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ÍSLANDS

Report
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Hazard zoning for Bolungarvík
Technical report

VÍ-ÚR19
Reykjavík
October 2002

Contents

1 Introduction

This report is an assessment of avalanche hazard for the community of Bolungarvík carried out by the Icelandic Meteorological Office (IMO). The assessment is done according to a regulation on hazard zoning due to avalanches and landslides, classifications and utilisation of hazard zones, and preparation of provisional hazard zoning issued by the Ministry for the Environment in July 2000.

Similar reports have been published for Neskaupstaður, Siglufjörður, Seyðisfjörður, Eskifjörður and Ísafjörður (Thorsteinn Arnalds *et al.*, 2001a,b,c 2002a,b,c)

1.1 Work process

The main participants in this work were Krisján Ágústsson, Tómas Jóhannesson, Thorsteinn Arnalds, Hörður Þór Sigurðsson, Esther H. Jensen (IMO), Siegfried Sauermoser (Austrian Foresttechnical Service), Thomas Glade and Rainer Bell (University of Bonn).

Other employees of the IMO have also contributed to the work. Halldór Björnsson and Þóranna Pálsdóttir have analysed the weather preceding avalanche cycles. Leah Tracy has drawn maps in the report and the local snow observer, Jóhann Hannibalsson, participated in the field work and assisted in many other ways.

Halldór Pétursson (Icelandic Institute of Natural History) has compiled debris flow chronicles and Thorsteinn Sæmundsson (Natural Research Center of NW Iceland) has carried out a geological study on the sedimentary cover below Traðarhyrna.

The work on this project started in the summer of 2000. A field investigation was carried out in the autumn of 2000 when Siegfried Sauermoser and Kristján Ágústsson mapped the potential avalanche paths together with the local snow observer, Jóhann Hannibalsson. Esther H. Jensen, Thomas Glade and Rainer Bell investigated debris flow and rock fall conditions.

The following items were the subject of the field investigations regarding avalanche conditions:

a) *Topographic conditions, i.e.* the topography of the starting zone, track and runout area.

b) *Climatic conditions* would be dealt with mostly on a regional basis, but locally the effect of the regional climate on snow accumulation in starting areas would be discussed.

c) *Assessment*. The group would give its general opinion of the avalanche hazard in a particular path. This would be done by quantifying the size of the starting areas and their relative frequency with respect to other paths.

These descriptions form the basis of the final report presented here.

In the debris flow and rockfall investigation, similarly, potential starting areas and runout zones were mapped and the recurrence time estimated.

A hazard zoning committee for Bolungarvík was nominated by the Ministry for the Environment in May 2002 with the members Snjólfur Ólafsson, professor at the University of Iceland, chairman, Ólafur Kristjánsson, major of Bolungarvík, Elías Jónatansson, chairman of the council for the environment for the Bolungarvík village, and Gunnar Guðni Tómasson, engineer at VST Consulting Engineers, Ltd. The first meeting of the committee with the IMO staff was held on 30 May 2002.

To strengthen the basis of the hazard zoning, two-dimensional model calculations were carried out by Advanced Simulation Technologies (AVL) of Graz, Austria (Tómas Jóhannesson *et al.*, 2001).

Detailed analysis of the climate and weather preceding avalanche cycles in the Ísafjarðardjúp area on the NW peninsula has been carried out by Halldór Björnsson (2002).

Based on the background data described above the hazard zones were delineated. The delineation was carried out by Thorsteinn, Tómas and Kristján.

1.2 Organisation of the report

The first part of the report is an overview of the general topographic and climatic conditions in the area and a review of the settlement history and former work on hazard related investigations. The investigated area is shown on Map 1.

The next two sections contain a more detailed description of avalanche areas in Traðarhyrna and Ernir in which following items are addressed:

Topographic conditions: Physical characteristics of the starting zone, track and runout area.

Local climatic conditions: Characteristics of the starting areas with respect to snow accumulation.

Assessment: Discussion of the avalanche conditions and qualitative hazard analysis.

Model estimates: Model results are the basis of the hazard zoning.

Conclusion: Hazard evaluation and proposed hazard zoning.

Finally, there is a summary of the results of the project.

There are four appendices in the report. In appendix A technical concepts and notation are explained. Those are parameters like runout indices (r) and runout angle (α). Furthermore, definitions of α- and β-points and a description of the α/β-model are given in appendix A. A short description of recorded avalanches is given in appendix B and maps are in appendix C. Appendix D contains longitudinal sections along the paths and the results of runout modeling.

1.3 Methodologies and regulations

The hazard zoning presented in this report is based on Icelandic hazard zoning regulations that were issued in July 2000 after having been under development for several years. A summary of

Table 1. *Icelandic hazard zone definitions*

Zone	Lower level of local risk	Upper level of local risk	Construction allowed
C	$3 \cdot 10^{-4}$/yr	–	No new buildings, except for summer houses*, and buildings where people are seldom present.
B	$1 \cdot 10^{-4}$/yr	$3 \cdot 10^{-4}$/yr	Industrial buildings may be built without reinforcements. Domestic houses have to be reinforced. Existing hospitals, schools *etc*. can be enlarged and then have to be reinforced.
A	$0.3 \cdot 10^{-4}$/yr	$1 \cdot 10^{-4}$/yr	Houses where large gatherings are expected, such as schools, hospitals *etc*., have to be reinforced.

*If the risk is less than $5 \cdot 10^{-4}$ per year.

these regulations is included below.

Hazard zoning in Iceland has since 1995 been based on individual risk which is the yearly probability that a person living at a given place will be killed by an avalanche. The definition of hazard zones is based on the *local risk* defined as the annual probability of being killed given that a person is staying all the time in an unreinforced house. The *actual risk* can be found by taking into account the probability of the person being present in a house when an avalanche hits and the increased safety obtained by reinforcing houses. Increased safety by evacuations and other non-permanent safety measures are not taken into account in the hazard zoning. The authorities in Iceland have adopted the value $0.2 \cdot 10^{-4}$ per year as an accepted actual risk for avalanche hazard zoning (The Ministry for the Environment, 1997). This value corresponds to different values of the local risk for different types of constructions depending on the fraction of time people may be expected to spend in the buildings (typical values are assumed to be 75% in domestic houses, and 40% in commercial buildings). The regulations on hazard zoning (The Ministry for the Environment, 2000) defines three types of hazard zones, see Table 1.

These guidelines for zoning are tailored to attain the acceptable risk level of $0.2 \cdot 10^{-4}$ per year in residences when presence probability and increased safety provided by reinforcements have been taken into account. The risk in industrial buildings is probably somewhat higher.

The methodology used here to estimate avalanche risk in Bolungarvík was developed at the University of Iceland and the Icelandic Meteorological Office in the period 1995–1998. The methods are described by Kristján Jónasson *et al.* (1999).

According to the hazard zoning regulation of July 2000 account shall be taken to hazard due to debris flows and other landslides, rockfall and torrents in addition to snow avalanches and slushflows. Guidelines for hazard zoning with regard to such processes have been formulated by IMO (Tómas Jóhannesson and Kristján Ágústsson, 2002; see also Thorsteinn Arnalds *et al.*, 2002a).

This discussion is concluded by quoting §10 of the Icelandic regulations on how to proceed where formal risk calculation is impossible: “In areas, where it is not possible to estimate the risk formally due to insufficient information, a hazard map shall nevertheless be prepared according to §12 [§12 describes the risk zones of a hazard map]. In the preparation of the map an attempt should be made to estimate risk.”

1.4 Uncertainty

The estimation of avalanche risk is difficult in many areas. This is especially the case when dealing with a slope that from the topographical point of view has the characteristics of an avalanche path, but where no avalanches have been recorded. Accurate records of avalanches have only been kept for a few years or decades in many areas and the settlement may be quite recent. In such a situation, it is almost impossible to rule out the possibility that an avalanche hitting the settlement might be released from the slope. An attempt must then be made to strike a compromise that balances the lack of recorded avalanches and the possibility of avalanche release.

Another problem that must be addressed is the estimation of avalanche hazard in non-typical or low avalanche tracks. The available data about Icelandic avalanches was mostly collected from hills between 500 and 800 m high with large starting areas. The runout potential of avalanches from smaller slopes, both with a lower fall height and smaller starting areas, is not as well investigated.

While delimiting the hazard zones, an attempt has been made to classify the uncertainty in each area by dividing the uncertainty into three classes according to the level of uncertainty in the area. An uncertainty of $\frac{1}{2}$ means that the estimation could be wrong by half a hazard zone, *i.e.* the hazard lines may misalign by approximately $\frac{1}{2}$ of a hazard zone. Since the risk varies by a factor of 3 between the risk lines of the hazard map, the risk may be over- or underestimated by factor of $\sqrt{3}$. Similarly, classes 1 and 2 certainty mean that the zoning could be wrong by 1 and 2 zones in either direction, respectively, meaning that the risk could be over- or underestimated by factor of 3 or 3^2 respectively. Considering the “nominal” nature of avalanche risk estimates, it is not possible to attach a given significance level in a statistical sense to these uncertainty indicators. They are intended to mean that the work group considers it “unlikely” that the risk is over- or underestimated by the indicated uncertainty, but the meaning of “unlikely” is not further quantified.

The three chosen classes of uncertainty and their characteristics are:

$\frac{1}{2}$ Records of avalanches are available and the avalanche path is large and typical.

1 Some records of avalanches are available and the avalanche path is small or atypical.

2 No records of avalanches are available, but the topography indicates avalanche hazard.

The uncertainty of hazard zoning in areas where protective measures have been built will probably be in class 1 or 2.

2 General

The tertiary geological formation of Iceland consists, in general, of a relatively flat, layered basaltic lava pile. Individual lava layers are separated by sedimentary layers which are made of fossil soils, lake deposits, eroded material and scoria. The thickness of both types of layers varies from a few meters to some tens of meters. Generally the lava beds are thicker than the sedimentary layers.

The characteristic erosional form in these areas is a stepped profile of the upper part of the mountainside. The cliffs and cliffbands are made of individual thick lavas or a sequence of thinner lava layers separated only by scoria. The shelfs between the cliffs, usually gently sloping and covered with debris and in some cases vegetation, are the sedimentary layers. Below a talus is formed by rockfall from the cliffs. In the talus the size of stones and blocks increases downwards. Some lava layers are more competent than others and form cliffbands along the mountainside within the talus zone. The longitudinal section of an undisturbed slope below the cliffs is typically parabolic in shape.

Generally the slopes are cut by several gullies. They can be separated into two main types. First, small elongated depressions in the cliffs below the edges of the mountains with small and unclearly defined debris cones below. Second, large bowls in the cliffs which open in narrow gullies or canyons in the lowest part of the cliffs. Large debris cones have accumulated at the foothill below gullies of this type. The location and direction of the large gullies is mainly tectonically dependent and, to some extent, also their size.

Above the edges of the mountains there are in many cases large plateaus which are remnants of an old peneplain. These plateaus serve as catchment areas of snow which accumulates in the gullies below during snowdrift and snowstorms.

The NW part of Iceland as well as the E part are of tertiary age.

2.1 Topographic description

Bolungarvík is a shallow but wide side bay of the large fjord Ísafjarðardjúp which is located on the NW peninsula of Iceland (see Map 1 and Figure 1). Ísafjarðardjúp has a trend of approximately NW-SE and Bolungarvík is the outmost (westernmost) one of several bays and tributary fjords on its SW side.

Three main valleys open into Bolungarvík. The easternmost and largest is Syðridalur. It trends SSW and the mountains on its eastern side are Óshyrna by the sea and farther inland Hádegisfjall, Mærðarhorn and Heiðnafjall. The next valley to the west is Tungudalur with a slightly more westward trend than Syðridalur. The mountain Ernir separates these valleys. Finally, there is the Hlíðardalur valley with the same trend as Ísafjarðardjúp, *i.e.* NW. The mountain between Tungudalur and Hlíðardalur is called Tunguhorn and the mountain Bolafjall separates Hlíðardalur valley and Ísafjarðardjúp.

The areas below Traðarhyrna (Fig. 2), which is an eastward extension of Bolafjall, and the northern part of the mountainside of Ernir in Syðridalur are the subjects of this hazard evaluation.

Figure 1. *An overview of the area around Bolungarvík and Ísafjarðardjúp. © The National Land Survey of Iceland.*

Figure 2. *Bolungarvík and the names of the main landmarks. (Photo: © Mats Wibe Lund).*

The mountains are typical of the tertiary formation as described above. They reach above 600 m altitude with cliffs down to about 100–300 m a.s.l. below which there is talus. In the lava pile there is a horizon with relatively thick sediments including laterite and lignite. These sediments can be traced over large distances (Haukur Jóhannesson and Kristján Sæmundsson, 1989) and they are often reflected as a wide shelf in the mountains. The sediments are about 200 m a.s.l. in Traðarhyrna. In some places this shelf is called Breiðhilla.

Between the main mountain of Bolafjall and Traðarhyrna there is a deep gully, Bollagil. Traðarhyrna is conical in shape to S and SE reaching 620 m a.s.l. The side facing Ísafjarðardjúp is steep and cliffy as well as the uppermost part facing S and E. There are wide and rather shallow gullies in the upper part of the S and E face of Traðarhyrna. A prominent cliffband is above the Breiðhilla sediments and the gullies get narrower and deeper there. Below these cliffs and farthest to SE there is a wide and gently sloping shelf or terrasse. It is called Ufsir and it is at about 200 m wide at its widest. It gets narrower, both towards the sea and the valley, and more or less disappears on a short segment of the S slope of Traðarhyrna.

The main gullies or paths in Traðarhyrna counting from W to E are Bollagil, which separates Bolafjall and Traðarhyrna, Innragil, Traðargil and Ytragil. The three last mentioned gullies face S and are on the segment where the shelf of Ufsir/Breiðhilla is not prominent. Only Traðargil has a name by tradition, but the other two have been named by the staff of the IMO. The area of Innragil, Traðargil and Ytragil is collectively named “Gilin” in this report. On the SE face of Traðarhyrna above Ufsir there are further two gullies with similar characteristics as the uppermost parts of Innragil, Traðargil and Ytragil. They end in the cliffs above shelf Ufsir which here has its greatest width. The westernmost of the two gullies above Ufsir has been named Ystagil by the staff of the IMO, but the easternmost one has not been named.

The debris cones below Traðarhyrna are small. On the shelf of Breiðhilla/Ufsir there are debris cones in Bollagil and Ytragil and below the gullies to the east of that. At the foothill the largest debris cone is below Bollagil. Other debris cones at the foothill are small. Below Ufsir there are small hills, Ból, which are most likely a result of a landslide originating at the Ufsir edge. Otherwise the lower slopes and foothill are rather gentle and even. Boulders which are due to rockfall are found on the slopes and farther from the foothill there are also boulders which are probably transported by avalanches. The mountainside below Ufsir is covered with loose material but some cliffbands can be seen in it. The lower part of the slopes are more or less vegetated up to about 100 m altitude.

The mountain Ernir (Fig. 3), reaches about 680 m a.s.l. and on top of it there is an about 1.5 km^2 plateau. The edge of the plateau is at about 660 m a.s.l. The eastern side of Ernir is cut by several rather deep and sharp gullies which continue down to about 100 m a.s.l. The hillside is interrupted with cliffs down to similar altitude. The northern side of Ernir is mainly in the shape of two large bowls.

The village of Bolungarvík is located above the NW shore of the bay and below the mountain Traðarhyrna. It reaches from the shore to the foothill of the mountain and circles it from E at the sea to the S below Innragil.

Several stalls are located below the northeastern shoulder of Ernir as well as an electrical power

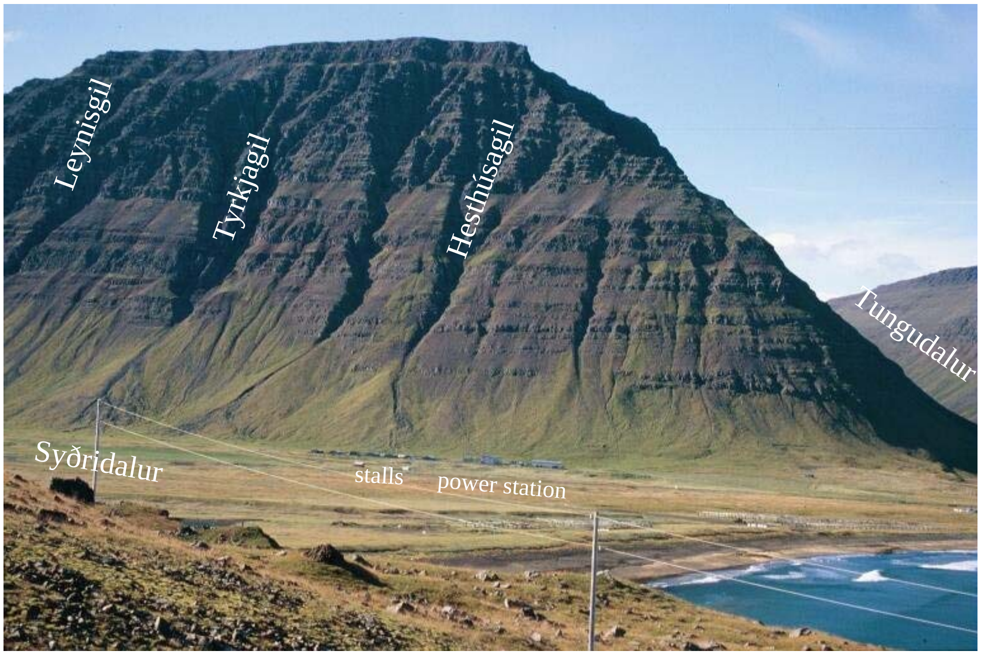

Figure 3. *The mountain Ernir and the names of the main landmarks. (Photo: Kristján Ágústsson).*

plant and constructions for distribution of electricity.

2.2 History of the settlement

Bolungarvík and the valleys above it were settled in the years 874 to 930 and the settlement has been continuous since then. The farm Tröð below Traðargil is believed to have been founded in the thirteenth century or even before that. Permanent inhabitants were farmers but fishermen came from surrounding areas and lived in provisory huts by the sea during wintertime. A village started to grow in the last decade of the nineteenth century. The population grew rapidly and in the year 1910 over 1000 inhabitants were registered there. The population in Bolungarvík reached a maximum of about 1250 people around 1980 and is about 950 today (Sólrún Geirsdóttir, 2000).

The oldest part of the village is by the NW shore of the Bolungarvík bay where most of the fishermens huts were originally located. Gradually the settlement developed in the direction of the Hlíðardalur valley. In the seventies the areas at the foothill of Traðarhyrna were planned and developed. Few domestic houses have been constructed in Bolungarvík after 1982 (Sólrún Geirsdóttir, 2000).

The first stalls below Ernir in Syðridalur were built in 1978 and two years later the power plant was constructed.

2.3 Chronicle

Map 2 shows recorded avalanches in Bolungarvík and Appendix B contains a list of the events.

No casualties have been caused by avalanches in Bolungarvík. Fatal avalanches have occurred close by in the bay Skálavík to the north, and below the steep mountainside Óshlíð to the south of Bolungarvík on the way to Hnífsdalur and Ísafjörður (Fig. 1). Some property damage has occurred and people have narrowly escaped accidents. The avalanche history of Bolungarvík has to be viewed with the respect to the recent settlement of the most endangered areas.

Systematic recording of avalanches in Bolungarvík started in 1990 and in 1995 a local snow observer was hired by the IMO. Avalanches in Traðarhyrna have been recorded in most years since the systematic recordings started. Most of them have stopped on the slope just above the settlement. Avalanches are also frequent in Ernir and most of them stop on the hillside or at the foothill.

In this short review only the most noteworthy avalanches that have starting areas within the investigated area are listed. Avalanches in Traðarhyrna and Ernir are listed separately. A more detailed description of individual events is given in appendix B and in the avalanche and landslide chronicle for Bolungarvík (IMO, 2002).

Traðarhyrna

Unclear historical sources say that around the year 1700 an avalanche went over the land where the innermost part of the settlement is now. Exact location is not known.

Around 1960 a long but narrow avalanche fell from Traðargil or Ytragil and reached far into the current settlement. It stopped a short distance above and to the west of a sheep shed which was close to the present apartment building at Stigahlíð 2–4.

In 1969 or 1970 an avalanche fell from the slope below Ufsir and stopped in the open area of Morðingjamýri. It passed some sheds which were used to dry fish.

Between 1968 and 1972 an avalanche from Traðargil or Ytragil or the slope between them reached into the area of the current settlement. It stopped about 50 m from a sheep shed which was close to the present apartment building at Stigahlíð 2–4.

Around 1970 an avalanche fell from Innragil and Traðargil. The easternmost part of it stopped above where the uppermost houses in the area are now but further west a tongue went almost all the way down to Þjóðólfsvegur.

In 1992 an approximately 300 m wide avalanche originating below Ufsir reached the road Stigahlíð.

In 1997 avalanches fell from Traðargil and Ytragil. One of these avalanches reached the houses at the street Dísarland and caused considerable damage.

Northernmost part of Ernir

In 1974 a large avalanche fell from the hillside above the where the stalls are now located. Its width was about 200 m and it stopped close to the road in Syðridalur.

In 1995 an avalanche fell from the gully above the stalls. Four stalls were damaged and five horses were killed. Four masts in a powerline were broken.

2.4 Previous hazard assessments

In 1994 work was carried out on hazard assessment for Bolungarvík according to earlier regulations. In association with that an avalanche chronicle was compiled (Jón Gunnar Egilsson, 1995). Due to the catastrophic avalanche accidents in 1995 in the NW-peninsula and the need to review the regulations this work was postponed.

In 1996 the IMO investigated possibilities for avalanche protection measures in ten villages in Iceland (Tómas Jóhannesson *et al.*, 1996). Preliminary proposals were made for protection measures for the settlement in the innermost part of Bolungarvík.

In 1997 the Icelandic Meteorological Office made plans for emergency evacuations of several communities in Iceland. The plans included a division of the communities into evacuation zones and description of the conditions when the individual zones should be evacuated. Such a plan was made for Bolungarvík (IMO, 1997). According to the plan a considerable part of the settled area below Traðarhyrna in Bolungarvík is a part of evacuation zones that need to be evacuated under extreme conditions.

After a final hazard map has been issued officially the evacuation plan will be revised to reflect the hazard zoning.

Work has continued on the design of avalanche defence structures in Bolungarvík and in connection with that preliminary hazard assessments have been made (Hnit and NGI, 1999; Orion, NGI and Verkfræðistofa Austurlands, 1999, 2001). According to these assessments, the hazard zone below Gilin in the innermost part of the settlement in Bolungarvík extends significantly below the Þjóðólfsvegur road.

2.5 Climatic conditions

General climatic conditions in the Ísafjarðardjúp area are described in the hazard zoning report for Ísafjörður and Hnífsdalur (Thorsteinn Arnalds *et al.*, 2002c) and climatic data for Bolungarvík and neighbouring stations can be found in appendix C in that report. A more detailed analysis of the climate of the area and weather preceding avalanche cycles in the neighbourhood of Ísafjarðardjúp has been carried out by Halldór Björnsson (2002). More limited analyses were previously done by Tómas Jóhannesson and Trausti Jónsson (1996) and Trausti Jónsson (1996).

According to these investigations the greatest avalanche hazard in Vesfirðir (the NW peninsula of Iceland) occurs during gale force northerly winds when cyclones (*i.e.* low pressure systems) pass north of Iceland, from the south or east. These cyclones direct a relatively warm air from the south, followed by intense precipitation, to the north of Iceland and cause extensive snow accumulation in the starting areas of many avalanche paths in Vestfirðir. The weather preceding many avalanches in the valleys inland of Bolungarvík is according to this description. The largest avalanches from the mountain Ernir above the stalls and from Heiðnafjall above the hydro-electric power plant Reiðhjallavirkjun in Syðridalur have fallen in avalanche cycles when large avalanches were released from other well know avalanche paths in the northern part of Vestfirðir.

Avalanches from Traðarhyrna above the settlement in Bolungarvík do not seem to be preceded by similar weather as the largest avalanches from the main avalanche paths in the area around Ísafjarðardjúp. Avalanches were not released from Traðarhyrna in the Súðavík and Flatreyri avalanche cycles in January and October 1995. The avalanches from Traðargil and Ytragil in the evening of 21 February 1997 were preceded by a day of intense snow fall in calm weather. There was light wind from the east in the village just before the avalanches were released and this can have lead to considerable snow drift from the outer part of the mountain into the starting areas of the avalanches. The 24 hour precipitation preceding the avalanches at the meteorological station in Bolungarvík was 27 mm. Wind speed at Þverfjall at 753 m a.s.l. (see Fig. 1) was 10–15 m/s from the N during the night and 5–10 m/s from the N and NE during the day before the avalanches fell.

2.6 Snow depth measurements in starting areas

Regular monitoring of snow depth in Traðarhyrna above the main settlement in Bolungarvík was initiated in the winter 1996/1997. The measurements have been carried out on eleven 3.0 to 4.5 m long stakes since the beginning. Three stakes are placed in the elevation range of the main gullies at 530 to 550 m a.s.l., another three in the range 290 to 310 m a.s.l. and five are in the lower part of the slope in the elevation range 150 to 220 m a.s.l.

The locations of the stakes are shown on Map 3. Several stakes have been lost in avalanches and rock falls or due to other causes during the period of the measurements, leading to some gaps in the snow depth time-series. The measurements are described by Sigurður Kiernan *et al.* (1998), Sigurður Kiernan and Tómas Jóhannesson (1998) and Sigurður Kiernan *et al.* (1999). The measurements and snow depth on the mountainside in general are also discussed in a report about avalanche protection measures for Bolungarvík by Orion, NGI and Verkfræðistofa Austurlands (1999).

For the lower or more exposed parts of the slope (stakes 4–11), the maximum vertical snow depth measured on the stakes is typically in the range 1–3 m. For the uppermost stakes that are located in the gullies, the maximum snow depth is much larger, reaching more than 5.5 m for stake boek02 in Traðargil. The greatest snow depths were in most cases measured in the winter 1998/1999.

Figures 4 and 5 show the measured snow depth at stakes boek02 and boek03 at 544 and 546 m a.s.l. in Traðargil and Ytragil for the six winters since the start of the measurements. The measured snow depth at stake boek02 in Traðargil is similar to the snow depth observed at stake isse00 in Seljalandshlíð above Seljalandsdalur in Ísafjörður (see Figure 3 in Thorsteinn Arnalds *et al.*,

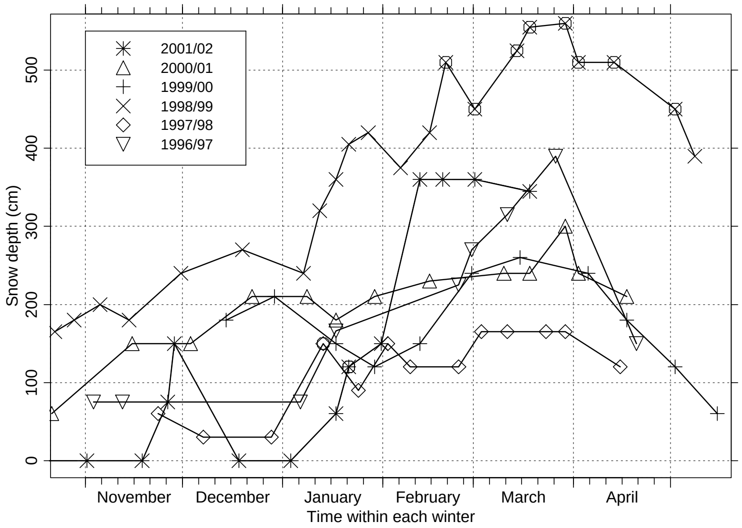

Figure 4. *Snow depth at the stake boek02 at 544 m a.s.l. in Traðargil. Data points, where the snow depth at buried stakes has been inferred, based on the measured variation of the snow depth at other nearby stakes, are denoted with a circle.*

2002c) which is located in an area that is well known for high snow accumulation.

Snow depth in the upper part of Traðarhyrna has once been measured geodetically from vertical aerial photographs that were taken on 2 May 1999. Contours were drawn showing the elevation of the surface of the snow pack (Figure 6). The contours seem to be sufficiently accurate to allow a rough determination of the vertical snow depth in the upper part of Traðarhyrna between 430 and 600 m a.s.l. Local errors in the contours of the snow surface on 2 May 1999, and also in the contours corresponding to the snow free surface, may be expected to lead to errors on the order of 1–2 metres in the derived vertical snow depth. The largest derived snow depths at three small locations between 430 and 470 m a.s.l. near the centre of Traðargil shown in Figure 6 may partly be due to such errors.

The largest snow depths are as expected found in the gullies and below the cliff band at 560 m a.s.l. with much lower snow depth on the ridges between the gullies. The snow depth in Traðargil and below the cliff band at 560 m a.s.l. appears to be larger than in Ytragil and Ystagil by about 2 m or more. The maximum snow depth of the winter may have been about 1 m larger than the snow depth indicated by the aerial photogrammetry. According to these results, the vertical snow depth on 2 May 1999 appears to have reached about 5–8 m where the snow is thickest in the gullies Traðargil, Ytragil and Ystagil, indicating a maximum vertical snow depth of about 6–9 m for the winter 1998/1999 at those locations. It should be born in mind that Figure 6 shows the distribution of snow at one particular point in time and that the distribution of snow on the mountainside may be different in different years.

Árni Jónsson and Jóhann Hannibalsson inspected snow depth in these gullies near the end of March 1999 in connection with the preparation of the abovementioned report about avalanche

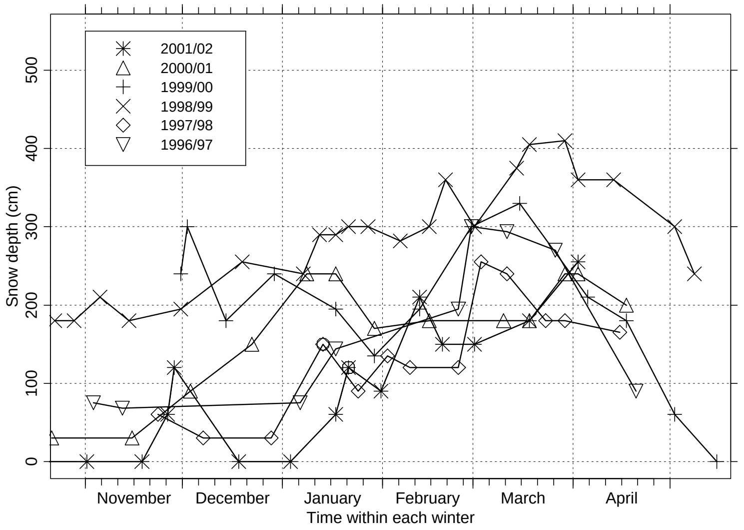

Figure 5. *Snow depth at the stake boek03 at 546 m a.s.l. in Ytragil. Data points, where the snow depth at buried stakes has been inferred, based on the measured variation of the snow depth at other nearby stakes, are denoted with a circle.*

protection measures for Bolungarvík (Orion, NGI and Verkfræðistofa Austurlands, 1999). They describe a cornice that was formed towards the east from the western margin of Traðargil where the snow depth was estimated in the range 5–8 m.

Measurements and return period analysis of snow depth at lowland stations (Kristján Jónasson and Trausti Jónsson, 1997) indicate that the snow depth tends to vary approximately synchronously at the stations. The snow depths in 1998/1999 are relatively large when viewed over the 30–40 year period spanned by the data at the meteorological stations. The snow depth data at the meteorological stations indicate that large snow depths on a time-scale of 30–40 years have been reached at these stations in the last few years. The greatest snow depths recorded in the mountains above Bolungarvík may, therefore, be expected to correspond to a return period on the order of several decades although the data from the mountains only extend over 6 years.

The snow depth measurements and other observations from the mountains show that drift snow is the main controlling factor for differences in the local snow depth in the mountainside. The measurements indicate that the snow depth does typically not exceed 2–3 m on the lower or more exposed parts of the mountain. The snow depth is greatest in the gullies Innragil, Traðargil, Ytragil and Ystagil and on the open slope directly below the cliffs near the top of the mountain, where the snow depth derived from the stake measurements has reached more than 5.5 m. The snow depth may be expected to be considerably larger than this in cornices at the margins of gullies and bowls as shown by the geodetically determined snow depth on 2 May 1999 and by direct field inspections. In such areas, the snow depth seems to be mostly controlled by the depth of depressions and other landscape features, rather than by the local amount of precipitation that falls as snow.

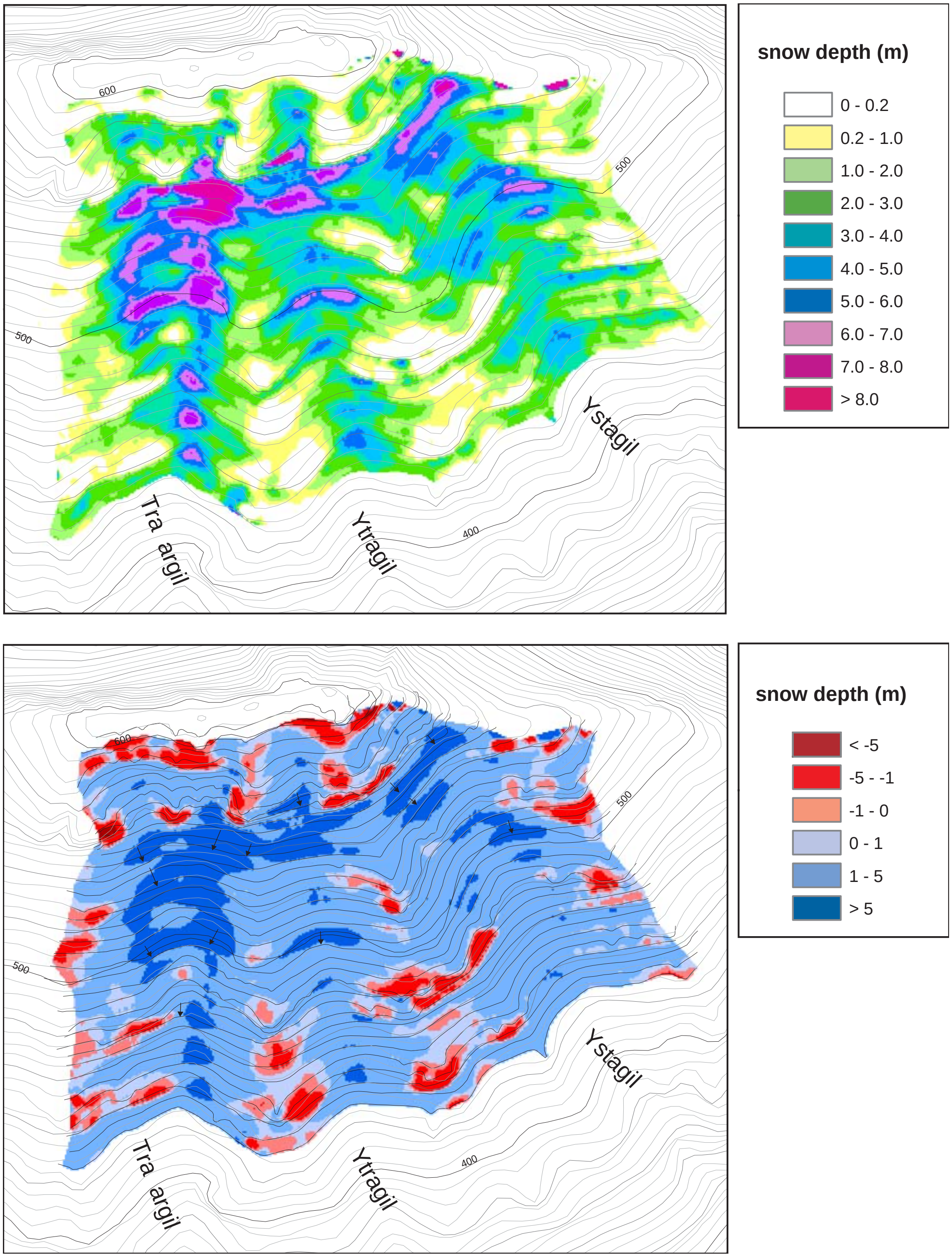

Figure 6. *Snow depth in the uppermost part of Traðarhyrna in the area of the gullies Traðargil, Ytragil and Ystagil (the caption is continued on the next page).*

Caption for Figure 6 continued. *The colour shading in the upper panel shows the vertical snow depth in areas where the derived snow depth was* > 0*. The contours show the elevation of the snow free surface.*
The colour shading in the lower panel shows the vertical snow depth in both the areas where the derived snow depth was > 0 *and also in area where the derived snow depth was* ≤ 0*, the latter arising from errors in the derived snow depth. The solid contours in the lower panel show the geometry of the mountain without snow on the ground and dashed contours show the geometry of the snow covered mountainside on 2 May 1999. The horizontal displacement of contours corresponding to the same altitude may be used to infer vertical snow depth as indicated with the arrows. The derived snow depth near the center of the gullies is in the range 5–8 m. The maximum snow depth during the winter may be expected to have been about 1 m larger than the derived snow depth on 2 May.*

2.7 Geological investigations

In 1999 a pilot investigation was made in Bolungarvík to see whether avalanche debris could be found in the sedimentary cover below Traðarhyrna (Thorsteinn Sæmundsson, 2002). Six about 2 m deep holes were dug at locations where it was expected to find undisturbed soil. Four of the holes were below Traðargil, one below Innragil and one below Ufsir in Morðingjamýri.

In short the conclusion of the investigation was that clear indications of avalanche transported material and debris flows could be traced through the settlement below Traðargil. Below the settlement, *i.e.* south of the road Þjóðólfsvegur, these layers were not seen. In Morðingjamýri, it turned out that the section was most likely disturbed.

2.8 Debris flow and rockfall hazard

As described before the current Icelandic regulation on hazard zoning requires the same criteria to be used for debris flow/rockfall hazard zoning as for avalanche hazard zoning, *i.e.* individual risk. Furthermore, the combined risk should be presented on one map. Therefore, debris flow hazard zoning should be done in synchronisation with avalanche hazard zoning.

A debris flow chronicle for Bolungarvík has been compiled by Halldór G. Pétursson (2000) and a geological study has been conducted by Thorsteinn Sæmundsson (2002) in order to identify indications of debris flow activity in soil sections. A geomorhological map of Traðarhyrna has been prepared and the runout of debris flows and rockfall in the area has been estimated by modeling (Esther H. Jensen, Thomas Glade and Rainer Bell, in preparation). The debris flow chronicle is included in the avalanche chronicle (IMO, 2002).

Debris flows and rockfall have not caused damage to the present settlement in Bolungarvík. Some damage has occurred on fields and fenches around them. Rockfall that reaches into the settled area does not seem to be frequent but it endangers parts of the settlement to some degree. Although debris flows and rockfall impose some threat to the inhabitants the debris flow and rockfall hazard must be considered to be insignificant compared to the snow avalanche hazard. It is therefore concluded that taking debris flows specifically into account will not significantly alter the risk and the hazard zoning. In spite of this it may be feasible or even advisable to take actions to prevent property damage due to debris flows at some locations in the village.

3 Traðarhyrna

The potential avalanche paths in the mountain Traðarhyrna are described here in separate sections for the areas Gilin, Ufsir and the lower slopes. The area *Gilin* consists of the gullies Innragil, Traðargil and Ytragil on the south side of the mountain. *Ufsir* is the area of the shelf Ufsir and above it where the hillside faces southeast. The *lower slopes* cover the area below Ufsir to the east and continues to the hillside below Gilin to the west.

3.1 Gilin

There are three gullies in the area, Innragil, Traðargil and Ytragil. The terrasse of Ufsir is not pronounced here. Some signs of it are seen in Ytragil where it slightly interrupts the otherwise parabolic shaped profile. Domestic houses are at the foothill. Most of the houses were built in 1977–1982. Just to the west of the settlement is Bollagil below which the farm Meirihlíð is located. Avalanches and debris flows have caused damage in this area as well as below Bollagil.

3.1.1 Topographic description

The starting areas and longitudinal sections (`bolu13aa`, `bolu13ab`, `bolu14aa` and `bolu15aa`) are shown on Map 3 and Drawings 1–4.

Starting areas

The physical characteristics of the starting areas are summarised in the following table. They reach from about 560 m a.s.l. down to about 400 m a.s.l. where there is a high cliffband. There are separate starting areas farther downhill which are not described here as they are treated in a separate section on the lower slopes.

The starting areas are elongated bowls or shallow gullies in the upper and middle part and become narrow gullies in the cliffs in the lower part. The surface consists of weathered debris which becomes gradually more interrupted by cliffs towards the sides.

No.	Upper border (m a.s.l.)	Lower border (m a.s.l.)	Average inclination	Average width	Surface area
1	560	400	38°	70 m	1.5 ha
2	560	400	38°	80 m	1.8 ha
3	560	400	38°	70 m	1.4 ha

Tracks

The tracks are between 400 m and 40–45 m a.s.l. where the β-point is located.

The surface consists of a scree with increasing vegetation downwards. Between 320 and 360 m a.s.l. the tracks are slightly confined where the width is about 40 m. This narrow cliffy part of the gully separates clearly the starting areas and the tracks.

The tracks are even and have parabolic shaped longitudinal sections which are typical of a glacial U valley starting with an inclination of 36° decreasing gradually to 10°.

The profile in Ytragil is slightly influenced by the terrasse of Ufsir. At the level of 240 m a.s.l. a small debris cone fills the terrasse here. The inclination is about 30° on this debris cone.

Runout areas

The runout areas are the bottom of the valley. The inclination is about 8° in the uppermost 100 m and then on average about 4° for the next 200 m. The surface is covered with vegetation.

The skiing area of Bolungarvík is located below Innragil and in connection with that a skilift and a hut are located there.

The runout zones below Traðar- and Ytragil are densely settled.

3.1.2 Local climatic conditions

Snow in the starting areas accumulates mainly by drift along the mountainside, *i.e.* both in W to NW directions and E to NE directions. Intense snow fall in calm weather is also associated with avalanche danger in the area as seen from the avalanches from Traðagil and Ytragil on 21 February 1997.

3.1.3 Assessment

Regarding the starting areas, the shape of the profiles and the local climatic conditions, these gullies are typical avalanche paths with frequent avalanches as the chronicle confirms. The generally convex shape of of the mountainside and the comparatively small size of the starting zones may be expected to reduce the runout distance to some extent (see further discussion in the next section).

According to snow depth measurements on stakes and geodetically measured snow depths on 2 May 1999 a slab with an average thickness of 2–4 m can be expected to be released under extreme conditions. This means that an extreme avalanche with volume on the order of 50 thousand m^3 can be expected to be released from each area. That volume will be further increased by entrainment of snow below the cliffs.

3.1.4 Model estimates

The results of the model calculations are shown on Map 3 and Drawings 1–4.

Below Innragil the constructions in the skiing area are above the β-point. The road Þjóðólfsvegur is between runout indices $r = 14$ and $r = 15$ and close to the α-point. One avalanche that has reached $r \approx 14$ is recorded in the last 30 years.

The uppermost houses below Traðargil are by the street Traðarland. They are about 50 m below the β-point and at runout indices between $r = 11$ and $r = 12$. The road Þjóðólfsvegur is between $r = 14$ and $r = 15$ and close to the α-point as below Innragil. Most of the recorded avalanches here are supposed to have started in the lower starting areas and three of them have reached runout index $r = 11$.

Below Ytragil, the uppermost houses by the street Dísarland are at the level of the β-point. They have runout indices $r \approx 10$. Two avalanches in the last 30 years have runout indices close to $r = 14$.

The SAMOS simulations show a slightly different direction of the avalanches in the runout area below Traðargil and Ytragil than indicated by the recorded avalanches. In this modeling, only avalanches released from starting areas 1–3 in the upper part of the mountain are simulated and the geometry of the mountainside corresponds to snow free conditions. Although the starting areas of individual avalanches are not known in all cases, it is known that several avalanches have started on the lower slopes. This and the absence of snowpack may explain the discrepancy between the simulated and observed directions. Due to this discrepancy, the simulated direction indicated by the SAMOS simulations must be used with caution in the delineation of hazard zones.

The SAMOS simulations confirm the expectation that lateral spreading below the gullies and the relatively small size of the starting areas lead to short runout compared with larger avalanche paths in other areas where SAMOS simulations have been carried out (Tómas Jóhannesson *et al.*, 2001). According to the simulations, the main starting zones in Neskaupstaður, which have areas in the range 8–18 ha, release avalanches that reach a runout index in the approximate range 15.5–16.5 for a release snow depth of 1.25 m and runout index in the range 17–18 for a snow depth of 2.5 m. The much smaller starting zones 1–3 in Bolungarvík have starting areas below 2 ha and release avalanches that reach runout index 13.5–14 and 15–15.5 for snow depths of 1.25 and 2.5 m, respectively. Therefore, it is concluded that runout of avalanches from the Gilin area in Bolungarvík is approximately 2 runout indices shorter than the runout of avalanches with a comparable release snow depth in larger paths similar to the main avalanche paths in Neskaupstaður. This means that the runout below Gilin may be expected to be about two runout indices shorter compared with large paths that are more typical for paths in the dataset of recorded avalanches in Iceland on which the hazard zoning methodology described by Kristján Jónasson *et al.* (1999) is based. This is taken into consideration by shifting the runout distribution that is used in the risk computations towards the mountain by two runout indices. Thus, the relative exceedance probability of avalanches with runout index r below Gilin may be found as the probability corresponding to runout index $r + 2$ in table 5 in Kristján Jónasson *et al.* (1999).

The avalanche path with the highest frequency of avalanches according to the records is Traðargil. On the other hand there are recorded avalanches from Innragil and Ytragil with much longer runout than for Traðargil. Geological investigations below Traðargil, furthermore, indicate that avalanches with long runout distances have occurred there as mentioned earlier. There are no physical or geomorphologial indications for a significantly higher frequency of avalanches from Traðargil than from the other two gullies. Therefore, the hazard evaluation will be based on the same considerations for the three gullies. The frequency estimate for the gullies is carried out by combining the recorded avalanches from all the gullies and assuming that the frequency for each gully is 1/3 of their "combined" frequency. This is the same procedure as was previously used in Neskaupstaður (Thorsteinn Arnalds, 2001b). It is not probable that avalanches will start simultaneously in all the upper starting areas of the three gullies, although the shape of the tongues indicates that an avalanche released in upper starting areas may trigger an avalanche by its sides in the lower starting areas.

The avalanche records cover approximately 40 years of which the recordings during the last 10–12 years have been systematic and probably complete. The combined frequency for Gilin is $F_{14} = 0.05$ (two avalanches with $r \geq 14$ in 40 years) and thus $F_{14} = 0.015$ for each individual gully which corresponds to $F_{13} = 0.04$. Similarly, the combined frequency is $F_{13} = 0.075$ (three avalanches in 40 years) and thus $F_{13} = 0.025$ for each gully. The uppermost houses in the area were constructed around 1980. They are located approximately at runout index $r = 10$ below Ytragil and $r = 11$ below Traðargil. Avalanches from Traðargil and Ytragil have reached the houses two times during the period and 4 avalanches from these two gullies have reached runout index $r = 10$ or greater since 1980 (Innragil is neglected here because the records from there may be expected to be quite incomplete at low runout indices in the period). This leads to the estimate $F_{10} = 0.09$ for each gully. This corresponds to $F_{13} = 0.01$ which is much lower than the frequency derived on the basis of the longer avalanches.

As seen above, it is problematic to estimate the frequency of avalanches in this area that is consistent with the assumed shifted runout distribution. The frequency of avalanches that reach runout index greater than 10–11 may be expected to be about 5–8 times higher than the frequency of avalanches with $r \geq 13$. Thus, $F_{13} = 0.025$–0.04, as estimated above from the longest avalanches, leads to a frequency of 0.13–0.3 per year for avalanches that reach the uppermost houses in the settlement. This must be considered quite high in view of the avalanche history.

A frequency ≈ 0.1 per year for avalanches with runout exceeding $r = 13$ may be assumed to be appropriate for many typical avalanche paths with large starting areas in the Vestfirðir region and this estimate was for example used in the hazard zoning below Traðargil in Hnífsdalur (Thorsteinn Arnalds, 2002c). Assuming as done above that the lateral spreading of avalanches and the small starting area lead to shorter runout in Bolungarvík by about two runout index units, this frequency should correspond to $r \approx 11$ in Bolungarvík, leading to the estimate $F_{13} \approx 0.02$ per year below Gilin.

3.2 Ufsir

On the SE face of Traðarhyrna four potential starting areas are recognised. At the foothill there are living houses in the easternmost and westernmost part of the area and in the middle there is a quite large open space, Morðingjamýri. Three avalanches are recorded in the area. One of them stopped on the terrasse of Ufsir. The avalanche with the longest runout stopped in Morðingjamýri about 70 m below the street Stigahlíð. Its starting area is not known but most likely it is above the terrasse. Finally, an avalanche originating on the lower slopes reached the street Stigahlíð.

The starting areas and longitudinal sections (`bolu16aa`, `bolu17aa`, `bolu18aa` and `bolu19aa`) are shown on Map 3 and Drawings 5–8.

3.2.1 Topographic description

Starting area

Four potential starting areas are mapped in the Ufsir area and a summary of their physical characteristics is given in the following table.

The outer two of the starting areas (No. 6 and 7) have similar physical properties as the starting areas of Gilin.

Between Ytragil and the next large gully to the east, Ystagil, there is a triangular face where two starting areas are recognised (No. 4 and 5). These are much smaller than the other ones, lower in the mountain and with a slightly greater inclination.

No.	Upper border (m a.s.l.)	Lower border (m a.s.l.)	Average inclination	Average width	Surface area
4	425	370	40°	40 m	0.3 ha
5	450	370	40°	40 m	0.4 ha
6	560	400	38°	90 m	1.8 ha
7	540	400	38°	80 m	1.4 ha

Track

The tracks of the two areas farthest to E are from 400 m to about 30 m a.s.l. From 360 m to 300 m a.s.l. the tracks are in narrow gullies which have a width of about 40 m in the cliffs above Ufsir. From 280 m to 190 m a.s.l. they are on convex debris cones on the Ufsir terrasse. The average inclination of the terrasse is about 20°. From the edge of the terrasse the profile is convex at first and reaches 33° inclination at the point of inflection at 115 m a.s.l. At the foothill, between 60 and 30 m a.s.l., there are small hills of landslide material which interrupt the otherwise rather smooth surface (profile `bolu18aa` at 860 m horizontal distance). Behind them there are depressions which are up to 6 m deep. There is some vegetation on the shelf and slope below.

The tracks of the two small and innermost starting areas start at 370 m and end at 35–45 m a.s.l. They are similar to the other ones except in that the terrasse is not as pronounced.

Runout area

The transition from the hillside to the gently sloping lowland below is rather sharp. The uppermost 150 m of the runout area have an average inclination of 4°. The surface is covered with vegetation. The area is densely settled with houses were mostly constructed during the years 1966 to 1985.

3.2.2 Local climatic conditions

Snow in the starting areas accumulates mainly by drift along the mountainside *i.e.* both in W to SW directions and N to NE directions. It is not expected that much snow drifts over the mountain. In NNE wind directions, which are the main directions of snow fall and snow drift, snow is more likely to accumulate in the Gilin area than in the easternmost areas. This is partly because snow drifts from those areas and accumulates in the area of the Gilin and partly due to the closeness to the edge of the mountain. As in the Gilin area, intense snow fall in calm weather may also be expected to lead to avalanche danger in the area.

3.2.3 Assessment

Considering the interrupted avalanche path in this area, more energy loss is expected resulting in shorter runout distances than in the Gilin area. In addition, due to the small size of the two westernmost potential starting areas and their low altitude, still shorter runout is to be expected below them. There are no records of avalanches which can have originated in these two westernmost starting areas.

3.2.4 Model estimates

The β-point is at the street Stigahlíð in profile `bolu18aa` and `bolu19aa` and 50–100 m above the street in the others. The α-point is about 200 m below the street for the profiles `bolu17aa`, `bolu18aa` and `bolu19aa` and between runout indices $r = 14$ and $r = 15$.

The larger run of the SAMOS simulation terminates at runout index approximately equal to $r = 15$ which is near the α-point. This is not appreciably different from the SAMOS results in the Gilin area. The runout may be somewhat overpredicted by the SAMOS simulations for the Ufsir area because of interaction of avalanches released from the two adjacent gullies, where avalanches need not to be released simulataneously. When this effect is taken into account, the runout of extreme avalanches released from the upper starting zones above Ufsir may expected to be on the order of one runout index shorter than in the Gilin area for the same release snow depth.

3.3 Lower slopes of Traðarhyrna

This is the area below the cliffs in the Gilin area and below the edge of the Ufsir terrasse.

3.3.1 Topographic description

Starting area

Below Ufsir a separate starting area is defined. It starts at about 185 m a.s.l. and reaches down to about 100 m a.s.l. It is a slightly concave bowl in the generally convex hillside. The starting area is partly covered with vegetation and is partly a scree and has an area of 1.5 ha. The average inclination is 32°. Other potential starting areas are below cliffs farther west. They are within the avalanche tracks of the higher located starting areas and are not described separately here.

Track

The tracks from the marked starting area is the same as the lowest part of the tracks of the upper starting areas above Ufsir. The situation is the same in Gilin area.

Runout area

The runout areas are the same as for the upper starting areas.

3.3.2 Local climatic conditions

The starting areas of lower slopes have the same aspect as the upper starting areas. Due to the smoothness of the slope and the low altitude it is not expected that as much accumulation of snow can occur there as in the upper starting areas. This is confirmed by the stake measurements as described in section 2.6 on snow depth measurements. Intense snow fall in calm weather may be especially important with regard to avalanche danger arising from this starting zone since snow drift may be expected to transport snow from most parts of the lower slopes. The avalanches from Ytragil on 21 February 1997, which fell after snow fall in calm weather, is known to have been released from the lower part of the slope.

3.3.3 Assessment

It is not expected that avalanches originating in this area will reach far into the settlement because of the limited snow accumulation potential compared to the upper starting areas. Comparatively small avalanches from this part of the slopes may nevertheless reach the uppermost row of houses as has happened in the Gilin area. Avalanches from the upper starting areas entrain snow and trigger avalanches by their sides in the lower starting areas and as a result the runout and width of the avalanches increases.

3.3.4 Model estimates

The modeled runout of avalanches starting in these areas is shorter than for the corresponding upper starting areas and is not shown or discussed separately.

3.4 Conclusion

As discussed in the modeling subsection for Gilin, the longest avalanches there lead to the estimate $F_{13} = 0.025$–0.04, the shortest to the estimate $F_{13} \approx 0.01$, and a comparison with other avalanche paths in the region and a shifting by two runout indices based on the results of SAMOS simulations leads to $F_{13} \approx 0.02$ per year. Here it will be assumed that $F_{13} = 0.015$–0.02 per year strikes a balance between these partly inconsistent indications. A much higher frequency would lead to the conclusion that a house below one of the gullies should be hit by an avalanche every few years, but much lower frequency would make several avalanches with $r \approx 14$ from three gullies in only four decades very unlikely.

It is observed that the tongues of the recorded avalanches in Bolungarvík cover only a narrow sector of the runout areas, much smaller than for a typical avalanche path with a larger starting area. To some extent the exact location of the narrow tongues may be expected to be randomly fluctuating about the main direction of avalanches from respective gully, depending on the thickness of snow on the mountainside when the avalanche is released, the amount of snow entrained on the lower parts of the slope and other factors. Hazard zoning directly based on the frequency derived from the runout of the tip of the recorded avalanches will consequently lead to an overestimate of the risk. This effect needs to be taken into account in hazard zoning for unconfined paths, but here it needs to be taken into account due to the comparatively wide runout areas below narrow gullies. This effect is assumed to be most important below Ytragil where the hazard lines are pulled up by between 0.5 and 1 runout index. The hazard lines below Ytragil are drawn without a tongue form such that hazard line A is at $r = 15.6$, hazard line B at $r = 14.8$ and hazard line C at $r = 14$. The direction of avalanches from Traðargil and Innragil may be expected to be more consistent and therefore the hazard lines are only pulled up slightly there and the lines are drawn with a tongue form based on the results of the SAMOS computations. For Traðargil and Innragil, hazard line A is at $r \approx 16$, hazard line B at $r \approx 15.3$ and hazard line C at $r \approx 14.4$. Hazard line C is in each case close to the α-point and hazard line A is close to the $\alpha - \sigma$-point.

Two avalanches are recorded that terminated below Ufsir and one avalanche was released from the upper part of the mountain terminating on the Ufsir shelf. The furthest reaching avalanche has $r = 12.4$. In addition to the convex shape of the mountain and the lower potential for accumulation of snow, the terrasse may be expected to decrease the runout. It is estimated that this effect amounts to about 1 runout index compared to the Gilin area as discussed in the section about modeling. Based on this estimate and on the hazard zoning already carried out for the Gilin area, hazard line A below Ufsir is delineated at runout index $r = 15$ and lines B and C at $r = 14$ and $r = 13$, respectively. Hazard line A is close to the α-point and hazard line C is near the $\alpha + \sigma$-point.

The finer details in the shape of the lines, *i.e.* the their tongued shape, is based on the recorded avalanche history and on the SAMOS simulations.

The uncertainty of the zoning is considered to be medium (1).

The hazard zoning proposal is shown on Map 4.

4 Ernir

Avalanches from the eastward facing slope of the mountain Ernir are frequent. Here we only discuss the northernmost part of the mountainside below which a power station and stalls are located. Many avalanches have occurred in the area and they have caused damage to the stalls and killed horses.

4.1 Topographic description

The whole eastward facing slope of Ernir is rather uniform. The plateau on top of Ernir reaches as far north as the stalls. North of that there is a ridge which separates the eastern and the northern slopes of the mountain and accordingly the slope gets lower towards north. Above the stalls and further soutwards the edge of the mountain is about 660 m a.s.l. The rim above the power plant is at an altitude of 460 m. The inclination is rather uniform from the edge of the plateu and rim of the ridge down to about 150 m altitude, 40–50°. At the foothill there is a sharp change in the inclination and at 10 m altitude the land is flat.

Longitudinal sections of the mountain (`boer01` and `boer02`) are shown on Map 3 and on Drawings 9 and 10.

Starting areas

The mountainside has an inclination over 30° down to altitude of 60 m. There are cliffs down to about 100 m a.s.l. The gullies are sharp but not very deep and reach down to about 100 m altitude and there are not large bowls associated with them. Generally the surface is rough and there is not much weathered material in the gullies. Between 300–400 m a.s.l. there is a band along the hillside which is rather smooth and covered with weathered material.

The whole of the mountainside is a potential starting area. In particular, the gullies and depressions in the smooth zone at 300–400 m a.s.l. are possible release areas for avalanches.

Tracks

The β-point is at an elevation of about 10 m and about 50 m from the stalls towards the mountain. Below the cliffs the slope consists of scree material covered with vegetation. It is fairly smooth with occasional boulders. There is no clear distinction between the tracks and the starting areas.

There are power lines in the tracks.

Runout areas

The runout area is flat and the soil consists of sand covered with grass.

The oldest stalls in the runout zone were built in 1978 and the power plant was built in 1980.

4.2 Local climatic conditions

Snow can accumulate in the starting areas due to snowdrift along the mountainside and from the plateau on top during S to W wind directions. In W to N wind directions, snow may drift along the north side of the mountain and accumulate in lee of the ridge which separates the N and E sides of the mountain.

4.3 Assessment

Avalanches can start on the slope between the gullies as well as within them. Therefore, large avalanches which reach far out on the level terrain below the slope can occur as is indeed confirmed in the chronicle.

4.4 Model estimates

The results of the runout modeling, the α/β–model and the runout indices, are shown on Map 3 and on Drawings 9 and 10.

SAMOS simulations have not been carried out for this area.

The β-point is about 50 m from the houses in the direction towards the mountain. The houses are located at $r = 11$ and the α-point is 70 to 100 m below the houses. One recent avalanche has reached $r = 15$–16.

The frequency of avalanches is difficult to estimate due to a similar situation as in the Gilin area in Bolungarvík. It is assumed here that the same shifted runout distribution as in the Gilin area is appropriate. There are several recent avalanches reaching runout index in the range 10–11 indicating F_{11} on the order of 0.1 and thus $F_{13} \approx 0.02$. There is one avalanche with runout $r \geq 15$ in the last several decades indicating F_{15} on the order of 0.02 and thus $F_{13} \approx 0.2$ and $F_{11} \approx 1$. The higher frequency based on the longest avalanche is difficult to reconcile with the avalanche chronicle. It will be assumed here that the frequency estimate $F_{13} = 0.05$–0.1 is appropriate for the gully directly above the stalls.

4.5 Conclusion

There are no buildings in the area except the stalls and the power station. It was decided to locate hazard line A based on the estimate $F_{13} = 0.1$, corresponding to the upper limit of the frequency range, since this line will limit future utilisation of currently unused areas. Hazard line C was, on the other hand, located based on the estimate $F_{13} = 0.05$, corresponding to the lower limit of the frequency range because this was judged to be more likely frequency estimate. Hazard line A is then located at runout index $r = 17$ below the stalls, hazard line B is at $r = 16.3$, which is by the road in Syðridalur, and hazard line C at $r = 15.5$.

To the north of the stalls the edge of the mountain becomes lower and the hazard zones are closer to the mountain. The extension of the hazard zones in this area was determined by comparison with other mountainsides where hazard zoning has been carried out in areas where snow accumulation is low and avalanches are not frequent, such as Gleiðarhjalli in Ísafjörður.

The uncertainty of the zoning is considered to be medium (1).

The hazard zoning proposal is shown on Map 4.

5 Conclusion

About a third of the settlement below Traðarhyrna is located within hazard zones and about 50 domestic houses are within the category C hazard zone. The problem is most severe in the innermost part of the village where the hazard zones extend over essentially the entire settlement below Traðargil and Ytragil. All constructions within the investigated area below Ernir are within the category C hazard zone.

Several problems were faced in hazard zoning for Bolungarvík. The main problem is the short period covered by the avalanche chronicle and the limited data about the statistical distribution of avalanche runout for avalanche paths of the type encountered in Bolungarvík. The importance of continuing detailed recording of avalanches, rockfall and debris flows is stressed. The observations are the base for evacuations, construction of defence structures and eventual reevaluation of the hazard zoning. In spite of these problems, the data allow us to conclude with some certainty that a large part of the settlement below Traðargil and Ytragil are within a hazard zone. Further observations of avalanches and more data about snow depth in the mountain and other relevant parameters are unlikely to alter this conclusion.

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A Technical concepts and notation

α-angle: The slope of the line of sight from the stopping position of an avalanche to the top of the starting zone (see Figure 7).

β-angle: The slope of the line of sight, from the location in the avalanche path where the inclination of the slope is 10°, to the top of the starting zone (see Figure 7).

α/β-model: A topographical model used to predict avalanche runout or to transfer avalanches between paths. The model uses the β-angle to predict the α-angle of the longest recorded avalanche in a given path. The model was first derived by Lied and Bakkehøi (1980). The version of the model used in this project was derived by Tómas Jóhannesson (1998a, 1998b) using data on 45 Icelandic avalanches. The formula of the model is

$$\alpha = 0.85 \cdot \beta, \qquad \sigma = 2.2^\circ$$

where σ is standard deviation of the residuals from the model. It is customary to denote an avalanche with an α-angle $n\sigma$ lower than the predicted α-value as an avalanche with runout of $\alpha - n\sigma$ and conversely $\alpha + n\sigma$ if the α-angle is higher than given by the above equation. Note that as the α-angle is lower the runout is longer, and therefore $\alpha - \sigma$ corresponds to an avalanche with a longer runout distance than α.

PCM-model: A one-dimensional physical model used to simulate the flow of avalanches. The model has two parameters, μ, a Coulomb friction coefficient, and, M/D, an inverse drag coefficient. It was developed by Perla *et al.* (1980).

Runout index: The runout measured in hectometers of an avalanche that has been *transferred* (Sven Sigurðsson *et al.*, 1997) to the *standard path* making use of some transfer method. The runout index in this report is obtained by using the PCM-model with parameters lying on a predefined parameter axis. An avalanche that has a runout index of r_0 is referred to as an avalanche with $r = r_0$. The method was developed by Kristján Jónasson *et al.* (1999).

$F_{r_0}(F_{13})$: The expected frequency of avalanches with a runout index greater or equal than r_0. The value F_{13} is most often used, *i.e.* the frequency at the runout index $r_0 = 13$.

Figure 7. *The standard path. The* α*-angle is the expected runout angle of an avalanche according to the* α/β*-model.*

B Chronicle

This appendix lists recorded avalanches and landslides in Traðarhyrna and Ernir. The database number, date, runout index and a short description are given for each avalanche. The avalanches in Traðarhyrna and Ernir are listed separately. A more detailed description of the events is given in the avalanche and landslide chronicle for Bolungarvík (IMO, 2002).

Traðarhyrna

Number Date *Runout index*	**Description**
8051 around 1700 (?)	Old documents are said to mention an avalanche that fell down to the lowland where the innermost part of the village of Bolungarvík is now located. The time and location of this event is uncertain.
8041 1704	Debris flows damaged fields at the farm Tröð.
8002 around 1955	A small avalanche fell where there is now a ski lift to the west of the village.
8132 1950–1960	A small avalanche from Traðargil damaged a sheep shed to the west of farm Tröð.
8003 around 1957 *9.2*	A small avalanche from “Ytragil” or Traðargil stopped at about 50 m a.s.l. above the street Dísarland.
8052 around 1960 *14.1*	An avalanche from “Ytragil” or Traðargil fell a little to west of the farm Tröð and stopped a short distance above and west of a sheep shed that was located close to the present apartment building Stigahlíð 2–4.
8063 20th century	Debris flows often damaged fences in the neighbourhood of the farm Tröð where the streets Stigahlíð, Dísarland and Traðarland are currently located.
8053 1968–1972 *13.8*	An avalanche from “Ytragil” or Traðargil fell to east of the farm Tröð and stopped perhaps 50 m from a sheep shed that was located close to the present apartment building Stigahlíð 2–4.
8054 1969/1970 *12.4*	An avalanche from Ufsir stopped in Morðingjamýri, which is currently an open area in the settlement.
8055 around 1970 *14.0*	An avalanche was released from both “Innragil” and Traðargil or from the hillside below the gullies. Below Traðargil the avalanche terminated above the current Traðarland. Below “Innragil” a tongue from the avalanche is said to have reached almost down to Þjóðólfsvegur.

Number Date *Runout index*	**Description**
8036 spring 1970	A debris flow damaged a field west of the current settlement.
8057 Feb 1991 *9.2*	An avalanche from Traðargil stopped about 150 m above Traðarland 22.
8009 26.11.1992 *10.0*	An avalanche started at 2–300 m a.s.l. below Traðargil and stopped at the foot of the slope.
8010 26.11.1992 *10.1*	An avalanche with a fracture line below Ufsir stopped on or slightly above the road below the mountainside.
8011 20.2.1993 *8.7*	An avalanche that was released from Traðargil and Ytragil stopped at the foot of the slope.
8017 7.3.1993	An avalanche fell from Traðargil and stopped on the hillside above the farm Tröð.
8031 3.4.1994 *7.1*	A small avalanche fell from the hillside below “Ytragil” or Traðargil.
8058 mar 1995 *11.1*	An avalanche from Traðargil stopped 30–50 m above Traðarland 22. The tongue was only a few m wide.
8059 21.2.1997 *10.5*	An avalanche from Traðargil stopped just above Dísarland 14 or touched the house without causing damage.
8060 21.2.1997 *10.5*	An avalanche, that was released below “Ytragil”, damaged two houses at Dísarland 8 and 10.
8075 28.3.1997 *6.0*	An avalanche from Traðargil stopped at 110 m a.s.l.
8061 8.2.1998 *7.7*	An avalanche from Traðargil stopped at about 80 m a.s.l.
8091 4.11.1998 *8.2*	An avalanche from Traðargil stopped at about 70 m a.s.l.
8110 11.3.1999 *8.5*	An avalanche from “Innragil” stopped by the ski lift.

Number Date *Runout index*	**Description**
8109 11.3.1999 *7.2*	An avalanche, that was released from “Ytragil”, stopped at about 100 m a.s.l.
8107 11.3.1999	An avalanche from Traðargil stopped on a ridge below the gully.
8115 26.12.1999	An avalanche from Traðargil stopped at about 200 m a.s.l.
8124 1.4.2001 *8.7*	An avalanche from Traðargil stopped 75 m from Tröð.
8123 8.4.2001	An avalanche from Bollagil slightly damaged a ski lift.
8131 8.12.2001	An avalanche fell from Bollagil.
8140 8.12.2001	An avalanche from “Innragil” stopped below the cliffs.
8141 8.12.2001 *6.4*	An avalanche from “Ystagil” stopped in Ufsir.

Ernir

Number Date *Runout index*	**Description**
8040 26.5.1672	Debris flows damaged more than one third of the fields at Geirastaðir.
8043 8–9.1.1797	A debris flow possibly took the farm Geirastaðir.
8044 1896	A debris flow fell over fields at the farm Geirastaðir.
8046 2.9.1947	A debris flow from Skriðugil caused considerable damage, mostly to fields.
8047 2.9.1952	A debris flow by the farm Geirastaðir damaged a field.
8094 1953	Avalanche from the gully above Geirastaðir.
8006 1974 *15.3*	A large avalanche was released from the gully above the stables in Múrhúsaland. The avalanche was about 200 m wide and reached almost down to the road along the valley Syðridalur.

Number Date *Runout index*	**Description**
8008 26.11.1992 *6.8*	Small avalanches fell from every gully in the outer part of the mountain Ernir. The avalanches stopped in the hillside or at the foot of the slope.
8015 6.3.1993 *6.7*	An avalanche from the gully above the stables at Múrhúsaland stopped at the foot of the slope.
8020 19.3.1993	An avalanche from the gully above the stables in Múrhúsaland stopped on the ridge below the gully.
8023 30.4.1993	An avalanche fell from Geirastaðahlíð south of the stables.
8030 3.4.1994	An avalanche fell from Geirastaðahlíð south of the stables.
8067 jan 1995 *8.2*	Small avalanches fell from Hesthúsagil.
8034 21.2.1995 *11.1*	An avalanche from the gully above the stables in Múrhúsaland damaged four of the stables and killed five horses.
8068 25.10.1995	Avalanche fell from Skriðugil in the mountain Ernir.
8070 21.1.1997	An avalanche fell from the next gully to the south of the gully above the stables.
8071 21.2.1997 *6.4*	An avalanche fell from a gully in the northern part of Ernir.
8073 7.3.1997 *7.0*	An avalanche fell from Geirastaðahlíð above the buildings of Orkubú Vestfjarða north of the stables.
8079 7.3.1997 *7.6*	An avalanche was released from the gully above the stables and stopped about 50 m above the uppermost high voltage line.
8064 9.3.1997 *8.0*	An avalanche fell from the gully above the stables in Ernir.
8081 10.3.1997	An avalanche fell from a gully in Ernir to the south of the stables and stopped about 10 m from the high voltage line.
8074 26.3.1997	An avalanche was released from the gully above the farm Geirastaðir and stopped by the high voltage line.

Number Date *Runout index*	**Description**
8084 28.3.1997 *6.5*	Avalanches fell from all gullies in Ernishlíð from Múrhús to Geirastaðir, except the gully above Geirastaðir.
8089 27.10.1998 *7.6*	An avalanche fell from mountainside above the buildings of Orkubú Vestfjarða.
8090 27.10.1998 *7.6*	An avalanche fell from the gully above the stables.
8121 27.10.1998	An avalanche fell from the mountainside above the buildings of Orkubú Vestfjarða.
8092 2.1.1999	An avalanche fell near Miðdalsskarð in Ernir.
8093 16.1.1999 *7.4*	An avalanche fell from the mountain above the buildings of Orkubú Vestfjarða.
8095 16.1.1999	An avalanche from the gully above the stables stopped on the ridge below the gully.
8097 2.2.1999	Avalanches fell from two gullies to the south of the stables.
8098 4.2.1999	An avalanche fell from mountainside above the buildings of Orkubú Vestfjarða.
8099 20.2.1999	An avalanche was released from the gully above the farm Geirastaðir and stopped about 67 m from the farmhouses.
8103 21.2.1999	An avalanche fell from the gully to the south of the stables.
8102 21.2.1999 *6.5*	An avalanche fell from the mountain above the buildings of Orkubú Vestfjarða.
8104 21.2.1999 *8.8*	An avalanche from the gully above the stables stopped at the lower high voltage line.
8105 12.3.1999	An avalanche fell from the gully to the south of the stables.
8112 12.3.1999 *9.3*	An avalanche from the gully above the stables stopped at 30 m a.s.l.
8113 13.3.1999 *8.8*	An avalanche fell from the mountain above the buildings of Orkubú Vestfjarða and stopped by the lower high voltage line.

Number Date *Runout index*	**Description**
8106 16.4.1999	An avalanche from the gully above the stables stopped on the ridge below the gully.
8116 31.12.1999	An avalanche fell from the gully above the stables.
8118 14.3.2000	An avalanche fell from the gully to the south of the stables.
8117 14.3.2000	An avalanche fell from Tyrkjagil in Ernir.
8119 15.3.2000	An avalanche from the gully above the stables stopped about 50 m below the gully.
8120 15.3.2000	An avalanche fell from Tyrkjagil in Ernir.
8143 2.2.2002 *7.3*	An avalanche from the gully above the stables stopped at 60 m a.s.l.
8128 11–12.2.2002 *7.0*	An avalanche fell from the mountain above the buildings of Orkubú Vestfjarða and stopped at about 35 m a.s.l.
8129 16.2.2002	An avalanche fell from Tyrkjagil in Ernir.
8145 1.4.2002	An avalanche fell from Ernir.

C Maps

Map 1. An overview of Bolungarvík and surroundings and the boundary of the investigated area (A4, 1:25 000).

Map 2. Recorded avalanches in Traðarhyrna and northern part of Ernir (A3, 1:10 000).

Map 3. Results of model estimates in Traðarhyrna and northern part of Ernir (A3, 1:10 000).

Map 4. Proposed hazard zoning for the investigated area (A3, 1:10 000).

D Profile drawings

Drawing no.	**Profile ID**	**Avalanche path**
1	bolu13aa	Traðarhyrna, Innragil west
2	bolu13ab	Traðarhyrna, Innragil east
3	bolu14aa	Traðarhyrna, Traðargil
4	bolu15aa	Traðarhyrna, Ytragil
5	bolu16aa	Traðarhyrna, between the Gullies and Ufsir
6	bolu17aa	Traðarhyrna, Ufsir, west
7	bolu18aa	Traðarhyrna, Ufsir, middle
8	bolu19aa	Traðarhyrna, Ufsir, east
9	boer01aa	Ernir, Hesthúsagil
10	boer02aa	Ernir, above the power station