003885355.

Bonzanigo, L., E. Eberhardt & S. Loew (2007a,b). Long-term investigation of a deep-seated creeping landslide in crystalline rock. Part I. Geological and hydromechanical factors controlling the Campo Vallemaggia landslide / Part II. Mitigation measures and numerical modelling of deep drainage at Campo Vallemaggia. *Canadian Geotechnical Journal*, *44*, 1157-1180 / 1180–1199.

Costa, J. E. (1984). Physical geomorphology of debris flows. In: Costa, J.E., & J. P. Fleisher (eds.): *Developments and Applications of Geomorphology*. New York, Springer, 268–317.

Esther Hlíðar Jensen (2001). *Hætta á skyndilegu jarðskriði úr brún Þófans á Seyðisfirði (Danger of a sudden landslide from the edge of Þófi in Seyðisfjörður).* Icelandic Meteorological Office, memo EHJ-2001/01.

Esther Hlíðar Jensen & Tómas Jóhannesson (2002). *Hætta á jarðskriði úr brún Þófans á Seyðisfirði – Samantekt á niðurstöðum mælinga (Danger of a landslide from the edge of Þófi in Seyðisfjörður – Summary of results of measurements).* Icelandic Meteorological Office, memo EHJ-2002-03.

Halldór G. Pétursson & Þorsteinn Sæmundsson (1998). *Saga skriðufalla á Seyðisfirði. 1882–1997 (History of landslides in Seyðisfjörður 1882–1997).* Icelandic Meteorological Office, report 98024.

Halldór G. Pétursson (2003). *Nokkur skriðuföll við aðstæður sem svipað gæti til Þófans á Seyðisfirði (Some landslides from locations that might resemble the Þófi area in Seyðisfjörður).* The Icelandic Institute of Natural History, memo dated 17.03.2003.

Harpa Grímsdóttir (1997). *Byggingarár húsa á Seyðisfirði (The construction years of buildings in Seyðisfjörður).* Icelandic Meteorological Office, report 97016.

Höskuldur Búi Jónsson (2003). *Sprungur í jarðvegi ofan Seyðisfjarðarkaupstaðar (Surface fractures in loose materials above the town of Seyðisfjörður).* The Icelandic Institute of Natural History, report NI-03001.

Jón Kristinn Helgason, Tómas Jóhannesson, Árni Hjartarson & Halldór G. Pétursson (2014). *Ofanflóðahættumat fyrir Kjalarnes neðan Esjuhlíða. Greinargerð með hættumatskorti (Hazard zoning for Kjalarnes).* Icelandic Meteorological Office, report 2014-004.

Jón Skúlason (2003). *Þófar – Seyðisfirði – Athugun á stæðni (Þófar – Seyðisfjörður – Investigation of the stability of loose materials).* Almenna verkfræðistofan hf, report dated October 2003.

Jón Skúlason & Ágúst Guðmundsson (2004). *Botnar, Seyðisfirði – Athuganir á lausum jarðlögum (Botnar, Seyðisfirði – Investigations of loose materials).* Almenna og Jarðfræðistofan, report dated December 2004.

Kristján Ágústsson (1988). *Könnun á snjóflóðahættu á Seyðisfirði (Avalanche chronicle and avalanche hazard in Seyðisfjörður).* Icelandic Meteorological Office, report.

Kristján Ágústsson (2002). *Snjóflóðasaga Seyðisfjarðar (Avalanche chronicle of Seyðisfjörður).* Icelandic Meteorological Office, report 02009.

Kristján Jónasson, Sven Þ. Sigurðsson & Þorsteinn Arnalds (1999). *Estimation of Avalanche Risk.* Icelandic Meteorological Office, report R99001.

Kristján Jónasson & Þorsteinn Arnalds (1997). *Pilot Hazard Zoning for Seyðisfjörður. IMO hazard zoning for the north side.* Icelandic Meteorological Office, report 97035.

Margreth, S. (2015). *Analysis of the hazard situation and the proposed mitigation measures in Patreksfjörður and Bíldudalur, Iceland.* WSL Institute for Snow- and Avalanche Research, SLF Expert Report G2015.21.

NGI (1997). *Seyðisfjörður. Assessment of natural hazard zones.* Norwegian Geotechnical Institute, report 974080-1. (Authors Karstein Lied og Ulrik Domaas).

Ólafur Jónsson (1992). *Skriðuföll og snjóflóð. I (Landslides and snow avalanches. I).* Reykjavík, Bókaútgáfan Skjaldborg.

Ólafur Jónsson & Halldór G. Pétursson (1992). *Skriðuföll og snjóflóð. II. Skriðuannáll (Landslides and snow avalanches. II. Landslide chronicle).* Reykjavík, Bókaútgáfan Skjaldborg.

Ólafur Jónsson, Sigurjón Rist & Jóhannes Sigvaldason (1992). *Skriðuföll og snjóflóð. III. Snjóflóðaannáll (Landslides and snow avalanches. III. Snow avalanche chronicle).* Reykjavík, Bókaútgáfan Skjaldborg.

Óskar Knudsen & Guðrún Larsen (2013) *Skriðuset í jarðvegi í Seyðisfjarðarkaupstað og Botnum (Landslide sediments in soils within the town of Seyðisfjörður and in Botnar).* Jarðfræðistofan, report dated October 2013.

Parriaux A., C. Bonnard & L. Tacher (2010). *Rutschungen: Hydrogeologie und Sanierungsmethoden durch Drainage und Sanierungsmethoden durch Drainage*. Leitfaden. Bundesamt für Umwelt (BAFU), Bern, Umwelt-Wissen No. 1023, 128 pp.

Prochaska, A. B., P. M. Santi, J. D. Higgins & S. H. Cannon (2008). A study of methods to estimate debris flow velocity. Landslides, **5**, 431–444. doi: 10.1007/s10346-008-0137-0.

Sigurjón Hauksson (2014). *Rannsóknir í Þófum og Botnum á Seyðisfirði. Yfirlit 16. júní 2014 (Research of the Þófi and Botnar areas in Seyðisfjörður for the past 15 years Summary written by Sigurjón Hauksson at Verkfræðistofa Austurlands, 16 June 2014).* Efla consulting engineers, memo dated 16.6.2014, in Icelandic, translated with some modifications by Jón Kristinn Helgason and Tómas Jóhannesson in July 2015.

Sigurjón Hauksson (2015). *Ofanflóðavarnir á Seyðisfirði. Yfirlit í febrúar 2015 (Snow avalanche and landslide protection measures for Seyðisfjörður. Overview in February 2015).* Efla consulting engineers, memo dated 10.2.2015.

Sigurjón Jónsson (2007). *A survey of active landslide movement in east Iceland from satellite interferometry*. Icelandic Meteorological Office, report 07004.

Tómas Jóhannesson, Karstein Lied, Stefan Margreth & Frode Sandersen (1996). *An overview of the need for avalanche protection measures in Iceland*. Icelandic Meteorological Office, report R96004.

Tómas Jóhannesson, P. Gauer, D. Issler & K. Lied (eds.) (2009). *The design of avalanche protection dams. Recent practical and theoretical developments*. Brussels, Directorate-General for Research, Environment Directorate, European Commission, Report EUR 23339, 195 pp. doi: 10.2777/12871.

Tómas Jóhannesson & Kristján Ágústsson (2002). *Hættumat vegna aurskriðna, grjóthruns, krapaflóða og aurblandaðra vatns- og krapaflóða í bröttum farvegum (Hazard zoning because of debris flows, rockfall and slushflows in steep paths)*. Icelandic Meteorological Office, memo TóJ/Kri-2002/01.

Tómas Jóhannesson (2002). *Áhrif varnargarðs í 650 m h.y.s. á Brún í Bjólfi á Seyðisfirði á legu hættumatslína (The effect of a catching dam at 650 m a.s.l. at Brún in Bjólfur in Seyðisfjöður on hazard lines)*. Icelandic Meteorological Office, memo TóJ-2002/03.

Tómas Jóhannesson, Árni Hjartarson & Halldór G. Pétursson (2010). *Ofanflóðahættumat fyrir Kerhóla á Kjalarnesi (Hazard zoning for Kerhólar in Kjalarnes)*. Icelandic Meteorological Office, report 2010-004.

Tómas Jóhannesson & Eiríkur Gíslason (2011). *Endurskoðun á ofanflóðahættumati fyrir Seyðisfjörð eftir byggingu varnargarða á Brún í Bjólfi (Revision of hazard zoning for Seyðisfjörður after the construction of a catching dam Brún in Bjólfur)*. Icelandic Meteorological Office, report draft 2011-003 distributed for public comments.

The Ministry for the Environment (2000). *Reglugerð nr. 505/2000 um hættumat vegna ofanflóða, flokkun og nýtingu hættusvæða og gerð bráðabirgðahættumats (Regulation on hazard zoning due to snow- and landslides, classification and utilisation of hazard zones, and preparation of provisional hazard zoning)*.

The Ministry for the Environment (2007). *Reglugerð nr. 495/2007 um breytingu á reglugerð um hættumat vegna ofanflóða, flokkun og nýtingu hættusvæða og gerð bráðabirgðahættumats (Modification of regulation on hazard zoning due to snow- and landslides, classification and utilisation of hazard zones and preparation of provisional hazard zoning)*.

VA & NGI (1998). *Assessment of snow avalanche hazard and defence structures in Bjólfur area.* Verkfræðistofa Austurlands, report VA-9807, Norwegian Geotechnical Institute, report NGI-970479-1. (Authors Sigurjón Hauksson and Karstein Lied).

VA & NGI (2003). *Snjóflóðavarnir á Seyðisfirði. Aldan og Bakkahverfi. Frumathugun. (Snow avalanche protection measures for Seyðisfjörður. Aldan and Bakkahverfi. Appraisal)*. Verkfræðistofa Austurlands, report VA-0156, Norwegian Geotechnical Institute, report NGI-2002-1036. (Authors Sigurjón Hauksson and Karstein Lied).

Þorsteinn Arnalds, Kristján Jónasson, and Sven Sigurðsson (2004). Avalanche hazard zoning in Iceland based on individual risk. *Annals of Glaciology*, **38**, 285–290.

Þorsteinn Arnalds, Siegfried Sauermoser, Tómas Jóhannesson & Esther H. Jensen (2002). *Hazard zoning for Seyðisfjörður.* Icelandic Meteorological Office, report 02010.

Þorsteinn Sæmundsson & Halldór G. Pétursson (1999). *Mat á aurskriðu- og grjóthrunshættu við Seyðisfjarðarkaupstað (Assessment of debris flow and rockfall hazard in the town of Seyðisfjörður)*. Icelandic Meteorological Office, report 99003.

WLV (1997). *Hazard zone plan. Seydisfjördur north.* Austrian Foresttechnical Service in Torrent and Avalanche Control, Austria. (Author Siegfried Sauermoser).

Appendices

I Figures

This appendix contains several photographs that illustrate the conditions in Neðri-Botnar where a number of drainage ditches are proposed in section 7.

Figure 26. Neðri-Botnar, view towards east.

Figure 27. Neðri-Botnar, view towards west.

Figure 28. Neðri-Botnar, lake at the upper margin.

Figure 29. The lower part of Nautaklauf depression in the eastern part of Botnabrún.

Figure 30. The upper part of Nautaklauf depression in the eastern part of Botnabrún.

Figure 31. The upper part of Nautaklauf depression, view towards west.

II Maps

Map 1. Location map (A4, 1:15 000).
Southern Seyðisfjörður.

Map 2. Landslide inventory (A3, 1:10 000).
Documented historical landslides from Þófi to Botnabrún in Seyðisfjörður. Potential starting areas for landslides described in section 4 are also shown.

Map 3. Geological map of S-Seyðisfjörður (A3, 1:10 000).
Reproduced from Ágúst Guðmundsson and others (2003, map 1). Locations and depth of boreholes and the results of hole loggings are shown. The map shows the results of geological mapping with colours and texture explained in the map legend: 1: basalt bedrock, 2: comparatively dry sediments, rich in fines with stones and boulders of varying size, 3: very wet sediments, rich in fines with stones and boulders of varying size, 4: talus, unstable surface slope, 5: talus, comparatively stable but creeping slowly down the slope, 6: rock glacier sediments, consolidated, comparatively stable, 7: frozen sediments, permafrost, slowly creeping down the slope, 8: glacier moraine left by debris-covered glaciers. The map also shows locations of surface cracks (solid and dashed violet curves), debris flow channels (arrows), basalt dikes (purple solid curves) and bedrock faults (long-dashed red curves) and bedrock displacements along faults (red hatched curves).

Map 4. Geological map of Þófi (A4, 1:5 000).
Reproduced from Ágúst Guðmundsson and others (2003, map 2). Locations and depth of boreholes and the results of hole loggings are shown. See explanations in the caption of Map 3.

Map 5. Geological map of Neðri-Botnar (A4, 1:5 000).
Reproduced from Ágúst Guðmundsson and others (2003, map 3). Locations and depth of boreholes and the results of hole loggings are shown. See explanations in the caption of Map 3.

Map 6. Measurements of the movement of loose materials: Þófi. (A3, 1:2 500).
GPS measurements of the movement of loose materials in Þófi 2003–2014.

Map 7. Measurements of the movement of loose materials: Neðri-Botnar. (A3, 1:5 000).
GPS measurements of the movement of loose materials in Neðri-Botnar 2003–2014.

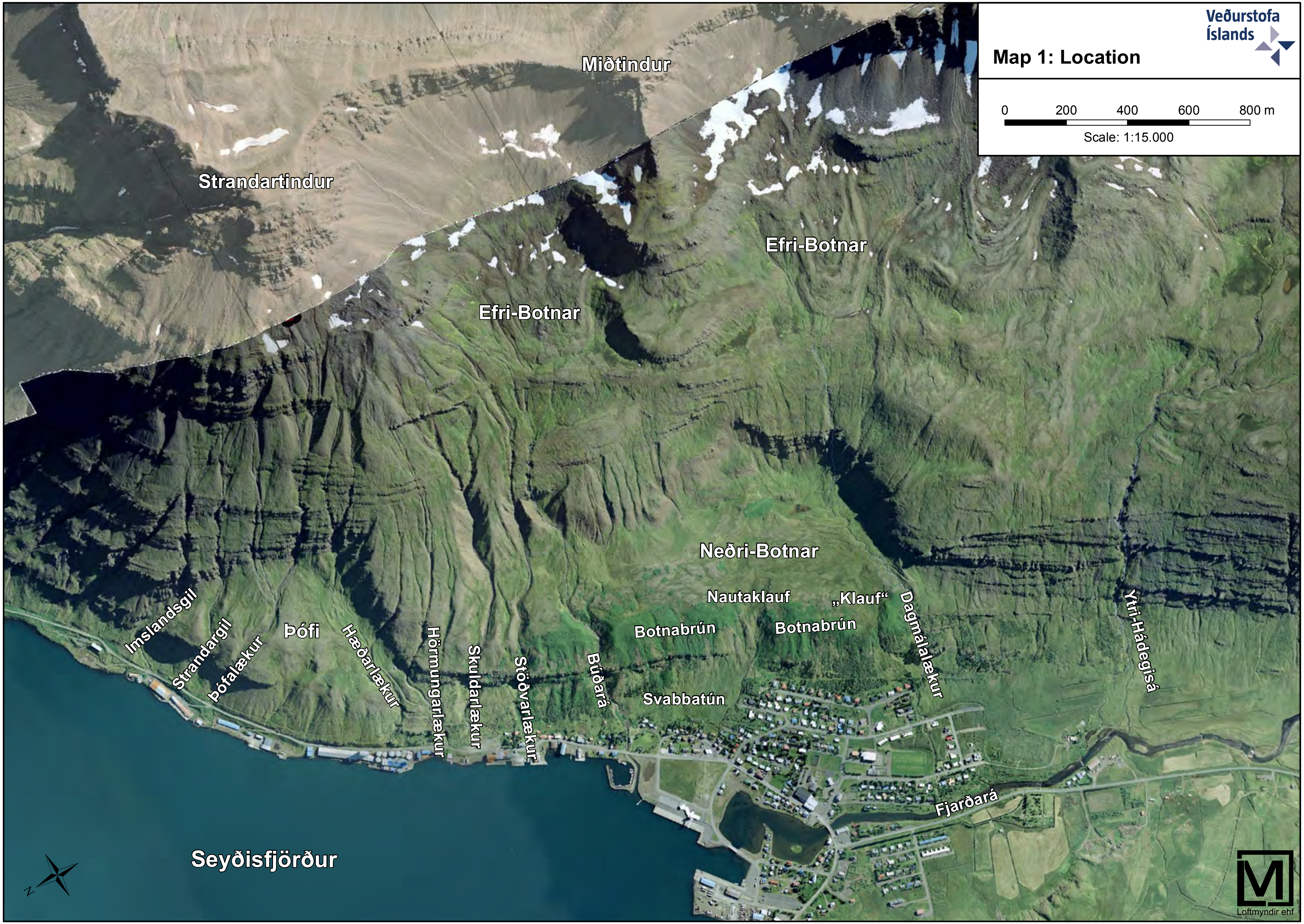
Map 8. Prehistoric landslides (A4, 1:7 500).
Potential source areas and likely extent of large prehistoric landslides (A, B, C, see Tables 1 and 2 for further information) that have been identified in exploratory pits within the settlement of Seyðisfjörður (reproduced from Árni Hjartarson, 2015, landslide outlines interpreted based on Óskar Knudsen and Guðrún Larsen, 2014). Landslide C is described by Óskar Knudsen and Guðrún Larsen (2014) as a single large slide but is here reinterpreted as two separate slides from Klauf and Búðarárgil, respectively. The identification of Búðarárgil as a source area for the easternmost slide is based on weak evidence, this part of the slide could equivalently have come from Nautaklauf as further discussed by Árni Hjartarson (2015).

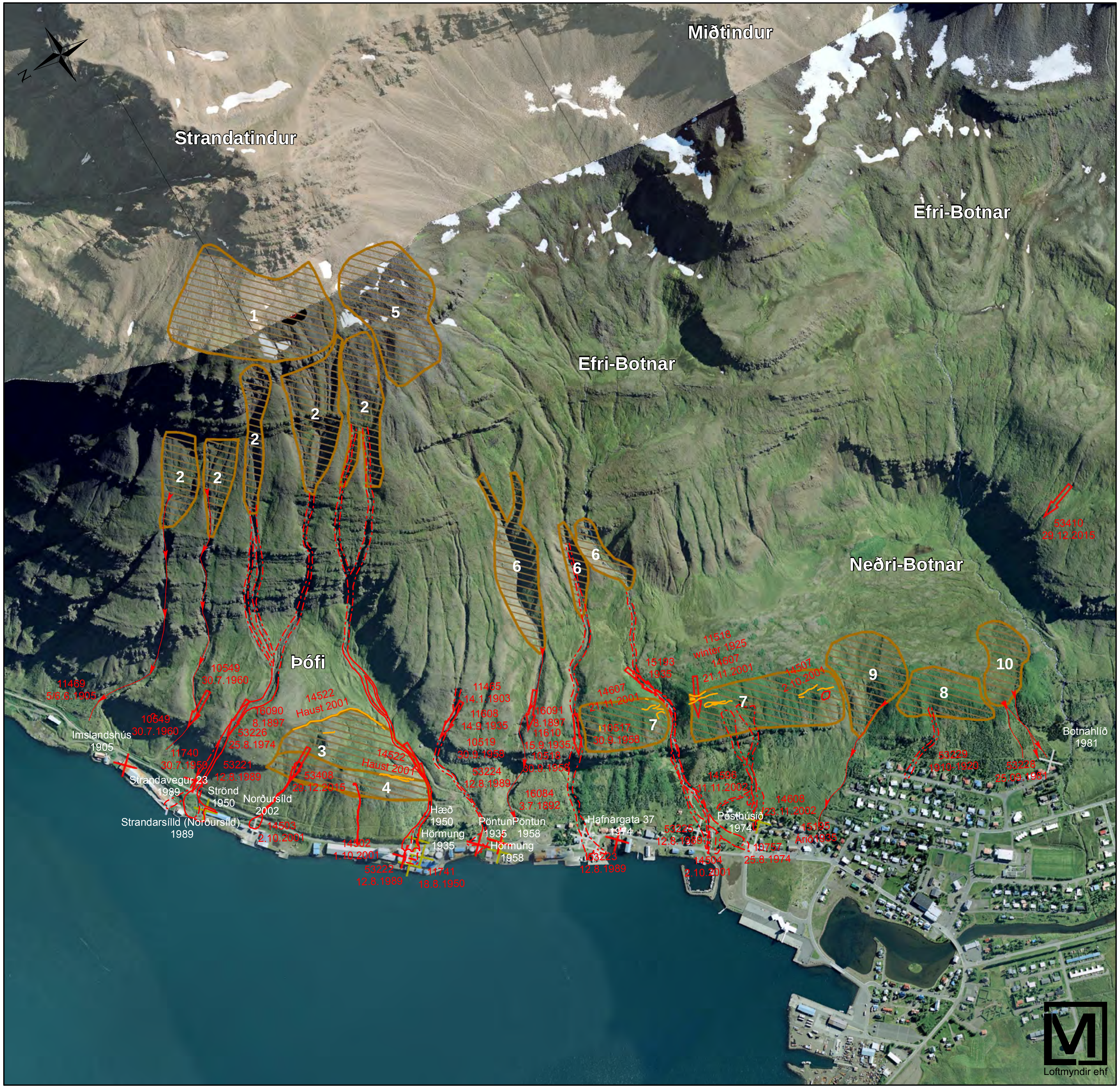
Map 9. Mitigation measures below Botnahlíð. (A3, 1:5 000).

Proposed layout of catching dams and debris retention basins below Botnahlíð and drainage ditches in the depressions above Nautaklauf and Klauf in Neðri-Botnar. Green hatched areas ("Constructions" in the map legend) show locations where erosion prevention measures may be needed where water flows into and out of the retention basins. A larger version of this map in scale 1:2000 is available in PDF format for download at the IMO publication web.

Map 10. Mitigation measures for Þófi (A3, 1:5 000).

Proposed layout of drainage measures, dam and debris retention basin on Þófi and dams and direct protection measures for buildings below Þófi. Green hatched areas ("Constructions" in the map legend) show locations where erosion prevention measures may be needed where water flows into and out of the retention basin. A larger version of this map in scale 1:2000 is available in PDF format for download at the IMO publication web.


Veðurstofa Íslands
Map 1: Location
0 200 400 600 800 m
Scale: 1:15.000
Miðtindur
Strandartindur
Efri-Botnar
Efri-Botnar
Neðri-Botnar
Nautaklauf
„Klauf“
Botnabrún
Botnabrún
Imslandsgil
Strandargil
Þófalækur
Þófi
Hæðarlækur
Hörmungarlækur
Skuldarlækur
Stöðvarlækur
Búðará
Svabbatún
Dagmálalækur
Ytri-Hádegisá
Fjarðará
Seyðisfjörður
Loftmyndir ehf



Map 2:

Landslide inventory

Historical landslides southeast of Fjarðará River

Potential source areas for landslides

Outlines

- Landslide outline, GPS measured
- Landslide outline, certain
- Landslide outline, inaccurate
- Landslide outline, poorly known
- Landslide outline, in sea
- Cracks in soil, GPS measured

Crude location

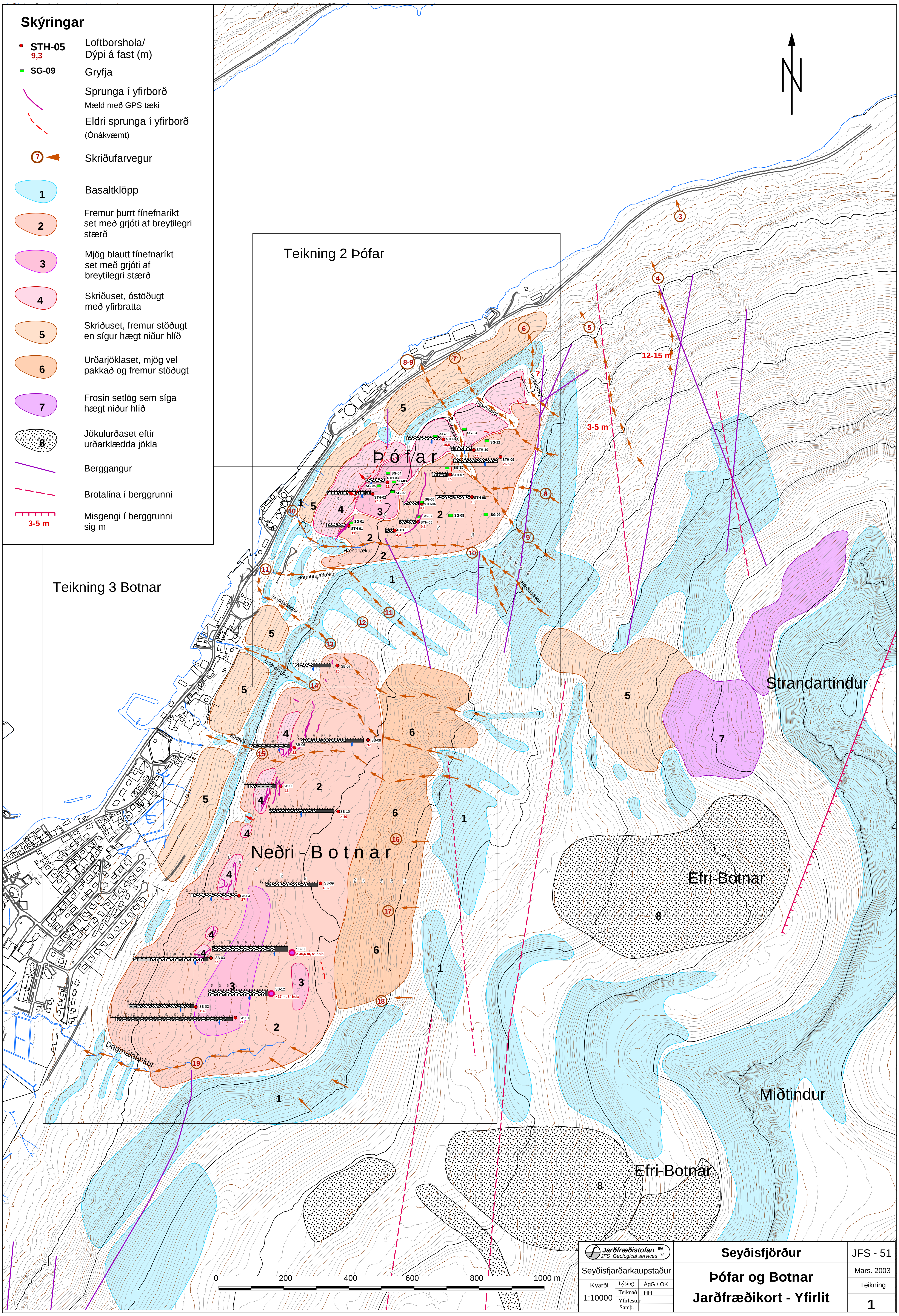
- Landslide path
- Landslide location and direction

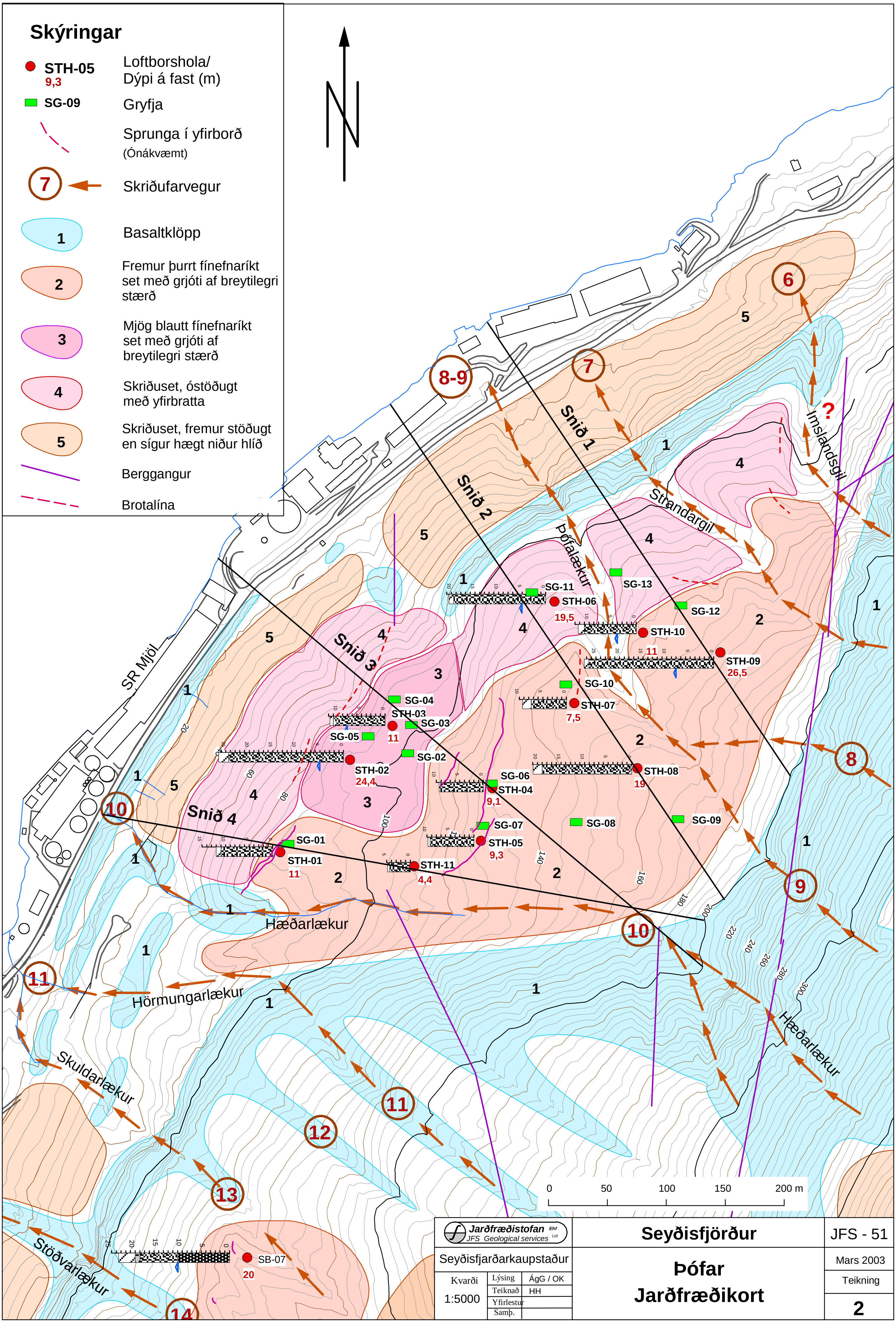
Damages

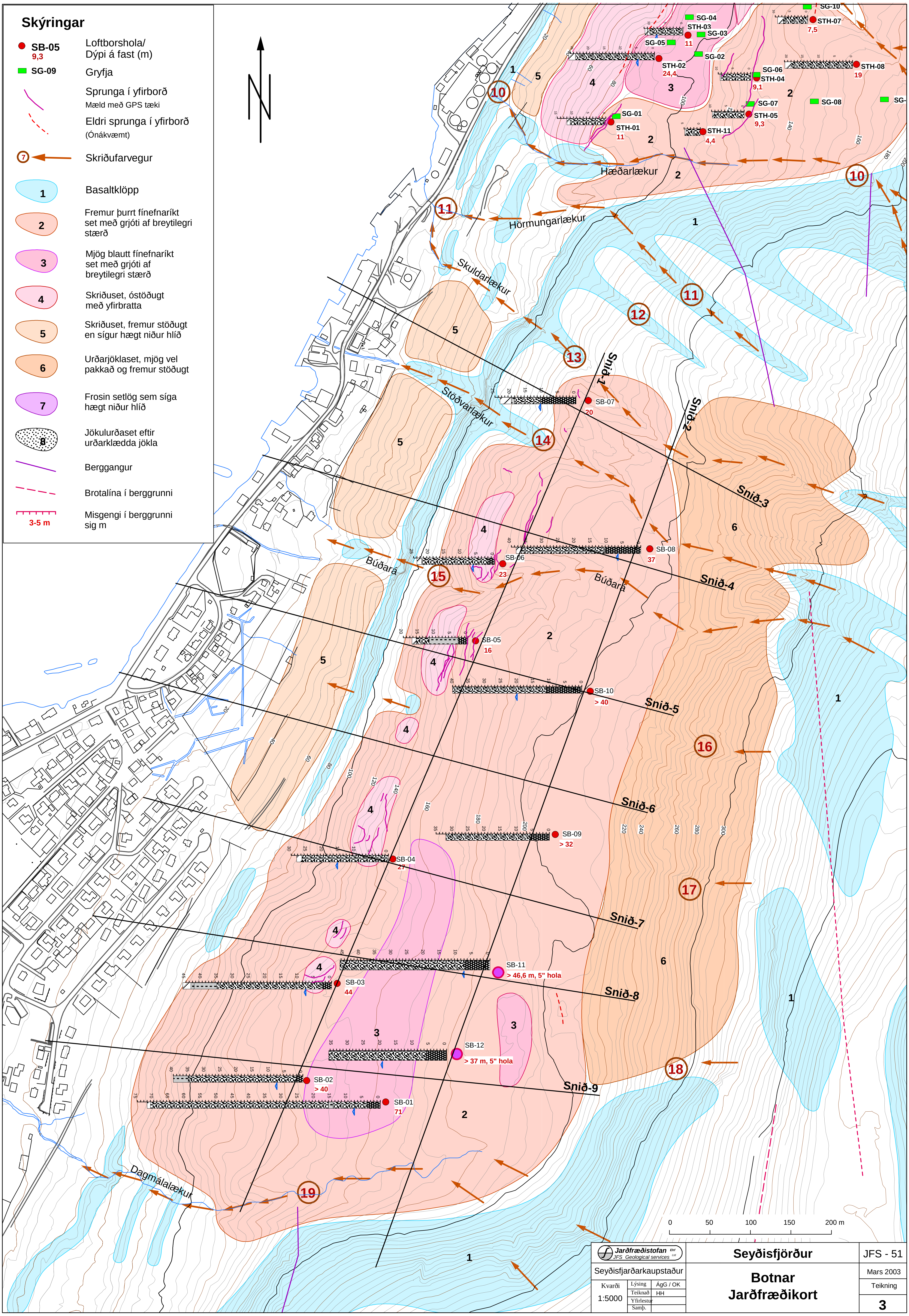
- Damages to the area around the house
- House damaged
- House destroyed

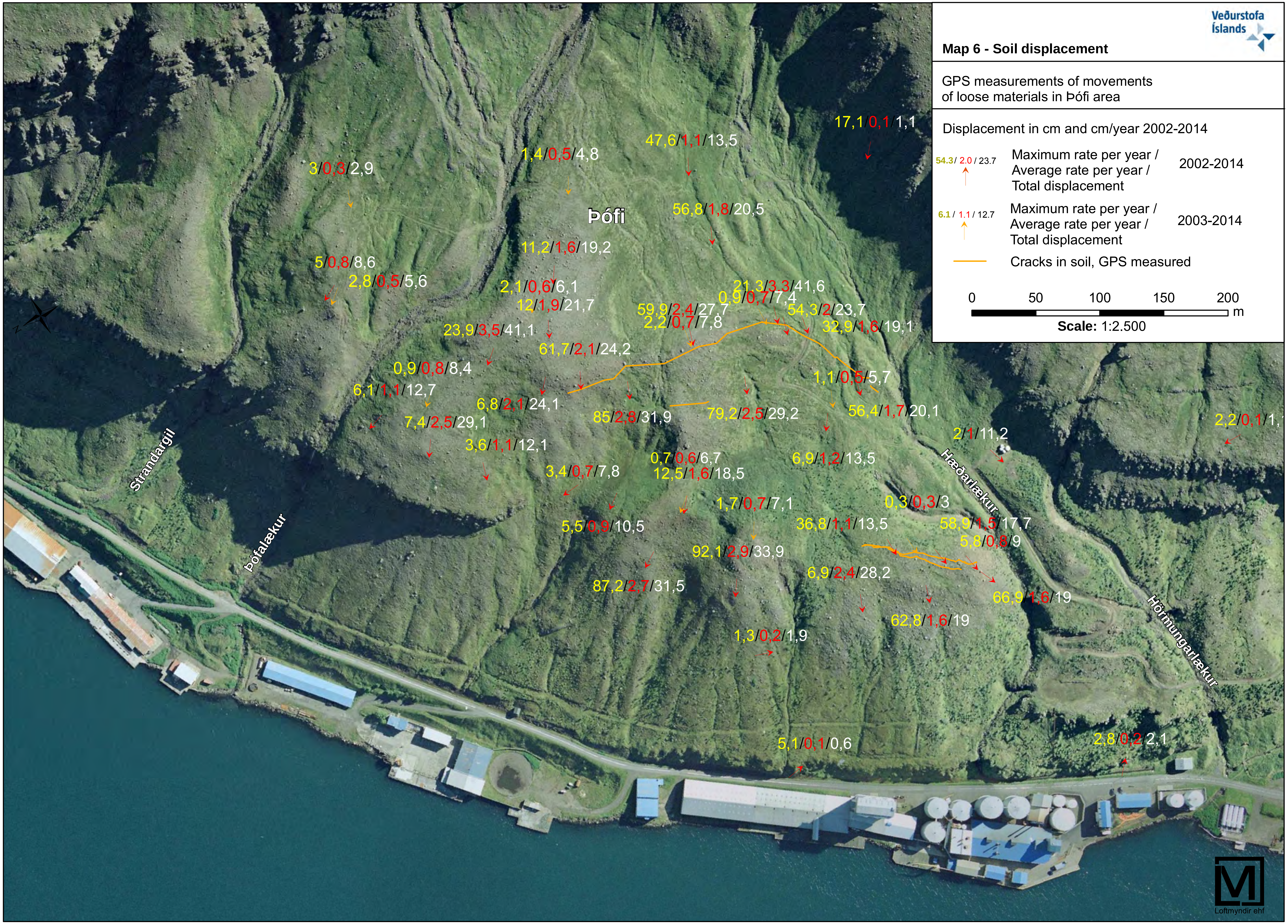
0 100 200 400 600 800 m

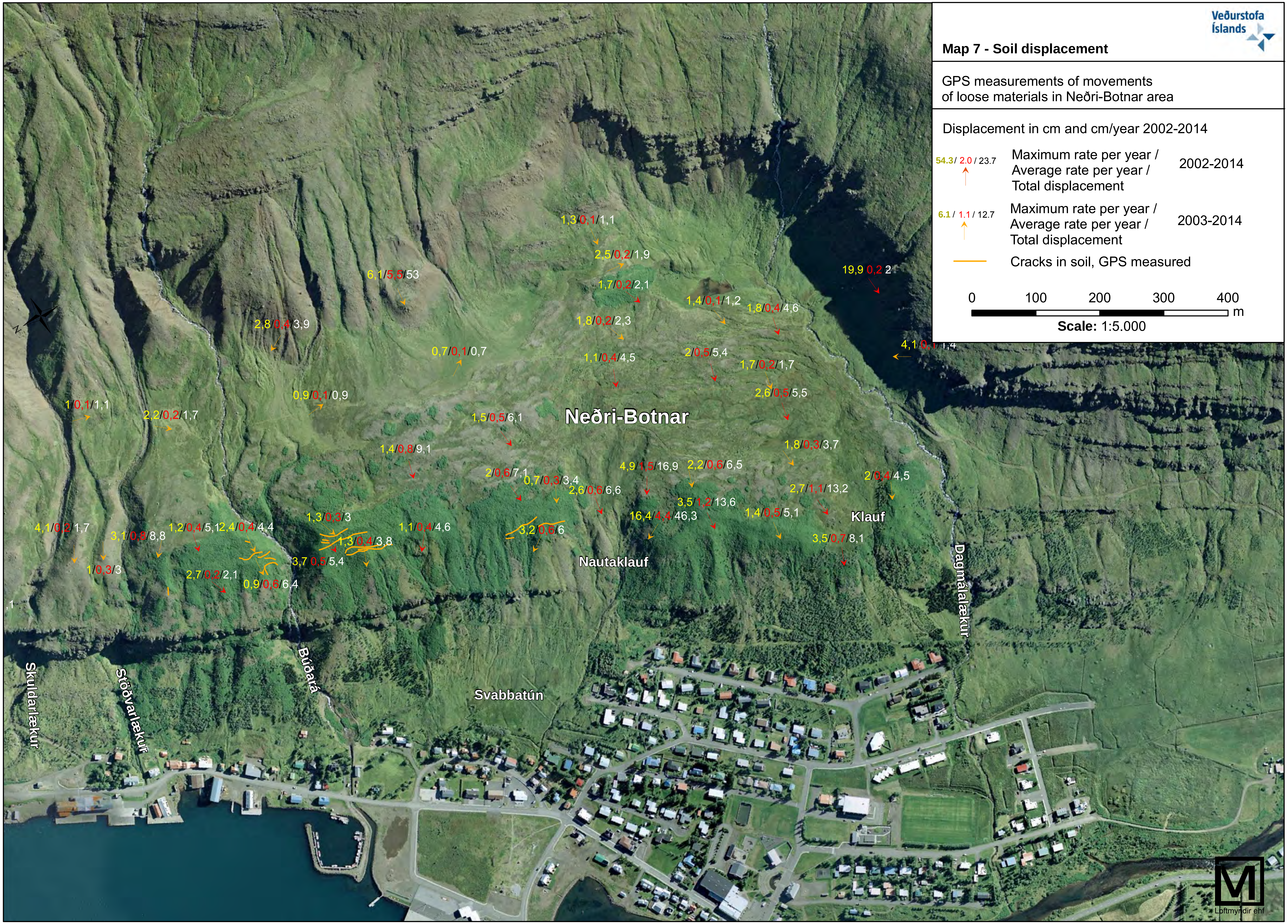
Scale: 1:10.000

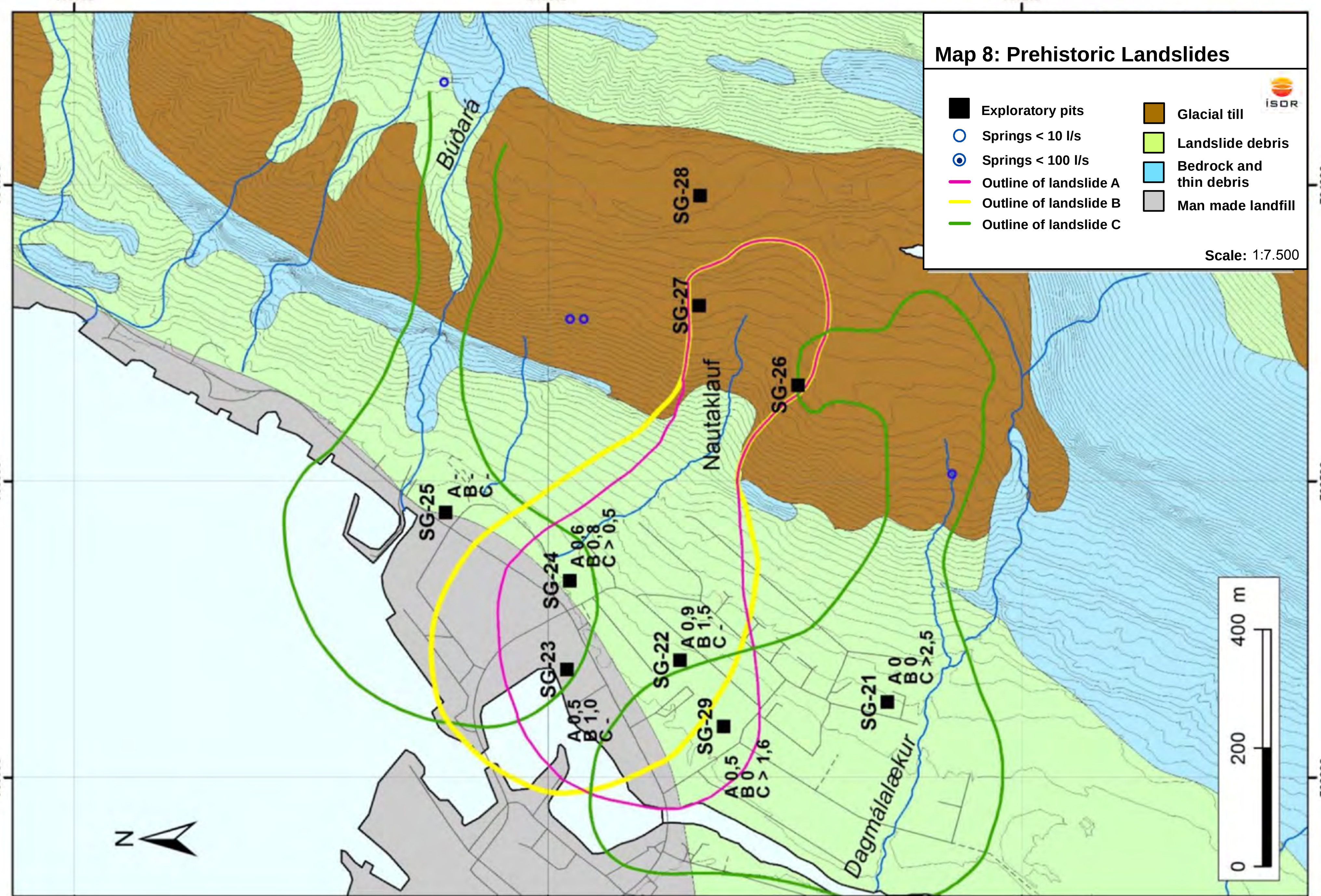

Skýringar
STH-05 9,3 Loftborshola/ Dýpi á fast (m)
SG-09 Gryfja
Sprunga í yfirborð
Mæld með GPS tæki
Eldri sprunga í yfirborð
(Ónákvæmt)
Skriðufarvegur
1 Basaltklöpp
2 Fremur þurrt fínefnaríkt set með grjóti af breytilegri stærð
3 Mjög blautt fínefnaríkt set með grjóti af breytilegri stærð
4 Skriðuset, óstöðugt með yfirbratta
5 Skriðuset, fremur stöðugt en sígur hægt niður hlíð
6 Urðarjökulset, mjög vel pakkað og fremur stöðugt
7 Frosin setlög sem síga hægt niður hlíð
8 Jökulurðaset eftir urðarklædda jökla
Berggangur
Brotalína í berggrunni
3-5 m Misgengi í berggrunni sig m
Teikning 2 Þófar
Teikning 3 Botnar
Þ ó f a r
Neðri - B o t n a r
Strandartindur
Efri-Botnar
Miðtindur
Hæðarlækur
Hörmungarlækur
Skuldarlækur
Stöðvarlækur
Búðará
Dagmálalækur
12-15 m
3-5 m
0 200 400 600 800 1000 m
Jarðfræðistofan JFS Geological services
Seyðisfjörður
JFS - 51
Seyðisfjarðarkaupstaður
Mars. 2003
Kvarði 1:10000
Lýsing ÁgG / OK
Teiknað HH
Yfirlestur
Samþ.
Þófar og Botnar
Jarðfræðikort - Yfirlit
Teikning 1


Skýringar
STH-05 9,3 Loftborshola/ Dýpi á fast (m)
SG-09 Gryfja
Sprunga í yfirborð (Ónákvæmt)
7 Skriðufarvegur
1 Basaltklöpp
2 Fremur þurrt fínefnaríkt set með grjóti af breytilegri stærð
3 Mjög blautt fínefnaríkt set með grjóti af breytilegri stærð
4 Skriðuset, óstöðugt með yfirbratta
5 Skriðuset, fremur stöðugt en sígur hægt niður hlíð
Berggangur
Brotalína
SR Mjöl
Snið 1
Snið 2
Snið 3
Snið 4
Strandargil
Imslandsgil
Þófalækur
Hæðarlækur
Hörmungarlækur
Skuldarlækur
Stöðvarlækur
SG-11
STH-06 19,5
SG-13
SG-12
STH-10 11
STH-09 26,5
SG-10
STH-07 7,5
SG-04
STH-03 11
SG-03
SG-05
SG-02
STH-02 24,4
SG-06
STH-04 9,1
STH-08 19
SG-07
STH-05 9,3
SG-08
SG-09
SG-01
STH-01 11
STH-11 4,4
SB-07 20
0 50 100 150 200 m
Jarðfræðistofan Ehf
JFS Geological services Ltd
Seyðisfjörður
JFS - 51
Seyðisfjarðarkaupstaður
Mars 2003
Kvarði 1:5000
Lýsing ÁgG / OK
Teiknað HH
Yfirlestur
Samþ.
Þófar
Jarðfræðikort
Teikning 2

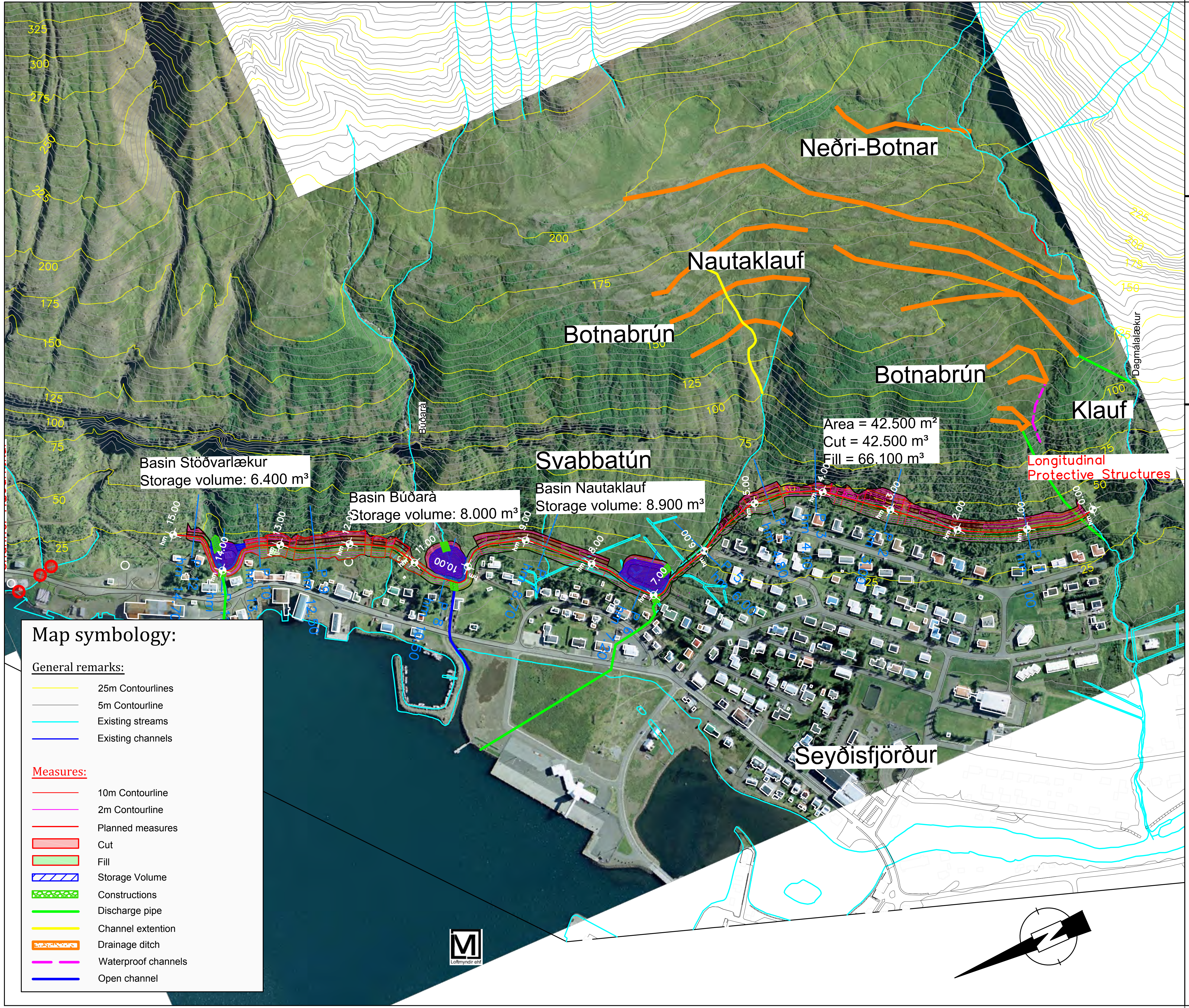

Skýringar
SB-05 9,3 Loftborshola/ Dýpi á fast (m)
SG-09 Gryfja
Sprunga í yfirborð
Mæld með GPS tæki
Eldri sprunga í yfirborð
(Ónákvæmt)
7 Skriðufarvegur
1 Basaltklöpp
2 Fremur þurrt fínefnaríkt set með grjóti af breytilegri stærð
3 Mjög blautt fínefnaríkt set með grjóti af breytilegri stærð
4 Skriðuset, óstöðugt með yfirbratta
5 Skriðuset, fremur stöðugt en sígur hægt niður hlíð
6 Urðarjöklaset, mjög vel pakkað og fremur stöðugt
7 Frosin setlög sem síga hægt niður hlíð
8 Jökulurðaset eftir urðarklædda jökla
Berggangur
Brotalína í berggrunni
3-5 m Misgengi í berggrunni sig m
Hæðarlækur
Hörmungarlækur
Skuldarlækur
Stöðvarlækur
Búðará
Dagmálalækur
Snið-1
Snið-2
Snið-3
Snið-4
Snið-5
Snið-6
Snið-7
Snið-8
Snið-9
SB-07 20
SB-08 37
SB-06 23
SB-05 16
SB-10 > 40
SB-09 > 32
SB-04 27
SB-11 > 46,6 m, 5" hola
SB-03 44
SB-12 > 37 m, 5" hola
SB-02 > 40
SB-01 71
STH-07 7,5
STH-02 24,4
STH-08 19
STH-04 9,1
STH-05 9,3
STH-01 11
STH-11 4,4
STH-03 11
SG-10
SG-04
SG-03
SG-05
SG-02
SG-06
SG-07
SG-08
SG-01
0 50 100 150 200 m
Jarðfræðistofan ehf
JFS Geological services
Seyðisfjarðarkaupstaður
Kvarði 1:5000
Lýsing ÁgG / OK
Teiknað HH
Yfirlestur
Samþ.
Seyðisfjörður
Botnar
Jarðfræðikort
JFS - 51
Mars 2003
Teikning
3


Veðurstofa Íslands
Map 6 - Soil displacement
GPS measurements of movements of loose materials in Þófi area
Displacement in cm and cm/year 2002-2014
54.3 / 2.0 / 23.7
Maximum rate per year / Average rate per year / Total displacement
2002-2014
6.1 / 1.1 / 12.7
Maximum rate per year / Average rate per year / Total displacement
2003-2014
Cracks in soil, GPS measured
0 50 100 150 200 m
Scale: 1:2.500
Þófi
Strandargil
Þófalækur
Hæðarlækur
Hörmungarlækur
17,1/0,1/1,1
47,6/1,1/13,5
1,4/0,5/4,8
3/0,3/2,9
56,8/1,8/20,5
11,2/1,6/19,2
5/0,8/8,6
2,8/0,5/5,6
2,1/0,6/6,1
12/1,9/21,7
21,3/3,3/41,6
0,9/0,7/7,4
59,9/2,4/27,7
2,2/0,7/7,8
54,3/2/23,7
32,9/1,6/19,1
23,9/3,5/41,1
61,7/2,1/24,2
0,9/0,8/8,4
6,1/1,1/12,7
1,1/0,5/5,7
6,8/2,1/24,1
85/2,8/31,9
79,2/2,5/29,2
56,4/1,7/20,1
7,4/2,5/29,1
2/1/11,2
2,2/0,1/1,
3,6/1,1/12,1
0,7/0,6/6,7
12,5/1,6/18,5
6,9/1,2/13,5
3,4/0,7/7,8
1,7/0,7/7,1
0,3/0,3/3
36,8/1,1/13,5
58,9/1,5/17,7
5,5/0,9/10,5
5,8/0,8/9
92,1/2,9/33,9
6,9/2,4/28,2
87,2/2,7/31,5
66,9/1,6/19
62,8/1,6/19
1,3/0,2/1,9
5,1/0,1/0,6
2,8/0,2/2,1
Loftmyndir ehf


Veðurstofa Íslands
Map 7 - Soil displacement
GPS measurements of movements
of loose materials in Neðri-Botnar area
Displacement in cm and cm/year 2002-2014
54.3/ 2.0 / 23.7
Maximum rate per year /
Average rate per year /
Total displacement
2002-2014
6.1 / 1.1 / 12.7
Maximum rate per year /
Average rate per year /
Total displacement
2003-2014
Cracks in soil, GPS measured
0
100
200
300
400
m
Scale: 1:5.000
Neðri-Botnar
Nautaklauf
Klauf
Svabbatún
Skuldarlækur
Stöðvarlækur
Búðará
Dagmálalækur
Loftmyndir ehf



Map 8: Prehistoric Landslides
Exploratory pits
Springs < 10 l/s
Springs < 100 l/s
Outline of landslide A
Outline of landslide B
Outline of landslide C
Glacial till
Landslide debris
Bedrock and thin debris
Man made landfill
ÍSOR
Scale: 1:7.500
0
200
400 m
N
Búðará
Nautaklauf
Dagmálalækur
SG-21
SG-22
SG-23
SG-24
SG-25
SG-26
SG-27
SG-28
SG-29
539200
538400
537600
734000
733500
733000



Veðurstofa Íslands

Icelandic Meteorological Office

Mitigation measures below Botnahlið

Draft planning

Index	Planänderung	Datum	Bearbeiter	Prüfer

Site map 9

Scale 1:5.000

Planinhalt

Projektnr.	**50336**
Plan Nr.	**B-L1**
Ausfertigung	
Datum	2016-04-27
Bearbeitet	Buttler, Thaler
Geprüft	Illmer

Ingenieurbüro Illmer Daniel e.U.
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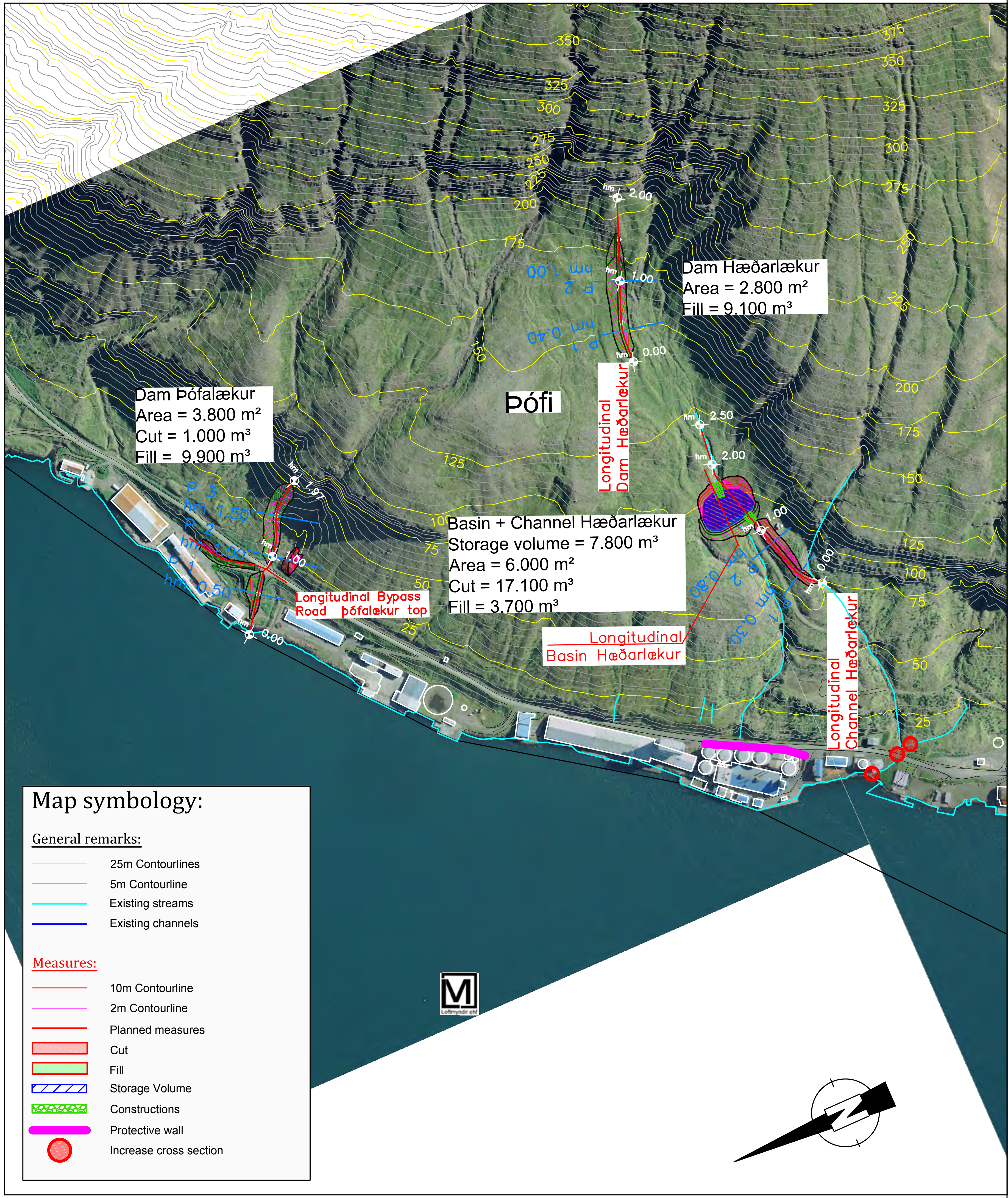
A-6166 Fulpmes
Tel./Fax: ++43 (0)5225 62148-22
E: office@ib-illmer.at
W:www.ib-illmer.at

Planer

plansize: 550x297 mm



Veðurstofa Íslands

Icelandic Meteorological Office

Mitigation measures for ĩ · fi

Draft planning

Index	Planänderung	Datum	Bearbeiter	Prüfer

Site map 10

Scale 1:5.000

Planinhalt

Projektnr.	**50336**
Plan Nr.	**B-L2**
Ausfertigung	
Datum	**2016-04-27**
Bearbeitet	**Buttler, Thaler**
Geprüft	**Illmer**

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Planer

plansize: 450x297 mm