DEBRIS FLOW TRIGGERED BY RAPID SNOWMELT: A CASE STUDY IN THE GLEIÐARHJALLI AREA, NORTHWESTERN ICELAND

BY

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ABSTRACT. Debris flows in the Gleiðarhjalli area in northwestern Iceland occurred after a sudden and intensive snowmelt period during 10–12 June, 1999. The area, in the northwestern part of the town of Ísafjörður, was chosen for a detailed study. Meteorological data and bedrock conditions, triggering mechanisms and geomorphological and human impacts were examined. This paper describes and emphasises the role of rapid snowmelt as a mechanism for the release of debris flows in a subpolar basaltic fjord setting. Post-event mapping of erosional and depositional landforms showed strong geomorphic impacts of debris flows and their role in mass transfer in a mountainous environment. The estimated denudation rate for the single event is 0.29 mm/km^2. The use of a new lichen growth curve provides relative dating of previous unreported events. Finally, the paper estimates the mean return period for debris-flow events in the Gleiðarhjalli area as 4–5 years, thus constituting a serious threat to the community.

Key words: debris flows, rapid snowmelt, geomorphic impact, lichenometry, northwestern Iceland.

Introduction

Research on factors triggering debris-flow and rockfall activity has, until recently, mainly focused on rainfall intensity (e.g. Caine 1980; Rapp 1960, 1987; Kotarba 1992; Van Steijn 1996; Jonasson and Nyberg 1999; Vedin *et al*. 1999; Beylich and Sandberg 2005), and authors have mostly under-rated the role of snowmelt (Bertran *et al*. 2004). Snowmelt is, however, very important, especially in Iceland where a succession of atmospheric lows and very changeable temperature during the winter contribute to sudden melting of the snow cover on large amounts of loose debris. The aim of this paper is to highlight the role played by rapid snowmelt in debris-flow release, as demonstrated by several events which occurred in the middle of June 1999 in northwestern Iceland (Fig. 1) and to present the geomorphic impact of snowmelt-triggered debris flows.

The bedrock in the region is of Miocene age (14–16 million years). It is mostly made up of jointed basaltic lava flows, erupted sub-aerially. Individual flows vary in thickness from 2 to 30 m, and are usually separated by lithified sedimentary horizons, from a few centimetres up to tens of metres thick. The lava beds usually dip towards the southeast (Dagley *et al*. 1967; Kristjansson *et al*. 1975; Sæmundsson 1980). The lava pile is intersected by basaltic dykes with a general SW–NE trend. Deep, glacially sculptured fjords and valleys characterise the landscape. The mountain summits, which reach about 600–700 m a.s.l. along the coast, are usually relatively flat and extensive. The mountain slopes are usually steep, with average slope angles ranging from 25 to 35°, covered by talus in the lower parts and terminating in steep cliffs at the head of the slope.

The study site, in the Gleiðarhjalli area, is located on the western side of a small tributary fjord, Skutulsfjörður, on the southern bank of the Ísafjarðardjúp fjord, in northwestern Iceland (Fig. 1). The Gleiðarhjalli area is approximately 1500 m long and consists of a 400–500 m wide bench on the eastern side of Eyrarfjall mountain, which rises to a height of about 450–500 m a.s.l. above which the slope extends to the summit plateau at 700 m (Fig. 2). The bench surface is covered with thick sediments, up to 20–35 m thick, perched on the edge of the bench. Sparse vegetation (mosses and locally patches of phanerogam species, such as *Saxifraga oppositifolia*, *Silene acaulis*, *Dryas*

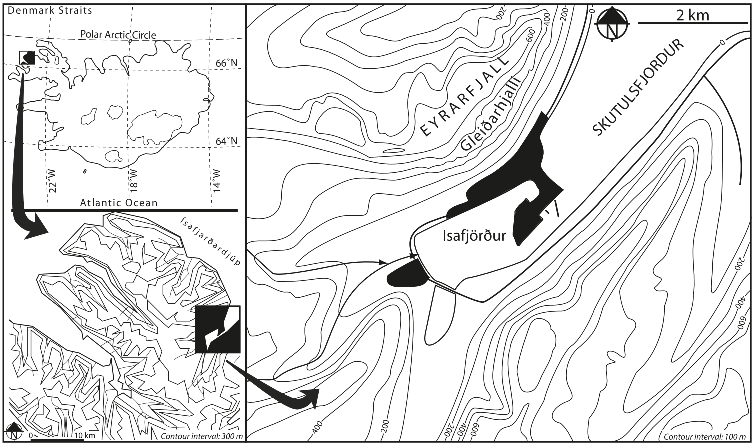

Fig. 1. The regional and local setting of the study site in the Gleiðarhjalli area, north-western Iceland. Black areas indicate the inhabited regions

Fig. 2. The Gleiðarhjalli bench, on the eastern side of Eyrarfjall mountain. The image shows the fresh debris flows from June 1999, above the town of Ísafjörður (photo A. Decaulne)

octopetala) covers the finer sediments at the surface but extensive boulder fields, with rocks up to 30–40 metric tons, also dominate, with a sparse cover of lichens (Fig. 3). Above the bench a 150–200 m high cliff wall with a talus apron forms the highest part of Eyrarfjall mountain. The town of Ísafjörður, with 3500 inhabitants, is located below the Gleiðarhjalli bench. The uppermost buildings are at around 30–40 m a.s.l. (The Urðarvegn Street). Above, a 470–500 m high slope rises steeply to the bench edge. The slope is covered with thick talus material, and has an average angle of around 25–35°. In the uppermost part of the slope, there is a 30–70 m high rockwall, dissected by numerous chutes.

Methods

Triggering factors of the June 1999 debris-flow events were analysed using available meteorological data observed at sea level in the closest stations, including air temperature, precipitation, wind direction and wind speed, to assess the influence of sudden snowmelt on these flows. The release of the debris flows was witnessed by the authors in the field. During the most active period, direct observations and measurements were made. The geomorphic impact of the debris-flow event was assessed by comparing topographic surveys of the debris flows along their longitudinal profiles, with measurements taken in the same area immediately

Fig. 3. The surface of the Gleiðarhjalli bench (450 to 500 m a.s.l.), composed of unconsolidated material of various sizes. On the right is Eyrarfjall mountain and on the left is the edge of the bench (photo Þ. Sæmundsson)

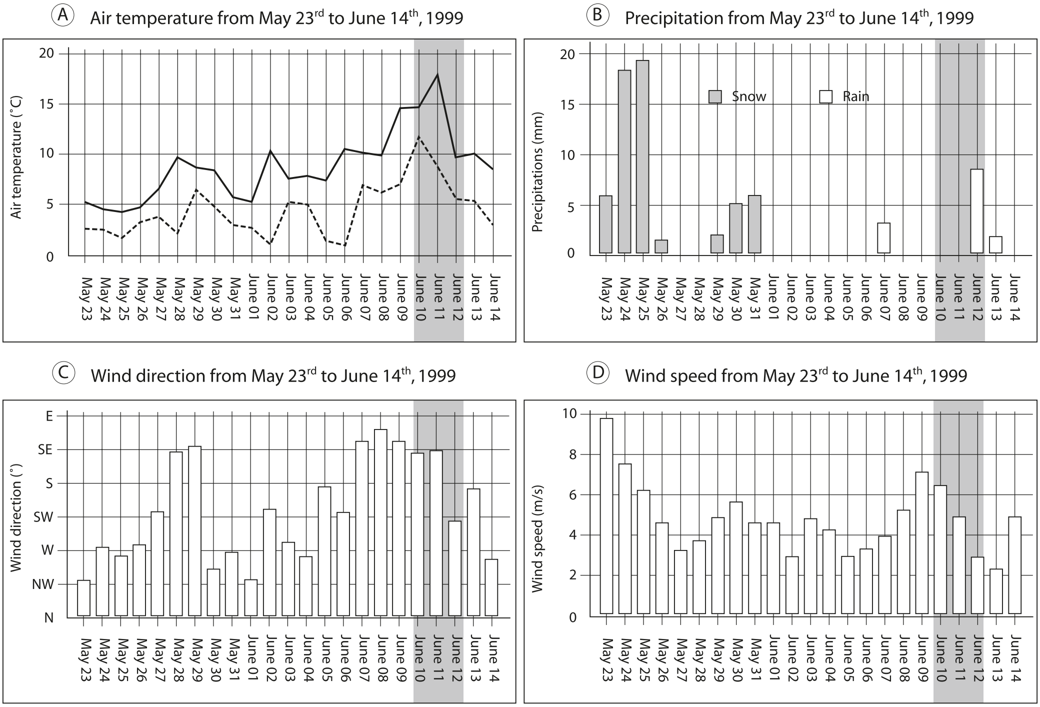

Fig. 4. Meteorological data (temperatures, rainfall and wind) that led to rapid snowmelt and debris-flow release in the Gleiðarhjalli area. The debris-flow period is highlighted by grey shading. Minimal air temperatures are indicated by a dashed line and maximum air temperatures by a full one

before the event. Interpretation of aerial photographs, combined with field observations, was used to draw a map of the impacts of the 10–12 June, 1999 event. Debris-flow volume estimates were derived from morphometric properties of the deposits. Suspended sediment transport by the debris flow was sampled with a 500 ml container plunged into the flow, just after the passage of the main debris-flow pulse, when it was safe to access the channel. In order to place these events in the context of

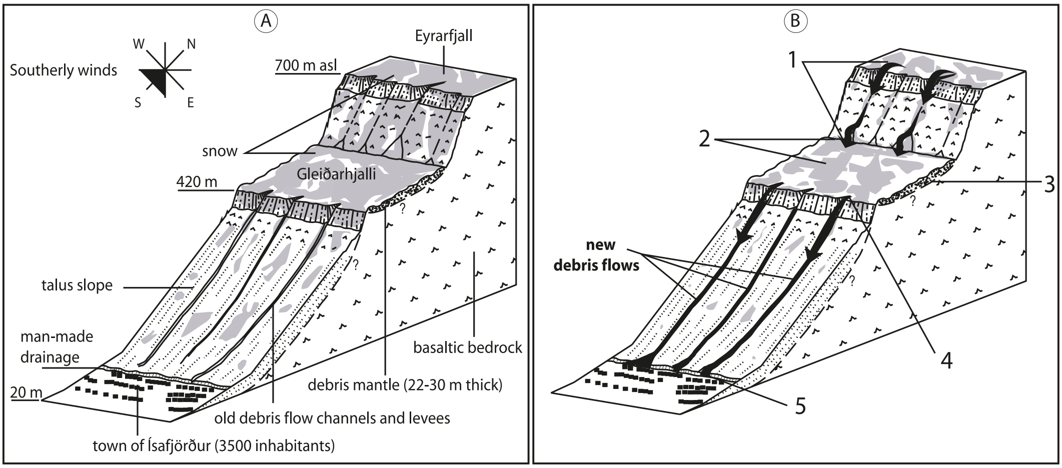

Fig. 5. Sketch of the 1999 debris-flow event in the Gleiðarhjalli area. (A) Schematic situation prior to the event, on 9 June, 1999. (B) Schematic situation during the event: 1, the summit snow from Eyrarfjall mountain suddenly melts and flows onto the basaltic rock face; 2, on Gleiðarhjalli bench, the meltwater infiltrates into the regolith; 3, the water is unable to seep because of the impermeable basaltic bedrock; 4, the subsurface runoff appears at the edge of Gleiðarhjalli, erodes the material, generates rotational slides and debris flows downslope; 5, the debris flows run down the talus slope and fill the artificial drainage dykes at the foot of the slope, just above the first houses

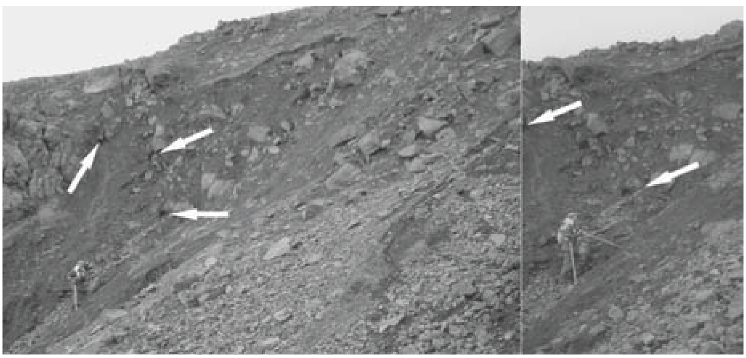

Fig. 6. Detailed views of the source area of debris flow no. 1, at the edge of Gleiðarhjalli. The resurgence of the sub-surface flow within the debris mantle occur in a few 'springs' at the margin of the source area (shown by white arrows) (photos Þ. Sæmundsson and A. Decaulne)

longer-term slope processes, lichenometric data were also collected along the debris-flow tracks, on well defined geomorphic units such as channel, levées and lobes. Measurements was collected over the full altitudinal range of the deposits from 0 to 500 m a.s.l. The average size of the five largest lichen thalli of *Rhizocarpon geographicum* species was measured along the entire debris-flow track. Only approximately circular specimens were measured with a ruler to the nearest millimetre. Using the suggested nomenclature for *Rhizocarpon* species (Innes 1985), the measurements refer to the sub-genus *Rhizocarpon* and include section *alpicola* and *geographicum*, as most of *Rhizocarpon* lichens are divided into numerous species and subspecies (Karlén 1973; Rapp and Nyberg 1981). A new preliminary lichen growth curve was established in the study area, based on lichen measurements on the surface of four boulders for which time of exposure was known. Combined with data from published sources, a dating curve covering the last century was constructed.

Throughout the paper the term 'event' refers to a debris-flow episode that triggers from one to several channels during a given period.

Triggering factors and release of the debris flows

The main factors contributing to the debris-flow events can be divided into two types. Firstly, the weather conditions contributed to the mass move-

Fig. 7. A mass of debris flowing down in channel no. 1, showing the high density of the flow, transporting material of heterogeneous size, ranging from clay to boulders of up to 1.5 m in diameter (photo A. Decaulne)

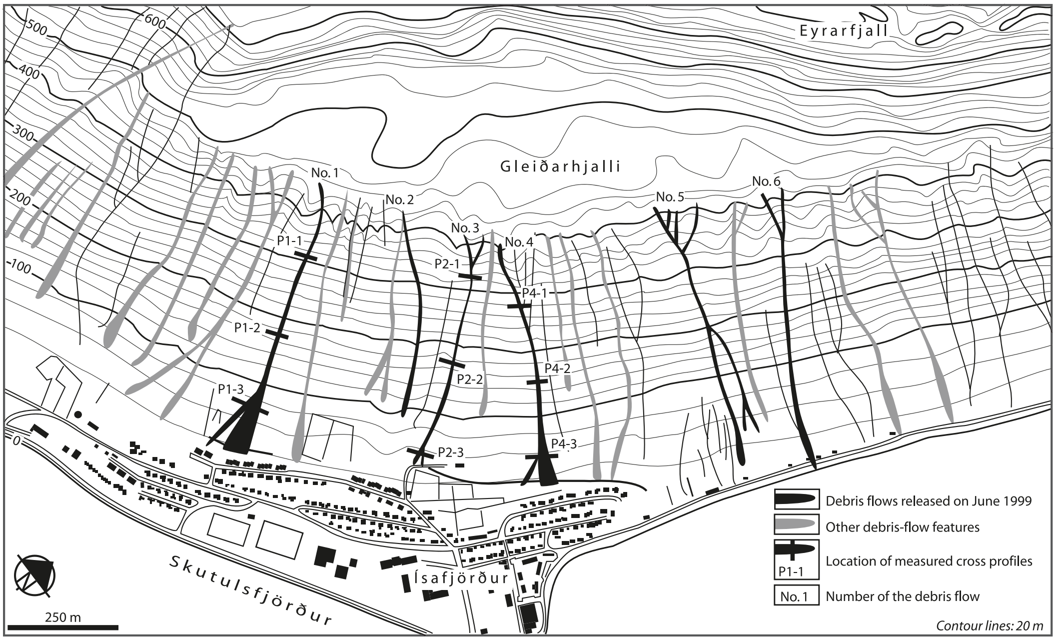

Fig. 8. The main debris-flow tracks released from Gleiðarhjalli on June 1999. Locations of measured transects are indicated

ments. During the four-week period before the debris-flow release, the weather had undergone considerable changes (Fig. 4). In the middle part of May air temperatures reached 10 to 11°C. A snowstorm in the period 21 to 25 May resulted in 46 mm of sleet and rain recorded at the weather station in the Hnífsdalur valley and 68 mm in the town of Bolungarvík (2 km and 12 km, respectively, west of the study area). The air temperature at sea level was 1 to 4°C during this period, indicating a rather heavy wet snow accumulation in the mountains. During the following two weeks only small amounts of precipitation were measured and the air temperature slowly increased. On 10 June, the air temperature rose dramatically to between 14 and 17°C in connection with a 10–15 m/s southerly wind triggering an intensive snowmelt. Secondly, in the Gleiðarhjalli area the topography and the morpho-

Table 1. Observations of debris flows nos 1 and 4 during the 10–12 June, 1999 event

	Debris flow no. 1		Debris flow no. 4	
Date	No. of pulses	Time of the pulses	No. of pulses	Time of the pulses
June 10	1	23:30	1	22:00
June 11	1	14:00	1	09:35
	1	16:30	1	12:00
	2	18:20		
	4 to 7	21:00 to 23:30		
June 12	1	02:00	1	06:00
	1	02:30	1	12:00
	1	03:00		
	1	06:00		

logy of steep slopes covered with a huge amount of material are prone to mass movements and high runoff.

The intensive snowmelt began on 10 June and lasted almost continuously until 12 June. The meltwater from the uppermost parts of the Eyrarfjall Mountain down to the Gleiðarhjalli bench infiltrated into the sediments. After percolating into the debris mantle, the meltwater hit the impermeable basaltic bedrock and ran through sub-surface conduits to the edge of the bench (Fig. 5). The flow between the sediment mantle and the bedrock caused erosion of the debris mantle at the edge of Gleiðarhjalli, where the sub-surface flow came out of the bench material in several 'springs' (Fig. 6). The front of the sediment mantle became unstable, initially supplying small pulses of sediment to the stream resulting in a change in water colour. Eventually a larger rockfall began, before collapsing into a slide which generated debris flows downslope.

Each of the debris-flow events started with 'a rockfall phase' followed by 'a debris-flow phase'. This behaviour is due to the composition of the sediment mantle covering the Gleiðarhjalli bench, where the grain size varies from large boulders down to silt and clay. As the sediment front collapses, large volumes roll downslope, and much debris mixes into the meltwater creating a dense fluid (Fig. 7). Between these two phases the meltwater stream was almost emptied as the collapsed sediment in the uppermost part of the slope temporarily dammed the flow. Debris flows were observed in six individual channels, as shown on Fig. 8, but the main activity was concentrated in gullies no. 1 and no. 4. All these debris flows were of the type 'associated with gully erosion', where the flows 'strictly follow the pre-existing gullies' (Larsson 1982). The rockfall activity occurred over the whole slope.

Geomorphic impact

In the most active channels, the phases of rockfall and channelised debris flow were repeated several times, resulting in a series of sediment pulses. Table 1 documents the activity of debris flows in channels no. 1 and no. 4, which reached the foot of the slope. In debris flow no. 1, activity lasted almost 30 hours and up to 16 pulses were recorded; the spacing of the pulses was irregular and their maximum frequency was observed late in the evening of 11 June. The following day, pulses were of smaller volume. In debris flow no. 4, activity was less intense but lasted 36 hours, and only five pulses were recorded, with long and irregular spaces in between. Debris flows in channels no. 5 and no. 6 occurred during the nights of 10 and 11 June and, although not fully observed, debris flow no. 6 was recorded on the morning of 11 June when it obstructed the main road. Debris flows in channels no. 2 and no. 3 were smaller. They contained fewer boulders and had a larger proportion of gravel- to clay-size material. The trails of these flows were visible on 11 June. In general, the progress of the events, especially the occurrence of pulses within the larger debris flows, was similar to the observations witnessed during debris flows in Longyeardalen, Spitsbergen, in July 1972 (Larsson 1982). The main difference was that in the present example the flow was strictly limited to pre-existing channels and the runoff originated from snowmelt rather than rainfall.

During this debris-flow event significant amounts of boulders, blocks, gravel and matrix sediment were transported from the Gleiðarhjalli bench down the talus slope. The importance of the material deposited during the June 1999 event is obvious when compared to previous debris-flow features measured in the area. All the previous channels were widened and deepened, and the le-

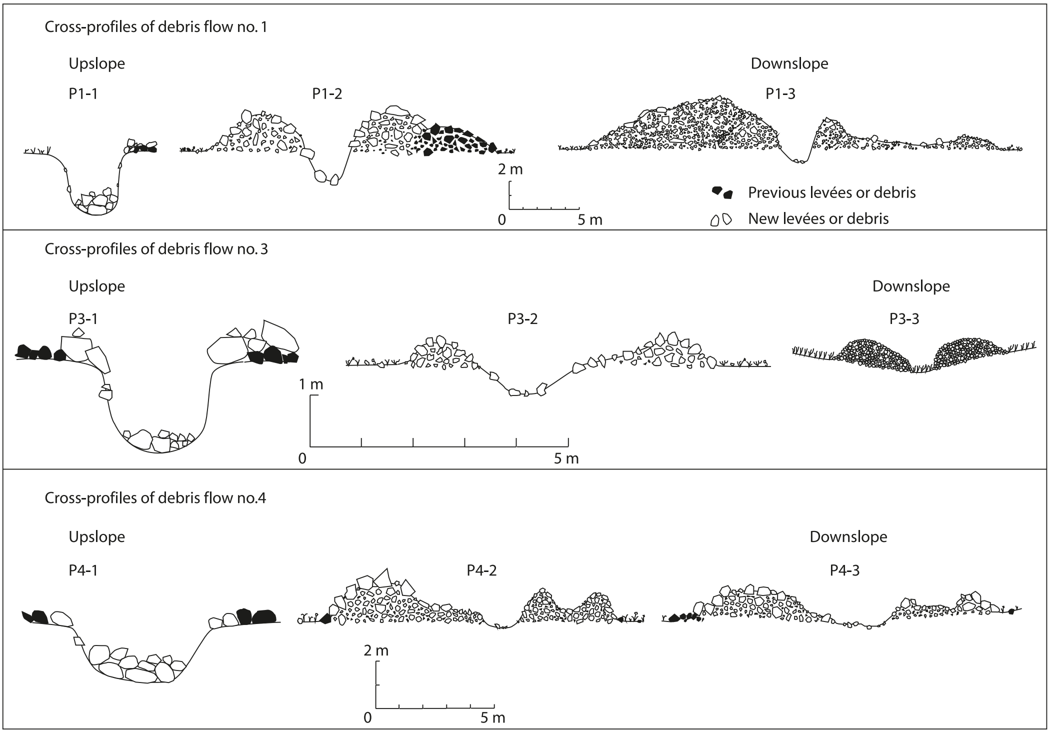

Fig. 9. Cross-profiles from channels nos 1, 3 and 4, showing the geomorphic impacts of the debris flows and the associated erosional and depositional landforms

Table 2. Dimensions of the debris-flow features in the Gleiðarhjalli area

(A) *Before the June 1999 event*					
Nos.	Debris-flow length (m)	Debris-flow width (m)	Channel width (m)	Channel depth (m)	
1	350	5 to 12	1 to 4	0.5 to 3.5	
2	300	1 to 3	0.4 to 1	0.1 to 1.5	
3	370	1 to 4	1	0.1 to 1.5	
4	380	4 to 10	1 to 3	0.7 to 3.5	
5	380	2 to 8	1 to 3	0.5 to 2	
6	420	6 to 16	0.5 to 6	2 to 3.5	
(B) *After the June 1999 event*					
Nos.	Debris-flow length (m)	Debris-flow width (m)	Channel width (m)	Channel depth(m)	Estimated volume (m^3)
1	380	6 to 70	4 to 8	1.5 to 5	3000
2	350	2 to 4	0.5 to 1	0.2 to 1	100
3	390	1 to 5.5	0.5 to 2	0.2 to 1.5	100
4	380	6 to 30	3 to 5	1.5 to 4	1000
5	400	4 to 15	2 to 4	1 to 3	800
6	420	6 to 16	3 to 6	2 to 3.5	1000

Fig. 10. Erosional and depositional landforms in middle and lower sections of debris flow no. 1 (photo A. Decaulne)

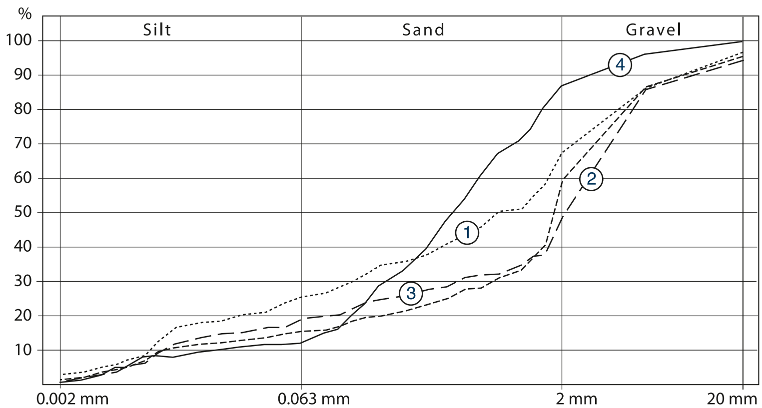

Fig. 11. Grain-size curves of fine matrix sediment collected in debris-flow channels nos 1, 2, 3 and 4

vées were widened and thickened (Table 2). From the estimated volumes ranging from 70 to 3000 m^3, the debris flows can be classified as medium scale (debris flows in channels nos 1, 4, 5 and 6) and small scale (debris flows in channels nos 2 and 3), using the nomenclature of Innes (1983).

Figure 9 illustrates cross-profiles of debris flows in channels nos 1, 3 and 4, showing the topographic changes resulting from the event (see Fig. 8 for locations of the measured cross-profiles). The geomorphic impacts of the debris flows are greatest in the uppermost part of the flow track where there is incision (Decaulne and Sæmundsson 2005). This short section of incision (about 50–70 m long) is visible on each debris flow (P1–1, P3–1 and P4–1) and reaches 5 m in debris flow no. 1. In some cases the bottom of the channel was congested with large boulders, deposited in the last pulses of the flow which failed to reach the bottom of the slope. Parallel levées characterise the middle parts of the flows. This middle section has the greatest length (250–370 m) and shows an asymmetric cross-section. The debris flow follows the track of a previously eroded channel between levées that act as natural walls. The material of the levées settles preferentially on one or other side of the channel (P1–2, P3–2 and P4–2). Therefore in this section of the flow the track is characterised by both erosional and depositional forms (Fig. 10). In the final third of the flow track the mean slope angle is lower than 15°, thus debris-flow speed decreases and material is spread on the slope surface rather than dissecting it. Here, debris flows are wider, with uneven and asymmetric levées bordering a channel that is only slightly dissecting the slope surface (P1–3, P3–3 and P4–3), hence accumulation landforms dominate.

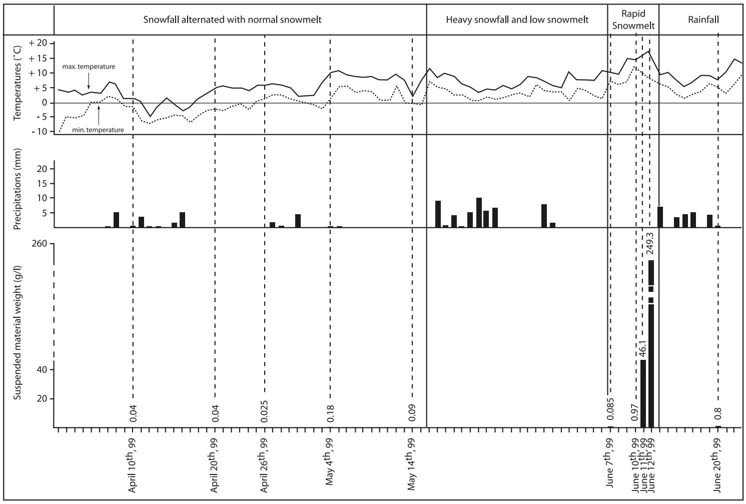

Fig. 12. Suspended sediment transport in channel no. 4 from April to June 1999, underlining the role of debris flows in fine material transport

Fig. 13. The suspended sediment plume from the debris flows entering Skutulsfjörður fjord (photo A. Decaulne)

Matrix sediment samples taken in the main axis of debris-flow channels nos 1, 2, 3 and 4 were analysed (Fig. 11). Coarse sediments dominate the deposits. The skewness index is strongly positive and sorting is poor, as shown by the Krumbein and Trask index (Table 3). Moreover, finer material represents from 10 to 30% of the sample, giving the flow its dense and thick properties, and is non-cohesive and granular.

Sampling of the suspended sediment transport in channel no. 4 during the peak of debris-flow activity shows that the fluvial sediment load of the flow after the pulse of debris was close to 300 g/l. Other sampling collected during this period showed values of more than 40 g/l (Decaulne 2001b). It appears that the concentration of suspended sediment is closely associated with weather conditions: fol-

Table 3. Sedimentological characteristics of samples from debris-flow channels

no. Channel	Skewness index	Krumbein index	Trask index
1	3.7	1.18	2.1
2	0.67	1.35	2.09
3	1.01	1.65	3.87
4	10.9	0.54	2.71

Table 4. Documented occurrence of debris flow in the Isafjorður area

Channels	Date of the event	Volume of material transferred in the debris flow (m^3)
1	1965	800
2	1977	400
3	1943, 1965, 1996	1000, 800, 3000
4	1943, 1999	3000, 3000
5	1943, 1977	2000, 800
6	1951, 1965, 1998, 1998, 1999	100, 100, 100, 100, 100
7	1999	500
8	1983, 1987	600, 500
9	1934, 1965, 1996, 1999	3000, 1000, 1000, 1000
10	1996	700
11	1996	700
12	1955, 1965, 1977, 1987	1500, 1500, 1500, 1500
13	1955, 1977, 1987	800, 800, 800
14	1955, 1977, 1987, 1999	1500, 1500, 1500, 1500
15	1955, 1977	1500, 1500
16	1955, 1977	1500, 1500
	20th century	44 700 m^3

lowing 'normal' snowmelt concentrations of 0.2 g/l during the winter are typical; similarly following rainfall concentrations of 1 g/l are common, but heavy snowfall followed by rapid snowmelt produces by far the highest values (Fig. 12). A large part of this sediment load reached the sea through drainage lines as streamload, and is clearly seen in the colour of the sea water (Fig. 13). When compared with other results, these suspended sediment concentrations, studied for the debris-flow event in Gleiðarhjalli, are more than 75 times those reported by Jonasson and Nyberg (1999) in the Abisko area, north Sweden, where the concentration exceeded 4 g/l in the Abiskojokka river. In that study the surroundings were affected by rapid mass movements released during a heavy rainstorm.

The geomorphic impact of these particular debris flows was assessed upon the calculation of the volume of debris transported in the flows. Given the catchment area of 4.5 km^2 and a total volume of material estimated at 6000 m^3, the average denudation rate is about 1.3 mm, or 0.29 mm/km^2. As debris-flow events have occurred several times since 1934 in the area (Table 4), resulting in the transport of approximately 45 000 m^3 of material, the long-term average denudation rate in the Gleiðarhjalli area is estimated at 10 mm over the 20th century. This calculation is based on geomorphic evidence of the preserved deposits and does not take account of the fine sediment transported in the flow, therefore it is a minimum estimate.

Table 5. Classification of debris-flow generations recognized by lichenometry, based on average size of the five largest lichen thalli of *Rhizocarpon geographicum* (mm)

Generations	Debris flow no. 1	Debris flow no. 3	Debris flow no. 4
A	–	2	–
B	5	5	5
C	–	–	8
D	10	10	10
E	15	15	–
F	20	–	–
G		Not measurable	

Previous debris-flow deposits are covered by patchy pioneer vegetation of flowers, grass and moss in the channel (*Alchemilla alpina*, *Taraxacum* sp. and *Pilosella islandica*, *Carex* sp., *Equisetum* sp. and *Rhacomitrium lanuginosum*). Vegetation on the levées is mainly composed of lichens such as *Umbilicaria* sp. and *Rhizocarpon geographicum*, among others. Vegetation is an indicator of the stability and age of the deposits, and the lichen *Rhizocarpon geographicum* is well-known as a useful indicator of the relative age of the substrate (Nyberg 1985; Evans *et al*. 1999). By using lichen measurements on the Gleiðarhjalli area, at least seven generations of debris flows were distinguished along channels nos 1, 3 and 4 (Table 5), ranging from recent debris-flow events, with small lichens, to older material with degraded non-measurable thalli of *Rhizocarpon geographicum* (lichen species competing on the rocky surface). Chronological control of the measured diameters of the lichen thalli was

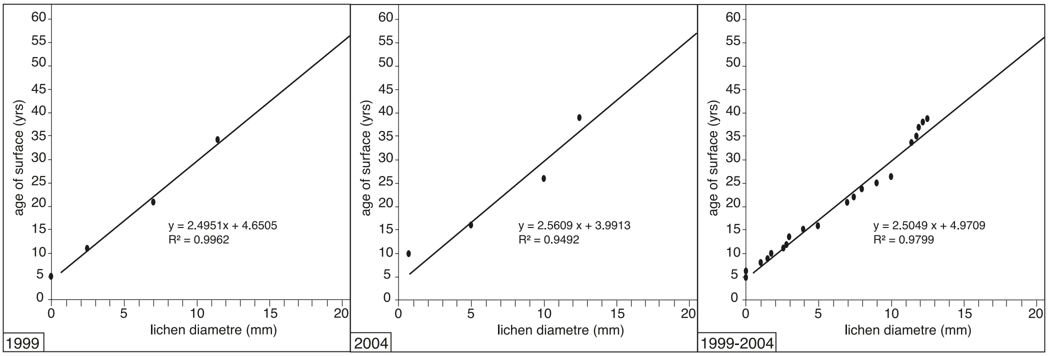

Fig. 14. The construction of the lichen growth curve from *Rhizocarpon geographicum* species, in the Gleiðarhjalli area

provided through the direct observation of four large boulders that fell downslope in 1965, 1978, 1988 and 1994. On the surface of these well-dated boulders, diameters of *Rhizocarpon geographicum* thalli are measured from August 1999 onwards, providing direct evidence of the lichen growth rates.

A lichenometric growth curve is drawn for the Gleiðarhjalli area (Fig. 14). The new curve illustrates the short span of time that is required for the appearance of the first measurable lichen thallus, which is only seven years for the study area. This indicates that there have been several debris flows of small and medium magnitude in the Gleiðarhjalli area during the last 50 years which were not documented in records. From Table 6, it is clear that the lichenometric data provide important historical evidence, even though the lichen growth curve still needs further refinement to be used as a dating technique for the Gleiðarhjalli area. According to the lichen measurements in channels nos 1, 3 and 4, indications of debris-flow activity were observed in the years 1958, 1972, 1976 and 1983, when large debris-flow events occurred in the Gleiðarhjalli area while the historical reports do not mention activity in those channels.

Impact on community

The 1999 debris flows caused substantial damage and major inconvenience to town life in Ísafjörður but did not result in loss of life. Debris flow in channel no. 5 passed over the main road, and debris flows in channels nos 1, 3 and 4 were stopped just 10 m above the uppermost houses by the artificial drainage ditches. Nevertheless, water and fine-grained material flooded into gardens, sewer systems and roads (Fig. 6). In order to protect residents, 48 homes were evacuated on the night of 11 June. Five gardens were damaged by the flows, and cellars in the uppermost houses were flooded. The uppermost streets down towards the sea (Urðarvegur, Seljalandsvegur and Vallartún) were covered by debris and a large part of the sewer system was damaged.

Even though the artificial drainage channels caught part of the debris-flow material, at least 16 houses were directly threatened by the two largest debris flows (nos 1 and 4) during the event. The drainage system was almost filled by the first pulses, which came down on 10 June at 22:00 hours in channel no. 4 and at 23:30 hours in channel no. 1. The artificial drainage ditches were emptied by a

Table. 6. Correspondence between lichenometric and historic data in the Gleiðarhjalli area (modified from Decaulne and Sæmundsson 2003)

Debris-flow channel no. 1		Debris-flow channel no. 3		Debris-flow channel no. 4	
Historical records	Lichenometric data	Historical records	Lichenometric data	Historical records	Lichenometric data
1943	1976				
	1964				
	1952				
	1942	No records	1983	1965	1976
				1934	1964

Table. 7. Return periods of large debris-flow events in Arctic and Subarctic environment

Location	Return period (yrs)	Reference
Iceland (NW)	4 to >20	This study
Spitsbergen	80 – 500	André, (1990)
Scandinavia	20 – 300	Rapp, (1987)
Swedish Lappland	5 – 400	Rapp and Nyberg, (1981)
Swedish Lappland	200 – 300	Nyberg, (1985)

mechanical digger while the second pulses arrived and started to overflow roads, almost avoiding catastrophic damage (Decaulne 2001a, 2002).

Discussion

This case study provides an example of debris flows triggered primarily by snowmelt. This is not an isolated incident in Iceland and several similar cases were observed in northwestern Iceland during the spring of 1983, 1987 and 1991, and throughout the northern part of the country during the spring of 1995 (Sæmundsson *et al*. 2003). However, snowmelt is not the only triggering mechanism in the Gleiðarhjalli area. Sæmundsson and Pétursson (1999) recorded various debris flows triggered by rainfall, partly by long-lasting (1942, 1943, 1956 and 1996) and partly by heavy events (1936, 1965, 1977). In the Gleiðarhjalli area, debris flows can be released during all seasons. Rapid snowmelt may have occurred in January (e.g. 1972) and in December (e.g. 1991) as well as in June (1934, 1983, 1999). Heavy or long-lasting rainfall may have occurred all year round, triggering debris flows in January (e.g. 1935), April (e.g. 1955), August (e.g. 1936) and September (e.g. 1943, 1969, 1996).

The debris-flow frequency in the Gleiðarhjalli area during the last century is uncertain due to lack of documents and incomplete lichenometric data. Field observations can determine short return period events (a few months) of low magnitude (<100 m^3): observations were made of a debris flow of 30 m^3 released by snowmelt in May 1998 and another one of 50 m^3 was released after a long period of rainfall in the same channel in August 1998 (Decaulne 2001b). The lichenometric observations have been useful in filling gaps in historical records, even though more observations of the lichen growth rates are required to improve regional relationships. The limitations of lichenometry are that debris-flow deposits of large magnitude tend to bury the landforms of previous events, and short time events cannot be readily distinguished.

Historical records in the actual area show at least 20 debris-flow events that have threatened properties and human lives in the area during the last century (Sæmundsson and Pétursson 1999); most reported events are of large magnitude, and the historical data largely ignore events that do not reach inhabited areas or cause damage to communities. Nevertheless, a combination of fieldwork, historical and lichenometric methods offers an approach that can be used to estimate the debris-flow return periods. For instance, one debris-flow event is triggered in the Gleiðarhjalli area every 4–5 years on average (Decaulne and Sæmundsson 2003). This estimated return period is even shorter when considering the total number of recorded debris flows (i.e. all the active paths, whether they have been dated or not). At least 110 debris flows were triggered during the last 104 years in 24 events; the debris-flow return period is less than 1 year (Decaulne 2004). The calculation of debris-flow return periods according to magnitude gives more useful results and strongly suggests a longer return period as the debris-flow volume increases: the return period is 4.1 years for debris flows carrying 500 m^3 or less; 5.5 years for debris flows of 1000 m^3 or more (reaching the foot of the slope, i.e. the first houses); and 20 years for flows of more than 1500 m^3 (Decaulne and Sæmundsson 2003). These return periods are substantially shorter than those reported from other arctic and sub-arctic regions where the usual range is from 20 to 500 years (Table 7).

Conclusions

The strong geomorphic impact of debris flow in the Gleiðarhjalli area, northwestern Iceland, is the result of two main factors. Firstly, the geomorphological setting is characterized by a bench of impermeable basaltic bedrock covered with a thick debris mantle. Secondly, the rapidly changeable weather conditions of both polar and Atlantic origin bring both heavy and long periods of rain or snowfall, and temperature changes that induce rapid snowmelt and strong uncontrolled discharge. The estimated debris-flow frequency in the area is very high, with one debris-flow event reaching the bottom of the slope every 5 years. High frequency of occurrence and strong geomorphic impact, and the sensitivity to sudden runoff, means that the debris-flow activity in this region represents a relevant threat to the local inhabitants. The danger is mainly due to the location of the settlement on a narrow tract of land between a steep rockwall and the sea, and has significantly increased through the last century (Decaulne 2004, 2005a, b). However, geomorphological studies can help the local population in evaluating risks, planning remedial measures and developing warning signs for debris-flow events, e.g. increasing turbidity in the streamflow and rockfall activity. Moreover, case studies of the present kind can supply substantial advice for the location of constructions that are likely to divert the most dangerous debris flows from the settlements.

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