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The triggering factors of the Móafellshyrna debris slide in northern Iceland: Intense precipitation, earthquake activity and thawing of mountain permafrost

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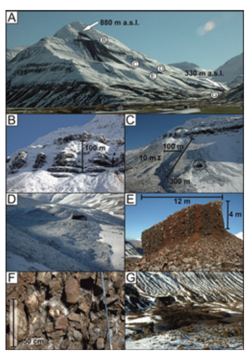
HIGHLIGHTS

- Intense precipitation, earthquake activity and thawing of mountain permafrost may have contributed to the slide
- The presence of ice-cemented blocks show that thawing of ground ice may have played an important role as a triggering factor
- The knowledge of the detailed distribution of mountain permafrost in Iceland is poorly constrained.
- The slide shows indications of degrading of discontinuous permafrost in Iceland

GRAPHICAL ABSTRACT



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ABSTRACT

On the 20th September 2012, a large debris slide occurred in the Móafellshyrna Mountain in the Tröllaskagi peninsula, central north Iceland. Our work describes and discusses the relative importance of the three factors that may have contributed to the failure of the slope: intense precipitation, earthquake activity and thawing of ground ice. We use data from weather stations, seismometers, witness reports and field observations to examine these factors. The slide initiated after an unusually warm and dry summer followed by a month of heavy precipitation. Furthermore, the slide occurred after three seismic episodes, whose epicentres were located ~60 km NNE of Móafellshyrna Mountain. The main source of material for the slide was ice-rich colluvium perched on a topographic bench. Blocks of ice-cemented colluvium slid and then broke off the frontal part of the talus slope, and the landslide also involved a component of debris slide, which mobilized around 312,000–480,000 m^3 (as estimated from field data and aerial images of erosional morphologies). From our analysis we infer that intense precipitation and seismic activity prior to the slide are the main preparatory factors for the slide. The presence of ice-cemented blocks in the slide's deposits leads us to infer that deep thawing of ground ice was likely the final triggering factor. Ice-cemented blocks of debris have been observed in the deposits of two other recent landslides in northern Iceland, in the Torfufell Mountain and the Árnesfjall Mountain. This suggests that discontinuous mountain permafrost is degrading in Iceland, consistent with the decadal trend of increasing atmospheric temperature in Iceland. This study highlights a newly identified hazard in Iceland: landslides as a result of ground ice thaw.

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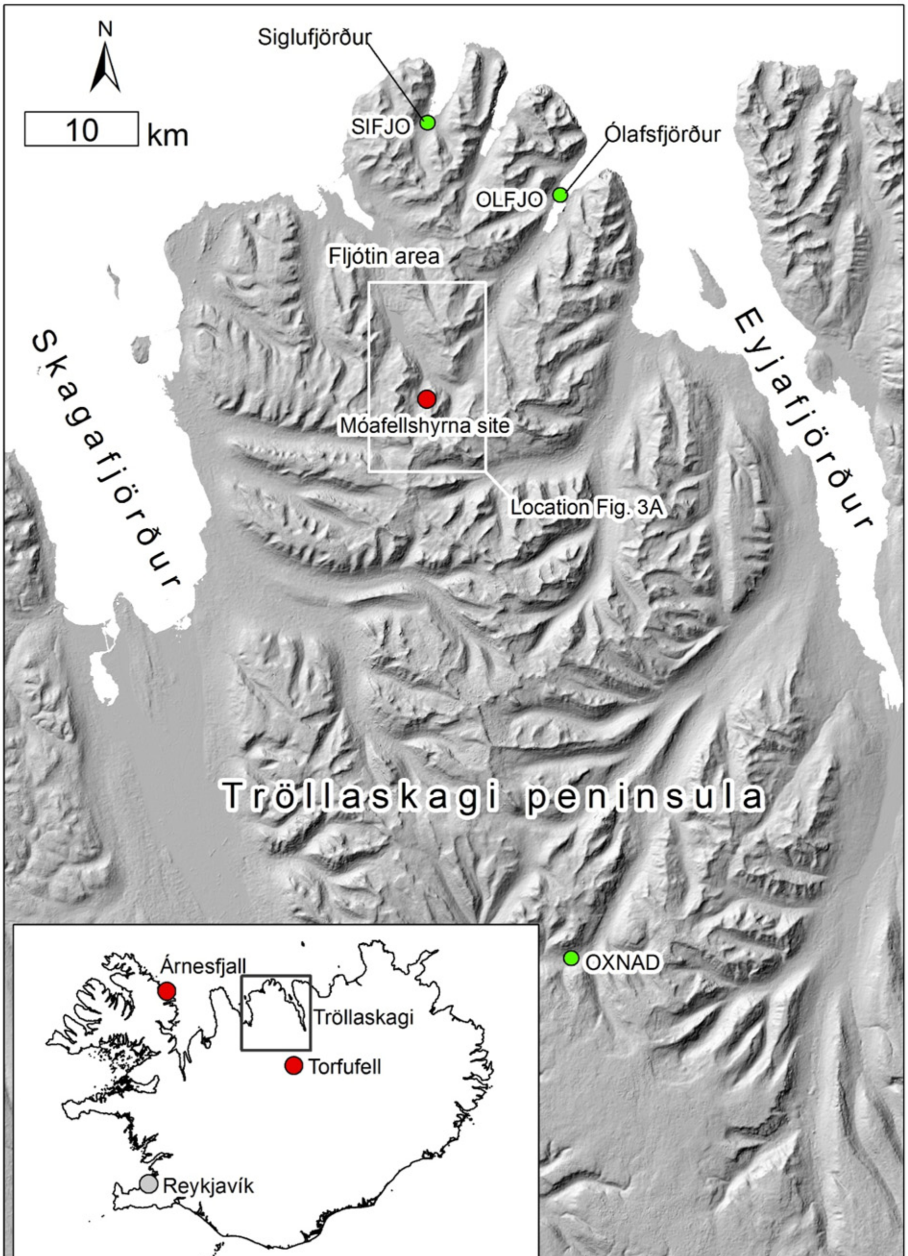
Knowledge of the detailed distribution of mountain permafrost in colluvium on the island is poorly constrained and should be a priority for future research in order to identify zones at risk from this hazard.

1. Introduction

On the 20th September 2012, the local residents of the Þrasastaðir farm in the Fljótin area (Tröllaskagi peninsula, central north Iceland; Figs. 1, 3), heard a loud rumbling noise coming from the Móafellshyrna Mountain, as a large debris slide descended the north-western side of the mountain (Fig. 3). Nine days after the failure, we observed large blocks of ice-cemented deposits within the debris slide deposits.



Station name	Station ID	Altitude	Years analysed	Precipitation	Temperature
Siglufjörður	SIFJO	6.0 m a.s.l.	2012	X	X
Öxnadalsheiði	OXNAD	540.0 m a.s.l.	2005 - 2012	-	X
Ólafsfjörður	OLFJO	5.0 m a.s.l.	2000 - 2012	X	X

Fig. 1. The Móafellshyrna site, located in the Tröllaskagi peninsula, northern Iceland (see Fig. 3 for detailed location), and the location of the weather stations used for this study. The hillshaded digital elevation model used as a basis of this map is from the Digital Elevation Model over Europe (EU-DEM) from the Global Monitoring for Environment and Security service for geospatial reference data access project (GMES RDA). The table provides details on the Icelandic Meteorological Office weather stations, whose datasets have been used for this study. Symbols “X” and “-“mean that data are or are not available at the stations, respectively.

Rapid mass movements, including rock falls, rock avalanches, debris flows and debris slides, are common geomorphological processes in Iceland and present a significant and direct threat to many towns, villages and farmhouses (Decaulne, 2005, 2007). Precipitation, snow melt, temperature variations and earthquake activity are the most common triggering factors for landslides in Iceland (Sæmundsson et al., 2003; Sæmundsson and Decaulne, 2007; Decaulne and Sæmundsson, 2007). However, during the last decade, three, somewhat unusual, rapid mass movements have occurred in northern Iceland: on the Torfufell Mountain (Eyjafjörður valley, central north Iceland) on 14th October 2011, on the Móafellshyrna Mountain on 20th September 2012 (case study of this paper), and on the Árnesfjall Mountain (Westfjords) on 10th July 2014 (Sæmundsson et al., 2013; Sæmundsson et al., 2014a, 2014b). In all these landslides ice-cemented debris was found within the deposits, a phenomenon that has never been reported previously in Iceland. The source areas of these slides are all located on steep (~45–60°) NW to NE facing-slopes, where discontinuous permafrost might be expected (e.g. Gorbunov, 1988; King, 1986). The source areas at Torfufell and Móafellshyrna are located at elevations of 750–870 m a.s.l., within the zone of discontinuous permafrost in Iceland as calculated by Etzelmüller et al. (2007a), whereas at Árnesfjall the source area is located at about 400 m a.s.l., which is much lower altitude than ever observed for mountain permafrost in Iceland (Etzelmüller et al., 2007a). Intense precipitation was recorded prior to all of these slides (Sæmundsson et al., 2013; Sæmundsson et al., 2014a, 2014b). In this paper, we present the case study of the Móafellshyrna debris slide, where we examine three factors could have contributed to this failure: intense precipitation, earthquake activity and ground-ice degradation (via increased annual temperatures). We emphasise the field evidence of ground ice-thaw, because permafrost degradation has never previously been considered as a triggering factor for gravitational mass movements in Iceland, although permafrost degradation is considered to be an preparatory factor for paraglacial slope failure (McColl, 2012).

In the following sections we describe a) the state of knowledge of permafrost in Iceland, b) seismic conditions in Iceland and their role in previous mass wasting events, c) general meteorological conditions in Iceland. We then report our results, reconstructing the conditions that favoured the occurrence of the landslide. We then discuss our results, dividing the factors that induced the landslide into, i) preparatory and ii) triggering (as per McColl, 2012). We finally posit that Móafellshyrna landslide was preconditioned by combination of intense precipitation in the weeks prior to the slide and the seismic activity on 18th and 19th September and that the degradation of ground-ice was the final trigger.

1.1. Permafrost distribution in Iceland

During the last decade our knowledge of the regional distribution of permafrost in Iceland has increased considerably (e.g. Etzelmüller et al., 2007a, 2007b; Farbrot et al., 2007a, 2007b; Kellere-Pirklbauer et al., 2007; Lilleören et al., 2013; Kneisel et al., 2007; Kneisel, 2010). There are several published works on permafrost in the central highlands of Iceland dating back to the 1950s, and these studies focused on geomorphological features, such as palsas and patterned ground (e.g., Thorarinsson, 1951, 1964; Friedman et al., 1971; Schunke, 1974; Stingl and Herrmann, 1976; Priesnitz and Schunke, 1978; Hirakawa, 1986; Thorhallsdottir, 1994, 1996, 1997; Sæmundsson et al., 2012). These works both mapped permafrost conditions and a recent study at the Orravatnsrústir palsa site, NE of the Hofsjökull ice cap, showed clear indications of declining permafrost conditions from 2000 to 2010 in the highlands (Sæmundsson et al., 2012). Studies have also sought to better define the spatial distribution of mountain permafrost in Iceland. Such studies used inventories of rock glaciers and stable ice-corded moraines combined with meteorological data analyses (e.g., Etzelmüller et al., 2007a, b; Farbrot et al., 2007a, b; Kellere-Pirklbauer et al., 2007; Lilleören et al., 2013) and Electrical Resistivity Tomography (e.g., Kneisel et al., 2007; Kneisel, 2010; Sæmundsson et al., 2012). These works did not comment on the dynamics of the permafrost.

Etzelmüller et al. (2007a) published the first regional distribution map of mountain permafrost in Iceland. This was the first attempt to understand the overall extent of mountain permafrost on the island. The map was based on a model which used meteorological data calibrated with ground surface temperature data and validated using ground temperature data from four shallow boreholes and an inventory of rock glaciers. According to Etzelmüller et al. (2007a), mountain permafrost is widespread in the northern and eastern Iceland above 800–900 m, covering 8% of the island, or around 8.000 km^2.

A warming trend in atmospheric temperature has been observed in Iceland over the last two centuries. In Stykkishólmur in western Iceland records show an increase of about 0.7 °C per century (Nawri and Björnsson, 2010; Jónsson, 2008). From 1975 to 2008 the warming rate was much higher or about 0.35 °C per decade (Ministry for the Environment of Iceland, 2010). However, so far relatively little attention has been paid to the consequences of the recent climate change on the possible degradation of mountain permafrost in Iceland.

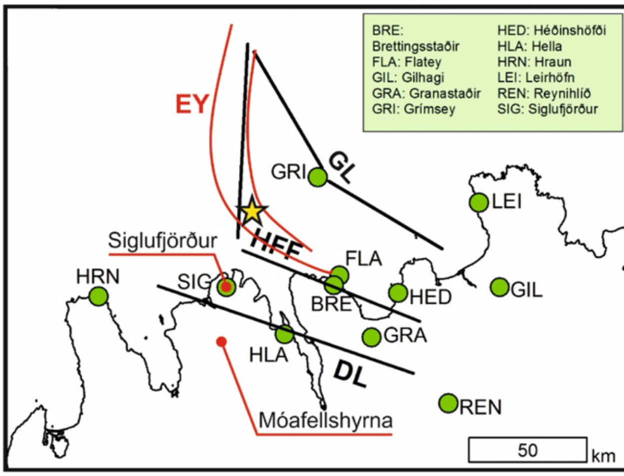
1.2. Seismic activity in northern Iceland

The seismic activity in Iceland is related to its position on the Mid-Atlantic plate boundary, which crosses the island and its location over the Icelandic Hotspot (e.g. Tryggvason et al., 1983; Wolfe et al., 1997; Allen et al., 2002; Bjarnason, 2008; Einarsson, 2008; Thordarson and Hoskuldsson, 2002). The seismic activity in the northernmost region of the island is related to the Tjörnes Fracture Zone (Einarsson and Björnsson, 1979; Sæmundsson, 1974), which is defined by three seismically active lineaments - the Grímsey Oblique Rift, the Húsavík Flatey Fault and the Dalvík lineament; (e.g., Sæmundsson, 1974; Gudmundsson, 2000, 2006) - and includes the Eyjafjarðaráll N-S extensional graben, located north offshore the Tröllaskagi peninsula (Fig. 2). It was activity on this fault system which caused the earthquakes prior to the Móafellshyrna slide.

Earthquakes are known to have triggered landslide and rockfall activity in Iceland in the past (e.g. Jónsson, 1957; Jónsson and Pétursson, 1992; Thorarinsson, 1937; Thorarinsson et al., 1959; Halldórsson, 1984; Jensen, 2000; Sæmundsson et al., 2003; Ágústsson and Pétursson, 2013), but no study has explored in detail the influence of earthquake activity as a preparatory and/or triggering factor on rockfall or landslides in Iceland, as has been done elsewhere in the world (e.g., Harp and Jibson, 1996; Yin et al., 2009). The above mentioned Icelandic studies relate mass movements to larger earthquakes than those prior to the slide in Móafellshyrna, e.g. in June 2000, when two earthquakes of magnitude 6.4 occurred in Iceland, with the epicentre in the middle of the southern lowlands. Rockfall activity was reported as a result of this event as far as 75 km from the epicentre (Sæmundsson et al., 2003).

1.3. General weather conditions in Iceland

Weather patterns in Iceland are highly variable, with frequent and strong variation in precipitation and temperature; this is mainly because Iceland is located on the main path taken by North Atlantic low-pressure systems (Einarsson, 1984). The mean annual air temperature for the period 1971–2000 was 4–5 °C in the south, 3–4 °C in the east and west and 2–3 °C in northern coastal parts of the country (Tveito et al., 2000). Hence precipitation can fall as both snow and rain. The two main dominant precipitation wind direction in the Tröllaskagi area are NE and SW (Brynjólfsson and Ólafsson, 2008; Arnalds et al., 2001). The precipitation is heaviest during strong NE winds. Consequently, mean annual precipitation increases from about 500–1000 mm per year in the central and northern parts of the country to more than 3000 mm/yr in the southeast (Crochet et al., 2007). During the winter months from October to April the precipitation in the outer part of the Tröllaskagi peninsula is almost exclusive snow or sleet and



Earthquakes	
Time	Magnitude (Richter scale)
19th September 2012, 7.57 am	M 4.5
19th September 2012, 8.28 am	M 4.3
20th September 2012, 9.27 am	M 4.2

Fig. 2. The structural elements of the Tjörnes Fracture Zone marked in black (Grímsey lineament (GOR), Húsavík-Flatey fault (HFF) and Dalvík lineament (DL); from Stefánsson et al., 2008) and the Eyjafjarðaráll graben marked in red (EY); the position of the epicentre zone for the earthquakes preceding the Móafellshyrna slide is marked with a yellow star, the Icelandic Meteorological Office (IMO) seismometers in the area marked with the green dots and the labels refer to their abbreviated names, as given in full in the key. On the right are reported the timing and magnitude of the earthquake sequence in the Eyjafjarðaráll graben from 19th to 20th September 2012.
(from Gudmundsson et al., 2014)

the main part of the snow avalanche activity is associated with strong north-easterly wind. The northern part of Tröllaskagi peninsula is generally a heavy snow prone area and Siglufjörður and Fljótin area are generally considered to be one of the heaviest snow prone areas in Iceland (Arnalds et al., 2001).

2. Geographic and geologic setting of Móafellshyrna

The Tröllaskagi peninsula is a mountain massif located between the Eyjafjörður fjord in the east and the Skagafjörður fjord in the west (Fig. 1). The peninsula is topped by flat summits reaching up to 1000–1500 m a.s.l. and sculptured by glacial erosion with glacially carved fjords, valleys and cirques. Such over-steepened landscapes are recognised as one of the key pre-conditioning factors for failures (McColl, 2012). Over 150 alpine glaciers, mainly north facing, have been mapped in this massif (Sigurðsson and Williams, 2008).

The bedrock in the outermost part of the Tröllaskagi peninsula falls within the Tertiary basalt series (16–3.3 M years; e.g., Moorbath et al., 1968; McDougall et al., 1984; Watkins and Walker, 1977). This series is mostly jointed basaltic lava flows, composed of 2 to 30 m thick individual flows separated by lithified sedimentary horizons (from few centimetres up to tenths of meters thick) (Sæmundsson, 1979; Sæmundsson et al., 1980). The bedrock is heavily jointed and intersected by dikes, and the general dip angle of the lava beds is towards the southwest (Sæmundsson et al., 1980; Johannesson and Sæmundsson, 2009; Hjartarson and Sæmundsson, 2014).

The Tröllaskagi peninsula is located on the main path of the North Atlantic low pressure system, with a variable and turbulent weather. Winters are long and mild and summers brief and cool (Einarsson, 1984). The Mean Annual Air Temperature (MAAT) for the period 1971–2000 was 2–3 °C in the northern coastal areas (Tveito et al., 2000; Crochet et al., 2007). The data series for the Tröllaskagi area between 1940 and 1970 show MAAT of 2–4 °C in the coastal areas and −2 to −4 °C at the summits (Einarsson, 1984). According to Crochet et al. (2007), the annual precipitation from 1971 to 2000 in the Tröllaskagi area varies from 1000 to 1500 mm in the coastal lowlands up to 2000–2500 mm on the summits. Localised orographic effects mean that in the Tröllaskagi peninsula precipitation is higher near the coastline when there are northerly winds (Brynjólfsson and Ólafsson, 2008). Conversely, the precipitation is likely to be higher in the lowlands in the interior of the Tröllaskagi peninsula area than at the coast during periods with southerly winds. In the mountains of the peninsular the orographic effect would also play a role during southerly winds precipitation may in fact be even higher at a higher elevation. According to Arnalds et al. (2001), more than half of the recorded precipitation in Siglufjörður occurs throughout the winter months (Oct–Apr), where the precipitation is almost exclusively snow or sleet. This can also be said about the rest of Tröllaskagi peninsula. Avalanches during winter months in Tröllaskagi peninsula can be associated with strong north-easterly winds with snowfall or snowfall during south-westerly winds associated with lower wind speed. Slush flows are not common in Tröllaskagi area.

The Móafellshyrna Mountain is located in the Fljótin area in the outermost part of the Tröllaskagi peninsula in central north Iceland (Figs. 1, 3). The mountain is 1044 m high, with narrow alpine-mountain ridge orientated in the north-south direction. It is located between the Móafellsdalur tributary valley in the west and the Hvarfdalur tributary valley in the east (Fig. 3). In the outermost part of the western valley side of Móafellsdalur are old remnants of a landslide that originated from the western mountain side. The age of these old landslide deposits is not known. Jónsson (1957, 1976) stated that the landslide activity in Iceland was most intense shortly after the last deglaciation. His statement has been confirmed by later studies (e.g. Jónsson et al., 2004; Sigurgeirsson and Hjartarson, 2011; Mercier et al., 2012, 2013; Coquin et al., 2015, 2016; Decaulne et al., 2016). The farm Þrasastaðir, the innermost inhabited farm in the Stífludalur valley, is situated on the northern side of the Stífludalur on the northern side of the Fljótaá River facing the Móafellshyrna mountain. The residents of the farm witnessed and observed the slide (Fig. 3) and their report is given in Section 4.1.

The landscape in the Fljótin area is predominantly carved by glacial erosion. The area was heavily glaciated during the maximum extent of the last glaciation, but the deglaciation history of the area is not well documented. Researchers suggest that the area was deglaciated in Early Preboreal times (e.g., Norðdahl and Pétursson, 2005; Norðdahl et al., 2008; Ingólfsson et al., 2010; Coquin et al., 2016). The upper part of the valley sides (up to 600–900 m a.s.l.) are often very steep, with fractured and loose bedrock produced by, erosion during deglaciation, unloading by the glacier, frost shattering and freeze-thaw processes, while the lower parts are more gentle and generally covered by glacial deposits or talus.

3. Methods

The triggering factors of the Móafellshyrna debris slide event in September 2012 were analysed using meteorological data from the

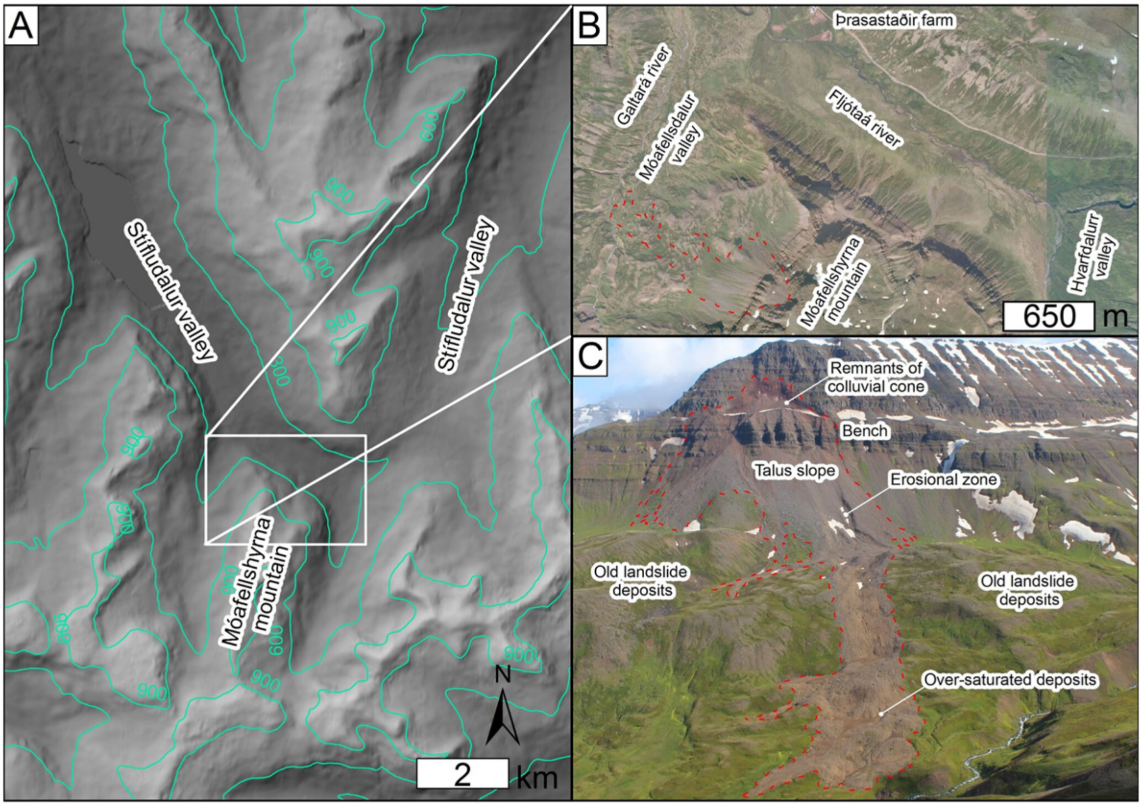


Fig. 3. Geographical setting of Móafellshyrna mountain (see Fig. 1 for location). (A) Hillshaded digital elevation model and contours (in green, metres above sea level) of the Móafellshyrna region. Elevation data are from EU-DEM from GMES RDA. (B) Aerial photograph of the Móafellshyrna site taken before the slide in 2012 from the website Samsyn. (C) Oblique photo of the Móafellshyrna debris slide in July 2015 taken by Costanza Morino. In panels B and C the perimeter of the slide is marked with red dashed line taken from the trimble data for the deposits and reconstructed from photographs for the upper part, in C this line has been manually traced onto the oblique image.

Icelandic Meteorological Office (IMO) for the three months prior to the slide and for the period 2010–2012. Data for the seismic activity of the north coast were also obtained from the IMO. We also interviewed the inhabitants of the valley and performed our own field investigations.

3.1. Meteorological data

Only two weather stations in the northern part of the Tröllaskagi peninsula measure precipitation, one located in the town of Siglufjörður at 6 m a.s.l. (35 km north of the site) and the other one in the town of Ólafsfjörður at 5 m a.s.l. (21 km northeast of the site). Three weather-stations were used for this study that collect temperature records: two operated by IMO - Siglufjörður (WMO (World Meteorological Organization) ID: 4157), Ólafsfjörður (WMO ID: 4155) and one station located at the Öxnadalsheiði highlands pass (WMO ID: 4859) at 540 m a.s.l. operated by the Icelandic Road and Coastal Administration (Fig. 1). A problem in our approach is that the majority of the stations used to establish mean atmospheric temperatures are located near the coast and therefore at low altitudes. This leads to a potential bias when evaluating trends in temperature, because such stations may not be representative of the atmospheric temperatures experienced in the highlands. To overcome this, we applied the environmental lapse rate of 0.649 °C per 100 m (Sheridan et al., 2010) to the mean temperatures recorded at all three stations as an estimate of the temperature at the source zone of the Móafellshyrna debris slide. We do not attempt to correct the precipitation data collected near the coast for the inland conditions, because this would not only require a temperature correction, but we would need to take into account variations in wind speed, wind direction and pressure in a meteorological model, which is beyond the scope of this paper.

3.2. Direct report from witnesses

The local residents of the farm Þrasastaðir witnessed the release of the landslide, and were interviewed on the day of the event regarding the earthquake activity prior to the slide, timing of the slide and the events that occurred during the first few hours of the slide. The slide was photographed by the first author only a few hours after it had occurred. Ongoing rockfall activity on the slope prohibited more detailed observations immediately after the event. It was not considered safe to perform field analysis until 29th September 2012, when direct observations and measurements were made. The site was revisited in summer 2015 to track changes in the slide.

3.3. Field measurements and survey

The boundary of the landslide body was mapped on the 29th June 2012 with Trimble GEOXT from the GeoExplorer CE series with an accuracy of 1–2 m. Thickness measurements of the slide were performed both with direct measurements in the field on 29th September 2012 and from aerial photographs and erosional and depositional features mapped. For geomorphological mapping both ground photographs and aerial photographs from the National Land Survey of Iceland (www.lmi.is) and Loftmyndir ehf (www.map.is) and the UK's Natural Environment Research Council Airborne Research and Survey Facility (NERC ARSF) flown in 2015 were used in concert with field observations. Landslide volume estimates were derived from morphometric properties of the deposits measured directly in the field and from aerial photographs.

4. Results

4.1. Witness report

The residents of the Þrasastaðir farm, located at the junction between the Móafellsdalur and the Stífludalur valleys and 1.7 km from the terminal deposits of the landslide (Fig. 3), were interviewed only few hours after the slide. They recounted that on the 20th of September 2012 at around 12:30 they heard a rumbling noise, which originated from the Móafellshyrna mountain. They also recounted that a black tension crack, in the snow covered mountain, progressively formed above the colluvial cone at around 850 m a.s.l. They saw large blocks of debris that broke off the frontal part of the cone and fell onto the talus slope below. This activity was most intense in the first 1–1.5 h, but they reported that there were intermittent noises and rock fall activity throughout the day.

The residents of the Þrasastaðir farm felt all the three earthquakes that occurred on the 19th and 20th September, with the last one only 3 h before the debris slide event. It was estimated that less than 1 m of snow was on the ground at the time of the slide.

4.2. The debris slide morphology

The debris slide detached from a main scarp at an elevation of 880 m a.s.l. (Fig. 4A). The source material of the landslide was a colluvial cone composed of talus deposits perched on a topographic bench at 790 m a.s.l. (Fig. 3C), and lying against a rockwall composed of lava and tephra layers of the Tertiary Basalt formation dipping less than 10° towards SSW. The colluvial material comprises a mixture of materials derived from the above rockwall (basalt with intercalated sediment layers) and under nominal conditions (with or without ice) should lie stable against the rockwall under the angle of repose.

The colluvial material partially slid off the steep rockwall ledge at the edge of the bench, as described by the local residents. From field observations and aerial photographs we estimate that the horizontal displacement in the upper part of the cone was around 40 m (Fig. 4A). Later observations revealed that the bedrock was exposed from beneath the colluvium as it slid (at the time of the slide it was hidden by a thin veneer of mud, which was later cleaned by rainfall). Part of the colluvial deposits remained perched on the topographic bench after the event (Fig. 3C, 4B). Based on field observation, we estimated that the thickness of the frontal part of the still ice-cemented colluvial cone that was preserved at the edge of the bench after the slide was around 20–30 m thick (Fig. 4B). As the colluvial cone slid off the rockwall edge, large blocks of ice-cemented debris broke off and fell onto the talus slope located below the topographic bench (Fig. 3C). Fig. 3B shows decametre-scale blocks of ice cemented colluvium that have remained on the bench. A 300 m long, 80–100 m wide and 8–10 m deep channel was carved into the talus slope deposits (Fig. 3C, 4C), entraining further material to the landslide. This channel shows that the landslide materials must already have been fluidised (saturated) in order to scour out this channel.

At 495–505 m a.s.l. at the foot of the talus slope, we observed that both loose muddy debris and blocks of ice-cemented deposits comprised the landslide deposits (Figs. 4C, D, E). We infer that these ice cemented blocks had fallen from the topographic bench, as they had the same aspect and size of those still perched in the source area (Fig. 4B). These blocks ranged from less than 1 m up to 12 m wide and from less than 1 m up to 10 m tall. The ice-cemented blocks were composed of layers of sand to boulder-size (up to 50 cm in long-axis) angular rock fragments (Fig. 4F), interbedded with layers composed of clay to sand-size materials. The red colour of the horizons of fine material (Fig. 4E) derives from the original source material, namely paleo-soils interbedded in the lava layers composing the Tertiary Basalt Formation. Nine days after the failure, from visual inspections we estimated a content of ground ice that was cementing the blocks of around 15–20% of the total volume (Fig. 4F), i.e. pore-filling ice, rather than excess ice. No massive ice deposits were observed.

Some of the landslide deposits came to rest below the talus slope at 495–505 m a.s.l. (Fig. 4D), where the average slope angle is less than 10°, but the rest traversed down the mountain slope, finally stopping at 330 m elevation (Fig. 4G), a few meters from the river Galtará draining the bottom of the valley (Fig. 3). The part of the material that continued down the mountain side is composed of clay to boulder-size material which followed a well-defined path with distinct lateral boundaries. The deposit boundaries are upstanding with 1–2 m of relief. The lack of sorting in the deposits, their lobate planform and their upstanding boundaries are consistent with this landslide being classed as a debris side transforming to a debris avalanche from the Hungr et al. (2001, 2014) classification, i.e. loose debris fluidised by the inclusion of water exceeding the pore-space (Iverson, 1997) without a well-defined central channel and generally shallow motion. This shows that water volumes of 20–40% of the final deposits were required to mobilise this flow and that it was not a dry rock avalanche.

Based on aerial photographs the dimensions of the upper colluvial cone perched on the bench was around 80 m in height and around 150 m wide at the lower end prior to the slide. Based on photographs taken after the slide the total movement of the cone was estimated around 40 m and the frontal part of the cone perched on the bench was 150 m wide and about 20–30 m thick (Fig. 4B). Based on these dimensions we estimated that the volume of the deposits that broke off the frontal part of the cone and fell down onto the lower talus had a volume up to ~120,000–180,000 m^3. From the dimensions of the channel carved into the lower talus on the southern side of the slide (with 80–100 m, depth 8–10 m, length 300 m) (Fig. 4C) we calculated that an additional volume of ~192,000–300,000 m^3 of material was mobilized. Combining these volumes gives an estimate of the total volume of material mobilized in the event of 312,000–480,000 m^3. From GPS measurements the areal extent of the landslide is ~0.3 km^2, giving an average depth of deposits of 1–2 m, consistent with our direct observations of thickness at the deposit-boundaries.

4.3. Antecedent conditions

4.3.1. Precipitation

The spring and summer months preceding the Móafellshyrna event were dry, and the autumn was unusually wet (Figs. 5, 6) (Jónsson, 2013). From April until 28th August 2012, dry conditions prevailed in the outer part of the Tröllaskagi peninsula, with only one day with precipitation greater than 10 mm: 23rd to 24th July, when 70 to 90 mm of rain was recorded at Siglufjörður and Ólafsfjörður weather stations (Fig. 7).

From 20th August to 20th September around 1/3 of the precipitation for 2012 fell in the area (~400–550 mm). For comparison, the average annual precipitation in the town of Ólafsfjörður is ~400 mm for the period 2000–2012 (Figs. 5 & 6). In detail, from 28th August to 8th September the cumulative precipitation in Siglufjörður was 190 mm and 120 mm in Ólafsfjörður, with an additional 30 to 40 mm precipitation at these stations on the 3rd, 6th and 7th September. From 9th to 11th September an unseasonal and severe snowstorm hit the north eastern and northern parts of the country (Jónsson, 2013; Hermannsdóttir, 2012). Following this snowfall, around 100 mm rain was measured in only 2 days at Siglufjörður and almost 150 mm at Ólafsfjörður. The precipitation continued from 11th to 17th September either as snow, sleet or rain at these weather stations. From September 17th to 19th less than 10 mm of precipitation was recorded, but at the time of the event 540 mm precipitation had been recorded in Siglufjörður and 490 mm at Ólafsfjörður weather stations since 23rd July, which corresponds to 40–45% of the mean annual precipitation from 2000 to 2012 (Fig. 5). The monthly precipitation data from Ólafsfjörður station from 2000 to

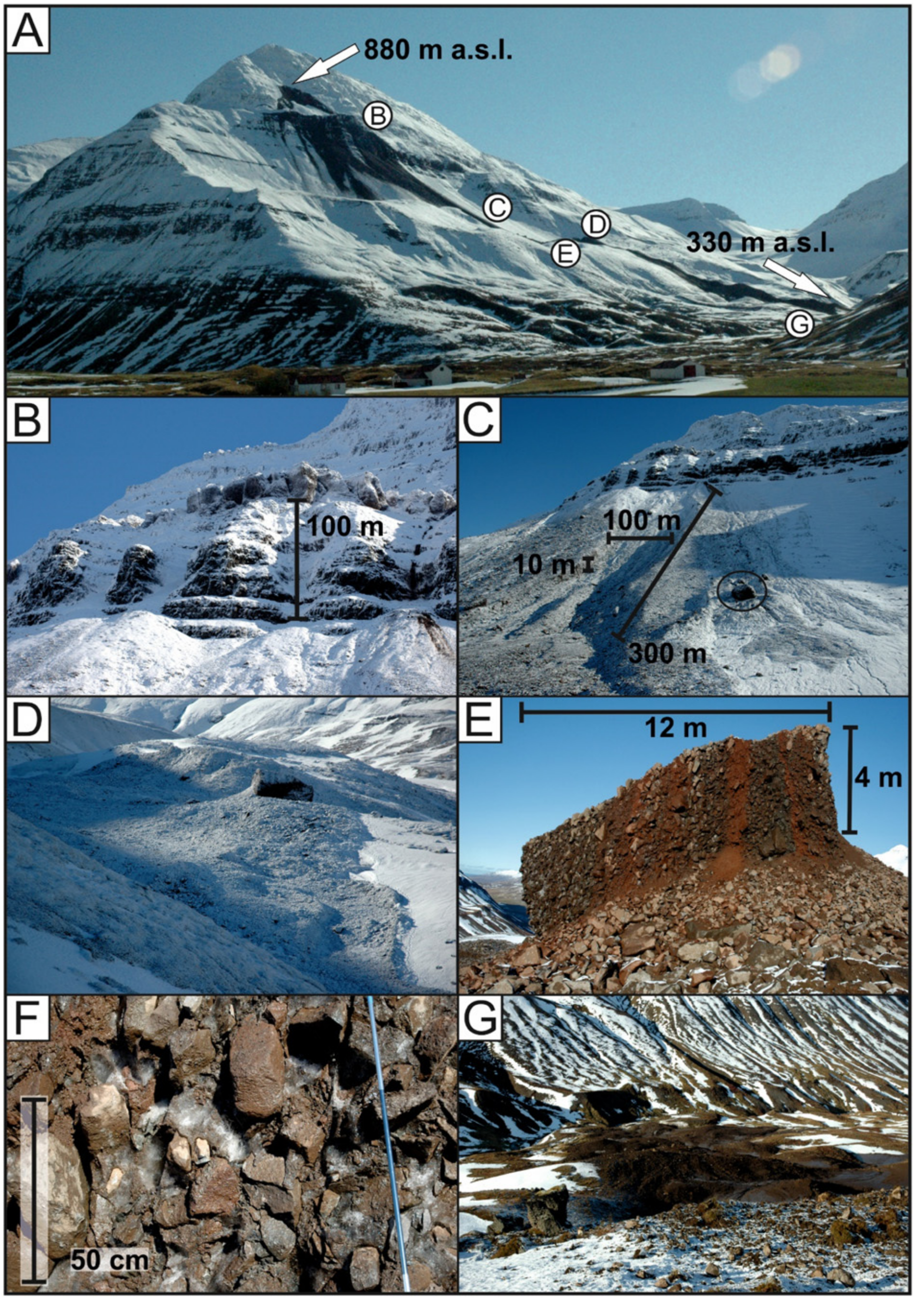


Fig. 4. (A) An overview of the western side of the Móafellshyrna Mountain after the debris slide. The uppermost and lowermost elevation limits of the debris slide path are labelled in m a.s.l. as are the locations of panels B to G. (B) The ice-cemented blocks perched, up to 20 m in thickness on the 100 m high rockwall. (C) The erosional area in the lower talus slope below the rockwall. Note the large block of ice-cemented deposits on the right. (D) Landslide debris and an ice-cemented block resting at 495–505 m a.s.l. (E) The same large block of ice-cemented deposits as in D, around 12 m wide and 4 m high. (F) Close up of the block in E showing stratified deposits of coarse angular clasts with an icy matrix. (G) Looking downwards onto the deposits in the terminal part of the slide.
Photos: Þ. Sæmundsson, A taken on the 20th September and B-G taken on the 29th September 2012.

2012 show that September is the month with maximum precipitation for any given year, with a range between 70 and 250 mm (Figs. 5 & 6). The year of 2012, however, had precipitation exceeding the average for this month (Fig. 5).

Unfortunately, there is no weather station located in the mountainous region of Tröllaskagi area and as previously mentioned there is no weather station in Fljótin area. This means that we cannot report absolute precipitation data for the Móafellshyrna site, but it is reasonable to assume that on a month by month basis the trends should be similar to those of surrounding weather stations. Predicting whether precipitation falls as snow or rain at Móafellshyrna is outside the scope of this study and is complicated by a number of factors including snow drifting, wind-dependant snowmelt and variable orographic effects dependant on wind direction (Brynjólfsson and Ólafsson, 2008) – see Section 1.3. Snow was visible on the ground on the day of the slide and was less than 1 m thick from eye witness accounts (equivalent to ~100 mm of precipitation, depending on snow density) Therefore, the majority of the precipitation received up to 20th September had been absorbed by the ground. The fact that snow was present on the ground argues against a sudden influx of water into the ground via snowmelt, known to trigger other mass wasting phenomena in Iceland (e.g. Decaulne et al., 2005). Hence, we did not pursue an analysis of the wind data from the weather stations, because this would only be important if melt or precipitation were the primary triggers for the slide.

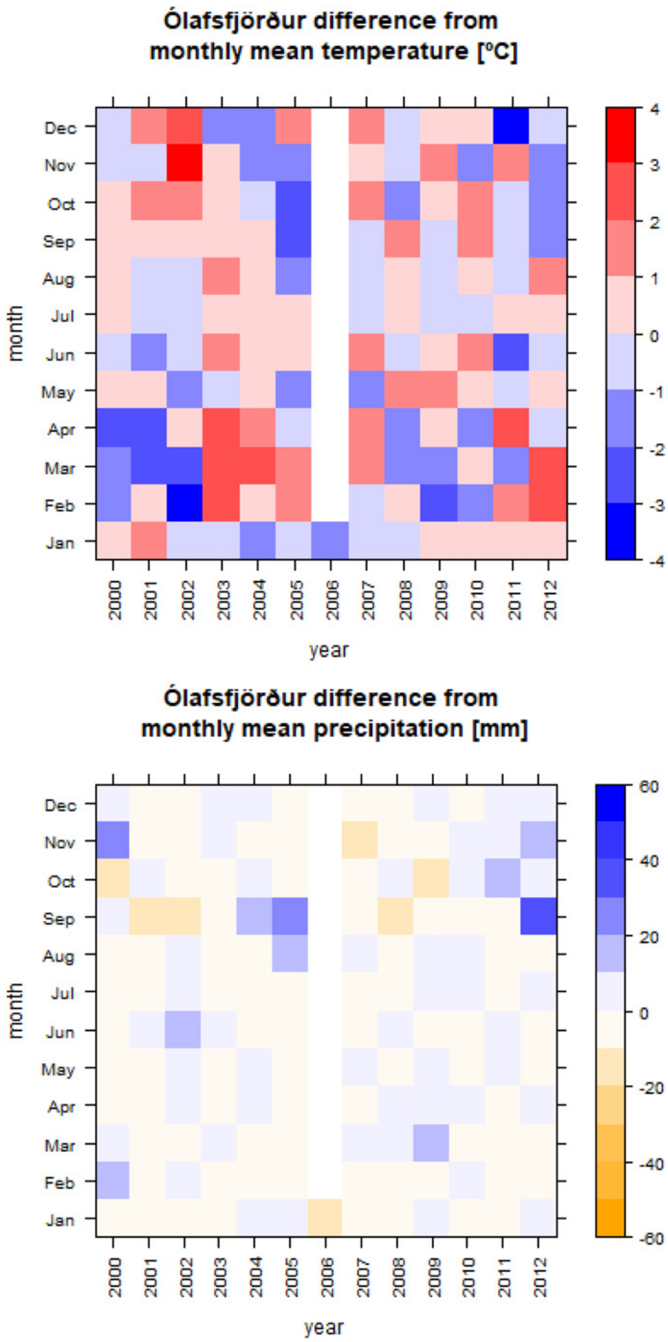


Fig. 5. Matrix plots of the difference between the average monthly temperature (top) and precipitation (bottom) and the average value for that month for the period 2000–2012 for the Ólafsfjörður station.
(Data supplied by the IMO in 2016).

4.3.2. Temperature

The temperature patterns in 2012 were also unusual, the summer and spring were unusually warm on the whole, but the autumn was particularly cold (Fig. 5; Jónsson, 2013). The average temperature measured in the town of Ólafsjörður was in 10.4 °C July and 10.9 °C in August in 2012. The average temperatures for these months for the period 2000–2012 are 9.8 °C and 9.6 °C respectively. The average temperature for September 2012 was on the other hand 5.7 °C compared to the average temperature of 7.2 °C for 2000–2012.

The average daily air temperature from 6th to 20th September at the Siglufjörður and Ólafsfjörður stations ranged from 3 to 6 °C and at the Öxnadalsheiði weather station fluctuated around zero, but lowered to approximately −3 °C the night before the slide (Fig. 7). Our corrected temperature data indicate average daily temperatures of at the altitude of the Móafellshyrna slide of around −1 to −2 °C in the days preceding the slide and hence night-time temperatures would have been even lower. During the evening of 19th September, a drop below 0 °C in the atmospheric temperature in the mountains was measured in the Öxnadalsheiði weather station (Fig. 7). The snow on the ground at the time of the Móafellshyrna debris slide shows that similar sub-freezing conditions also prevailed at this altitude prior to the slide. These low temperatures combined with the snow cover are strong evidence that sudden influx of water from precipitation was not the trigger for the Móafellshyrna slide.

4.3.3. Earthquake sequence

In the Eyjafjarðaráll graben, three earthquakes with magnitudes M 4.2 to M 4.5 were registered on 19th and 20th September (Gudmundsson et al., 2014). Their epicentres are located 25–27 km north-northeast of the town of Siglufjörður, and 60 km north-northeast of the Móafellshyrna site (Fig. 4). On the morning of 19th September, one day prior to the slide, two earthquakes with magnitudes M 4.5 and M 4.3 occurred at 07:57 and 08:28 respectively. A number of smaller aftershocks continued to occur throughout the day following these earthquakes. Another earthquake of magnitude M 4.2, occurred at 9:27 on the 20th September, approximately three hours prior to the first observations of the Móafellshyrna slide (Fig. 4).

5. Discussion

The Móafellshyrna debris slide is a rare example of a gravitational mass movement where three triggering factors may have contributed to the failure of the slope: heavy precipitation, earthquake activity and ground ice degradation (via rising average surface temperatures). We infer that precipitation was the main preparatory factor for this debris slide for the following reasons. Heavy prolonged precipitation was recorded across the area, where nearly half of the usual annual precipitation fell in less than one month (Fig. 5). Many case studies have shown that high magnitude water input, either by rainfall (Rapp and Nyberg, 1981) or snowmelt (Decaulne, 2007), leads to oversaturation of soil directly triggering debris flows and shallow landslides. These studies also point out the role of intense rainfall as a preparatory (rather than direct trigger) factor to failure (e.g. Rapp, 1964, 1985, 1995; Johnson and Rahn, 1970; Johnson and Rodine, 1984; Rapp and Nyberg, 1981; Addisson, 1987; Innes, 1989; Luckman, 1992; Becht, 1995; Sæmundsson et al., 2003, Decaulne, 2007, Sæmundsson and Decaulne, 2007, Guzzetti et al., 2007). However, the role of water infiltration in triggering of shallow landslides and debris flow in permafrost areas is rarely well documented (Harris and Gustafsson, 1993). We do not favour sudden water input as a direct trigger of the Móafellshyrna debris slide, because snow was present on the ground at the time of the failure. However, we think this is a necessary pre-condition for the failure to occur.

The direct influence of the seismic activity and associated ground acceleration on the motion of the debris in the source area seems unlikely, as the event did not occur immediately following any seismic event. Earthquakes are a common triggering factor for landslide activity and are considered as a major cause for landslides worldwide (e.g. Keefer, 1984, 1994, 2002; Malamud et al., 2004). Yet, no other debris flow or rockfall activity was reported on the northern part of the Tröllaskagi area on 19th or 20th September, which might be expected if ground acceleration were sufficient to trigger mass movement. However, the short time interval (3 h) between the last earthquake and the failure indicates a possible connection between the slide and the seismic events.

Selby (1993) argued that "stability of the slope, orientation of the earthquake in relation to the slide mass, earthquake magnitude, focal depth, seismic attenuation and after-shock distribution" are factors that determine whether earthquakes trigger landslides. According to Keefer (1984), the maximum area likely to be affected by landslides in

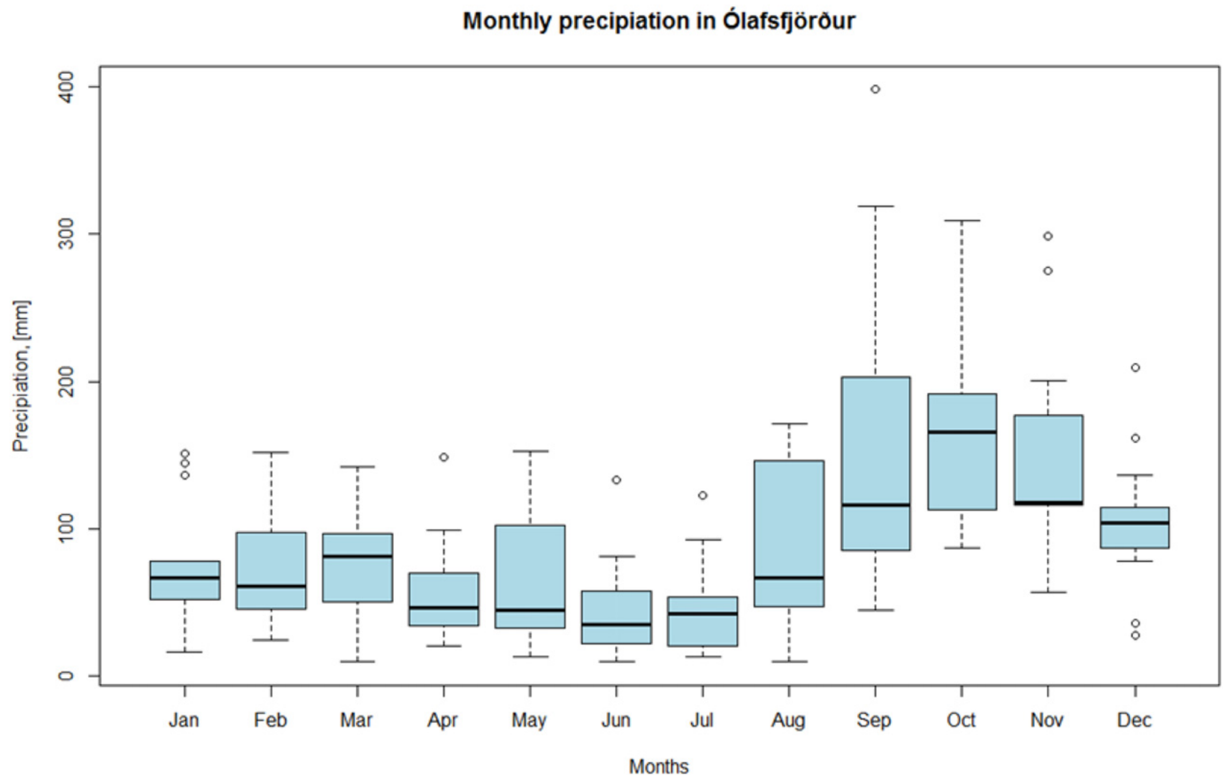


Fig. 6. A boxplot of the precipitation data from the Ólafsfjörður station for each month between the years 2000 to 2012 (Data from IMO, 2016). The end of the dotted lines is where the max and min values of precipitation were measured for each month, excluding the outliers that are displayed as dots. The blue boxes is where the 50% of accumulated measured precipitation falls and the black lines are the medians of each month.

a seismic event increases from approximately 0 km^2 at M = 4.0 up to 500.000 km^2 at M = 9.2. According to Malamud et al. (2004) the lowest earthquake-magnitude is M 4.3 ± 0.4. for triggering gravitational mass movements. Tatard et al. (2010) state that earthquakes of M4 and lower have little or no influence on landslide triggering. Nevertheless, several studies (e.g., Sassa et al., 2007; Walter and Joswig, 2008) mention that small earthquakes (maximum M 3.6 in southern Italy according to Del Gaudio et al., 2000) and repeated shocks can influence hydrogeological settings and can possibly cause landslides, sometimes with delay between the earthquake and the mass movement. Jibson et al. (1994) also discuss delayed landslide movements, from larger earthquakes (M 7.0), and state that the simplest explanation for the delay is a change in the ground-water conditions. Based on the above mentioned studies, it is unlikely that an earthquake of M 4.3 was the only triggering factor for the Móafellshyrna debris slide, having taken place 60 km away from the epicentre. On the other hand, since the Móafellshyrna slide occurred only 3 h after a seismic event, the seismic sequence is likely playing some indirect role.

The ground water flow system of the colluvial cone composing the source material of the Móafellshyrna landslide is expected to be very limited. This is due to several factors: i) the catchment area above the source area is not very large (around 350 m long); ii) the colluvial cone is confined uphill by a vertical rockwall, and downhill by the edge of the topographic bench; iii) the presence of ground ice cementing the deposits; iv) the sub-horizontal dipping of the bedrock layers where the deposits are perched. However, it has been shown that talus slopes can contain multiple and distinct groundwater flow systems beneath or within them, and that they have a rapid and localised response to precipitation and melt inputs (Roy and Hayashi, 2009; McClymont et al., 2010). One component of the groundwater flow in the colluvial cone of Móafellshyrna may originate in the pervasive system of sub-horizontal and sub-vertical discontinuities affecting the bedrock. If a groundwater system was present before the failure, the response of the water table should be rapid. Since seismic activity can release water by coseismic liquefaction or consolidation of loose sediments (e.g., Manga et al., 2003; Montgomery and Manga, 2003), a change in the hydrogeological equilibrium of the colluvial cone caused by seismic activity could have contributed to the occurrence of the failure.

Field evidence from the Móafellshyrna debris slide strongly suggests the involvement of ground ice thaw in triggering the event. Because the month of the event had temperatures lower than average and the days prior to the event were mostly below zero Celsius (as evidenced by snow on the ground), we do not think thaw water from the ground ice in the perched talus contributed significantly to the event. However, longer term, deeper thawing caused by an annual rise in temperature and therefore a shift in the permafrost table, including an anomalously warm preceding summer, we believe is a more likely contributor. In recent years, there has been an increasing interest worldwide in the influence of climate warming and associated decline of mountain permafrost on the occurrence of mass wasting phenomena (e.g., Rebetez et al., 1997; Gruber et al., 2004; Gruber and Haeberli, 2007; Fischer et al., 2006; Sattler et al., 2011; Stoffel and Huggel, 2012; Damm and Felderer, 2013; Stoffel et al., 2014). The increasing frequency of rapid mass movements, such as debris flows, debris slides, rock falls and rock avalanches, in mountainous areas have been linked in several cases with mountain permafrost degradation (e.g., Clague et al., 2012; Wirz et al., 2013; Barboux et al., 2015; Darrow et al., 2016; Haeberli et al., 2016). Loss of ice-cementation, the presence of segregated ice, increased hydrostatic pressure and the associated reduction of shear strength can all lead to reduction of stability with increasing atmospheric temperature via permafrost degradation (e.g., Gruber and Haeberli, 2007; Krautblatter et al., 2013; Pogliotti et al., 2015). Although, these previous studies have focused on the stability of massive rock masses, a similar (perhaps exaggerated) effect might be expected in ice cemented talus.

The increase of mean annual temperature, which has been observed in Iceland over the last few decades (Björnsson et al., 2008), should be

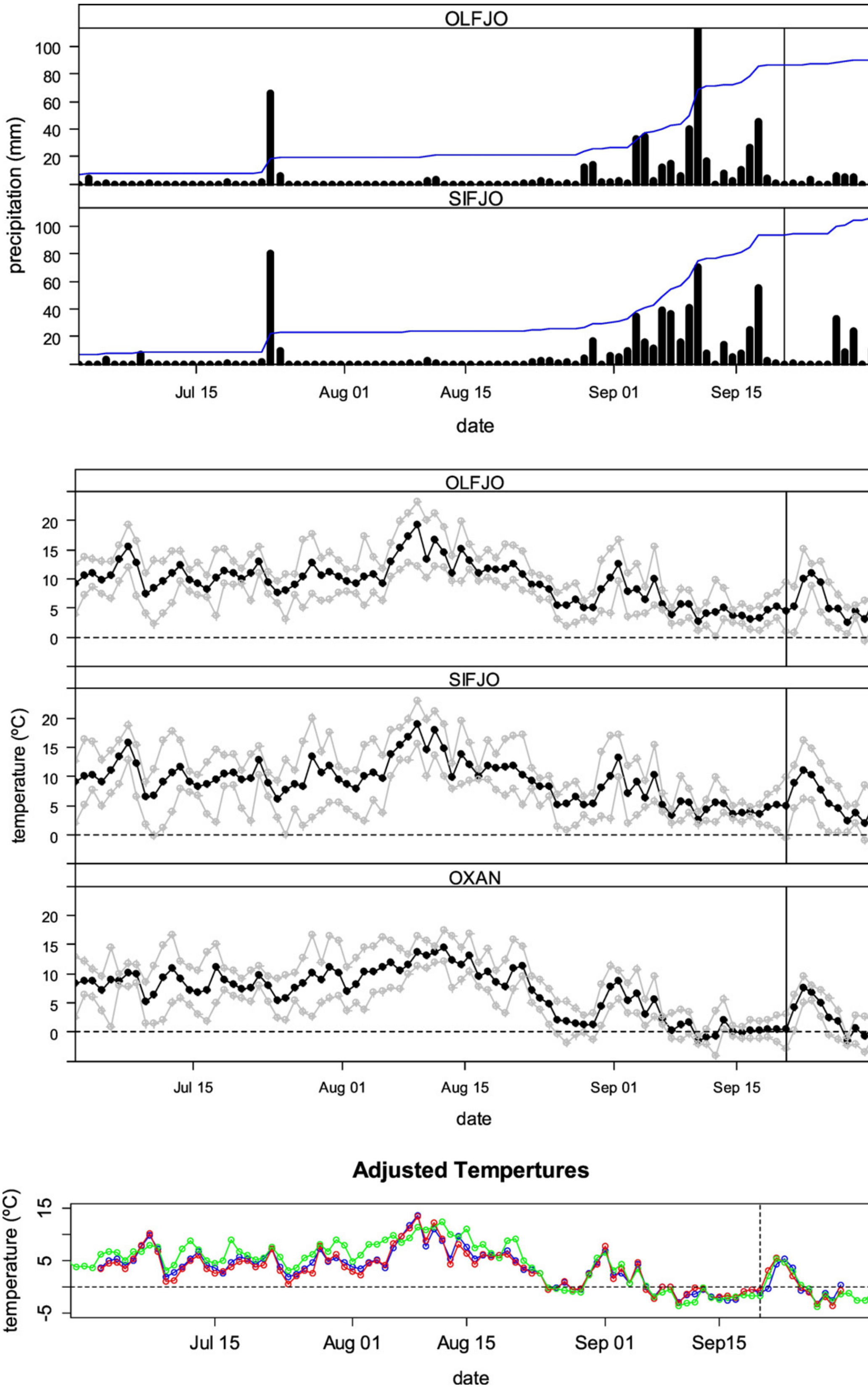


Fig. 7. Top: daily precipitation (black bars), cumulative precipitation (blue lines) for temperature measurements from the Siglufjörður (SIFJO) and Ólafsfjörður (OLFJO) weather stations. Middle: daily temperature data from the Siglufjörður (SIFJO), Ólafsfjörður (OLFJO) and Öxnadalsheiði (OXAN) weather stations. Bottom: mean temperature data for all three stations adjusted to 880 m altitude of Móafellshyrna (red = SIFJO, green = OXAN and blue = OLFJO). All data from 1st July to 30th September 2012.
(Data obtained from IMO in 2016).

leading to degradation of discontinuous permafrost in Iceland, which is thought to be present in the Tröllaskagi peninsula (Etzelmüller et al., 2007a). Our observations of the ice-cemented deposits shows that the Móafellshyrna slide originated from deposits containing pore-filling ground ice and equally that these deposits were still frozen at the time of the slide. Together these argue for a permafrost origin for this ground ice. The increasing average temperatures over the last decades (Björnsson et al., 2008; Jónsson, 2013) before the event may have initiated the degradation of ground ice in the talus cone where the slide initiated, but not from the top-down, but from the base-up. This thawing may have: i) lubricated of the base of the cemented colluvial cone, ii) lowered the effective friction angle (cohesion), and hence iii) caused the slow movement of the colluvial cone perched on the bench and the sliding along a detachment surface of the whole ice-cemented mass. The warming of the rock mass onto which the colluvial deposit was previously cemented could have been brought about by a combination of propagation of the thermal wave through the rock mass from the warmer southeast-facing side (e.g., Noetzli et al., 2007) and the delivery of warmer liquid water (derived from the intense precipitation) to the talus-rock interface from the south-westward dipping strata. Hence, the rupture occurred beneath the permafrost table. Perhaps the ice-cemented colluvium was in effect forming an underground "ice dam" that was holding back water saturated debris until its own weight and the seismic shaking caused it to fail. However, we cannot substantiate this link with certainty as we lack direct temperature measurements in the talus cone. Our hypothesis is supported by the slow widening of the tension crack at the top of the source area as observed by the eyewitnesses and the fact that the landslide was fluidised (a water content higher than expected for such a small catchment) even as it fell down the talus slope (causing the channelized erosion).

Ice-cemented deposits have been observed in two other landslides in Iceland, e.g. on the Torfufell mountain (source area at ~750 m a.s.l.) and the Árnesfjall Mountain (source area at ~350 m a.s.l.). These further events provide additional evidence to support our hypothesis that the lower limit of permafrost degradation extents to lower altitudes. The source zones for the Móafellshyrna and the Torfufell slides are at the lower elevation limit of discontinuous mountain permafrost in northern Iceland (i.e., 840 m a.s.l.; Etzelmüller et al., 2007a). On the other hand, the source zone of the slide in the Árnesfjall Mountain is at an unexpected much lower elevation, which shows that the knowledge of mountain permafrost in Iceland is incomplete. The setting of talus perched on benches is not a rare situation in Iceland because of the sub-horizontal basalt layers create topographic benches on which loose material can accumulate. Hence investigating whether those with permafrost conditions, particularly above inhabited areas, contain ground ice and establishing its condition, should be a priority.

6. Conclusions

The debris slide in the Móafellshyrna Mountain began with a slow movement of a perched colluvial cone, as described by the local residents of Þrasastaðir. This colluvium is composed of stratified ice-cemented deposits at 840 m elevation and large blocks and boulders broke off the frontal part of the cone and fell onto the talus slope below. The mass movement transformed into a rapid debris slide, travelling down the mountainside with the final deposits coming to rest at 330 m a.s.l. The total volume of the slide is estimated to be around 312,000–480,000 m^3 (including the initial mass and mass added via bulking), covering an area of 0.3 km^2.

We suggest that heavy precipitation prior to the slide was the main preparatory factor, with over 400 mm of precipitation recorded in one month prior to the event after an unusually dry summer season. The influence of seismic activity is unclear, but the close temporal association between the last earthquake series and the failure suggests that the shaking could have pre-conditioned the landslide weakening the cohesion between the ice-cemented colluvium and the bedrock and/or changing of the hydrology. The presence of ice-cementing the source colluvium at 880 m confirms the presence of discontinuous mountain permafrost at that elevation. We suggest that the partial thaw of these deposits was a trigger for the failure for three reasons: i) the landslide followed an usually warm spring and summer, ii) mean annual air temperatures are generally increasing in Iceland and iii) the colluvial cone initially slid as a single cohesive mass suggesting basal lubrication/melting. The fact that two other recent landslides contain similar ice cemented deposits suggests that mountain permafrost degradation could be more prevalent in triggering landslides in Iceland than has previously been thought.

The ice-cemented deposits within the slides of the Móafellshyrna, Torfufell and Árnesfjall Mountains have highlighted the need for a more detailed understanding of the distribution and condition of mountain permafrost within perched talus deposits in Iceland. Future studies should focus on the relationship between rapid mass wasting processes and the degradation of mountain permafrost in such deposits Iceland. These three landslides occurred in uninhabited areas, but future similar landslides might not, and therefore they could pose a potential hazard to society and infrastructure in the island.

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