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Triggering factors for rapid mass movements in Iceland

T. Saemundsson
Natural Research Centre of Northwestern Iceland, Saudarkrokur, Iceland

H.G. Petursson
Icelandic Institute of Natural History, Akureyri, Iceland

A. Decaulne
Maison de la Recherche / Université Blaise Pascal, Lab de Géographie Physique – UMR 6042 – CNRS 4, Clermont-Ferrand, France

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ABSTRACT: Rapid mass movements, both involving debris, snow and water, are considered to be a large and direct threat to numbers of towns and villages in Iceland. During the last century 193 persons have lost their lives in avalanches and landslide accidents in Iceland. Snow avalanches alone have claimed 166 lives and landslides 27 lives. Event though mass movements are common in most places in the country, the types, causes and susceptibility varies considerably. This is mainly due to different types of topography, geological condition and climate.
The most common triggering factor for rapid mass movements in Iceland is heavy precipitation, usually connected with strong wind. During the warmer months, from May to September / October, heavy rainfall often causes debris flow and rock fall activity, mainly though in the southeastern, eastern and central northern parts of the island. This type of rapid mass movements usually reaches its maximum peak during the autumn months. The amount of precipitation needed to trigger debris flows, the so-called threshold condition, is somewhat different and strongly depends on the wind direction. During the colder winter months, from October to April, heavy snowfall usually connected with strong wind often causes snow avalanches, mainly though in the eastern, central northern and northwestern part of the island. The activity reaches the maximum peak from December to February. Heavy rainfall frequently occurs also during the colder winter months, often causing slush flows and wet snow avalanches. Snowmelt is an important triggering factor for rapid mass-movements in Iceland. During the intensive snowmelt period in the spring months, from April to June, rock fall, debris flows, slush flows and wet snow avalanche activity is common. Rock fall activity is common over the whole island, but debris flows caused by snowmelt are far most common in central north and northwest parts of the island. Another important triggering factor for rapid mass movements in Iceland are earthquakes. They have caused series of rock fall, debris flow and snow avalanche activity, both in the active volcanic zones and in the transform fault zones in the southern lowlands and in the central northern costal areas.

1 INTRODUCTION

Rapid mass movements, which can involve mixtures of debris, snow and water, can either occur in cold or warm environments. They can be triggered either by climatic factors, by internal forces such as earthquakes, different types of erosion or simply by human activity. To be able to prevent both human and economical losses, it is crucial to understand and be able to recognize the factors that trigger different types of rapid mass movements.

The catastrophic snow avalanche accidents in northwestern Iceland in 1995 can be regarded as a turning point in awareness and research effort put into rapid mass movements in Iceland. This type of natural hazard was mostly ignored before those incidences and little or no effort was put into research or protection work. Now on the other hand, it is accepted that rapid mass movement activity is large and direct threat to many towns, villages and farms in Iceland. Even though a lot of work has been put into this field during the last years it is still a long way to go.

According to written sources, at least 680 lives have been lost in snow avalanche accidents alone in Iceland since 1180. This number is only a minimum value and dose not includes fatal accidents caused by debris flow, rock fall or landslide activity in this period. Over the previous century rapid mass movements, involving debris, water and snow have caused many catastrophic accidents. Since 1901, 193 people have lost their lives, where 166 perished in snow avalanches and 27 in landslide activity. Snow avalanches in populated areas have clamed 107 lives and 59 in unpopulated areas. Six have lost their lives in landslide activity in populated areas and 21 in unpopulated areas (Jonsson et al. 1992, Petursson 1997, Johannesson & Arnalds 2000).

2 LANDSCAPE CHARACTERISTICS

2.1 *Bedrock*

Iceland is a volcanic island located on the North Atlantic spreading ridge, which separates the North American and the Eurasian continental plates. The bedrock or the lava pile is made up of basaltic volcanic rocks and relatively thin sedimentary horizons. The lava pile of Iceland has been divided into three statigraphical units, based on age and appearance; the Tertiary series, the early Quaternary series and the late Quaternary series and the lava fields of the volcanic zones (Fig. 1) (Saemundsson 1980, Johannesson & Sæmundsson 1989).

The oldest bedrock (3-16 m.y.) the Tertiary series occurs in the eastern, central northern and western part of the island (Fig. 1). It is mostly made up of jointed basaltic lava flows, erupted subaerially, individual flows varying in thickness from 2-30 m and usually separated by lithified sedimentary horizons varying in thickness from few centimeters up to tenths of meters. Acidic rocks and intrusions are found locally in buried central volcanoes, which also have been centers of tectonic activity.

The Early Quaternary series form a zone intermediate between the Tertiary basaltic areas and the active volcanic zone (Fig. 1). More variation occurs there in the general bedrock composition, the main reason being that, during that time interval (3-0.7 m.y.) Iceland was periodically covered with glaciers. The lava pile from this time consists predominantly of sub-glacial volcanic material erupted during glacial periods, made of pillow lavas, various types of breccias and hyaloclastites. This material is commonly interstratified with extensive sub-aerial lava flows erupted during interglacial periods. Sediment horizons from this time are also much ticker than in the Tertiary, due to much more erosion and landscape formation connected with the glacial activity.

The youngest bedrock the Late Quaternary series (< 0.7 m.y.) consists of hyaloclastic volcanic ridges and table mountains erupted subglacially in glacial periods and interstadial glacially sculptured lava flows. It also consists of the postglacial lava fields of the active volcanic zone (Fig. 1).

2.2 *The landscape*

The bedrock of Iceland has been sculptured by glacial, fluvial and marine erosion. The landscape characteristics are variable around the island and reflect the age of the bedrock and its composition.

The main topological features in the Tertiary areas in the northwestern, central northern and eastern parts of the island are glacially eroded, U-shaped fjords and valleys cut into the extensive highlands plateaus (Fig. 2A). The fjord and valley sides are often steep, with an average height up to 6-800 m. The upper parts of the slopes are often nearly vertical cliffs whereas the lower parts are covered with various glaciogenic landforms and sediments and talus material (Fig. 2B).

In Southern Iceland large glaciers and extensive sandur plains characterize the landscape in association with extensive mountains massive formed during the Quaternary period. Due to both glacial and marine erosion steep slopes and high cliffs up to 500 m have been cut into the mountains.

Hyaloclastics ridges and table mountains with steep slopes and extensive lava fields characterize the landscapes in the volcanic active zones in the central part of Iceland.

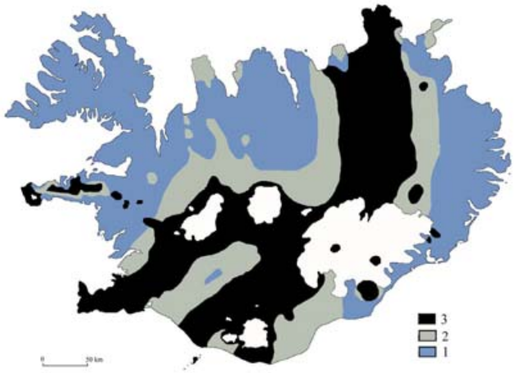


Figure 1. Simplified geological map of the bedrock condition in Iceland. 1: The Tertiary series; 2: The Early Quarternary series & 3: The Late Quaternary series and the active volcanic zone (redrawn after Einarsson 1991).

A

B

Figure 2. Landscape characteristics in Iceland. A. View over glacially eroded U-shaped fjord, the Seydisfjordur fjord, in eastern Iceland. B. A steep mountainside in Northwestern Iceland. Note the cliffs in the upper part and the steep talus in the lower part (Photos: Saemundsson 1996).

2.3 *Climate*

According to the Köppen-Geiger system of climate classification, Iceland is located at the junction between the temperate and the arctic climatic regions. The climate is categorized as cool temperate and maritime, with cool summers and mild winters. The weather in Iceland is constantly changing with high variation in precipitation and temperature. This is mainly due to the fact that Iceland is located near the main low-pressure pathway over the North Atlantic Ocean, The Icelandic Low. The mean annual temperature is higher in the southern part of the island than in the northern part, due to higher winter temperatures in the south. The mean annual precipitation is highest in the southern and southeastern parts of the island (Fig. 3). This is mainly due to the fact that the prevailing winds producing precipitation are southerly and southeasterly lose their moisture over the southern highlands (Einarsson 1984).

2.4 *Soil*

The steep slopes in the Tertiary basaltic areas in Iceland are usually covered by glacial till in the lower part, but the upper part is usually steep, terminating into cliffs. The till covered areas are often covered by talus, colluvium and humus material, with high permeability. Due to the high permeability this soil is strongly influenced by frost penetration. The valley bottoms are usually dominated by fluvial and glaciofluvial sediments.

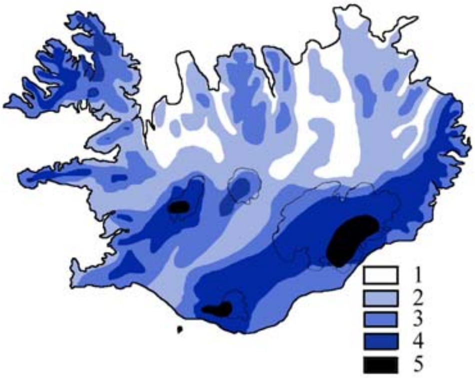


Figure 3. The mean annual precipitation in Iceland for the period 1931-1960 (modified from Einarsson 1991): 1. < 600 mm; 2. 600 – 1199 mm; 3. 1200 – 1999 mm; 4. 2000 – 3999 mm and 5. > 4000 mm.

3 RAPID MASS MOVEMENTS IN ICELAND

Rapid mass movement activity is very common in Iceland. Evidence can clearly been seen in the mountain slopes around the island. This process is also a direct threat to many towns, villages and farms. Until recently, little research has been put into these types of natural phenomena, such as causes, behavior and triggering factors.

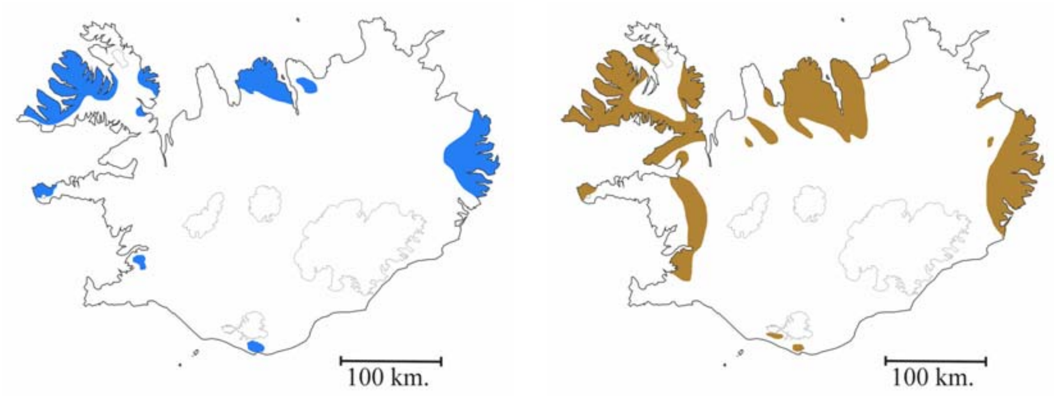
At the present, data on snow avalanches and landslides is collected by The Icelandic Meteorological Office and The Icelandic Institute of Natural History, and the inventory records are stored at those locations. All present work on rapid mass movement in Iceland is though build on Jonsson's pioneer work on the snow avalanches and landslides inventory (Jonsson 1957, Jonsson et al. 1992) and his work on rockslide avalanches in Iceland (Jonsson 1976)

Debris flows, are by definition known as spontaneous, gravitational and rapid mass movements consisting of a mixture of water and debris, occurring on steep slopes and along streams channels (Innes 1983). Debris flow activity is common all over the island, both in the tertiary basaltic areas, in the western, northwestern, northern and eastern parts of Iceland and also in areas near the active volcanic zone.

Rock fall is a gravitational movement of a mass of fragmented bedrock falling from cliffs or steep headwalls. It can involve material from small rocks up to large blocks. Rock fall activity is common in Iceland, as demonstrated by huge talus formation underneath every steep slope and high cliff around the country. This process is both related to the general bedrock condition and climate. The lava flows in the Icelandic bedrock are usually both porous and jointed and therefore easily fractured and loosed by the freezing and thawing processes and therefore the rock fall activity is highest during the springtime and the intensive snowmelt period. The largest talus formations are found in bedrock made of early and late Quaternary series but very large talus formation are not so uncommon in the tertiary bedrock, were favorable conditions persist.

Snow avalanches are one type of rapid mass movement and are categorized after the water content in powder avalanches, dry avalanches, wet avalanches and slush flows. Snow and water is the main component in this type of mass movement but the significant of debris transport has been highly underestimated (Blikra & Nemec 1998, Blikra & Saemundsson 1998). The snow avalanche activity is high in Iceland and this type of mass movement directly threatens many towns, villages and farms.

The postglacial rockslide activity has been high in Iceland. They are most frequent in the Tertiary basaltic areas and in some areas characterize the landscape (Jonsson 1976). It has been suggested that the majority of them occurred shortly after the deglaciation, but the age distribution is not clearly known (Jonsson 1976, Whalley et al. 1983). Some recent rockslide activity has been described (Kjartansson 1967, Sigurdsson & Williams 1991, Gudmundsson 1997) but at the moment research activity on this phenomenon is not high in Iceland.



A B

Figure 4. A: The main snow avalanche hazard areas in Iceland. The most threatened areas are in the eastern, central northern and northwestern parts of the island, in the Tertiary basaltic areas. B: The main debris flow and rock fall hazard areas in Iceland. As for the snow avalanche hazards these areas are also associated with the Tertiary basaltic areas (modified after Valsson & Sigurbjornsson 1996).

4 TRIGGERING FACTORS

The triggering factors for rapid mass movements vary considerably, not only because of the different types of mass movement involved, but also due to the interaction between local bedrock condition, topography, soil condition, slope inclination, slope aspect and climate condition. The main factors triggering mass movement in Iceland are precipitation, snow or rain, either intensive or long lasting, snowdrift, snowmelt and earthquakes. Of those factors heavy precipitation is the most common triggering factor for rapid mass movements in Iceland.

4.1 *Heavy rainfall / snowfall*

Heavy precipitation, snow and/or rain, is one of the most common triggering factors for rapid mass movements in Iceland. During the cold winter months from October to May heavy snowfall and snowdrift are the main causes for snow avalanches activity. The highest activity is in February although snow avalanches have been reported in all months except June and July.

The most common weather condition triggering snow avalanche activity in Iceland is heavy snowfall and snowdrift in strong north or northeasterly wind. As shown on Figure 4A the snow avalanche areas in Iceland predominantly match the Tertiary basaltic areas. These areas have their own landscape characteristics and therefore different snow accumulation and triggering mechanics (Bjornsson 1980).

During the warmer months, from May to October heavy precipitation can been expected nearly all around the island. As described before, the mean annular precipitation is highest in the southern and eastern parts, but examples of intensive rainfall triggering debris flow activity are known from most parts of the country. The threshold condition or the amount of rain needed to trigger debris flow activity is on the other hand uncertain for most parts of the island, except in the eastern part. As shown in Figure 4B the debris flow areas in Iceland also predominantly matches the Tertiary basaltic areas, as the snow avalanche areas.

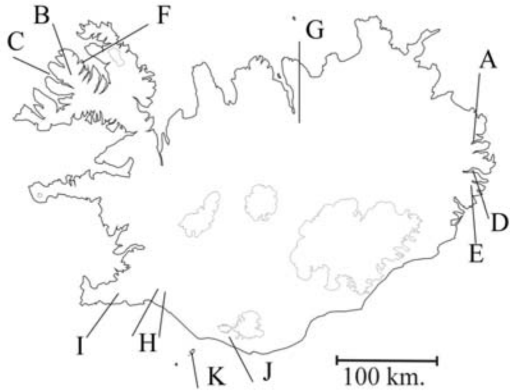


Figure 5. Location map of the areas mentioned in the text. A. The Seydisfjordur fjord; B. The Vestfirdir area; C. The town of Flateyri in the Onundarfjordur fjord; D, The Eskifjordur / Reydarfjordur fjords; E. The Breiddalur valley; F. The Gleidarhjalli area; G. The Solvadalur valley, in the innermost part of the Eyjafjordur area; H. The southern lowlands; I. The Reykjanes peninsula; J. The Eyjafjöll Mountain massive & K. The Vestmannaeyjar islands.

4.1.1 *The threshold condition, examples from central eastern Iceland*

A comparison was made between the climatic record and the debris flow history in the Seydisfjordur fjord, in central east Iceland, in order to be able to understand the connection between climate and debris flow activity (Fig. 5, loc. A) (Saemundsson & Petursson 1999a). Detailed weather data and debris flow record exists for that area, from 1961 to 1996. During this period, days with specified weather criteria were selected and compared with the known debris flow history. The weather criteria used, was that the 24 hours precipitation had to exceed 50 mm and the mean 24 hours temperature had to exceed 4°C. These weather criteria were selected in order to sort out numerous days when the precipitation fell as snow. During this time interval thirty-nine days fulfilled this criterion, mainly from August to October. Only six days with debris flow activity occurred, one due to snowmelt and five due to heavy rainfall. The 24 hours precipitation was around or exceeded 100 mm in northeast wind, during four of these debris flow activity days and in one instance it exceeded 60 mm, in southerly wind. Apart from these six debris flow days the 24 hours precipitation exceeded 50 mm or more thirty-three times without any debris flow activity. During only six of these days the precipitation exceeded 80 mm or more, but the wind direction was only in two instances from the northeast. The debris flow history from the Seydisfjordur fjord reaches back to the year 1882. From 1935 to 1960, or from the year when weather data records started in this region, four debris flow days were reported all with 24 hours rainfall exceeding 80 mm and the wind blowing from the northeast. Judging from these data it is evident that debris flow activity is predominantly triggered by heavy rainfall, in northeasterly wind in the Seydisfjordur area. The amount of precipitation needed to trigger debris flow activity lies between 80-100 mm. This is somewhat similar to research records from Norway (Sandersen 1996, Sandersen et al. 1996, Sandersen 1997).

According to Sandersen there is a direct connection between the amount of precipitation and the duration of rainfall. The amount of precipitation needed if the rainfall lasts 3 hours is 2% of the annual precipitation, 3% for six hours, 4.4% for twelve hours and 6.5% for 24 hours. In the years from 1961 to 1996 debris flow history for the Seydisfjordur fjord only 24 hours rainfall records exists. If this is compared to the mean annual precipitation for the time interval 1960-1990 from the Dalartangi weather station, which is around 1400 mm, the threshold condition should be around 90 mm (Saemundsson & Petursson 1999a).

4.1.2 *The October snowstorm in Northwestern Iceland in 1995*

In late October a series of snow avalanches occurred in the Vestfirdir peninsula in Northwestern Iceland (Fig. 5, loc. B). The weather conditions causing the snowstorm were somewhat unusual for the time of the year it occurred. During this time unusual and unfavorable atmospheric circumstances were over the North Atlantic Ocean. In Europe the late summer air masses were still dominating but cold winter air dominated Greenland and surrounding areas. This condition led to a series of powerful low-pressure areas passing over the island, with heavy precipitation and very strong north winds in the northern and northwestern parts of the islands. These weather conditions caused a series of large snow avalanches in the Vestfirdir fjords, some of them reaching down into populated areas. In one avalanche, hitting the town of Flateyri in the Onundarfjordur fjord twenty persons lost their lives and enormous economical damages occurred (Fig. 5, loc. C) (Haraldsdottir 1998).

4.1.3 *The September rainstorms in Eastern Iceland in 1999*

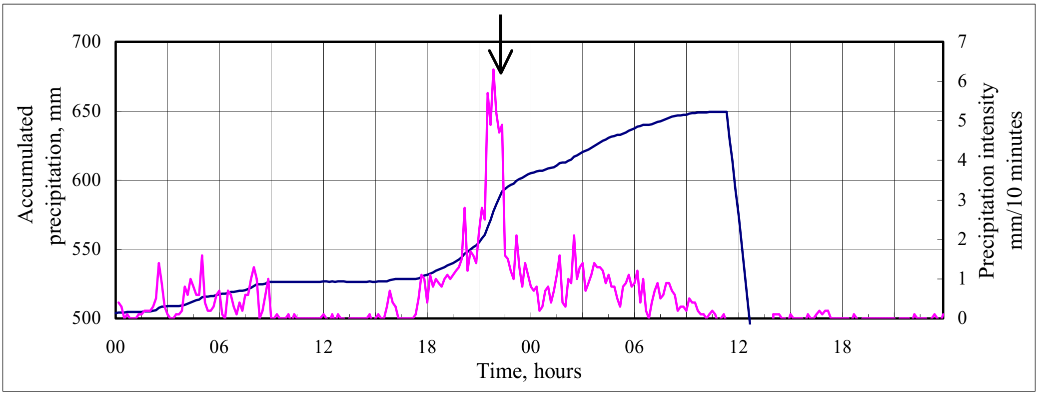
Two heavy autumn rainstorms hit eastern Iceland in September 1999 with unusual intensive rainfall. The first one occurred during the 8th and 9th triggered debris flow activity in the Seydisfjordur fjord (Fig. 5, loc. A) and the second during the 17th triggering debris flow activity in the Eskifjordur Reydarfjordur fjords and in the Breiddalur area (Fig. 5, loc. D&E) (Petursson & Saemundsson 2000).

During the 8th and 9th of September a heavy autumn storm hit eastern Iceland coursing intensive rainfall in the Seydisfjordur fjord. At least seven large debris flows were triggered on the northern side of the fjord, just outside the town of Seydisfjordur (Fig. 5, loc. A). The amount of precipitation that fell during this storm was about 100 mm in 16 hours, between 20:00 on the 8th to 12:00 on the 9th, but the major part of the rain fell in only 6 to 7 hours. The most intensive precipitation period was between 21:30 and 22:30, when about 30 mm fell (Fig. 6A). Soon afterwards, or around midnight the debris flows occurred. Smaller debris flows were also observed on the southern side of the fjord, but the timing of them is not known (Petursson & Saemundsson 2000).

During the 17th of September another heavy autumn storm hit eastern Iceland triggering debris flow activity. During this storm the debris flow activity was more geographically spread along the eastern coast, but though mostly concentrated in two areas, the Holmatindur Mountain in the Reydarfjordur / Eskifjordur area and the To Mountain in the Breiddalur area (Fig. 5, loc. D&E). Between these two areas, small individual flows were also observed. The debris flow activity in the Holmatindur Mountain occurred early morning of the 17th. In the Eskifjordur fjord the precipitation reached some 100 mm in only 8 hours, from 00:00 to 08:00 on the 17th, and it seem that most of the flows from Holmatindur, fell between 05:30 to 06:30, after more or less continuous 6 to 7 hours heavy rainfall (Fig. 6B). In Breiddalur area about 14 big and small debris flows occurred in about 2 km wide zone along the shoulder of the To Mountain. One debris flow fell directly on the farm Toarsel causing considerable damage on buildings and hayfields. The measured precipitation between the 16th and 17th in Breiddalur was 150 mm (Petursson & Saemundsson 2000).

4.2 *Snowmelt*

Snowmelt is a common triggering factor for debris flow, rock fall and slush flow activity in Iceland. The snowmelt, both caused by solar radiation, heavy wind or rainfall, triggering debris flow and rock fall activity is usually highest during the spring months, but due to the constantly changing weather condition it can occur during other times of the year as well. The landslide susceptibility to snowmelt is on the other hand not as common in the eastern part of the country as in the northwestern part. For example in the Gleidarhjalli area in Northwestern Iceland (Fig. 5, loc. F) snowmelt, both due to solar radiation and rainfall, causes about 50% of the total debris flow and rock fall activity (Saemundsson & Petursson 1999b, Decaulne 2001). This ratio is estimated around 15-25% in Central North Iceland but only within 5% of the debris flow and rock fall activity is caused by snowmelt in Eastern Iceland.



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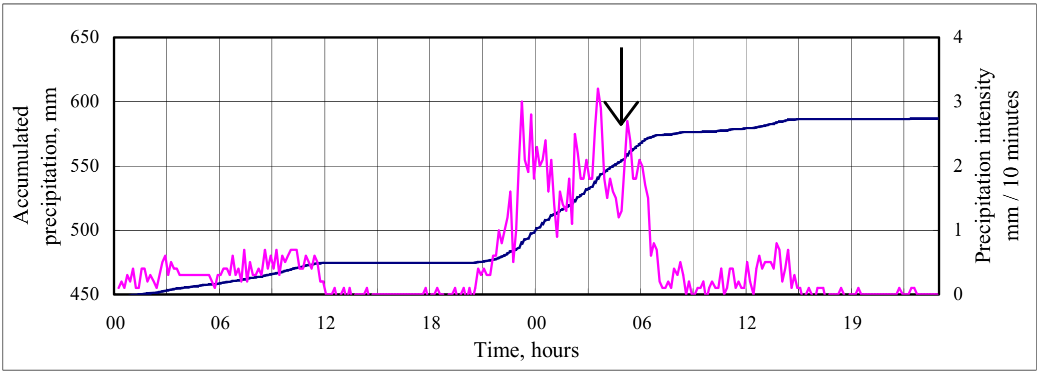

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Figure 6. Accumulated precipitation and precipitation during ten minute intervals in A. The Seydisfjordur fjord on the 8th and 9th of September 1999. B. The Eskifjordur fjord on the 16th and 17th of September 1999. The arrows indicate the timing of the debris flow events (redrawn from Petursson & Saemundsson 2000).

4.2.1 *The snowmelt period in Central North Iceland in June 1995*

An intensive snowmelt period occurred in the spring of 1995 in Central North Iceland. The first snow in the winter 1994-95 accumulated on unfrozen ground early in the autumn and thus insulated it. The winter was cold and snowy, with no major snowmelt periods. In late May and early June, after a cold spring time a sudden rise in the temperature caused an intensive snowmelt period. Due to the snow cover insulation of the ground during the whole winter the soil was unfrozen and the melt water percolated directly into the ground and destabilized the soil in the mountain slopes. This situation led to an unusually high groundwater level, witch eventually brought about a great number of debris flows and flooding of rivers. Many small debris flows occurred in the outer valley parts of Central Northern Iceland, mainly causing damages to vegetation and roads. On the 29th of June a large debris slide occurred in the Solvadalur valley, in the innermost part of the Eyjafjordur area (Fig. 5, loc. G). This slide, which was initiated as a part of a 6000 to 9000 years old rockslide fell down the mountainside 150 m south of the farm Thormodsstadir, is among the largest debris slide that has occurred in Iceland at least during the 20th century (Fig. 7) (Saemundsson & Petursson 2000).

Figure 7. The Solvadalur debris slide, in the innermost part of the Eyjafjordur area. The uppermost part of the debris slide is located at about 550 to 600 m a.s.l. Its scarp is about 150 m wide and 300 m long. The slide is 900 to 1000 m long and about 400 to 500 m wide at the lower end. The total volume of the debris slide is estimated between 600.000 and 800.000 m^3. The debris slide fell into the canyon below and dammed it up. As the dam collapsed debris rich flood wave burst down the river about 40 km towards the sea (Saemundsson & Petursson 2000).

4.2.2 *The snowmelt period in Northwest Iceland in June 1999*

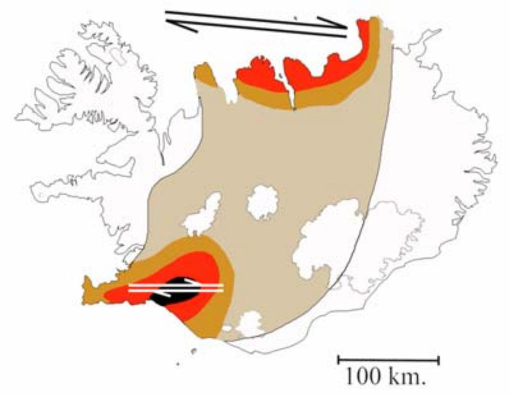
An intensive snowmelt period that occurred in the Vestfirdir area in Northwest Iceland from 10th to 12th of June 1999 triggered a series of debris flows and rock fall activity in the Gleidarhjalli plateau, above the town of Isafjordur (Fig. 5, loc. F and Fig. 8). After a relative mild weather in early May a sudden cooling occurred on 21st of May with four days of snow precipitation and snowdrift in the mountains and sleet in the lowlands. The accumulated precipitation measured in the lowlands reached between 50-70 mm. From the 24th of May to the 10th of June now precipitation was measured and the air temperature was low. A sudden weather change occurred on the 10th of June. The air temperature rose up to 14-17° C and the wind was 10-15 m/s from the south. This led to a sudden and intensive snowmelt period triggering debris flow and rock fall activity in the Gleidarhjalli area. The activity began only few hours after the snowmelt had begun and continued until the 12th of June. The debris flow and rock fall activity was observed in at least 6 channels, some of them affecting living areas but without any serious damages.

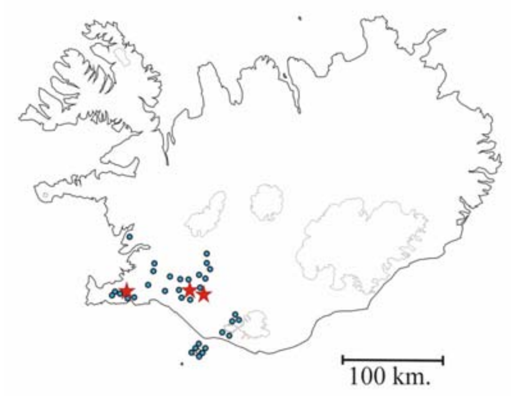
Debris flow and rock fall activity is common in the Gleidarhjalli area and during the last 103 years 22 debris flow and rock fall events have been recorded. At least 50 % of these events have been triggered by snowmelt or snowmelt associated with rain (Saemundsson & Petursson 1999b, Decaulne 2001).

4.3 *Earthquakes*

Most of the earthquake activity in Iceland is concentrated to the volcanic zones, the transform fault zones in the southern lowland, and on the sea bottom off the northern coast (Fig. 9A). The earthquakes originating in the volcanic zones are seldom larger in magnitude than 5 on the Richter scale. On the other hand, the largest earthquakes of the transform fault zones reach in magnitude up to 7 on the Richter scale. Therefore rock fall and debris flows connected with earthquakes on the volcanic zones are usually only observed locally around the epicenters, but records of rock fall about 75-100 km distance from the epicenters of the large earthquakes of the transform faults zones, are not uncommon.

Figure 8. The Gleidarhjalli area, in the Eyrarfjall Mountain above the town of Isafjordur. The Mountain is about 700 m high but the lower plateau, the Gleidarhjalli plateau, is around 500 m high. The surface of the plateau is covered with up to 10 m thick sediments, composed of morainic sediments and boulders. The debris flow and rock fall activity was triggered by melt water flowing from the plateau and down the slope, releasing sediments from the edge of the plateau. Note the fresh debris flow channels. (Photo Saemundsson 1999).





A B

Figure 9. A. Earthquake areas in and around Iceland. The brown colure indicates the active zone; the black arrows indicate the transform fault zone in the southern lowlands and outside the northern coast. The dark brown area indicates the highest risk zone and the lighter colors lower risk. B. The June 2000 earthquake in southern Iceland. The stars indicate the epicenter of the three earthquakes occurring in June and the dots indicate areas affected by rock fall activity (modified from Valsson & Sigurbjornsson 1996, Einarsson 1991).

Rock falls from steep slopes or cliffs is most common in connection with earthquakes, debris flows or slides have been observed and even snow avalanches, all depending on which season of the year the earthquake occurred.

4.3.1 *The earthquakes in southern Iceland in June 2000*

At 15:40 on the 17th of June 2000 an earthquake, about 6.4 on the Richter scale occurred, with epicenter in middle of the southern lowland (Fig. 5, loc. H and Fig. 9B). Few minutes later another earthquake about 5 on the Richter scale, with epicenter in the Reykjanes peninsula followed (Fig. 5, loc. I and Fig. 9B). Immediately rock falls started, both from the high hyaloclastic cliffs of the Eyjafjoll Mountain massive and the Vestmannaeyjar islands (Fig. 5, loc. J&K) off the southern coast, but also from lower cliffs and slopes nearer the epicenter. The most distant rock fall was observed about 75 km from the epicenter. On the Reykjanes peninsula a rock fall was observed from the cliffs and the slopes around the epicenter (Fig. 9B). A few days later at 0:51 GMT on the 21st of

June, another earthquake also about 6.4 on the Richter scale followed, now with epicenter a bit further to the west, than the one on the 17th (Fig. 9B). High rock fall activity also followed this earthquake and few debris flows from wet slopes or steep mires were observed.

5 DISCUSSION

As clearly can be seen by the above examples, many towns, villages and farms are under a large and direct threat by different types of rapid mass movements in Iceland. It is therefore very important to be able to understand and recognize the various triggering mechanisms and the threshold conditions for the different types of rapid mass movements.

The landscape and the climate conditions in Iceland provide favorable circumstances for rapid mass movements, such as the fractured volcanic bedrock, steep debris rich slopes, the constantly changing climate condition and not at least the earthquake activity.

Snow avalanches cause the largest mass movement threat in Iceland, but much effort has been put into snow avalanche research and hazard mapping during the last years. On the other hand the threat of land slides activity, i.e. debris flows, rock fall and rockslides is still clearly underestimated. It is crucial to put more research effort into the general behavior and triggering mechanism of these types of mass movements.

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REFERENCES

Bjornsson, H. 1980. Avalanche activity in Iceland, climate condition, and terrain features. *Journal of Glaciology* 26 (94): 13-23.

Blikra, L.H. & Nemec, W. 1998. Postglacial colluvium in western Norway: depositional processes, facies and palaeoclimatic record. *Sedimentology* 45: 909-959.

Blikra, L.H. & Saemundsson, Th. 1998: The potential of sedimentology and stratigraphy in avalanche-hazard research. In: E. Hestnes (ed.), *25 years of snow avalanche research*. Oslo, the Norwegian Geotechnical Institute: 12-16.

Decaulne, A. 2001. Dynamique des versants et risques naturels dans les fjords d'Islande du Nord-Ouest; l'impact géomorphologique et humain des avalanches et des debris flows. *PhD Dissertation*, Department of Geography, University of Clermont-Ferrand, France: 391p.

Einarsson, M.A. 1984. Climate in Iceland. In: H. van.Loon (ed.), *World survey of climatology, 15, climate of the oceans:* 673-697. Amsterdam: Elesvier.

Einarsson, Th. 1991. *Geology of Iceland, rocks and landscape*. Mal og menning, Reykjavik.

Gudmundsson, H.J. 1997. A review of the Holocene environmental history of Iceland. *Quaternary Science Reviews* 16: 81-92.

Haraldsdottir, S.H. 1998. The avalanche of Flateyri, Iceland October 26th 1995 and the avalanche history. In: E. Hestnes (ed.), *25 years of snow avalanche research*. Oslo, Norwegian Geotechnical Institute: 122-127.

Innes, J.L. 1983. Debris flows. *Progress in Physical Geography* 7: 469-501.

Johannesson, H. & Saemundsson, K. 1989. Geological map of Iceland. 1:500,000. Bedrock geology. Museum of Natural history and the Icelandic Geodetic Survey, Reykjavik.
Johannesson, T. & Arnalds, Th. 2000. Accidents and economic damage due to snow avalanches and landslides in Iceland. *Jokull* 50: 81-94.
Jonsson, O. 1957. *Skridufoll og snjoflod I-II.* Bokautgafan Nordri, Akureyri. (in Icelandic)
Jonsson, O. 1976. *Berghlaup.* Raektunarfelag Nordurlands, Akureyri. (in Icelandic)
Jonsson, O, Petursson, H.G., Rist, S. & Sigvaldason, J. 1992. *Skridufoll og snjoflod I-III.* Reykjavík, Bokautgafan Skjaldborg. (in Icelandic)
Kjartansson, G. 1967. The Steinholtshlaup, Central-South-Iceland, on January 15th 1967. *Jokull 17*: 249-262.
Petursson, H.G. 1997: Skridur og skridufoll. *Natturufraedistofnun Islands – Arsrit 1996:* 12-21. (in Icelandic)
Petursson, H.G. & Saemundsson, Th. 2000. The connection between rapid mass-movement and extreme precipitation, examples from Eastern Iceland. In: A.J. Russell & P.M. Marren (eds), *Iceland 2000: Modern processes and past environments.* Keele University, Dep. Geogr. Occa.Papers Series No. 21: 84.
Sandersen, F. 1996. Influence of meteorological factors on rock falls and rock slides in Norway. NGI-Report 585910-8.
Sandersen, F. 1997. The influence of meteorological factors on the initiation of debris flows in Norway. In: J.A. Matthews, D. Brunsden, B. Frenzel, B. Gläser & M.M. Weiß (eds), *Rapid mass movements as a source of climatic evidence for the Holocene.* Paläoklimaforschung Paleoclimate Research 19: 321-332.
Sandersen, F.; Bakkehøi, S.; Hestnes, E. & Lied, K. 1996. The influence of meteorological factors on the initiation of debris flows, rockfalls, rockslides and rockmass stability. In: K. Senneset (ed.), *Landslides*, 97-114. Rotterdam: Balkema.
Saemundsson, K. 1980. Outline of the geology of Iceland. *Jokull* 29: 7-28.
Saemundsson, Th. & Petursson, H.G. 1999a. Mat a aurskridu- og grjothrunshaettu vid Seydisfjardarkaupstad. Vedurstofa Islands. Greinargerd VI-G99003-UR02. (in Icelandic)
Saemundsson. Th. & Petursson, H.G. 1999b. Skriduhaetta a Isafirdi og Hnifsdal. Vedurstofa Islands. Greinargerd VI-G99024-UR14. (in Icelandic)
Saemundsson, Th. & Petursson, H.G. 2000. The Solvadalur debris-slide. *Local Authorities Confronting Disasters and Emergencies, Reykjavk, Iceland. Abstract book*: 26.
Sigurdsson, O. & Williams, R.S. jr. 1991. Rockslides on the terminus of "Jokulsargilssjokull", southern Iceland. *Geografiska Annaler* 73A: 129-140.
Valsson, T. & Sigurbjornsson, R. 1996. Natturuva a Islandi. *Arkitektur, Vertaekni and Skipulag* 17: 15-40. (in Icelandic)
Whalley, W.B., Douglas, G.R. & Jonsson, A. 1983. The magnitude and frequency of large rockslides in Iceland in the postglacial. *Geografiska Annaler* 65A: 99-110.