Paraglacial exposure and collapse of glacial sediment: The 2013 landslide onto Svínafellsjökull, southeast Iceland

Daniel Ben-Yehoshua1,2 | Þorsteinn Sæmundsson2 | Jón Kristinn Helgason3 | Joaquin M. C. Belart2,4 | Jón Viðar Sigurðsson5 | Sigurður Erlingsson1

1Faculty of Civil and Environmental Engineering, University of Iceland, Reykjavík, Iceland
2Institute of Earth Sciences, University of Iceland, Askja, Reykjavík, Iceland
3Icelandic Meteorological Office, Reykjavík, Iceland
4National Land Survey of Iceland, Akranes, Iceland
5Iceland Glaciological Society, Reykjavík, Iceland

Correspondence
Daniel Ben-Yehoshua, Faculty of Civil and Environmental Engineering, University of Iceland, Reykjavík, Iceland.
Email: dby@hi.is

Funding information
Icelandic Centre for Research, Grant/Award Number: 207136-052; Landsvirkjun, Grant/Award Number: NÝR-09; University of Iceland Research Fund, Grant/Award Number: 156364

Abstract
In the last 130 years, Icelandic glaciers have experienced significant mass loss, and numerous paraglacial slope failures have been documented in the country. One such failure occurred in late February 2013, when a large landslide fell onto the Svínafellsjökull outlet glacier in southeast Iceland. Digital elevation models and aerial imagery were used to quantify the glacial and paraglacial changes leading up to the event, reconstructing the processes that occurred during the landslide and the effects of the debris on the glacier surface. Between 1994 and 2013, glacier thinning and glacier-retreat exposed a steep lateral moraine perched on bedrock which later failed and caused the landslide. Increased pore-water pressure after an intense rainstorm and potential fluvial erosion at the toe of the source area are considered to be the primary trigger mechanisms. Morphological evidence indicates multiple phases of movement in the source area and a highly water-rich debris avalanche on Svínafellsjökull. The debris reached a runout distance of almost 4 km and affected an area of about 1.7 km². The estimated displaced volume of the slide is $5.33 \pm 0.08 \times 10^6$ m³, making it the largest documented landslide originating from unconsolidated material in Iceland. The glacier surface ablation beneath the debris deposits was reduced due to insulation, whereas increased glacier thinning was observed surrounding the deposits, resulting in an up to 35 m height difference between the debris-free and the debris-covered ice by 2020. This study shows that large catastrophic landslides can originate from, and result in the formation of ice-cored or frozen sediment complexes and highlights the potential risk coming from similar slopes around the world as glaciers continue to recede and the number of paraglacial landslides increases.

KEYWORDS
debris slide, glacier retreat, ice-cored moraine, landslide, paraglacial adjustment

INTRODUCTION

Large gravitational mass-movements often occur within the paraglacial period of enhanced geomorphological activity conditioned by deglaciation (Ballantyne, 2002a; Porter, Smart, & Irvine-Fynn, 2019) in both rock and sediment slopes (Ballantyne, 2002b). Retreating valley glaciers often leave behind lateral moraines which are deposited on glacially eroded bedrock. These moraines can be extremely steep (up to around 70°) and can remain stable for decades after deglaciation (Curry, Sands, & Porter, 2009) but may become unstable at a certain threshold (Blair, 1994).

Destabilization of paraglacial slopes is widely associated with glacier recession (Cody et al., 2020; Coe, Bessette-Kirton, & Geertsema, 2018; Evans & Clague, 1994; Kos et al., 2016; McColl & Davies, 2013) and/or degradation of permafrost (Czekirda et al., 2019; Gruber & Haeberli, 2007; McColl, 2015; Morino et al., 2019; Sæmundsson...
et al., 2018) or thawing of buried ice (Holm, Bovis, & Jakob, 2004; Schomacker & Kjær, 2008; Tonkin et al., 2016). In recently deglaciated mountain valleys, debris flows are the most dominant agent of erosion of sediment-mantled rock slopes (Ballantyne, 2002b; Cody et al., 2020). Most commonly, the adjustment of sediment-mantled slopes occurs through long-term accumulation of small-scale mass movements (Curry, Cleasby, & Zukowskyj, 2006). Large failures of lateral moraines are less documented but have been associated with fast glacier thinning/retreat rates (Blair, 1994; Cody et al., 2020; Hewitt, 2013; Kumar et al., 2019). Ice-cored lateral moraines are especially susceptible to rapid failure due to a loss of binding force within the sediment during thawing and the simultaneous creation of new pathways for water (Ewertowski & Tomczyk, 2020; Patton, Rathburn, & Capps, 2019). The release mechanisms for ice-cored glacial sediment are usually a combination of slumping, transitional sliding, debris flows and block falls (Ballantyne, 2002b). Catastrophic landslides are often triggered by certain short-term factors such as increased pore-water pressure and/or erosive undercutting through flooding, both commonly caused by increased precipitation, often in combination with snowmelt (Crosta & Frattini, 2008; Decaulne et al., 2010; Sæmundsson, Petursson, & Decaulne, 2003; Wieczorek, 1996). Seismic activity is also a common trigger for gravitational mass movements (McColl, 2015; Sæmundsson, Petursson, & Decaulne, 2003), particularly in geological settings such as Iceland (Einarsson, 1991; Sigmundsson et al., 2020). Paraglacial slope failures commonly emplace debris on glacier surfaces (Deline et al., 2014) where, depending on the thickness, it insulates the underlying ice efficiently (Reznichenko et al., 2010; Sæmundsson et al., 2011; Shugar et al., 2012). Large amounts of debris on a glacier surface often leads to the formation of dead-ice environments at the glacier margin (Shulmeister et al., 2009) and can form atypical moraine complexes after glacier retreat (Deline et al., 2014; Reznichenko, Davies, & Alexander, 2011).

Most glaciers on the south coast of Iceland reached their Little Ice Age (LIA) maximum extent around 1890 (Björnsson, 2017; Evans, Archer, & Wilson, 1999; Evans et al., 2019; Gudmundsson, 1997; Gudmundsson, Björnsson, & Pálsson, 2017; Þórarinsson, 1943; Sigurðsson, 2005). After the LIA, the glaciers retreated at a relatively constant rate until 1970–1980 when a period of slow but significant glacier advance started, lasting until 1994 (Adalgeirsdóttir et al., 2020; Evans et al., 2019; Sigurðsson, 2010). Since 1994, Icelandic glaciers have been retreating at varying rates, with the highest rate of ice loss between 1994 and 2010, and mostly slower rates since then (Adalgeirsdóttir et al., 2020). Observations from the Stykkishólmar weather station show a temperature rise of about 0.7°C over the 20th century and an increase of about 0.5°C per decade between 2000 and 2015 (Adalgeirsdóttir et al., 2020; Björnsson et al., 2018; Jónsson et al., 2014). During this time, summer air temperatures appear to have been the strongest driver of glacier recession in the southeast region (Bradwell, Sigurðsson, & Everest, 2013; Chandler, Evans, & Roberts, 2016). Iceland’s average annual precipitation increased from 1500 mm/yr to 1600–1700 mm/yr between 1980 and 2015 (Björnsson et al., 2018). Measurements from glacial rivers in Iceland show mechanical erosion rates of up to 10,200 t/km²/yr which rank among the highest documented values worldwide (Louvat, Gislason, & Allègre, 2008). These high rates are attributed to the presence of relatively young, glassy, volcanic bedrock in heavily glaciated terrain. Gravitational mass movements are ubiquitous in Iceland and pose a significant threat to settlements and other infrastructure in almost every part of the country (Bell & Glade, 2004; Decaulne & Sæmundsson, 2007; limer et al., 2016). Over the last decades, several large paraglacial slope failures of different types have been reported in Iceland (Table 1) and their timing generally coincides with periods of glacial retreat (Hanna, Jónsson, & Box, 2004; Hannesdóttir et al., 2015; Sæmundsson & Margeirsson, 2016). When looking at large slope failures (> 10⁵ m³) in several high mountain regions of the world there seems to be a trend of increasing frequency in the last three decades compared to the previous part of the 20th century (Fischer, 2009; Huggel, Clague, & Korup, 2012; Liu, Wu, & Gao, 2021). This trend seems to be true for Iceland too, but must be further investigated to avoid statistical bias caused by more reported landslides as a result of improving remote sensing techniques.

In line with the apparent trend of increasing paraglacial slope instabilities, a landslide in late February 2013 resulted in a large debris avalanche onto Svinafellsjökull, an outlet glacier on the western slopes of the Öræfajökull volcano, southeast Iceland (Figures 1 and 2). The landslide occurred after a strong rain event and involved a large debris volume which covered a significant part of Svinafellsjökull glacier surface, but hitherto there have been no published studies of the event or the long-term effects of the debris on the glacier. We present the investigation of the causes and effects of the landslide as a process-based quantification study of paraglacial activity and its implications for geomorphic change and landslide hazard in freshly deglaciated terrain.

2 | GEOGRAPHIC AND GEOLOGIC SETTING

Iceland is located in the North Atlantic Ocean just below the Arctic Circle. The country’s landscape is dominated by volcanoes and glaciers and is exposed to a cool North Atlantic maritime climate. Located in the southeast of the country, Vatnajökull is Iceland’s largest ice cap with 28 temperate outlet glaciers distributed around its margins (Björnsson, 2017). The Öræfajökull central volcano is covered by an ice cap that forms the southernmost part of Vatnajökull. The summit plateau is just over 1800 m above sea level (a.s.l.), and north of it, Hvanndaðshnjúkur peak (2110 m a.s.l.) forms Iceland’s highest summit (Figure 1).

Öræfajökull ice cap has the highest mass-balance sensitivity to changes in temperatures and precipitation in Iceland (Belart et al., 2020). Adding to the complexity of the location, the volcano has produced two major eruptions in 1362 and 1727 which led to tephra fall, earthquakes, and extensive ice melt resulting in jökulhuflaps (Þórarinsson, 1958; Roberts & Gudmundsson, 2015).

One of the outlet glaciers on the western slope of Öræfajökull ice cap is Svinafellsjökull, which emerges from the plateau of the ice cap and runs down a 1000 m high, steep, and heavily crevassed slope between Hvanndaðshnjúkur and the peaks of Mount Hrútsfjall. The glacier is aligned northeast to southwest and flows for about 7 km through a steep valley confined by Mount Svinafell to the south and Mount Hrútsfjall to the north. The ablation area of Svinafellsjökull has
lowered between 60 and 100 m during 1945–2011 (Belart et al., 2020) and formed two proglacial lakes at the glacier snout (Gudmundsson et al., 2020).

Below the northeast face of Skárðatindur peak (the highest summit of Mount Svínafell) the Dyrhamarsjökull outlet glacier, a former tributary glacier, flows towards Svínafellsjökull from the southeast.

The source area of the slide is located at the former confluence of Svinafellsjökull and Dyrhamarsjökull at the area around N64.0131°, E16.785° (red star in Figures 1 and 2). Due to its location just below the steep northeast face of Skárðatindur peak (Figure 3), the source area only receives direct solar radiation during morning hours in the middle of summer.

Mount Svinafell consists mostly of sub-glacially erupted basic to intermediate lavas and a number of tillites, all of which are younger than 0.781 Ma (Helgason & Duncan, 2013). These lithologies have been emplaced upon older (1.945–2.581 Ma) tholeiite basalts lavas.

**TABLE 1** Significant paraglacial slope failures in Iceland

| Place                        | Type                        | Year    | Reference                                                                 |
|------------------------------|-----------------------------|---------|---------------------------------------------------------------------------|
| Steinsholtsjökull            | Rock avalanche              | 1967    | Kjartansson (1967)                                                       |
| Jökulsjargilisjökull         | Rock avalanche              | ~ 1976  | Sigurdsson and Williams (1991)                                             |
| Krossárjökull                | Debris flow                 | 2003    | Torfason and Jónsson (2005)                                               |
| Mosakambur                   | Rockfall                    | ~ 2004  | Sigurdsson (2010)                                                         |
| Morsárijökull                | Rock avalanche              | 2007    | Decauville et al. (2010); Sæmundsson et al. (2011)                        |
| Svinafellsjökull             | Debris slide/avalanche      | 2013    | This study                                                                |
| Þverártingsjökull (west)      | Debris avalanche             | ~ 1999  | IMO – NL database                                                          |
| Tungnakvislaþjökull          | DSGSDb                      | ~ 1945–ongoing | Sæmundsson et al. (2020)                                      |
| Tindfjallajökull             | DSGSDb                      | late 1990s–ongoing | Arnar (2021)                                          |
| Mount Hríutsfjall (south)     | Rockslide                   | early 2000s–ongoing | This study                                           |
| Mount Svinafell              | DSGSDb                      | ~ 2004–ongoing | Sæmundsson et al. (2019)                                        |
| Mount Miðaftanstindur        | Rockslide                   | ~ 2014–ongoing | Smith (2020)                                             |

*aJoint database of Icelandic Meteorological Office (IMO) and Icelandic Institute of Natural History (data available upon request).

bDSGSD – deep seated gravitational slope deformation.
Digital elevation models used in this study include: (Helgason & Duncan, 2013). East of Skardatindur peak, an intrusion of rhyolitic/dacitic composition has been described in a geological map by Roberts and Gudmundsson (2015). In their map, the source area of the landslide addressed in this study is marked as ‘Holocene sediments and tephra on flanks’. This formation is deposited on top of the tertiary basaltic lava layers identified by Helgason and Duncan (2013).

Since the LIA the valley which hosts Svinafellsjökull has been undergoing rapid changes (Adalgeirsdottir et al., 2020; Everest et al., 2017; Gudmundsson et al., 2020). Not only has Svinafellsjökull retreated and thinned substantially, but gravitational mass movements such as rock fall and serac collapses are daily occurrences in the valley. In addition to the landslide addressed in this article, a deep-seated gravitational slope deformation (DSGSD) of about 60 to 100 m³ is being investigated on adjacent Mount Svinafell (Sæmundsson et al., 2019), and a previously undocumented slow moving rock slope failure on the south side of Mount Hrútsfjall (latitude 64.030732°, longitude 16.773265°) was recently discovered. In 2007, a large rock avalanche occurred on Morsárjökull glacier, 10 km north of Svinafellsjökull (Decault et al., 2010; Sæmundsson et al., 2011).

Geomorphological analysis of proglacial moraines of three neighbouring outlet glaciers indicates that Svinafellsjökull has had comparatively high supraglacial and englacial sediment input (Thompson, 1988; Lee, Maclachlan, & Eyles, 2018), which suggests higher gravitational mass-movement activity in the valley. This collection of evidence highlights the fast rate at which the paraglacial environment at the outlet glaciers of Öræfajökull ice cap, and particularly in the Svinafellsjökull valley, adjusts to glacier retreat.

The glacial outwash plains around Öræfajökull volcano experience a relatively mild oceanic climate with a mean annual temperature range of about 11°C and around 150 days of precipitation per year (Einarsson, 1984; IMO, 2020). Average temperatures during winter months are typically around 0-4°C, and daily minima are rarely lower than −5°C at Fagurhólsmýri weather station, approximately 20 km southeast of Svinafellsjökull. Mean annual precipitation is around 1800 mm south and west of Öræfajökull volcano (Bradwell, Sigurdson, & Everest, 2013). However, the precipitation increases dramatically on the slopes of Öræfajökull volcano with an annual average of up to 10,000 mm (water equivalent) at the summit plateau (Crochet et al., 2007). The source area of the slide described in this article is located halfway between the glacial outwash plain and the summit of Öræfajökull volcano, and therefore the annual precipitation at the site is expected to be between 1800 and 10,000 mm/yr.

### TABLE 2 Digital elevation models used in this study

| Year | Ground sampling distance (m) | Positional accuracy (± m) | Method/reference |
|------|-----------------------------|---------------------------|------------------|
| 1994 | 5                           | 0.5                       | Photogrammetry (Belart et al., 2020) |
| 2003 | 10                          | 0.8                       | Photogrammetry (Loftmyndir ehf.) |
| 2011 | 2                           | <0.5                      | LiDAR (Johannesson et al., 2013) |
| 2013 | 2                           | 1                         | ArcticDEM (Porter et al., 2018) |
| 2019 | 0.2                         | ~5                        | Photogrammetry (this project) |
| 2020 | 4                           | 1                         | Pléiades imagery (Sigmundsson, 2019) |
The volume \( V \) was calculated (Equation 1) by multiplying the average negative elevation change \( \overline{dh} \) in the source area by the size of the source area \( A_s \):

\[
V = |\overline{dh} \cdot A_s|
\tag{1}
\]

The uncertainty was calculated (Equation 2) by using the normalized median absolute deviation (NMAD) approach explained in Höhle and Höhle (2009) and Berthier et al. (2014).

\[
\text{NMAD} = 1.4826 \cdot \text{median}(|\Delta h_j - m_{\Delta h}|)
\tag{2}
\]

where \( \Delta h_j \) stands for the individual errors and \( m_{\Delta h} \) denotes the median of the errors.

The elevation data from 2011 was subtracted from the 2013 data in an area unaffected by the slide right next to the source area with a similar aspect direction and slope angle (Figure 4). After the DEM co-registration, the average elevation difference in stable areas should be zero. With the value for NMAD, we can calculate (Equation 3) the volume uncertainty \( \Delta V \):

\[
\Delta V = \text{NMAD} \cdot A_s
\tag{3}
\]

To compare the runout of the landslide with other events, the Heim’s ratio \( \mu_H \) (a.k.a., apparent friction) was calculated (Equation 4) (Lucas, Mangeney, & Ampuero, 2014; Parez & Aharonov, 2015; Peruzzetto et al., 2020) using the ratio:

\[
\mu_H = \tan(a) = \frac{H}{L}
\tag{4}
\]

where \( H \) is the total drop height, \( L \) is the total horizontal travel distance along the flow path and \( a \) is the angle of reach. These numbers were measured from the respective elevation data in QGIS 3.16.1 along the profile E–F in Figure 5. The area covered by the debris after the slide is referred to as \( A_d \).

Oblique aerial photographs of Mount Svinafell were taken during a helicopter survey in 2019. These images were compiled in the photogrammetry software Pix4D to create a three-dimensional-mesh and DEM for qualitative geomorphological analysis.

Morphological maps were created in QGIS 3.16.1 by qualitative analysis of available elevation data and aerial photographs. Only landforms and other morphological features in the direct vicinity of the area affected by the landslide were mapped.

The water catchment and the drainage network were calculated from the 2011 LiDAR (light detection and ranging) DEM with the ‘Generate Watershed’ tool in Global Mapper 20 by setting ‘Stream Cell Count’ to 500 and selecting ‘Discard Stream Starts Less than 100 m in length’. Subglacial and englacial water runoff was not considered in these calculations. Therefore, we regard these data as a rough estimate of the surface water drainage.
Daily precipitation and temperature data have been collected since 1964 at the Skaftafell farm, about 10 km west of the source area. A reading of the rain gauge is taken daily at 09:00 h and the temperature is measured every 10 min. The analysed precipitation record spans from 1 March 1964 to 31 December 2020.

Information about the timing of the landslide was collected through conversations and email communication with inhabitants of the Svínafell and Skaftafell settlements.

Table 3

| Parameter                          | Value       |
|-----------------------------------|-------------|
| Size of the source area (A_s)     | 205,852 m²  |
| Average elevation change (dh)     | −25.92 m    |
| Volume of removed material (V)    | 5,336,095 m³|
| NMADa                             | 0.41 m      |
| Resulting volume uncertainty (ΔV) | ±83,936 m³ (1.6%) |

*NMAD – normalized median absolute deviation.

![Figure 6](image-url)

**Figure 6** Morphological maps of the source area of the slide. Both maps show the same area at the same scale. (a) Pre-slide morphologic map (2011) showing the location of the lateral moraine overlaid by colluvial debris on top of glacially scoured bedrock. Profile A–B is a cross-section view of Dyrhamarsjökull illustrating the elevation change between 1994 and 2011 and subsequent loss of buttressing of the moraine surface on the right. The respective glacier margins of the same years are marked in the same map. (b) Post-slide morphology showing the landscape change within the source area in 2013. It shows clearly that most of the collapsed material was lateral moraine and the overlying colluvium. Profile C–D is illustrated in Figure 12 [Color figure can be viewed at wileyonlinelibrary.com]

Data from a seismic station about 5 km southwest of the source area was inspected but did not show any sign of landslide-triggered seismic signal during the timeframe in question and is therefore not included in this study.

4 | RESULTS

4.1 | Dimensions of displaced material

Based on the calculations described in Section 3, the respective parameters of the source area were computed and are shown in Table 3.

The calculated volume removed from the source area is $5.3 \pm 0.08 \times 10^6$ m³, which makes it one of the largest documented landslides in Iceland and the largest originating from unconsolidated material. The removal of material from the source area and its deposition on Svinafellsjökull are shown in Figure 5 by red and blue.
colour coding, respectively. After flowing 400 m towards the northwest on the initial failure slope and down Dyrhamarsjökull, the material filled up a meltwater channel with debris up to 38 m thick and then turned west down Svinafellsjökull. From there the debris moved down the southern margin of the glacier and partly reached its centreline. The landslide deposits affected an area ($A_d$) of approximately 1.7 km$^2$ and travelled a horizontal distance of ($L$) 3.95 km from the highest point of the source area to the farthest point of the deposit. The vertical fall height of the deposits was from 750 m down to 244 m, resulting in a total drop height ($H$) of 506 m. The Heim’s ratio can thus be calculated at $\mu_H = 0.128$, giving an angle of reach ($\alpha$) of 7.8°.

4.2 | Glacial retreat

Svinafellsjökull and Dyrhamarsjökull glaciers have retreated and thinned substantially since the mid-1990s. As shown in Figure 6(a), in 1994, Dyrhamarsjökull was still contributing to Svinafellsjökull, and the glacier surface reached high up on the lateral moraine. By 2003, Dyrhamarsjökull had thinned but still laterally supported the moraine. By 2011, the glacier surface of Dyrhamarsjökull next to the source area had thinned by more than 80 m compared to 1994, forming its own separate snout, disconnected from Svinafellsjökull. This averages to an elevation change rate of about $-4.7$ m/yr in that timeframe.

4.3 | Meteorological conditions prior to the event

The landslide most likely occurred around 20:00 h on 27 February 2013. An intensive rainstorm occurred between the morning of the 24th and the morning of the 26th in southeast Iceland with the general wind direction coming from the southwest. According to the weather forecast by the Icelandic Meteorological Office (IMO) from 24 to 25 February 2013 (IMO, 2013), the precipitation peak of the storm was expected between 06:00 h and 12:00 h on the 25th. Temperatures at elevations below 2000 m were expected to be above freezing, and expected precipitation on the western slopes of Öræfajökull volcano was above 10 mm/h. A flood warning was issued by the IMO for several rivers in south Iceland but not for the southeast. About 9 km northwest of the source area of the debris slide, the weather station in Skáftafell recorded 307 mm of cumulative precipitation between 09:00 h on 24 February and 09:00 h on 26 February and temperatures of over 8°C in the timeframe between 18 and 28 February (Figure 7).

This means that 17% of the average annual precipitation (1793 mm – source IMO) fell in 48 h during a 10-day warm spell. The cumulative precipitation since the last freezing temperatures in Skáftafell was almost 400 mm. Figure 8 shows the 30 days with the highest measured precipitation at the Skáftafell weather station between 1 March 1964 and 31 December 2020. This illustrates that over the entire timeframe, there were only 3 days with higher precipitation than that of the 24–26 February 2013. When the two red bars on the histogram are considered as a single rain event, they constitute the highest precipitation measured for a 48-h period during the entire timeframe. In addition to occurring during the days leading up to the slide, this unusually intense rainfall caused significant snowmelt in the mountains and resulted in flooding in southeast Iceland, destroying paths, walking bridges, flood protections and a dam at a local hydro-power station at the Bújargil gorge (Hreinsdóttir, 2013). The slide most likely occurred a day after the intensive rain ceased at Skáftafell. According to the weather forecast from 26 February 2013, the western slopes of Öræfajökull volcano were still expected to experience some (~1 mm/3 h) precipitation in the evening of 27 February. It has to be kept in mind that this is only the value forecasted by the IMO, and no absolute measurements are available for the source area specifically.

4.4 | Timing of the event

After the rainstorm, the visibility on Svinafellsjökull remained poor due to rain and low clouds, so the debris on the glacier was not noticed until 28 February 2013. There were no eyewitnesses of the event or seismic measurements which could identify the exact timing. However, a ranger at the Skáftafell national park was outside, about 9 km away from the slide site, on the evening of 27 February and heard an ‘enormous rumbling noise’ lasting for up to 20 s at around 20:00 h. He thought it sounded like a large rockslide but was not able to identify the origin of the noise as it was dark.

4.5 | Morphological analysis

In order to understand the processes during the slide, the pre- and post-landslide morphology of the source area (Figure 6a,b) was analysed by comparing DEMs, morphological maps and aerial photographs.

![Figure 7: Temperature and precipitation measurements in Skáftafell from 16 February 2013 to 3 March 2013. The red line indicates 20:00 h on 27 February 2013 when the witness heard the noise, presumably caused by the landslide. The bar chart illustrates precipitation in mm/24 h, and the dashed line shows the cumulative precipitation since the last freezing event on 16 February 2013. [Color figure can be viewed at wileyonlinelibrary.com]
4.5.1 | Pre-slide morphology

The source area of the debris slide covers an area of about 200,000 m² and is located underneath the almost vertical northeast face of Skarðatindur peak, at the former confluence of Svinafellsjökull and Dyrhamarsjökull. As can be seen in Figure 3, the source material consisted mostly of unconsolidated lateral moraine, overlain by talus/colluvial material, and is hereafter referred to as the ‘sediment complex’. Some bedrock might have been involved during the slide, too. In 2011, the sediment complex was confined by the rock face of Skarðatindur peak to the west and south and by the glacier surface of Dyrhamarsjökull partially to the east. The aspect of the sediment complex surface is towards the northeast with slope angles of up to 46° (based on the 2011 DEM). The sediment complex sits on top of glacially eroded tertiary basalt layers (Helgason & Duncan, 2013). In the 2011 DEM, ice-flow parallel ridges can be identified within the lateral moraine as well as some short ice-flow transverse features which are marked as recessional moraines (Figure 6a). Since the source area is located at the former confluence of Dyrhamarsjökull and Svinafellsjökull, the lateral moraines just north of the source area show a bend towards the west as they start following the ice-flow direction of Svinafellsjökull. About 400 m north of the landslide source area, meltwater from Dyrhamarsjökull meets the southern lateral margin of Svinafellsjökull, and disappears into a drainage tunnel (~80 m × 40 m wide) below the glacier. Svinafellsjökull runs approximately northeast to southwest, and in the landslide deposition area, the slope dips at around 4° towards the southwest. Along the centreline of Svinafellsjökull, the glacier surface displays a slight trough and has a smooth surface with multiple meltwater channels, moulins and well-developed ogives. Closer to the lateral margins, the glacier becomes increasingly crevassed and debris covered.

Since high amounts of rain and meltwater are expected to be critical to the failure event, the pre-slide catchment area and the most likely surface runoff paths were calculated (Figure 9). The resulting catchment area is about 3.2 km² with an elevation difference of 1350 m (500–1850 m). Calculated surface runoff channels suggest that most of the surface runoff drained along the toe of the source area, illustrated by a bold dashed line in Figure 9.

4.5.2 | Post-slide morphology

The landslide displaced a large volume of moraine, colluvial material and potentially some bedrock. No usable aerial imagery of the landslide source area is available directly after the slide occurred. An elevation model from summer 2013 and a model created from 2019 aerial imagery were used to assess the site. During the landslide, the sediments were removed from the mountain slope and the underlying bedrock (brown unit in Figure 6b) was exposed. The head scarp is not visible on the available aerial imagery or DEMs but can be inferred from the highest line of removed material below Skarðatindur peak from dDEM11–13 (Figure 5). The landslide debris was deposited upon bedrock (green unit in Figure 6b), and on glacier surface (green grid on glacier in Figure 6b) and is poorly sorted (Figure 10c) with grain sizes varying from silt to boulders with diameters of up to 5 m. The deposits on Svinafellsjökull are between a few centimetres and 12 m thick (Figure 5) and are characterized by flow features like fluvial channels in the debris and sediment ridges (Figure 2) or an uneven and somewhat hummocky surface.

Landslide-flow-parallel sediment bands were identified on the debris covered bedrock on both sides of the canyon in front of Dyrhamarsjökull (Figure 6b). These bands are characterized by streaks of colour differences within the debris and are up to 200 m long.

**FIGURE 9** Catchment area. Note the main surface drainage channel running just below the 2013 source area leading to potential erosion at the base [Color figure can be viewed at wileyonlinelibrary.com]
In contrast to the described debris covered bedrock in the northern part of the source area, the southeast corner of the source area is characterized by three relatively flat and somewhat vegetated (observed in 2015) sediment terraces which were formed during the slide (pink unit in Figure 6b and indicated by arrows in Figure 10a). They face towards the northwest and are between 35° and 45° steep. A small segment of the southernmost part of the collapsed lateral moraine remained after the landslide (yellow unit east of the sediment terraces – Figure 6b).

Observations on the landslide debris in April 2013 revealed that it included a large number of scattered blocks of highly debris-rich glacial ice containing a wide range of grain sizes up to boulders (Figure 10b).

When comparing the DEMs from 2013 and 2020 on Svinafellsjökull, it becomes clear that the landslide deposit has been transported by glacier flow. Around the centreline of Svinafellsjökull, the debris front advanced approximately 1000 m, contrasting with 850 m at the southern glacier margin (dashed red line in Figure 5). This implies glacier surface velocities of about 143 m/yr and 121 m/yr respectively. Figure 11 illustrates the long-term effects of the landslide deposits on Svinafellsjökull glacier surface. Specifically, it compares glacier surface elevation change from 2011 to 2013 (dDEM11–13; Figure 11a) and from 2011 to 2020 (dDEM11–20; Figure 11b). The landslide debris can be identified by the blue-coloured area (relative elevation increase) on the glacier (disregarding the blue colours at the frontal glacier margin). It becomes clear that parts of the debris-covered ice in 2020 are more than 15 m higher than in 2011 and the surrounding debris-free glacier surface is up to 20 m lower. This shows that there is an up to 35 m height difference between the top of the debris-covered ice and the debris-free ice in 2020, compared to a 6 m height difference at the same relative location in 2013 (Figure 11a). Figure 11(b) illustrates that in an area of about 200 to 300 m around the debris deposits, the glacier surface has lowered significantly more than on most of the remaining ice-free glacier surface. This is additionally illustrated by the striking height difference shown in the 2013 and 2020 elevation profiles in Figure 11(a,b), respectively.

5 | INTERPRETATION AND DISCUSSION

In this section we reconstruct the 2013 landslide on Svinafellsjökull and discuss its precursors, triggering factors, the effects on the glacier surface, as well as its implications for paraglacial slopes in Iceland and similar settings around the world.

5.1 | Origin of the source material

The presented data indicate that the failed sediment complex consisted of lateral moraine and overlying colluvial material from Skarðatindur peak which were deposited upon a northeast dipping, glacially eroded, bedrock slope.

The lateral moraine was created by Dyrhamarsjökull when it was still connected to Svinafellsjökull. The age of the lateral moraine is not clear, but due to its position and size when compared to other south
coast glacier forelands, a LIA maximum age is likely (Bradwell, Sigurdsson, & Everest, 2013; Evans, Ewertowski, & Orton, 2017a, 2017b, 2019; Chandler et al., 2020).

5.2 Long-term destabilization of the slope

When comparing the DEMs in the profile in Figure 6(a), it becomes evident that Dyrhamarsjökull retreated and thinned for decades before the slide occurred. Between 1994 and 2011, the moraine complex which forms the source area of the discussed event became exposed as the ice of Dyrhamarsjökull thinned by up to 4.7 m/yr, creating a steep (46°) and unstable slope. This was a period of dramatic ice loss on all south Icelandic glaciers (Adalgeirsdóttir et al., 2020), creating unprecedented rates of moraine abandonment and paraglacial adjustment, especially within the mountainside reaches of glacier snouts (Bennett et al., 2010; Bennett & Evans, 2012). This rapid exposure of the moraine complex at Dyrhamarsjökull suggests a lack of response time for the moraine to incrementally adjust to the deglaciation.

Since a large number of blocks of highly debris-rich glacier ice were observed in the landslide debris (Figure 10b), it is likely that the lateral moraine was at least partly ice-cored, or permafrost preserved from the LIA was present within the sediment. Thawing of the ice within the moraine due to its recent rapid exposure would have exacerbated its destabilization (Holm, Bovis, & Jakob, 2004; Tonkin et al., 2016; Ewertowski & Tomczyk, 2020). Additionally, continuous rockfall from the steep northeast face of Skárðatindur peak has led to the accumulation of the colluvial material on top of the moraine, thereby increasing the normal load on the slope. The location of the source area at the former glacier confluence means that the sediment complex became exposed from two sides when Dyrhamarsjökull and Svínafellsjökull receded, making it more vulnerable to erosive forces than a straight lateral moraine.

5.3 Short-term destabilization of the slope

Three short-term destabilization factors are considered: (1) Increased pore pressure due to large amounts of water input into the sediment complex; (2) Increased volumetric water content adding more weight to the sediment complex; (3) Fluvial erosion at the toe of the sediment complex caused by a lateral meltwater channel.

As presented, a record-breaking amount of rain was measured in the days prior to the slide (25 and 26 February 2013). Due to the elevated temperature during the storm, it can be assumed that most of the precipitation on the western flanks of Örafajökull volcano fell as rain. The weather forecast from the IMO for 26 February 2013, suggests that the rain continued within the source area and further up on the mountain, even though rain had almost stopped in Skaftafell. Therefore, we assume that there was an ongoing rain event in the landslide source area that reached its precipitation peak during the storm 24–48 h before the slide occurred. Since the slide occurred in late February, the rain in combination with positive temperatures at up to 2000 m a.s.l., led to significant snow melt, which further contributed to the total runoff. This almost certainly infiltrated the sediment in the source area, increasing the pore pressure and consequently destabilizing the slope (Iverson, 2000). A concomitant increase in volumetric water content would also have added weight to the sediments, further favouring failure (Iverson, 2000). Percolation through...
the sediment to the contact with underlying basaltic bedrock would also have resulted in increased basal water pressure, leading to reduced shear strength at the soil-rock interface and thereby creating a sliding plane. The calculated catchment and drainage channels (Figure 9) suggest that surface water from an area of 3.2 km² may have drained through a lateral meltwater channel immediately below the toe of the sediment complex (bold dashed line in Figure 9). Since the calculations only take surface runoff over Dyrhamarsjökull into account and englacial or subglacial hydrology is disregarded, the model presented here is a simplification but can be used as an approximation to understand where meltwater channels would have formed. If this channel formed at the location where our model calculations predict it, a significant amount of water (rainwater + meltwater) drained just below the sediment complex and potentially undercutting the slope, destabilizing it further.

5.4 | Timing

Witness statements from Skáftafell indicate that the slide occurred around 20:00 h on 27 February 2013. However, there is no proof for the exact timing, and the possibility remains that the event happened earlier during the rainstorm. Assuming the reported timing of the slide is correct, the slide occurred more than 24 h after the peak of the rainstorm. This reflects the infiltration duration and subsequent elayed peak pore-water pressure within the sediment as described by Iverson (2000).

5.5 | Progression of the slide

Based on the presented data we attempt to reconstruct the most likely progression of the 2013 landslide on Svinafellsjökull. Morphological evidence indicates that multiple mass movement mechanisms were active during the progression of the slide. The landslide likely started as a retrogressive debris slide with a rotational component and then turned into a debris as it progressed down-glacier. While the northern part of the source area is characterized by poorly sorted, uneven debris deposits, the southern part is defined by the presence of distinct sediment terraces. This suggests granular flow and rotational slumping, respectively. By the time the slide reached Svinafellsjökull, it had likely developed into a debris avalanche. This is further supported by the wide distribution of the debris on Svinafellsjökull and channelized systems within the deposits (Zhou et al., 2019). Given that the source material at the time of slide initiation had a high water content, it is likely that debris avalanche formed shortly after the initiation of the slide. During its progression, the debris likely entrained dead ice from the source area, glacier ice, surface water, and snow along the flow path, further increasing the water content (Evans & Delaney, 2015). The fact that the debris was flowing over glacier ice is likely to have reduced frictional resistance and further increased the runout distance and deposition area (Iverson, 1997; Evans & Delaney, 2015).

5.6 | Effects on the glacier surface and implications for dead-ice environments

Between 2013 and 2020, the landslide debris was transported around 1000 m with the glacier flow (Figure 4). In that time period, a distinct
elevation difference of up to 35 m developed between the bare glacier surface and the debris-covered glacier, similar to that described from rock avalanches deposits on glaciers in Iceland (Samundsson et al., 2011) and in Alaska (Shreve, 1966; Shugar et al., 2012). This shows clearly that the debris is insulating the underlying ice very effectively as reported by Reznichenko et al. (2010) and Samundsson et al. (2011). The observed increased lowering of the immediately surrounding glacier ice (Figure 1) can be explained by the effect of increased surface melt due to a thin dust layer (Oerlemans, Giesen, & Van Den Broeke, 2009; Deline et al., 2014; Fyffe et al., 2020) derived from the landslide debris. Energy from solar radiation stored in the debris cover is being reemitted as long wave radiation (Cuffey & Paterson, 2010) and might lead to additional increased melting in the surrounding. The extent to which this sensible heat flux from the debris body on the glacier ice contributes to the augmented ablation rate in its vicinity must be tested in further studies.

These processes are likely to continue as the landslide material is transported towards the frontal glacier margin where they are going to accelerate the isolation of the debris covered glacier leading to incremental stagnation and the formation of a dead-ice environment. Therefore, the results of this study show that ice-cored/frozen sediments can be the origin and result of catastrophic paraglacial landslides. The evolution of dead-ice environments has been studied thoroughly at Icelandic outlet glaciers (Kjær & Krüger, 2001; Bennett et al., 2010; Bennett & Evans, 2012) but future studies on the evolution of landslide debris covered glaciers and the surroundings at Svínafellsjökull and Morsárjökull would help to understand occurring processes better. According to Thompson (1988) and Lee, Maclachlan, and Eyles (2018) the frontal moraine of Svínafellsjökull is characterized by a high percentage of supraglacial and englacial material which suggests that increased landslide activity at Svínafellsjökull has been ongoing throughout the formation of the moraine. The debris from the 2013 landslide will eventually be added to this moraine supporting this assumption.

5.7 | Implications for paraglacial slopes

Iceland’s glaciers have experienced significant ice loss since the LIA, a trend that will continue for the foreseeable future (Adalgeirsdóttir et al., 2020). An increased paraglacial response during this deglaciation period is therefore to be expected (Ballantyne, 2002a). In light of numerous gravitational mass movements and slope instabilities in Iceland during the last decades (Kjartansson, 1967; Sigurdsson & Williams, 1991; Samundsson et al., 2011), the 2013 landslide onto Svínafellsjökull confirms an apparent trend of increased paraglacial landslide activity in Iceland.

The event addressed in this study shows an extreme example of the modification of a recently deglaciated sediment-mantled slope. The process of moraine wasting through gravitational mass movement is well known in the literature (Ballantyne, 2002b; Ravel et al., 2018). Large mass movements of lateral moraines have been documented worldwide (Blair, 1994; Hewitt, 2013; Kumar et al., 2019; Cody et al., 2020) and are generally associated with rapid glacier retreat and thinning. Most failures involving lateral moraines discussed in the literature are slow-moving, which either indicates that catastrophic failures of lateral moraines are rare or that they are seldom documented. The large volume and runout involved in the catastrophic landslide in 2013 is rather unusual and likely the result of the combination of factors discussed in this article. Rapid lowering of the glacier surface and a potentially ice-cored moraine likely did not allow for gradual adjustment of the lateral moraine, which led to the catastrophic failure in combination with intensive rainfall, snowmelt, and potential fluvial undercutting of the slope. The proximity of the landslide source area to the snout of Dyrhámarsjökull indicates that the observed rapid glacier surface lowering was due to a combination of glacier retreat and surface ablation. Other paraglacial slopes at similar relative locations to glacier margins (e.g., Cody et al., 2020) may undergo a comparable loss of lateral support, and are thus likely to experience some form of increased paraglacial response. Blair (1994) observed a critical relief height between glacier surface and moraine crest at which sediment mantled slopes above Tasman Glacier, New Zealand, developed complex slope failure. The possibility of such a site-specific critical relief height in sediment-mantled slopes which are exposed by glacial thinning could indicate that large amounts of sediment stored on rock slopes will become unstable at a certain point during or after deglaciation. In 2020, lateral moraine crests were between 50 and 90 m higher than the Svinafellsjökull glacier surface. With continuing deglaciation of the valley these moraines will become further exposed and failure will become more likely. In the last decade, three slopes (the 2013 landslide discussed in this article, a DSGSD mentioned in Samundsson et al. (2019), and the slow moving rockslide on Mount Hrútsfjall [Table 1]) in the Svinafellsjökull valley have shown significant signs of deformation. This indicates that the entire valley surrounding Svinafellsjökull already experiences rapid modification of rock and sediment slopes. If glacier ice loss at Iceland’s outlet glaciers continues as predicted (Adalgeirsdóttir et al., 2020), the trend observed around Svinafellsjökull may become an example for other valleys hosting outlet glaciers. Björnsson et al. (2018) predicts that extreme precipitation events will become more frequent in Iceland, and the average annual precipitation is likely to increase alongside rising temperatures. Czekirda et al. (2019) observed a three- to four-decade long trend of permafrost degradation in certain regions in Iceland and predicts that this process will continue as temperatures increase further. Increasing exposure of paraglacial slopes, in combination with more frequent and more intense rain events and regional permafrost thawing, will undoubtedly increase the occurrence of paraglacial landslides in Iceland in the future. Therefore, it is necessary to monitor glacier margins regularly to track the exposure of potentially dangerous rock and sediment slopes.

6 | CONCLUSIONS

The landslide which fell onto the Svínafellsjökull in 2013 is an extreme example of paraglacial sediment-mantled slope adjustment. It is the largest documented landslide originating from unconsolidated paraglacial material in Iceland with a displaced volume of $5.3 \pm 0.08 \times 10^6$ m$^3$ and a runout distance of 3.95 km. The source material originated from an at least partly frozen or ice cored sediment mantled slope. The sediment mostly consisted of lateral moraine material with accumulated colluvium on top, located just below the northeast face of Skarðatindur peak. Our data clearly shows that the slope had been
exposed over several decades prior to 2013 by retreat and thinning of Dyrhómasjökull, which made it vulnerable to gravitational erosion and highlights the especially high landslide hazard just at the retreating frontal margin of glaciers.

Increased pore-water pressure within the sediment and at the bedrock interface caused by rain and snow melt after an intense rainstorm event is thought to be the main triggering factor of the slide. Our analysis indicates that the landslide was likely initiated at the toe in the northern part of the source area as a retrogressive debris slide, which led to a subsequent phase of sliding motion and multiple rotational failures that formed prominent sediment terraces in the southern part. During the runout over Dyrhómasjökull and Svínafellsjökull, the debris slide transformed into a debris avalanche. The debris-covered part of the glacier is efficiently insulated, and the surrounding debris-free glacier shows increased ablation rates which resulted in an up to 35 m high elevation difference from the debris-free surface by 2020. These processes will likely accelerate the evolution of the debris ice environment once the debris has been transported to the frontal glacier margin. The described event is an indicator for increased recent paraglacial activity at Iceland’s outlet glaciers and especially in the Svínafellsjökull valley where a cluster of slope instabilities is observed. This trend is likely to continue as deglaciation proceeds and heavy rain events are predicted to increase.

Finally, this landslide highlights the range of paraglacial slopes which can be affected by catastrophic failure and emphasizes the need to further investigate and monitor paraglacial sediment structures.

ACKNOWLEDGEMENTS
The Icelandic Centre for Research/RANNÍS (grant no. 207136-052), the Energy Research Fund (grant no. NÝR-09) by Landsvirkjun and The University of Iceland Research Fund (grant no. 156364) are thanked for funding this project. The reviewers are thanked for invaluable input during the peer review, greatly improving the quality of the article. The authors would like to thank Greta Hoe Wells and Sydney Raylee Gunnarson for proof reading. Loftmyndir ehf. is thanked for supporting this project with aerial imagery and elevation models. Guðmundur Ögmnundsson, former ranger in Skagafell is thanked for his witness statement regarding the timing of the event. We thank Susan Conway for sharing her view on the event. Svarmi ehf. is thanked for providing access to the Global Mapper Software. No usable seismic data was found and is thus not included in this study. However, the authors would like to thank Gunnar B. Guðmundsson, Jeremy D. Everest, Heiko Buxel, Richard R. Luckett and Páll Einarsson for the help with finding, providing, and analysing the available seismic datasets.

AUTHOR CONTRIBUTIONS
Daniel Ben-Yehoshua (conceptualization, methodology, investigation, writing – initial draft), Pórsunnar Sæmundsson (supervision, conceptualization, investigation, writing – reviewing and editing). Jón Kristinn Helgason (writing – reviewing and editing, resources, methodology). Jón Víðar Sigurðsson (writing – reviewing and editing, resources). Sigurður Erlingsson (Supervision, conceptualization, writing – reviewing and editing, funding acquisition).

DATA AVAILABILITY STATEMENT
All data used in this investigation is either freely available or has been granted permission to use. Loftmyndir ehf. has granted permission to distribute results and figures based on their data. Contact: Skúli Magnús Þorvaldsson skuli@loftmyndir.is.

The origin of all data is explained in the methods chapter.

ORCID
Daniel Ben-Yehoshua https://orcid.org/0000-0002-6609-2329
Pórsunnar Sæmundsson https://orcid.org/0000-0001-6671-9542
Jón Kristinn Helgason https://orcid.org/0000-0002-1697-5297
Joaquin M. C. Belort https://orcid.org/0000-0002-0853-8935
Sigurður Erlingsson https://orcid.org/0000-0002-4256-3034

REFERENCES
Adalgeirsísottir, G., Magnússon, E., Pálsson, F., Thorsteinsson, T., Berlart, J.M.C., Johannesson, T., Hannesdóttir, H., Sigurðsson, O., Gunnarsson, A., Einarsar, B., Berthier, E., Schmidt, L.S., Haraldsson, H.H. & Björnsson, H. (2020) Glacier Changes in Iceland From ~1890 to 2019. Frontiers in Earth Science, 8, 1–15. Available from: https://doi.org/10.3389/feart.2020.523646
Amar E. (2021). Geomorphological Mapping of a Paraglacial Slope Instability at the Southeastern Tindfjallajökull Glacier, Iceland, University of Iceland, MSc Thesis. Available from: http://hdl.handle.net/1946/39947
Ballantyne, C.K. (2002a) A general model of paraglacial landscape response. Holocene, 12(3), 371–376. Available from: https://doi.org/10.10119/0959683602H5539a
Ballantyne, C.K. (2002b) Paraglacial Geomorphology. Encyclopedia of Quaternary Science: Second Edition, 21, 553–565. Available from: https://doi.org/10.1006/978-0-444-53643-3.00089-3
Bellart, J.M.C., Magnússon, E., Berthier, E., Gunnlaugsson, A., Pálsson, F., Adalgeirsísottir, G., Johannesson, T., Thorsteinsson, T. & Björnsson, H. (2020) Mass Balance of 14 Icelandic Glaciers, 1945-2017: Spatial Variations and Links With Climate. Frontiers in Earth Science, 8(163), 1-15. Available from: https://doi.org/10.3389/feart.2020.00163
Belart, J.M.C., Magnússon, E., Berthier, E., Pálsson, F., Adalgeirsísottir, G. & Johannesson, T. (2019) The geodetic mass balance of Eyjafjallajökull ice cap for 1945-2014: Processing guidelines and relation to climate. Journal of Glaciology, 65, 395–409. Available from: https://doi.org/10.1017/jog.2019.16
Bell, R. & Glade, T. (2004) Quantitative risk analysis for landslides - Examples from Búldudalur, NW-Iceland. Natural Hazards and Earth System Science, 4(1), 117-131. Available from: https://doi.org/10.5194/nhess-4-117-2004
Bennett, G.L. & Evans, D.J.A. (2012) Glacier retreat and landform production on an overdeepened glacier foreland: The debris-charged glacial landsystem at Kviarjökull, Iceland. Earth Surface Processes and Landforms, 37(15), 1584–1602. Available from: https://doi.org/10.1002/esp.3259
Bennett, G.L., Evans, D.J.A., Carbonneau, P. & Twigg, D.R. (2010) Evolution of a debris-charged glacier landsystem, Kviarjökull, Iceland. Journal of Maps, 6, 40–67. Available from: https://doi.org/10.4113/jom.2010.1114
Berthier, E., Vincent, C., Magnússon, E., Gunnlaugsson, A. P., Pitte, P., Le Meur, E., Masiokas, M., Ruiz, L., Pálsson, F., Belart, J.M. & Wagnon, P. (2014) Glacier topography and elevation changes derived from Pèlades sub-meter stereo images. The Cryosphere, 8, 2275–2291. Available from: https://doi.org/10.5194/tc-8-2275-2014
Björnsson, H. (2017) The Glaciers of Iceland, 2nd edition. Paris: Atlantis Advances in Quaternary Science.

Björnsson, H. Sigurðsson BD, Davídsdóttir B, Ólafsson J, Ástþórsson OŠ, Ólafsdóttir S, Baldursson T, Jónsson T. (2018). Climate Change and its effects in Iceland (in Icelandic) - Loftslagsbreytningar og ahríf þeirra á Íslandi - Þýskla viðsíndafnafdar um loftslagsbreytningur 2018.
Sigmundsson, F., Einarsson, P., Belart, J.M.C., Hjartardóttir, A.R., Magnússon, E., Geirsson, H., Pálsson, F., Pedersen, G.B.M. & Druin, V. (2020) Slope deformation above the Tungnafjölsjökull outlet glacier in western part of the Mýrdalsjökull glacier. Abstract, 34th Nordic Geological Winter Meeting.

Sæmundsson, Þ., Helgason, J.K., Ben-Yehoshua, D. & Bergsson, B.H. (2019) Risk of major rock slope failure at the Svinafellsjökull mountain. SE Iceland. Geophysical Research Abstracts, EGU, 21, 9650.

Sæmundsson, Þ. & Margeirsson, G. (2016) Frequency, triggering factors and possible consequences of mass movements on outlet glaciers in Iceland. EGU General Assembly Conference Abstracts 2016: 4704 pp.

Sæmundsson, Þ., Morino, C., Helgason, J.K., Conway, S.J. & Pétursson, H.G. (2018) The triggering factors of the Møafellsheima debris slide in northern Iceland: Intense precipitation, earthquake activity and thawing of mountain permafrost. Science of the Total Environment, 621, 1163–1175. Available from: https://doi.org/10.1016/j.scitotenv.2017.10.111

Sæmundsson, Þ., Petursson, H.G. & Decaulne, A. (2003) Triggering factors for rapid mass movements in Iceland. International Conference on Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment, Proceedings, 1, 167–178.

Sæmundsson, Þ., Sigurðsson, I.A., Pétursson, H.G., Jónsson, H.P., Decaulne, A. & Roberts, M.J. (2011) The rock avalanche which fell on the Morsárjökull outlet glacier, 20th of March 2007. Náttúrfræðingurinn, 81, 132–141.

Schonacker, A. & Kjær, K.H. (2008) Quantification of dead-ice melting in ice-cored moraines at the high-Arctic glacier Holmstrømbreen, Svalbard. Boreas, 37, 211–225. Available from: https://doi.org/10.1111/j.1502-3885.2007.00014.x

Shreve, R.L. (1966) Sherman Landslide, Alaska. Science, 154(3757), 1639–1643. Available from: https://doi.org/10.1126/science.154.3757.1639

Shugar, D.H., Rabus, B.T., Clague, J.J. & Capps, D.M. (2012) The response of Black Rapids Glacier, Alaska, to the Denali earthquake rock avalanches. Journal of Geophysical Research: Earth Surface, 117(F1), 1–14. Available from: https://doi.org/10.1029/2011JF002011

Shulmeister, J., Davies, T.R., Evans, D.J.A., Hyatt, O.M. & Tovar, D.S. (2009) Catastrophic landslides, glacier behaviour and moraine formation - A view from an active plate margin. Quaternary Science Reviews, 28(11-12), 1085–1096. Available from: https://doi.org/10.1016/j.quascirev.2008.11.015

Sigmundsson, F. (2019) Icelandic Volcanoes SuperSite 2018–2019 [online] Available from: http://geo-gsnl.org/wp-content/ Documents/SuperSites/Iceland/Reports/Icelandic_Volcanoes_Biennial_Report_2018_2019r.pdf

Sigmundsson, F., Einarsson, P., Hjartardóttir, Á.R., Druin, V., Jónsdóttir, K., Arnadóttir, T., Geirsson, H., Hreinsdóttir, S., Li, S. & Ófeigsson, B.G. (2020) Geodynamics of Iceland and the signatures of plate spreading. Journal of Volcanology and Geothermal Research, 391, 106436. Available from: https://doi.org/10.1016/j.jvolgeores.2018.08.014

Sigmundsson, F. (2005) Variations of termini of glaciers in Iceland in recent centuries and their connection with climate. Developments in Quaternary Science, 5, 241–255. Available from: https://doi.org/10.1016/S1571-0866(05)80012-0

Sigmundsson, F. (2010) Variations of Mýrdalsjökull during Postglacial and Historical Times. Developments in Quaternary Science, 13, 69–78. Available from: https://doi.org/10.1016/j.scitotenv.2017.10.111

Sigurðsson, O. & Williams, R.S. (1991) Rockslides on the terminus of “Jökulsárgljúfur”, southern Iceland. Geografiska Annaler, Series a, 73 A, 129–140. Available from: https://doi.org/10.1080/04353676.1991.11880338

Smith, C.N. (2020) Structural Analysis of an Unstable Rock-Slope above Fjalljökull Glacier, SE Iceland. SIT Iceland: Climate Change and the Arctic, Final Project.

Thompson, A. (1988) Historical development of the proglacial landforms of Svinafellsjökull and Skartafellsjökull, southeast Iceland. Jökull, 38, 17–30.

Þórarinsson, S. (1943) Oscillations of the Iceland glaciers in the last 250 years. Geografiska Annaler, 25(1–2), 1–54. Available from: https://doi.org/10.1080/00467603.1943.11880716

Thorarinsdóttir, S. (1958) The Öræfajökull Eruption of 1362. Acta Naturalia Islandica. 2, 1–100.

Tonkin, T.N., Midgley, N.G., Cook, S.J. & Graham, D.J. (2016) Ice-cored moraine degradation mapped and quantified using an unmanned aerial vehicle: A case study from a polythermal glacier in Svalbard. Geomorphology, 258, 1–10. Available from: https://doi.org/10.1016/j.geomorph.2015.12.019

Torfason, H. & Jónsson, H.B. (2005) II. The risk assessment of eruptions and outburst floods from Mýrdalsjökull and Eyjafjallajökull (Hettumat vegna eldgosa og hlaua úr vestanverðum Mýrdalsjökull og Eyjafjallajökull). Geology of the northwest slope of Mýrdalsjökull (Jarfraði við Norðvestanverðan Mýrdalsjökull), Vol. 2. Reykjavík: Ríkisörgørglistjórin (The National Commissioner of Police), pp. 45–74.

Varnes, D.J. (1958) Landslide types and processes. Landslides and Engineering Practice, 24, 20–47.

Wieczorek, G.F. (1996) Landslides: investigation and mitigation. Chapter 4-Landslide triggering mechanisms. Transportation Research Board Special Report.

Zhou, G.G.D., Li, S., Song, D., Choi, C.E. & Chen, X. (2019) Depositional mechanisms and morphology of debris flow: physical modelling. Landslides, 16(2), 315–332. Available from: https://doi.org/10.1007/s10346-018-1095-9

How to cite this article: Ben-Yehoshua, D., Sæmundsson, Þ., Helgason, J.K., Belart, J.M.C., Sigurðsson, J.V. & Erlingsson, S. (2022) Paraglacial exposure and collapse of glacial sediment: The 2013 landslide onto Svinafellsjökull, southeast Iceland. Earth Surface Processes and Landforms, 47(10), 2612–2627. Available from: https://doi.org/10.1002/esp.5398