International Journal of Disaster Risk Reduction 58 (2021) 102187

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: http://www.elsevier.com/locate/ijdrr

Local knowledge of emerging hazards: Instability above an Icelandic glacier

Stephanie Matti [*], Helga Ögmundardóttir

University of Iceland, Sæmundargata 2, 102, Reykjavík, Iceland

ARTICLE INFO

Keywords:
Disaster risk reduction and management
Local knowledge
Landslide
Iceland
Emerging hazard
Svínafellsjökull

ABSTRACT

Climate change is contributing to shifts in the magnitude and scale of hazards, and the emergence of risks in areas where they were previously unknown. In south-east Iceland, a fracture in the mountainside of Svínafellsheiði threatens to cause between 60 and 100 million cubic metres of rock to fall onto the glacier below. A large landslide could break up the surface of the glacier, crash into the proglacial lake, and affect people and infrastructure downhill. In addition to the unprecedented scale, the Svínafellsheiði fracture represents the first time people and infrastructure have been exposed to this type of hazard in Iceland. In this article we examine the role of local knowledge in disaster risk reduction and management for communities that are facing a particular type of hazard for the first time. We argue that even when a community lacks experience with a specific type of hazard, local knowledge can still play a valuable role in hazard identification and risk management.

1. Introduction

In 2014, local farmers gathering sheep on the slopes above Svínafellsjökull outlet glacier in south-east Iceland discovered a fracture in the mountainside. It appeared to be 100 m long, and close to a cliff-edge that rises 400 m vertically above the glacier. The farmers monitored the fracture and made some basic measurements, before bringing it to the attention of scientists and disaster management authorities. The fracture is now understood to be 1.7 km long with approximately 60 million cubic metres of rock in motion [1; see Fig. 1]. If the entire section of the cliff collapses at once onto the glacier it may cause no further damage, however, a large landslide could break up the surface of the glacier, crash into the proglacial lake,[1] and cause a "fast-flowing slurry of rock, ice, water and even air" that could affect people and infrastructure downhill [2]. At the time of writing, the fracture was widening, and there was a high degree of uncertainty about the timing and ultimate form the large landslide would take.

Icelandic people have a long history of managing environmental risks including volcanic eruptions, glacial floods, surging glaciers and extreme weather. This has fostered traditions of local risk knowledge, and driven the development of advanced monitoring and warning systems, and disaster management protocols that have reduced casualty rates to almost zero [3]. However, large landslides onto glaciers—defined as landslides with a volume of more than one million cubic metres [4]—represent a relatively unknown hazard in Iceland. There is no record of a large landslide onto a glacier affecting people or infrastructure since the country was first settled in the 9th century. The massive scale of the Svínafellsheiði fracture also singles it out as unique in Icelandic history, with scientists predicting that it may result in "one of the largest mass movements in Iceland during the Holocene" [1].

There is broad consensus in the disaster risk reduction and management (DRRM) literature that local knowledge is a critical element of the coping capacity of local communities [5–7]. This local knowledge is often portrayed as being deeply rooted in a people's historic experience of similar hazards. Dominey-Howes and Minos-Minopoulos, for example, suggest that the "inherited memory" of a hazardous event is "a vital element of community resilience." [70]; 306) However, the IPCC has established that extreme events, which trigger disasters are increasingly likely to occur in places they were previously unknown due to climate change [8]. The role of local knowledge in DRRM for communities that are facing a particular type of hazard for the first time represents a gap in the literature that this study addresses, drawing on the case of the Svínafellsheiði fracture. In this article we argue that even when a community lacks experience with a specific type of hazard, local knowledge can still play an important role in DRRM, especially in the identification of hazards. However, when it comes to predicting the impact and suggesting survival strategies for new hazards, local knowledge plays a more varied role.

This article is structured as follows. The next section discusses the research design including literature review, study area, and

* Corresponding author.
E-mail addresses: sam33@hi.is (S. Matti), helgaog@hi.is (H. Ögmundardóttir).

[1] The Svínafellsjökull proglacial lake refers to a body of water dammed by the glacier and rock moraines during glacial retreat.

https://doi.org/10.1016/j.ijdrr.2021.102187
Received 28 October 2020; Received in revised form 16 February 2021; Accepted 9 March 2021
Available online 18 March 2021

methodology. Section 3 outlines the main natural hazards in the area. Section 4 examines local knowledge in the area as it relates to large landslides onto glaciers, and how this has been incorporated into DRRM processes. We conclude the findings in Section 5.

2. Research design

2.1. Literature review

In recent decades, DRRM scholarship and practice has embraced an increasingly holistic view of hazard risks, taking into account the resilience and underlying vulnerabilities of people living in exposed areas. Local and indigenous knowledge systems, defined by UNESCO as the "understandings, skills and philosophies developed by societies with long histories of interaction with their natural surroundings," are understood to play a critical role in improving the resilience of communities [76: 3]. Many terms have been used in the literature to refer to local knowledge, including indigenous knowledge, traditional knowledge, traditional ecological knowledge and folk knowledge [9]. These terms differ somewhat in terms of reference group and connotations but maintain significant cross-over in meaning. In this article, the term 'local knowledge' is preferred over 'indigenous' or 'traditional knowledge' as it avoids the static connotations associated with 'traditional knowledge', and has a broader scope that encompasses both indigenous and non-indigenous local knowledge [9,10].

Local knowledge is acquired by people through long-term local-scale observations, including about the environment, natural hazards and the weather [11,12]. Local knowledge is typically accrued from generation to generation, and tested over long periods of time [9]. This knowledge becomes embedded in practices, institutions, and rituals within the community [13,14]. While often depicted as static and hermetically sealed, recent scholarship has emphasised that local knowledge systems are complex, porous, dynamic, and constantly updated [15].

Since the 1990s, the endeavour to integrate local knowledge into the study and practice of DRRM has gained momentum [11,12,16–18]. Local knowledge is now understood to play an important role in DRRM, including helping communities develop resilience by: identifying signs that trigger early response; anticipating potential hazards intensified by climate change; becoming empowered in the implementation of DRRM activities; and improving recovery from the effects of disasters [5–7]. The importance of local knowledge in DRRM is recognised under the Sendai Framework for Disaster Risk Reduction (2015–2030), which calls on countries to complement scientific knowledge with local knowledge when developing and implementing DRRM strategies and policies [18].

A rich case study literature examines how communities have employed local knowledge to improve DRRM for a wide variety of hazards, including floods in China [19] and Zimbabwe [20], rock-ice avalanches in Peru [21], earthquakes in India/Pakistan [22], and tropical cyclones in Fiji and Tonga [23] to name but a few. While studies dealing with local knowledge and DRRM typically focus on developing countries, some studies point to the important but less well-understood role of local knowledge in developed countries such as Scotland, Finland [24], and other European countries [25]. A complementary body of scholarship examines the long-term transfer of hazard knowledge in Europe including in relation to flood practices in Germany [26], landslides and flood prevention in Italy [27], floods across Europe [28], and traditional disaster memory in Switzerland [29].

In the Icelandic context, several studies have examined local knowledge and DRRM practices in relation to Katla and Eyjafjallajökull, two volcanoes in southern Iceland [30–33]. Research into the rich local knowledge and folklore of the area has captured stories of the origin of Katla and predictions of future flood paths, as well as recollections of heroic escapes and ineffective responses [30,32,34] . Bird et al. assessed resident knowledge, behaviour and perceptions of risk relating to Katla [31], while subsequent research highlighted how inherited local knowledge has increased the resilience of inhabitants in the area [32]. This article adds to this body of research on the intersection of local knowledge and DRRM processes in developed countries, and sheds further light on landslide DRRM practices in Iceland.

In the literature, local knowledge is often portrayed as being rooted in people's historic experience of similar hazards [35]. For example, Iloka explains that local knowledge "has been gathered by ancestors who have experienced and recovered from the impacts of hazards and disasters, who then pass the knowledge down to their children." [72] : 30] Dominey-Howes and Minos-Minopoulos suggest that "inherited memory" of a hazardous event is "a vital element of community resilience." (2004, p. 306) The role of local knowledge in communities that are facing a particular type of hazard for the first time represents a gap in the literature that this study aims to address. Gaillard and Mercer argue that "local people and communities are not helpless in the face of natural

Fig. 1. Scientific monitoring visit to the fracture in August 2019. The fracture is visible on the surface as a trench, starting from the bottom right corner of the photograph and extending downhill.

hazards" and that "local knowledge is a valuable resource" [71]: 94]. We argue that even in cases where a community has an almost total lack of experience with a particular type of hazard, local knowledge can still be a valuable resource in identifying hazards and building resilience.

2.2. Study area

Located at the confluence of the North Atlantic and Arctic Oceans, Iceland is prone to a multitude of hazards including extreme storms, floods, earthquakes, volcanic eruptions, landslides, and avalanches. This study was conducted in the Öræfi district of south-eastern Iceland with a specific focus on the two hamlets exposed to the Svínafellsheiði fracture: Freysnes and Svínafell. The seven settlements of the district are spread around the base of Öræfajökull—a large ice-capped strato-volcano—separated by a series of steep outlet glaciers and their melt-water rivers. Sigurmundsson et al. have established that the district is one of the most vulnerable areas to glacier floods, volcanic eruptions and climate change in Iceland [74]. Öræfi had a permanent population of 151 people in 2018 [37], however, the number of people living and working in the area on a temporary or seasonal basis is much higher.

Freysnes is located 800 m beyond the terminus of the Svínafellsjökull outlet glacier while Svínafell lies approximately 2 km further south-east (see Fig. 2). In 2018, Freysnes consisted of 17 buildings including a hotel, farm, petrol station and several houses; it is also traversed by the country's main highway, locally known as the Ring Road (see Fig. 3). Svínafell consisted of 21 buildings including two farms, three guest-houses, a campground and several residential buildings. In recent decades, the district has shifted from a dependence on sheep farming to large-scale tourism including glacier walks on Svínafellsjökull. This has been part of a larger trend that has seen tourism in Iceland rise from 448,000 foreign visitors in 2010 to over 2.2 million in 2018 [38].

Many of the local inhabitants in Freysnes and Svínafell come from families that have lived in the district for generations, with some tracing their history back to 1300 AD. Both Freysnes and Svínafell are mentioned in early Icelandic literature, suggesting that they date from at least as early as 1000 AD [39]. Svínafell, for example, is mentioned in Njáls Saga: "Flosi dwelt at Swinefell, and was a mighty chief" [40 : Ch.94]. Iceland generally has a rich literary tradition of documenting events that started soon after the country was first settled. This has resulted in a wealth of detailed observations about the landscape, weather phenomena, volcanic eruptions, earthquakes, avalanches and other natural events [41].

3. Methods

The purpose of this study was to examine the role of local knowledge in the identification and management of the Svínafellsheiði fracture. This article presents the findings of an ethnographic study that used mixed methods, including participant observation, semi-structured interviews and open discussions, to review existing local knowledge as it applied to the Svínafellsheiði fracture and DRRM processes. This differs from a citizen science approach, in which inhabitants are directly engaged through the research process to gather data and develop knowledge to advance scientific inquiry [42]. The research was undertaken between August 2018 and November 2020 in Iceland.

A series of 53 semi-structured face-to-face interviews were conducted with 15 local inhabitants, nine glacier guides, eight foreign inhabitants, eight tourists, three DRRM experts, two scientists, two tourism experts, two search and rescue coordinators, and one national park ranger (see Table 1). Several local inhabitants were interviewed multiple times. Most people were interviewed individually, however five interviews were conducted with couples and one interview was conducted with a group of four local women together. Of the participants, 23 were female and 27 were male; all were aged between 20 and 75 years old. All interviews were conducted in English except one, which was conducted in Icelandic with the assistance of an interpreter. The proficiency of local inhabitants with English reflects the important role of tourism in the local economy. Participants were identified through snowball sampling. This was effective given the relatively small number of people exposed to the hazard [43].

Each interview typically lasted between one and one-and-a-half hours, and covered the interviewees' understanding of hazards in the area, local knowledge and practices, and their awareness of and involvement in DRRM processes. The questions were open-ended to allow important issues, perceptions and ideas to be raised and discussed. All interviews were audio-recorded, transcribed by the authors, and analysed together with field notes using *QSR NVivo 12*® (qualitative data analysis software). A bottom-up inductive analytical approach was taken to allow sub-themes and commonly held views to emerge from the data [44]. An advantage of this approach was that it gave voice to the experiences of local people [45]. In this paper, the interviews are referenced using the coding system presented in Table 1, which draws attention the role of the person interviewed.

In addition to semi-structured interviews, the first author actively conducted research while living in the community and working as a glacier guide from April till October 2019. This intensive and long-term involvement helped rule out spurious associations and enabled the authors to develop a deeper understanding of the topic [46]. Twelve additional trips to the study site were undertaken to participate in specific events relevant to the research including scientific monitoring missions (October 2018 and August 2019; see Fig. 1), formal public risk briefings (October 2018 and November 2020; see Fig. 6), and to assist gathering sheep on Svínafellsheiði (August 2020; see Fig. 5). Triangulation of the results reduced the chance of systematic bias and limitations associated with using a single data source [46]. In addition, the research findings were reviewed by several respondents including local inhabitants, scientists and risk managers, who provided feedback, and validated the results [46].

4. Hazards in the Öræfi district

4.1. Large landslides onto glaciers

The fracture in Svínafellsheiði is estimated to be 1.7 km in length with 60 million cubic metres of rock in motion [1; see Fig. 1]. If it collapses, 60 to 100 million cubic metres of rock and debris are predicted to fall onto the surface of the glacier approximately 400 m below [1,2]. A large landslide could break up the surface of the glacier, cause a tsunami in the proglacial lake, and affect the downhill settlements of Freysnes and Svínafell [2]. Scientific research presented at public scientific briefings suggest that the entire mass will release as a single landslide rather than several smaller slides, increasing the risk for downhill settlements (attended by first author, October 24, 2018).

DRRM of the fracture is coordinated by local police with the support of Civil Protection. Public briefings about the fracture are conducted on a roughly annual basis or when new findings become available. A green alert has been in place for the hazard since October 2018.[2] Risk management activities have focused on scientific monitoring, assessing the fracture, public information and reducing exposure. On June 22, 2018, local police together with Civil Protection issued an advisory:

> WARNING: Civil Protection advises against travel on Svínafellsjökull due to landslide danger. In particular, guided tours on the glacier are discouraged. Travelers are advised to stop only for a short while at viewpoints by the glacier tongue [47].

In early 2019, large warning signs were erected on the main roads leading to Svínafellsjökull, warning people about the hazard [see Fig. 4].

[2] Civil Protection classifies hazards as uncertainty phase (green alert), alert phase (yellow alert), and emergency/distress phase (red alert).

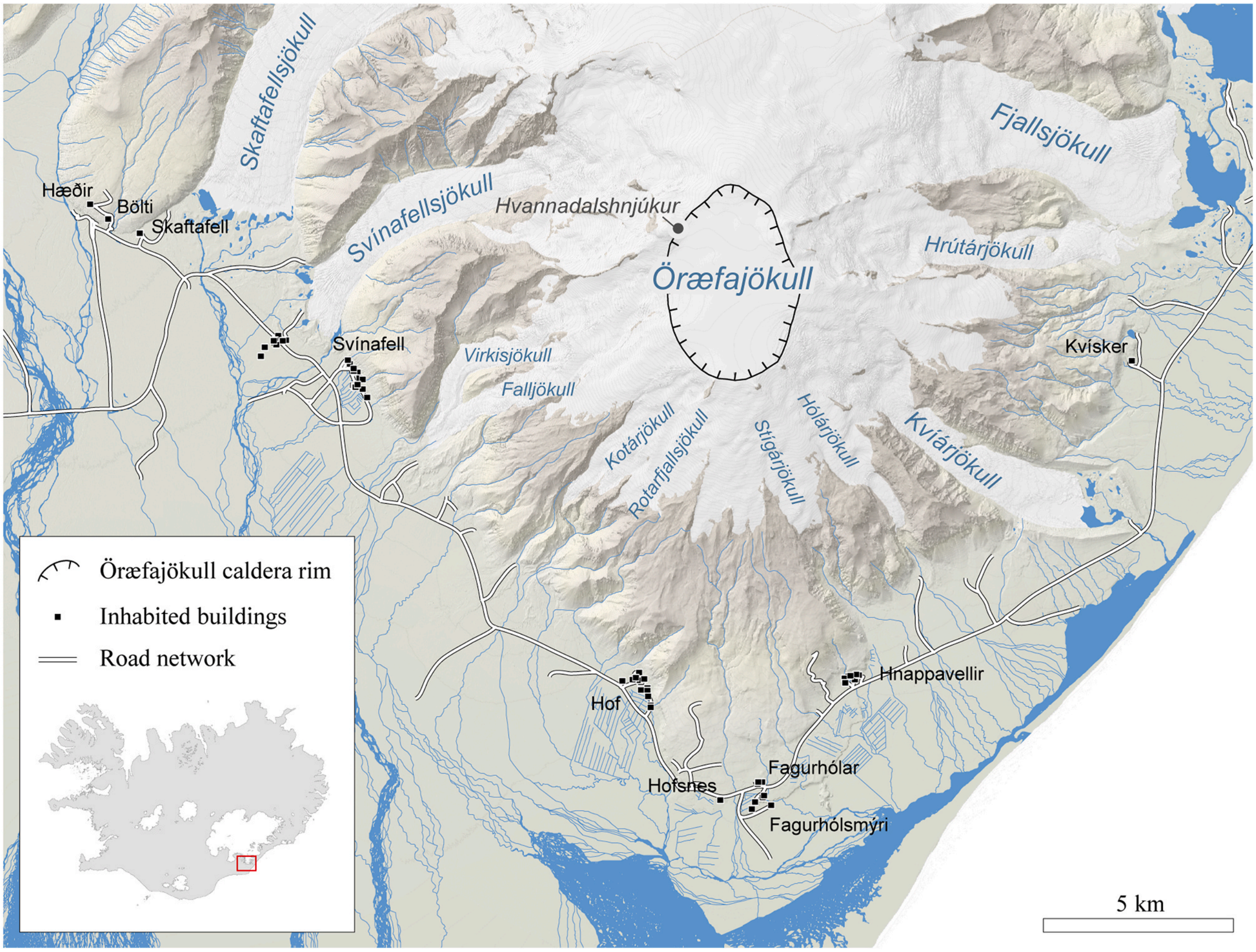

Fig. 2. Location of the Öræfi district [77].

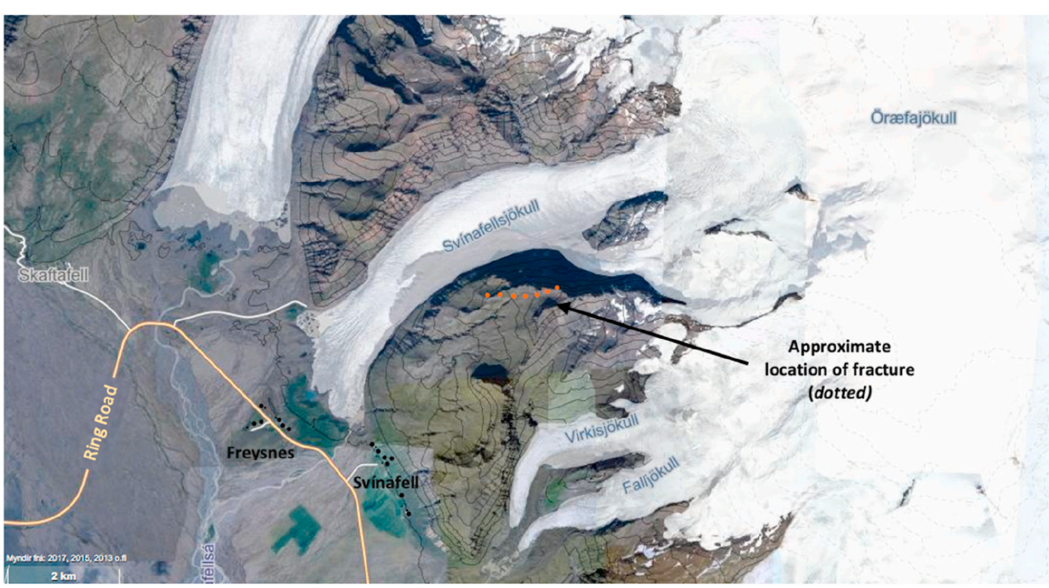

Fig. 3. Location of Freysnes and Svínafell settlements in relation to Svínafellsheiði fracture. Base map: map.is.

While outlet glaciers in the Öræfi district have been retreating since the end of the Little Ice Age in 1890, the rate of retreat has accelerated significantly since 2000 [48]. Hannesdóttir and Baldursson established that in the period since 2000, the mass loss per unit area of glaciers in south-east Iceland has been among the highest in the world [48]. From 1890 to 2010, Svínafellsjökull retreated approximately 800 m and

Table 1
Interviews.

Code	Role	Location	Date
RM.1.	Risk manager	Reykjavík	06-Oct-18
RM.2.	Risk manager	Reykjavík	22-Oct-18
RM.3.	Risk manager	Reykjavík	14-Dec-18
RM.4.	Risk manager	Öræfi	24-Oct-18
GG.1.	Glacier guide	Öræfi	18-Oct-18
GG.2.	Glacier guide	Reykjavík	19-Oct-18
GG.3.	Glacier guide	Reykjavík	30-Oct-18
GG.4.	Glacier guide	Reykjavík	23-Nov-19
GG.5.	Glacier guide	Reykjavík	25-Nov-19
GG.6.	Glacier guide	Öræfi	26-Nov-19
GG.7.	Glacier guide	Öræfi	27-Nov-19
GG.8–9.	Glacier guide	Öræfi	28-Nov-19
FI.1.	Foreign inhabitant	Reykjavík	24-Nov-19
FI.2.	Foreign inhabitant	Öræfi	26-Nov-19
FI.3–7.	Foreign inhabitant	Öræfi	27-Nov-19
FI.8.	Foreign inhabitant	Öræfi	23-Oct-18
LI.1.	Local inhabitant	Öræfi	16-Jul-19
LI.2.	Local inhabitant	Öræfi	17-Jul-19
LI.3.	Local inhabitant	Öræfi	27-Nov-19
LI.4.	Local inhabitant	Öræfi	26-Nov-19
LI.5–6.	Local inhabitant	Öræfi	27-Nov-19
LI.7–8.	Local inhabitant	Öræfi	24-Oct-18
LI.9.	Local inhabitant	Öræfi	25-Oct-18
LI.10.	Local inhabitants (x4)	Öræfi	27-Oct-20
LI.11.	Local inhabitants (x2)	Öræfi	28-Jun-20
LI.12–13.	Local inhabitant	Öræfi	28-Jun-20
LI.14.	Local inhabitant	Öræfi	29-Jun-20
LI.15.	Local inhabitant (in Icelandic)	Öræfi	29-Jun-20
S.1.	Scientist	Reykjavík	27-Sep-18
S.2.	Scientist	Reykjavík	04-Oct-18
S.3.	Scientist	Reykjavík	01-May-19
S.4.	Scientist	Reykjavík	13-Nov-18
T.1 - 8	Tourist	Öræfi	28-Nov-19
TE.1.	Tourism expert	Höfn	17-Oct-18
TE.2.	Tourism expert	Öræfi	26-Nov-19
NP.1.	National parks	Reykjavik	14-Dec-18
SAR.1.	Search and Rescue	Reykjavik	29-Jan-19
TE.1.	Tourism expert	Höfn	17-Oct-18
TE.2.	Tourism expert	Öræfi	26-Nov-19
NP.1.	National parks	Reykjavik	14-Dec-18
SAR.1.	Search and Rescue coordinators (x2)	Reykjavik	29-Jan-19

Fig. 4. Warning signs on access roads to Svínafellsjökull.

decreased in volume by 30 % [49]. The IPCC confirmed that climate change has played, and continues to play, a major role in the retreat of Icelandic glaciers [16]. As glaciers thin and recede, slopes that were previously buttressed by larger volumes of ice become unstable [50,51]. In Iceland and worldwide, landslides in recently deglaciated areas are predicted to become more frequent due to glacial retreat, heat waves, permafrost degradation, changes in precipitation and the expansion of glacial lakes [52–55]

Fig. 5. Local inhabitants gathering sheep on Svínafellsheiði.

Large landslides onto glaciers are rare in Iceland with only four recorded between 1950 and 2018; there is no record of this type of hazard affecting people or infrastructure [2,52,56,57]. The largest of these landslides occurred in 1967 when 15 million cubic metres of rock fell onto Steinsholtsjökull outlet glacier, north of the Eyjafjallajökull icecap. While less than half the debris was deposited on the glacier, it was enough to send a huge mass of air, ice, and water into the proglacial lake causing a wave 75 m high [52,58]. Two other large landslides took place in the Öræfi district: 4.5 million cubic metres fell on Morsárjökull in March 2007; and 5.4 million cubic metres fell on Svínafellsjökull, close to the current fracture, in February 2013 [2,56,57]. Based on current research, if the Svínafellsheiði fracture collapses in a single event, the mass movement would be between four and seven times as large as that on Steinsholtsjökull. In addition to the unprecedented scale, the Svínafellsheiði fracture represents the first time people and infrastructure have been exposed to this type of hazard in Iceland, and the first time a large landslide onto a glacier has been identified and the risk managed in advance [59]. These factors single it out as a new type of hazard in Öræfi and in Iceland more generally.

Areas exposed to the Svínafellsheiði fracture include the proglacial lake, glacier viewing area, terminal moraine, and areas behind the terminal moraine including Freysnes and two farms in Svínafell (formal public briefing attended by first author, October 24, 2018). In June 2018, an estimated 1500 people spent some period of time in the

Fig. 6. Town hall meeting about the fracture, Hof, October 24, 2018.

exposed area on an average day, this included local and non-local inhabitants, tourists, glacier guides and people driving on the road.[3]

4.2. Other hazards

Other hazards in the area have had a significant impact on the local environmental and the risk knowledge of inhabitants. In 1362, Öræfajökull erupted in what is considered the most powerful volcanic eruption in Iceland during historic times [60]. The eruption sent torrents of hot mud and water down outlet glaciers, destroying several settlements and depositing an estimated one billion cubic metres of volcanic ash across the surrounding area [39]. The annals of Oddi recorded in 1580 explain that "no living creature survived except one old woman and a mare." [61 : 489].

Although the next—and most recent—eruption of Öræfajökull in 1727 was smaller, eyewitness accounts still describe how the "glacier grew higher and swelled out one moment and then collapsed and sank inwards the next", the following day there were earthquakes and a "horrifying cracking sound as loud as thunder" [62 : 224-225]. These were followed by the eruption and glacial floods that "slewed down onto the lowland, like molten metal poured out of a melting-pot.'" [62 : 224-225]. More detailed accounts are provided of survival strategies from the 1727 floods including that "people saved themselves by getting on the tops of the houses" [63 : 14]. In July 2018, the Icelandic Meteorological Office announced that Öræfajökull was showing "clear signs of unrest" [56]; a year later the warning had been downgraded to normal levels.

Approximately 50 km north-east of Freysnes, the Grímsvötn volcano lies beneath 700 m of icecap. The most active volcano in Iceland, Grímsvötn typically erupts every ten years, sending glacial floods down the Skeiðarárjökull outlet glacier, 10 km east of Freysnes [64].

Historically, crossing glacial rivers in Öræfi was often treacherous. However, this hazard has faded since the construction of a bridge over Skeiðará river in 1974. Another hazard emerged during the Little Ice Age (1500–1890) as advancing glaciers engulfed several farms in the area; with glaciers in retreat, this no longer represents a threat. Snow avalanches are common in other regions of Iceland but have only caused damage or deaths in two sites in Öræfi since settlement [65]. Finally, the Öræfi district is prone to violent storms and hurricane-force winds especially in the winter months.

[3] In peak tourist season of early June 2018, rough estimates of daily exposure rates were as follows: 25 local and 55 non-local inhabitants in Freysnes (24 h), 4 local inhabitants in two Svínafell farms (24 h), up to 200 tourists at the hotel (14 h), 50 glacier guides (5 h), 800 tourists on glacier walks (3 h), 1200 people predominantly tourists passing on the road (0.25 h) (S.4, LI.1, GG.3; [36]. When glacier operations were moved to another glacier after 22 June 2018, the rate of exposure for guides and glacier tourists decreased from several hours in high-risk areas on the glacier surface to approximately 15 min in lower-risk areas along the road. However, roughly 1500 people still spent some period of time in the exposed area on an average day during peak season. (RM.2).

5. Results and discussion

This section presents the results of our research and discusses the findings. The first sub-section explores how knowledge of the land has been fostered through traditional sheep gathering practices, and how this led to the discovery of the fracture. The following sub-sections unpack the role of local knowledge in different aspects of DRRM including: understanding warning signs, predicting potential impact, planning response strategies, and participating in formal DRRM processes. Comparisons are made to local knowledge of other hazards in the area especially glacial flooding triggered by Grímsvötn. The findings are based on informal discussions, semi-structured interviews, study trips to the field site, and firsthand experience of the public risk briefings. In contrast to the area around Katla, the few mythical folklore stories told in Öræfi did not cover natural hazards.

5.1. Sheep gathering and knowledge of the land

Every year, sheep across Iceland are released to lowland pastures, common highland pastures and mountains to graze for the summer months. Then in the autumn, farmers scale the mountains, cross valleys and sweep through the lowlands gathering sheep and rounding them into communal pens. Sheep gathering has a long history in Iceland with written descriptions dating back to 1220 (Ref. [66]. While sheep farmers are now a minority of the population, norms derived from this practice remain embedded in Icelandic culture and continue to influence government decisions. Sheep farming practices continue to be largely carried out as they have been for centuries [67].

Farmers in Freysnes and Svínafell own approximately 1100 sheep out of an estimated 4000 sheep in the district (RM.2; LI.12). In the mountainous areas of Öræfi, the sheep are gathered on foot. On Svínafellsheiði, a team covers the landscape in a coordinated manner to ensure that no sheep is overlooked. Interviewees recalled hauling sheep up cliffs with ropes (LI.10), going deep into glacial crevasses to search for sheep (LI.15), and herding sheep across glaciers (LI.1; LI.3; LI.11). On Svínafellsheiði, four to ten people gather the sheep in a single day. For the whole district, the gathering takes about eight full days with several additional days to locate any missing sheep (LI.10; see Fig. 5).

The same people typically gather the sheep each year, with value placed on the skills and knowledge of veterans. Young or inexperienced people learn by listening to stories told by adults, and following their lead (LI.10; LI.12; LI.15). This acquisition of local knowledge resonates with Pálsson's analysis of how Icelandic fisherman learn their trade, by actively engaging with their environment [73].

From the perspective of hazard identification, an important element is that people move through the landscape differently to when they hike or conduct other activities in the mountains. Sheep gathering requires that people cover the area extensively and move through terrain where they would not normally venture:

> It's also a very different way of hiking the mountains when you're sheep herding because you're going to places where you would never have to go or you never think that you could go there. So you learn the to know the mountain in a very different way. (LI.10)

> For sheep herding, people go into places where nobody would dare to go because the sheep go crazy places. And people walk on a section with a drop of 200 m below and it's like 'yeah you just have to go there'. I think they're also pretty proud of it. They're like 'yeah we went there, nobody goes there'. (LI.10)

During and after the sheep gathering, people discuss how the gathering was conducted, how the sheep reacted, and anything else noteworthy (LI.13). This analysis is important for reviewing and updating the collective knowledge of local inhabitants.

Another important factor is the frequency. One inhabitant emphasised that "if you are just going once or twice in a lifetime you don't have the same feeling for the land as a farmer that goes twice each year" (LI.11). In this way, local people develop a practical and intimate knowledge of the landscape that they continue to update and renegotiate each year. A French glacier guide compared the in-depth knowledge Icelandic farmers have about the mountains to the situation in France:

> In Iceland the farmers do extensive farming with their sheep, so they have a better look at the mountains. Even though they don't live in the mountains—they're not there 24 hours a day—but they still go there. And they go everywhere, and they check and monitor their land. In Europe, there is nobody in the mountains, people just pass through the land. But if you don't go every year to the same areas, then you will not notice the change. They are closer to their land here. (GG.8)

In many ways the sheep gathering acts as an unofficial annual land survey conducted by people who have an intimate knowledge of the landscape. Typically this knowledge is not recorded but rather transferred from generation to generation orally and through the practice of sheep gathering. This unofficial survey has yielded important observations, including the discovery of the Svínafellsheiði fracture.

5.2. Discovery of the fracture

In 2014, farmers discovered the fracture in an area rarely visited except when gathering sheep. Based on local knowledge built up through sheep gathering, the farmers were aware that the fracture had not been there previously. None of the interviewees were surprised that farmers discovered the fracture when gathering sheep (LI.10; LI.12). Instead locals mentioned that "a farmer knows his land very well… they go year after year after year to the same places" (LI.13).

Before the fracture was discovered, there was a dearth of human and financial investment in the study of large landslides in Iceland. This is likely to be common in cases where a country has had little or no past experience with a certain type of hazard. A risk manager reflected that in Iceland:

> we have been researching *jökulhlaup* [glacial floods] for decades, but landslides are something that we haven't looked at much. If you go to the university here I guess you would easily find fifty or sixty people that have a good knowledge and have done some research in *jökulhlaup*, you probably find two or three that have done some real research on landslides (RM.2).

Prior to the discovery of the fracture, there had been no country-wide assessment of landslide risks. Given the general lack of scientific research into large landslides around glaciers, the local knowledge gained through sheep gathering proved critical in the discovery of the hazard. Local people were well-positioned to identify this new type of hazard based on their in-depth understanding of the terrain and conditions faced in the area.

5.3. Warnings signs

There is an expansive body of local knowledge in Öræfi about flooding triggered by Grímsvötn, which typically occurs every ten years. The short return period means that even young farmers have had first-hand experience of the floods (LI.12). Several interviewees recalled a farmer who could accurately predict glacial flooding in the 1960s, even when "scientists had no idea." (LI.15). He would observe the Skeiðarárjökull outlet glacier every morning from his window, and take note of its position (LI.13). Over time he observed that the glacier would rise in relation to the mountain several days before a flood emerged (LI.10; LI.11). A local woman recalled that "he told me himself that you see over the glacier to the mountain, when he saw it rising he said now the river is preparing to come." (LI.11). In this way, through regular monitoring and in-depth understanding of the surroundings developed over decades, he was able to predict flooding with a high degree of accuracy. Other flood indicators included a change of colour of the river water (LI.16) and a sulphuric smell (LI.13). People could build up this detailed knowledge because the flooding "was so regular and you had multiple floods in one lifetime, so people got a chance to actually study it, understand it and build up some knowledge" (LI.10). One interviewee explained that "people studied that [the flooding of rivers] really closely because it really mattered for their wellbeing and lives" (LI.10), others mentioned cases in which people had to flee the floodplains for their lives (LI.15).

In terms of Öræfajökull, interviewees indicated that an eruption would typically be preceded by a series of earthquakes and loud crack (LI.13). This has been supported by scientific investigation. Another warning sign was that silverware would become tarnished due to increased levels of sulphur in the air and water (LI.3; LI.11). In general, however, people noted that there were relatively few local stories and oral histories from the 1362 eruption with one woman reasoning that if "everyone died in the eruption, then if there were stories they wouldn't have survived…they would have died with the people." (LI.10).

The extensive body of local knowledge about warning signs of Grímsvötn flooding contrasts to the lack of information on warning signs for a large landslide from Svínafellsheiði. Following the 2013 landslide onto Svínafellsjökull, many locals were not aware of the collapse until several days later when they noticed it by coincidence (LI.10; LI.13; LI.16). One woman explained that "people were driving by the glacier and were like 'oh, there was a slide on it'" (LI.10). Only one local inhabitant interviewed was aware that something had happened at the time because his horses were distressed; he made the connection when he found out about the landslide days later (LI.11). A local glacier tour operator recalled that in the days before the landslide:

> there was very much rain and we cancelled tours. Then, when I came back, I didn't notice that the slide had fallen. It was very cloudy and rainy. Luckily, because of the terrible rain, nobody was on the glacier when it fell. (LI.15)

Based on this experience he reasoned that a large landslide resulting from the Svínafellsheiði fracture may be triggered by heavy rainfall (LI.15). Another local inhabitant believed that it would occur in early spring as the ground starts to thaw (LI.10), while a third mentioned that if he saw the sheep coming down from the mountain in the middle of summer, he would take this as an indication that "something is happening up in the mountains [such as an eruption or a landslide], then it would be better for us to go away" (LI.11). In discussing warnings, one local inhabitant commented that someone in her family would receive a premonition of the landslide and pass on the warning to other people in the community (LI.10). Finally, some inhabitants believed that the landslide would occur without any warnings based on their experience with volcanic eruptions: "even though the volcanoes are watched and measured a lot, there are many eruptions that come like [finger click] always as a surprise" (LI.5).

There was a high degree of uncertainty and a wide range of opinions expressed about when the fracture would collapse. One local inhabitant typified this doubt when she mentioned "we never know what's going to happen and we don't know if it's going to fall down in ten years, 20 years or tomorrow" (LI.6). This understanding has been informed by scientific investigations which suggest that it could collapse with less than 60 s warning (LI.7). Interviewees often referred to scientific knowledge when discussing warning signs and the timing, indicating a greater dependence on science for this type of hazard compared with other hazards in the area.

Part of this lack of understanding of warning signs may stem from the novelty of this hazard, however it may also reflect the nature of large landslides. Carey et al. point out that the exact location and timing of slope failures are notoriously difficult to predict in any context [21]. Compared with warrning signs for eruptions and glacial flooding, \people had a much lower level of confidence about meteorological or other conditions that may act as a warning sign or increase the risk of a large landslide. Some interviewees, however, drew on their experience of smaller landslides and other hazards in the area, to speculate on factors that may increase the likelihood of collapse (LI.3; LI.15).

In explaining the large body of local knowledge about Grímsvötn flooding, local inhabitants pointed to a number of factors including the short return period, the high potential danger, and the typically low mortality rate. The long return period of Öræfajökull eruptions and the high mortality rate of the 1362 eruption were associated with a lower level of local knowledge. The relative rarity of large landslides onto glaciers in Iceland and dearth of experience people have with this kind of hazard were understood to be key factors in the lack of local knowledge on warning signs.

5.4. Potential impact

As with warning signs, the detailed local knowledge related to the likely effects of Grímsvötn flooding contrasted with the relative lack of knowledge about the potential effects of a large landslide triggered by the Svínafellsheiði fracture. All local inhabitants interviewed had a detailed understanding of the different paths of historic floods triggered by Grímsvötn. The floods of 1913 and 1921, for example, were remembered to be particularly destructive for farming land (LI.11). The location of houses in Svínafell, traditionally built part-way up the slope, reflected these flood paths. Over the past hundred years, man-made flood barriers and dykes have been erected to alter the direction and intensity of these floods. In response, people have shifted several houses in Svínafell further downhill to flatter and more fertile areas (LI.16). However, some of these buildings are now potentially exposed to runout from a large landslide triggered by the Svínafellsheiði fracture.

An understanding of the areas that will be affected by a collapse of Svínafellsheiði fracture, and specifically whether the runout will affect Freysnes or if the settlement will be protected by the terminal moraine, has been contested between scientific and local knowledge. Scientists and risk managers interviewed between October 2018 and January 2019, predicted that Freysnes would be affected directly, cautioning that the land/ice/water/air slurry may become airborne after reaching the terminal moraine, with catastrophic results for Freysnes (RM.2, S.1, S.2). When presented to the local community in a formal public briefing, this interpretation was questioned by several locals during question time and in open discussions afterwards (attended by first author, October 24, 2018). Drawing on their experience with glacial floods, several locals maintained that the runout would follow the path of the rivers on either side on Freysnes rather than affecting the settlement itself (LI.2., LI.5.). "With floods caused by the glacier, the runoff has always come down these two rivers", one local reasoned, "why would this be any different?" (Informal discussion, October 24, 2018).

Updated scientific modelling conducted in mid-2019 suggested that the runout would likely follow the existing flood patterns and avoid Freysnes. Scientists predict, however, that the runout will be more likely to affect Freysnes as the volume in the proglacial lake increases (S.4). Even after the presentation of this updated modelling, some local inhabitants remained uncertain about the runout zone: "they believe that the moraine will be a shelter that divides the flood but we do not know how much flood will come, how much water. Maybe it won't just flood, maybe it will jump [due to the terminal moraine as first predicted by scientists]" (LI.12). Another interviewee added, "I hope so but you never know. It's really hard to calculate these things." (LI.12).

Even though people in the area have not faced a large landslide onto a glacier anywhere close to this size, they drew on typical impact patterns from other flooding hazards in an attempt to deduce potential effects. While local knowledge based on lessons learnt from glacial floods was ultimately supported by scientific investigation, these two forms of knowledge could have continued to run counter to each other.

5.5. Response

No large landslides have affected people or infrastructure in Öræfi. As a result, there are no stories of effective or ineffective responses for this specific type of hazard. This contrasts to the flooding from Grímsvötn. While flooding has not typically led to fatalities, people told many stories of survival and near-miss responses. These oral histories included stories of people collecting bird-eggs on nearby cliffs who were saved by people riding to warn them of an imminent flood. Other heroic stories involved people rowing into the floodwaters to rescue sheep (LI.15). Many interviewees also recalled stories of daring river crossings, with knowledge about how to cross rivers safely passed down through families (LI.11).

In general, there was a high degree of uncertainty about how people should respond to a large landslide caused by the fracture, including what is the safest places to take shelter. After attending public hazard briefings one local woman mentioned that she started to reconsider her previous plan of taking shelter in the basement of a nearby house, as scientists predicted that the house would be overrun by the landslide (LI.1.). She was left not knowing the safest way to react. Compared with other types of hazards experienced in the area, people did not have a clear idea of how to respond in the case of a large landslide, or the most effective survival strategies to follow.

5.6. DRRM processes

This study found that Icelandic authorities typically engaged and involved local communities in DRRM planning and preparedness activities for the Svínafellsheiði fracture. Based on their study of the DRRM response to warning signs of a potential eruption from Katla in 2006, Bird et al. determined that this participatory focus developed as a result of local inhabitants—especially those with local knowledge—rejecting top-down disaster management approaches [31].

Public hazard briefings represent a key forum whereby DRRM authorities drew on knowledge and experience of local inhabitants about the Svínafellsheiði fracture and surrounding area, to inform the development of DRRM plans (RM.2, RM.3; see Fig. 6). Bird et al. similarly identified public meetings as a forum where trust was developed between the locals and DRRM authorities in volcano risk management processes [69]. Planning workshops conducted in October 2018 by the

DRRM authorities with locals directly exposed to the Svínafellsheiði fracture, were interactive and involved frank discussion among participants. Local residents expressed their appreciation of the generally inclusive approach by authorities, with one local inhabitant reflecting that the authorities were "ready to listen to the people who live here." (LI.15).

There were several examples in which DRRM authorities and scientists were able to draw on local knowledge to improve their understanding of the hazard or the planned response. For example, one attendee remembered:

> In the last meeting, when they were presenting their findings, they showed some pictures that they took that morning from a plane. I think they said 'we think there is a new fracture here in Hafrafell' [next mountain west of Svínafellsheiði]. And then a farmer, said 'no, no, that is not a fracture, it is a sheep path. I always walk this path when I'm sheep herding.' And they said 'thank you for telling us so we don't have to hike up to find out that this is a path from the sheep not a new crack.' So that is an example of knowledge that farmers could add to the scientists. (LI.10)

The disaster management briefings mobilised the participation of the local population and played an important role in the exchange of information between the local community and authorities engaged in DRRM. While local inhabitants were typically involved in DRRM planning and preparedness, there were still areas of contention where local people did not feel that their voices were heard, including one DRRM decision that interviewees described as "a mistake" (LI.15). The main topics of contention involved specific policies, including the decision to limit access to the glacier for some activities but not restrict access entirely, and the decision to implement a no-build zone in the areas exposed to the fracture (LI.15). The effects of these decisions on the local community and their coping mechanisms warrant further investigation but lie beyond the scope of this article. Several interviewees were also frustrated that DRRM authorities did not always respect pre-arranged timeframes. For example one woman noted that "last autumn they said we would get answers in springtime, and now it is July and I think springtime is over. Maybe they are going to wait until the monitoring has been conducted for one year and I think that is in September or October, but why are they promising us springtime if it's not true." (LI.1). Such statements suggest that lapsed deadlines eroded local trust in the process. However, overall what emerges is a broadly participatory approach to DRRM in which authorities and scientists value, and draw on the knowledge of local inhabitants. That said, while local knowledge is taken into account, scientific knowledge still tended to be given greater weight for example in determining runout zones.

6. Conclusion

There is consensus in the DRRM literature about the importance of incorporating local knowledge [16,17]. With climate change, new hazards are increasingly emerging in areas where they were previously unknown. Building a better understanding of the role of local knowledge in DRRM in the context of emerging hazards is paramount. This ethnographic investigation of the Svínafellsheiði fracture helps illustrate how local knowledge has informed DRRM processes for a large landslide onto a glacier, a type of hazard that has not previously affected people or infrastructure in Iceland.

The case of the Svínafellsheiði fracture demonstrates how local knowledge can be instrumental in the discovery of emerging hazards. In the Öræfi district, local inhabitants develop skills and in-depth knowledge of the terrain through sheep gathering practices which, in many ways, acts as an unofficial annual land survey conducted by people who have an intimate knowledge of the landscape. Local people, especially those with customary practices of natural resource management, are often well positioned to identify changes in the terrain and conditions based on their in-depth understanding of their local area. This can be particularly important in the case of new hazards where large-scale funding for scientific research into a particular hazard is not yet available. The important role of local knowledge in discovering new types of hazards may be relevant to a range of slowly-emerging climate change-related hazards including floods, landslides, rising sea levels. The potential of local knowledge could be further capitalised upon in Öræfi and elsewhere, if inhabitants were engaged systematically through citizen science initiatives incorporated into formal DRRM processes. This represents an avenue for further investigation.

In terms of warning signs, potential impact and response, we found there was an extensive body of local knowledge pertaining to flooding from Grímsvötn, and, to a lesser extent, eruptions of Öræfajökull. Comments from local people suggest that there was a greater volume of hazard-specific local knowledge when a hazard had a relatively short return period, such as flooding from Grímsvötn, enabling people to make observations and test theories several times within a lifetime. A small number of local inhabitants attempted to draw lessons learnt from other types of hazards to better understand the warning signs and potential impact of Svínafellsheiði fracture, with varying success. Meanwhile, local knowledge of other hazards provided little guidance on how to respond in the case of a large landslide. These findings suggest that while it is important to draw on local knowledge, it may be less directly applicable for understanding the predicted impact and effective response strategies for new hazards.

Finally, this study found that local knowledge is not just relevant to DRRM processes in less developed and developing countries. McWilliam et al. argue that "local knowledge for DRR is particularly important in countries where government capabilities are limited." [68: 1]. This has been confirmed through a large body of scholarship. However, this case adds support to the contention that local knowledge is also important in countries with well-established and well-funded DRRM processes. Even in highly developed countries, implementing effective DRRM strategies requires an integrated approach that involves local inhabitants, scientists and DRRM authorities, bringing together the knowledge of all three groups.

Funding

This work was kindly supported by the Doctoral Grants of the University of Iceland Research Fund (Rannsóknasjóður Háskóla Íslands), Iceland [grant number 1010–101343, 2019–2022].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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