# Tectonic position, structure, and Holocene activity of the Hofsjökull volcanic system, central Iceland

**Ásta Rut Hjartardóttir* and Páll Einarsson**

Ásta Rut Hjartardóttir
Institute of Earth Sciences, University of Iceland
Askja, Sturlugata 7, 101 Reykjavík, Iceland
e-mail: astahj@hi.is

Páll Einarsson
Institute of Earth Sciences, University of Iceland
Askja, Sturlugata 7, 101 Reykjavík, Iceland
e-mail: palli@hi.is

*Corresponding author

## Abstract

The Hofsjökull volcanic system is located at the northern border of the Hreppar microplate on the Mid-Atlantic plate boundary in Iceland, between the more active Western and Eastern volcanic zones. In this study, fractures, and faults within the fissure swarms of the volcanic system were mapped and the throw and orientation of faults measured. This was done using both aerial photographs and ArcticDEM digital elevation models, as well as during fieldwork. The Hofsjökull volcanic system contains 3-4 fissure swarms extending northwards or southwards from the glacially covered Hofsjökull central volcano. Although these fissure swarms have been active during the Holocene, no clear sink holes were found along the faults, suggesting that they have been filled by sediments. This indicates that the fissure swarms have been less active than fissure swarms in other branches of the plate boundary in Iceland where GPS geodetic measurements show current spreading. Unbroken hyaloclastite covering a fault in the northern Hofsjökull fissure swarm suggests that this part of the northern Hofsjökull fissure swarm has not been active since the earliest part of Holocene, or during the latest stage of glaciation in the area. Still, the fault scarps in the northern Hofsjökull fissure swarm are rather sharp, indicating little erosion by glaciers.  This may suggest increased activity in the Hofsjökull fissure swarm during the end of the last glaciation or at the beginning of the Holocene, which is in line with other studies showing increased magmatic activity in Iceland during that period. Fractured Holocene lava flows in the southern and western Hofsjökull fissure swarms indicate that they have been active during the Holocene. The Kerlingarfjöll rhyolitic massif is located south of the Hofsjökull central volcano. The southern fissure swarms are located both east and west of Kerlingarfjöll, but no clear indications are found of the fissure swarm in the rhyolitic massif itself. This may occur as dike intrusions (which likely form the faults) are prevented from penetrating the rhyolite due to density differences, and/or due to the topographic high of Kerlingarfjöll.


**Keywords:** rift zones, Iceland, fissure swarms, dikes, density barriers

## 1. Introduction

The divergent segments of the plate boundary in Iceland are delineated by volcanic systems consisting of fissure swarms and central volcanoes (e.g. Einarsson, 2008; Sæmundsson, 1978). The fissure swarms radiate from the central volcanoes and consist of normal faults, open fissures, and eruptive fissures that are near-perpendicular to the local direction of spreading. They are defined as an area with a high density of faults and/or fissures, whereas their surroundings have few or no faults or fissures at all. These fissure swarms seem to be formed and reactivated during dike intrusions, which cause fault movements above the dike (Pollard et al., 1983; Rubin and Pollard, 1988; Sigurdsson, 1980). Sometimes the dikes reach the surface as fissure eruptions (Hjartardóttir et al., 2016b). The central volcanoes are typically basaltic, but with a component of silicic products. Many of them have caldera structures and an active geothermal system. The Hofsjökull volcanic system in Central Iceland has all these typical characteristics of the plate boundary systems, and yet it is located outside the currently most active segments of the plate boundary (Árnadóttir et al., 2009; Sigmundsson et al., 2020). It is located on the northern boundary of the Hreppar Microplate that was created by the shift in spreading in the southern part of Iceland from the Western Volcanic Zone (WVZ) to the Eastern Volcanic Zone (EVZ) (Fig. 1). This shift began about 3 Ma and is still in progress. The microplate was separated from the Eurasia plate by the propagating EVZ but has not fully been attached to the North America Plate. The spreading rate across the WVZ is about 4-5 mm/year near the Hengill triple junction and decreased northwards to almost zero at its northern end (Fig. 1) (LaFemina et al., 2005). Conversely, spreading rate across the EVZ increases northwards, from about 11 mm/year in the southwest to ~19 mm/year in the northeast (LaFemina et al., 2005). The pole of relative rotation of the microplate with respect to North America must therefore be near the northern end of the WVZ (Einarsson, 2008), so the relative plate velocity across the northern boundary of the microplate must be small, and possibly compressive in a N-S direction. This low velocity is consistent with low seismicity of the area. The Hofsjökull system, however, appears to contradict this simplified picture, as it would imply small or no divergent stresses along the Hofsjökull volcanic system. Both the central volcano and the fissure swarms are rather impressive structures, the former has a prominent caldera, and the latter have large-offset normal faults. In addition, the fissure swarms extend into the plates on both sides of the boundary and do not follow its trend. An added complication to the structural picture is presented by the Kerlingarfjöll central volcano that is located within the southern fissure swarms of Hofsjökull and is frequently taken to be a part of the Hofsjökull system. It has high proportion of rhyolitic products, and appears to have two buried calderas (Hjartarson et al., 2019). The local stress field of the Kerlingarfjöll central volcano could thus have influenced the southern Hofsjökull fissure swarms.

In this paper we try to clarify the structural position of the Hofsjökull volcanic system within the plate tectonic framework of Iceland. We find the extent of the Hofsjökull fissure swarms, their width and length by mapping fractures and delineating the outlines of those fractured areas. By measuring the throws of faults, we estimate the widening across the fissure swarms, also in the northern Hofsjökull fissure swarm which propagates into the North American plate. Various geological data, such as lava flows of a known age and information on glacial moraines, is used to acquire time constraints on the activity of the faults and fractures within the fissure swarms. The interaction between the Hofsjökull fissure swarms and the Kerlingafjöll rhyolitic massif will also be discussed, especially the influence of density differences on the propagation of shallow dike intrusions and eruptions. By doing this, the aim is to shed a light on how this volcanic system at the periphery of the active plate boundary works.

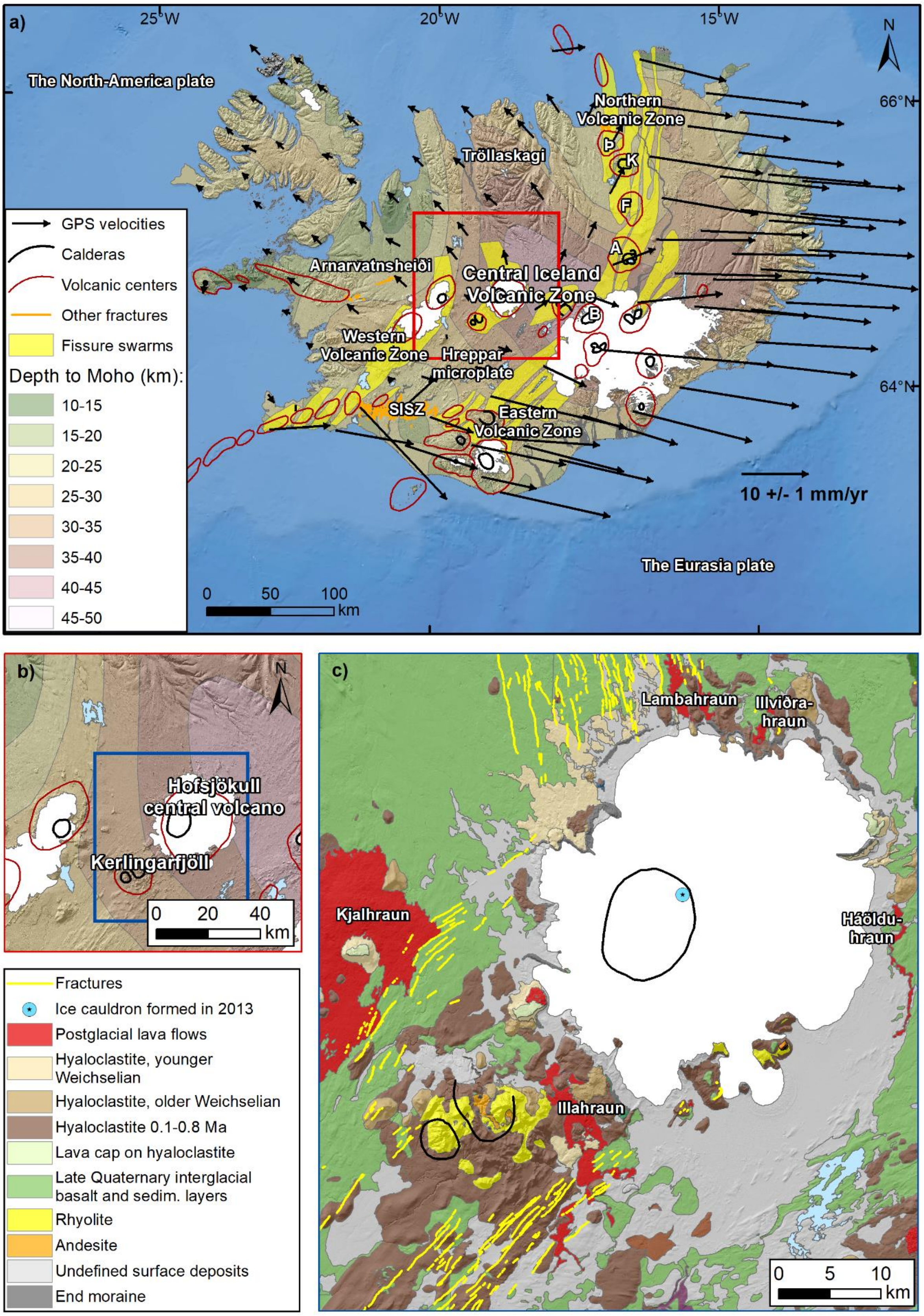



Fig. 1. a) Overview of the plate boundary in Iceland. Outlines of fissure swarms, calderas and volcanic centers delineate the plate boundaries, they are modified from Einarsson and

Sæmundsson (1987). The GPS vectors, spanning the time between 1993 and 2004, are from Árnadóttir et al. (2009) and Valsson et al. (2007). Information about the depth to the Moho (indicating crustal thickness) is from Brandsdóttir and Menke (2008). The black arrow at the lower right corner shows the scale of the vectors. The red frame indicates the location of Fig. 1b. Information on other fractures are from Hjartardóttir et al. (2016a); Hjartardóttir et al. (2016c); and Magnúsdóttir and Brandsdóttir (2011). Cartographic data are from the IS50 database of the National Land Survey of Iceland. Þ=Þeistareykir, K=Krafla, F=Fremrinámar, A=Askja, B=Bárðarbunga b) The Central Iceland Volcanic Zone. The blue frame indicates the location of Fig. 1c. c) A geological map of the Hofsjökull fissure swarm, data on bedrock geology are from Iceland Geosurvey (ÍSOR) (Hjartarson et al., 2019), the fractures were mapped by the authors of this paper.

## 2. Rifting events and episodes

Observations in Iceland during the last several decades have shown that most parts of the divergent plate boundaries are seismically inactive most of the time (Einarsson, 1991; Einarsson and Brandsdóttir, 2021; Jakobsdóttir, 2008). Large scale rifting has been observed twice in the last half century, during the Krafla rifting episode in 1975-1984 and Bárðarbunga dike injection and caldera collapse of 2014 (e.g. Dumont et al., 2018; Hjartardóttir et al., 2016b; Sigmundsson et al., 2015; Tryggvason, 1984). In both cases the rifting occurred along the fissure swarms of these volcanoes and the extension during the rifting was of the order of 5-8 m. During the time between such episodes the relative plate movements is taken up by aseismic deformation and stretching of the plate margins. Fissure swarms within the main plate boundary zones in Iceland appear to develop and deform in response to diking, while having little or no deformation during other times. During such rifting episodes, grabens above the propagating dikes subside. The subsidence is often around 1-6 m and is mostly taken up by the boundary faults of the graben (Hjartardóttir et al., 2016b; Saemundsson, 1992; Sigurdsson, 1980). Similar behavior has also been seen in rift zones in east Africa (e.g. Wright et al., 2006). The lack of non-magmatic fault movements has been suggested to be because it takes a long time before deviatoric stresses due to crustal movements alone build up to a level of reactivation. However, when magma is available, a dike intrusion can release the accumulated crustal stresses long before they would have been released if no magma was available (Sigmundsson, 2006). It has, however, been unclear whether and how such processes occur in the less active parts of the plate boundary in Iceland, such as in the Hofsjökull fissure swarm.

## 3. Geological settings

The fissure swarms extend at least 40 km to the north and 30 km to the south of the Hofsjökull central volcano (Einarsson and Sæmundsson, 1987) (Fig. 1a). The southern fissure swarm extends into the heavily faulted Hreppar microplate (Khodayar et al., 2020). Radio echo-soundings on the glacier show that the Hofsjökull central volcano has a 6 - 7 km wide and ~600 m deep caldera, which is covered by the Hofsjökull glacier (Björnsson, 1986; 1988). Despite the large caldera, no ash layers from the Holocene epoch have been associated with the Hofsjökull central volcano. It is nevertheless possible that several basaltic tephras of unknown origin, found in soil profiles around the Vatnajökull glacier, are from the Hofsjökull central volcano (Óladóttir et al., 2011). Most of the source vents of these postglacial lava flows are now beneath the Hofsjökull glacier and therefore not visible. The few source vents that can be seen are located so close to the glacier that it is not possible to determine whether they are individual vents or a part of an eruptive fissure. It has been poorly understood how often this volcano is activated and how far dikes have propagated in the fissure swarms. The uncertainty of the behavior of the Hofsjökull fissure swarm is further reinforced by its unique location between the Western Volcanic Zone and the Eastern and Northern Volcanic Zones. There are therefore no other fissure swarms in similar settings to which the activity of the Hofsjökull fissure swarm has a resemblance. Despite the low activity of the Hofsjökull central volcano, it is not completely inactive. In the summer of 2013, a jökulhlaup flood with sulfuric smell originated from the Hofsjökull glacier. Although earthquakes were not detected during this event, a new ice cauldron was found within the glacier after the flood, on the caldera boundary (Fig. 1). This suggests that there is a high-temperature geothermal area within the volcano. Geothermal areas are also found in the area north of the northern Hofsjökull fissure swarm (Torfason, 2003).

The age of the bedrock of the Hofsjökull fissure swarm increases with distance from the Hofsjökull central volcano (Jóhannesson and Sæmundsson, 1998a). A few unglaciated lava flows have been found around the glacier (Fig. 1) (Hjartarson et al., 2019; Jóhannesson and Sæmundsson, 1998b). The youngest lava flows are 3000-4500 years old, located just north of the Hofsjökull glacier (Fig. 1c) (Hjartarson et al., 2019). Several 4500-7000 years old lava flows are located in the southern Hofsjökull fissure swarm, close to the Hofsjökull glacier and early Holocene lava flows (>7000 years old) can be found east and west of the Hofsjökull glacier. In addition, the western Hofsjökull fissure swarm cuts the ~10.000 years old Kjalhraun lava (Fig. 1c) (Eason et al., 2015; Hjartarson et al., 2019). These postglacial lava flows are all found close to the Hofsjökull central volcano, with sources beneath or close to the edge of the glacier. Similarly, mafic hyaloclastite, less than 0,8 Ma old, is mostly found close to the central volcano (Hjartarson et al., 2019). Some of the hyaloclastite is from the Weichselian period, from ~10.000 to ~110.000 years old (Helmens, 2014). The youngest hyaloclastite is mostly located at the northwestern margin of the Hofsjökull glacier, although small patches of the youngest hyaloclastite can be found southwest of Hofsjökull (Fig. 1c) (Hjartarson et al., 2019). Basaltic and intermediate interglacial and supraglacial lavas and sediments of less than 0,8 Ma age can be found in up to ca 20 km distance north and south of the Hofsjökull glacier (Jóhannesson and Sæmundsson, 1998a). Both the southern and the northern Hofsjökull fissure swarms extend into basaltic and intermediate extrusive rocks and sediments of lower Pleistocene age (0,8-2,6 Ma) (Jóhannesson and Sæmundsson, 1998a).

The Kerlingarfjöll volcanic center is sometimes considered to be a part of the Hofsjökull volcanic system (Fig. 1). It is characterized by rhyolitic, intermediate and basaltic formations, generally formed subglacially (Flude et al., 2010; Grönvold, 1972; Stevenson et al., 2009), and altered by high-temperature geothermal activity (Torfason, 2003). The dating of rocks in Kerlingarfjöll indicates that the age of rocks there ranges approximately between 68.000 and 350.000 years (Flude et al., 2010). Two calderas have been identified within the area (Hjartarson et al., 2019).

## 4. Methods

The fractures and faults in the Hofsjökull fissure swarms were mapped in detail from aerial photographs from Loftmyndir Inc. These features appear to be mostly dilatational, since en-echelon arrangements, suggesting strike-slip faulting, are lacking. Eruptive fissures are also almost non-existent, most of them are buried under the Hofsjökull glacier. The ArcticDEM Digital Elevation Models (Porter et al., 2018) were used to improve the mapping of the faults.

The ArcticDEM was also used to study throws of faults and to make cross-sections of the grabens in the Hofsjökull fissure swarms, in a similar manner as has been done in the Western Volcanic Zone, Iceland (Hjartardóttir et al., 2016a; 2015). In the Western Hofsjökull fissure swarm, an ArcticDEM from 3rd of November 2013 and 3rd of November 2014 was used for this purpose.

The cross-sections were made by using the 3D Analyst tool in ArcMap. Each profile is measured perpendicular to the fault and profiles are measured with 200 m interval along the faults. The profiles were long enough so that the general topography could be measured and taken into account (see as an example the gently sloping topography at the beginning and end of the profile in Fig. 2). The throws of faults were measured from the profiles and the results registered into a point shapefile where the profile was taken. The points were then colored according to the throw of the fault.

Field work was done within the Hofsjökull fissure swarms in the summers of 2019 and 2020. The purpose of the field work was ground truthing. The throws of faults were measured by using Trimble ProXH and Trimble Pathfinder ProXR Differential GPS equipments. These profiles were then compared to the ones made by the ArcticDEM. The difference between these two methods is negligible (e.g. Fig. 2), and therefore it was concluded that the ArcticDEM could be used for this purpose.

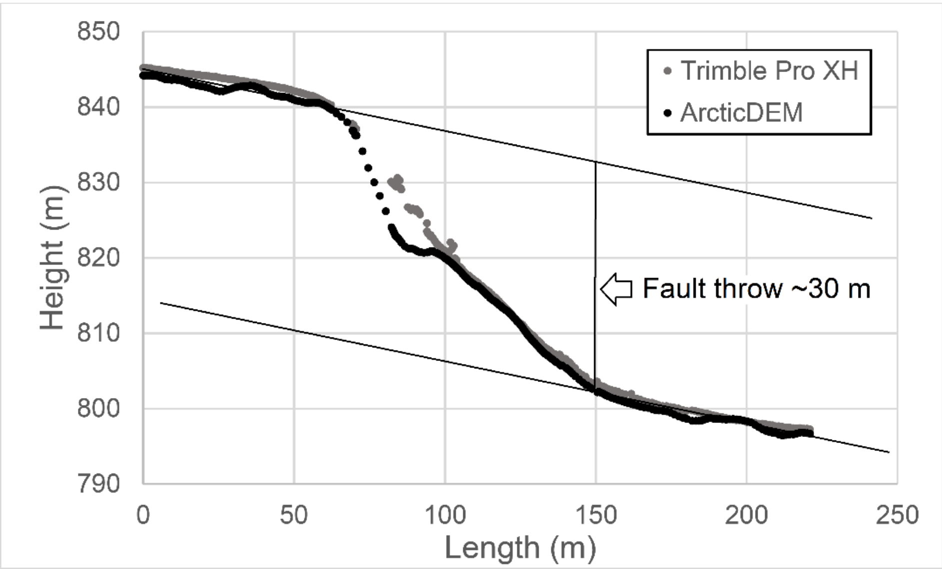



Fig. 2. An example of a comparison between a profile measured in the field with a Trimble ProXH GPS instrument and a profile measured from the ArcticDEM. The figure also shows how the throw of faults is measured. This profile is taken in the southern HFS. As can be seen from the graph, the relative height differences between these two methods is negligible.

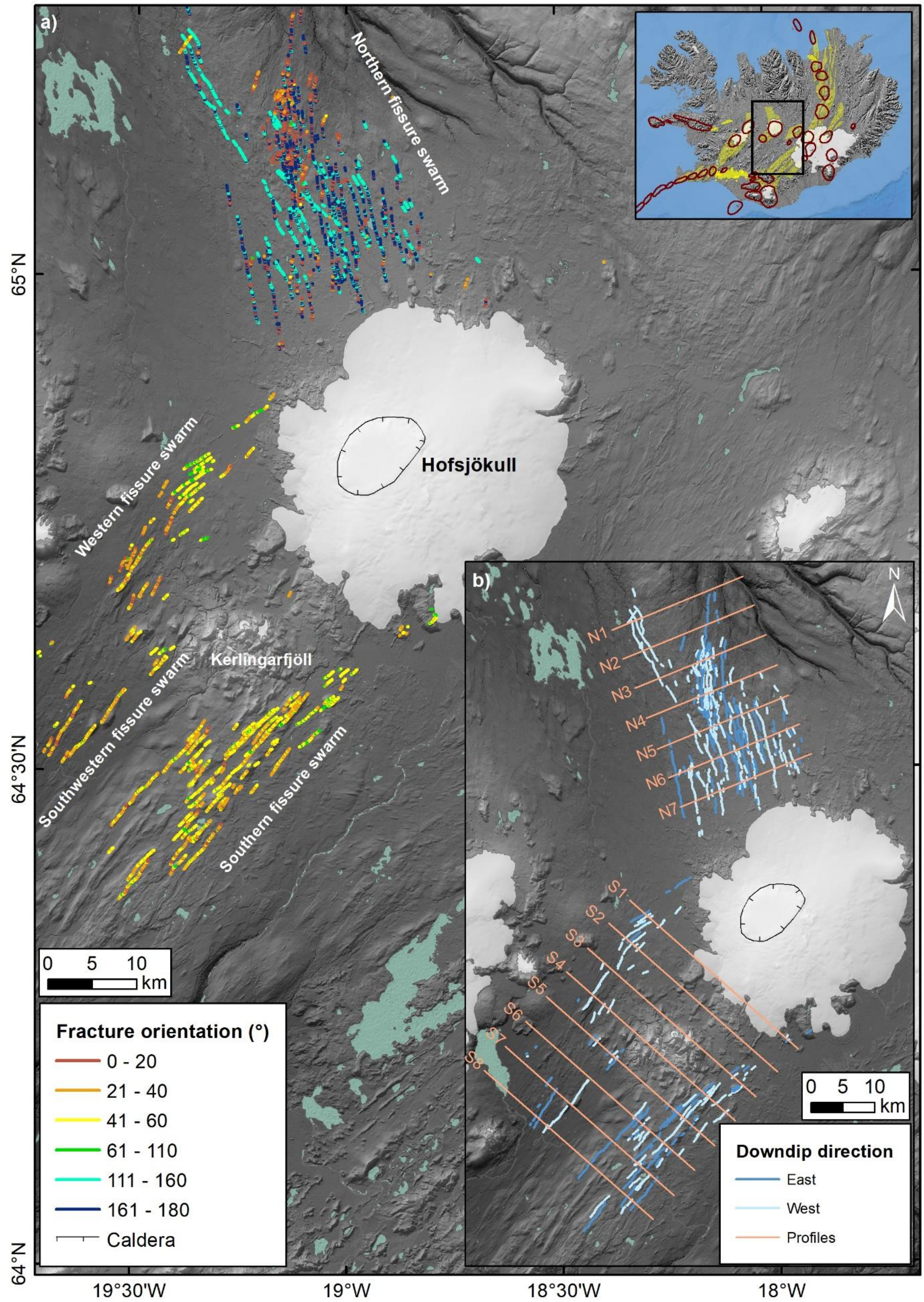



Fig. 3. a) Different segments of the Hofsjökull fissure swarm. Faults are colored according to their orientations. b) The downdip direction of faults. The location of profiles in Figs. 7 and 15

are shown. The digital elevation model in the background is from TanDEM-X, from the German Space Agency. Outlines of glaciers, rivers and lakes are from the IS50 database of the National Land Survey of Iceland.

## 5. Results

The Hofsjökull volcanic system has three to four fissure swarms, two to three extending to the south, and one extending to the north. In addition, Holocene volcanic eruptions have taken place at several places around the Hofsjökull glacier. The lava flows are visible although most of their eruptive vents have been obliterated by the glacier. Each of the fissure swarms has its own characteristics, they have different orientations, width, and extent (Fig. 3).

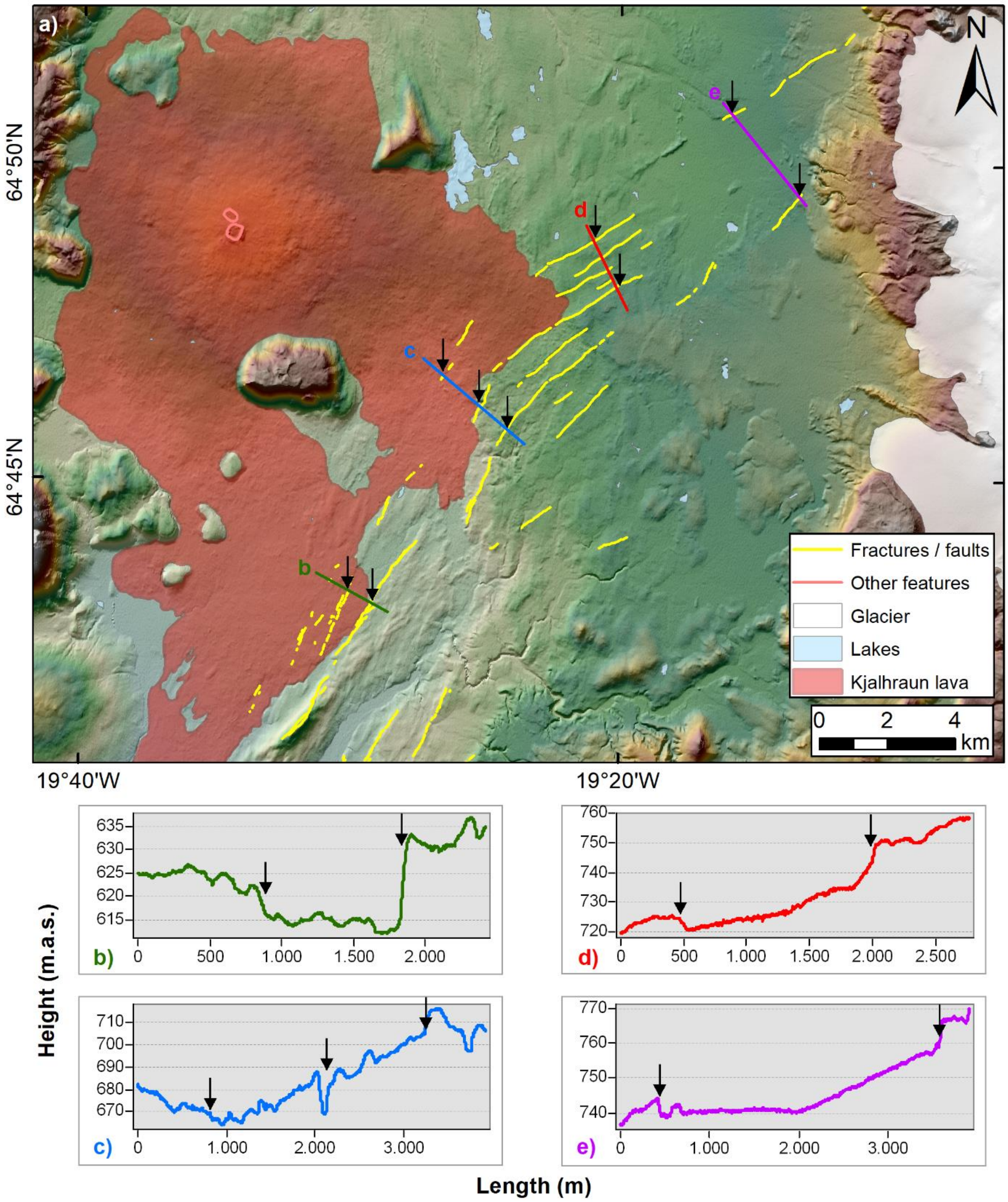



Fig. 4. The western Hofsjökull fissure swarm. a) The fissure swarm cuts the postglacial Kjalhraun lava. b)-e) Profiles across the fissure swarm. The location of the profiles is shown in a). The extent of the Kjalhraun lava is from Sinton et al. (2005). ArcticDEM courtesy of the Polar Geospatial Center.

### 5.1. The western Hofsjökull fissure swarm:

The western Hofsjökull fissure swarm extends from the western part of the Hofsjökull glacier. Its general direction is towards NNE, most commonly striking around 20-30°N. However, closest to the glacier, the fissure swarm gradually changes direction and is oriented more towards the NE, often striking 40-60°N (Figs. 3-5). Therefore, the fissure swarm appears to radiate away from the volcano beneath the glacier.

The length of the Western Hofsjökull fissure swarm is rather uncertain. It is at least ~30 km long, but fractures can be found to up to 40 km distance. The fissure swarm extends into the Hreppar microplate, where it merges with older fractures and faults. In addition, there is another fissure swarm slightly to the east of this one, extending towards the south from the western end of Kerlingarfjöll (Fig. 3, the southwestern fissure swarm). This fissure swarm is possibly the same one as the western Hofsjökull fissure swarm, but it could also be a separate entity and will therefore be described separately.

The western Hofsjökull fissure swarm is rather narrow, mostly about 6 km wide. It cuts the Kjalhraun lava, which is postglacial and has been estimated to be ~10.000 years old (Eason et al., 2015; Hjartarson et al., 2019). The throws of fractures and faults within the Kjalhraun lava are very little, on average only around 0.5 m, these are mostly tensional fractures (e.g. Fig. 4a and 4c). The older surface formations generally have greater offset (e.g. Fig. 4b), although the throw of faults in the northern part of the Western Hofsjökull fissure swarm is generally less than 10 m (Fig. 6).

Transects across the Western Hofsjökull fissure swarm indicate that it only consists of one graben (Figs. 4 and 7). The graben is about 1.5 km wide in the southern part (Fig. 4b, 4c and 4d), but about 3 km wide in the northernmost part (Fig. 4e).

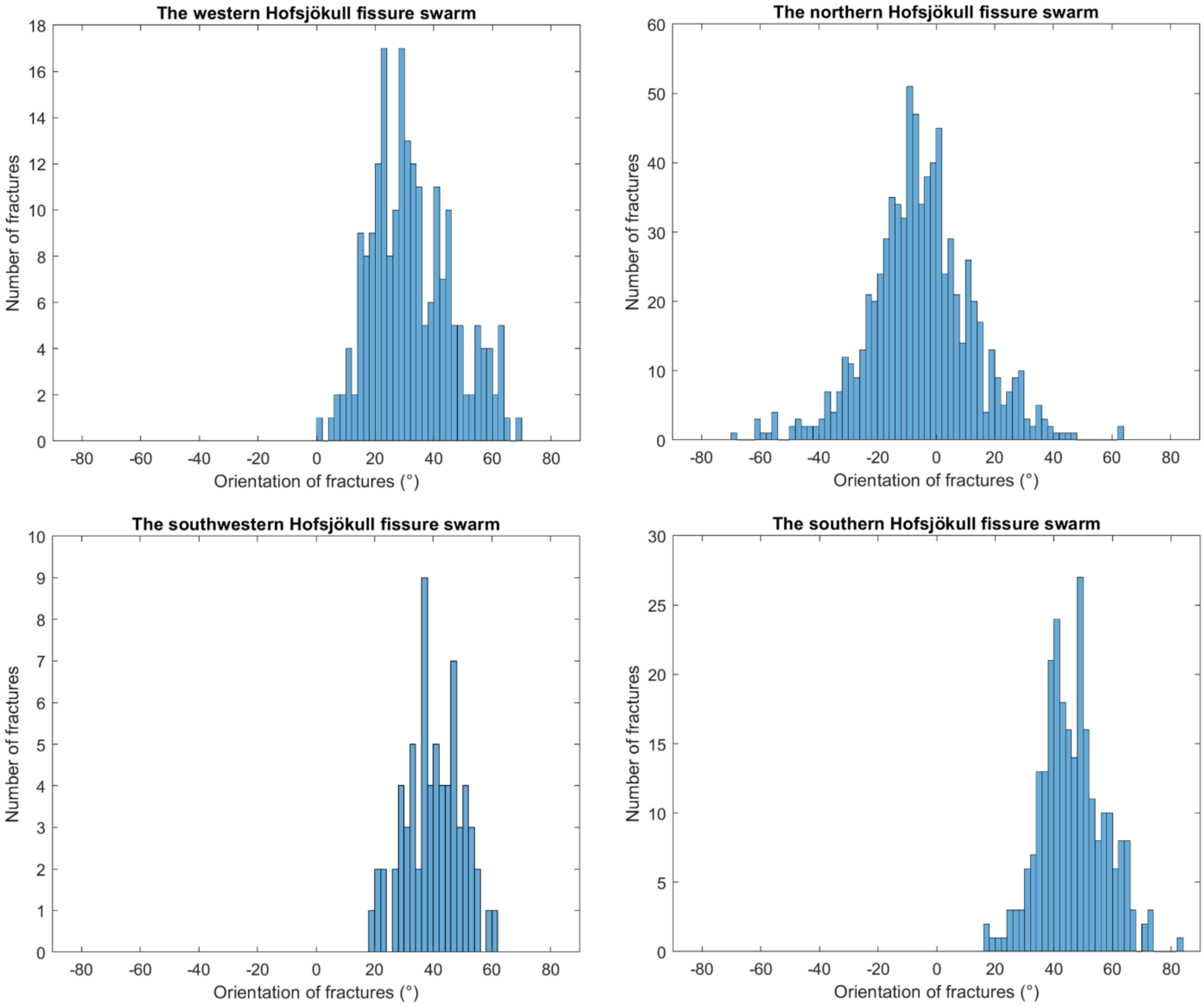



Fig. 5. Orientation of fractures in different fissure swarms of the Hofsjökull volcanic system. The orientation is represented in degrees from north, positive numbers indicating northeasterly orientation, negative numbers representing northwesterly orientations.

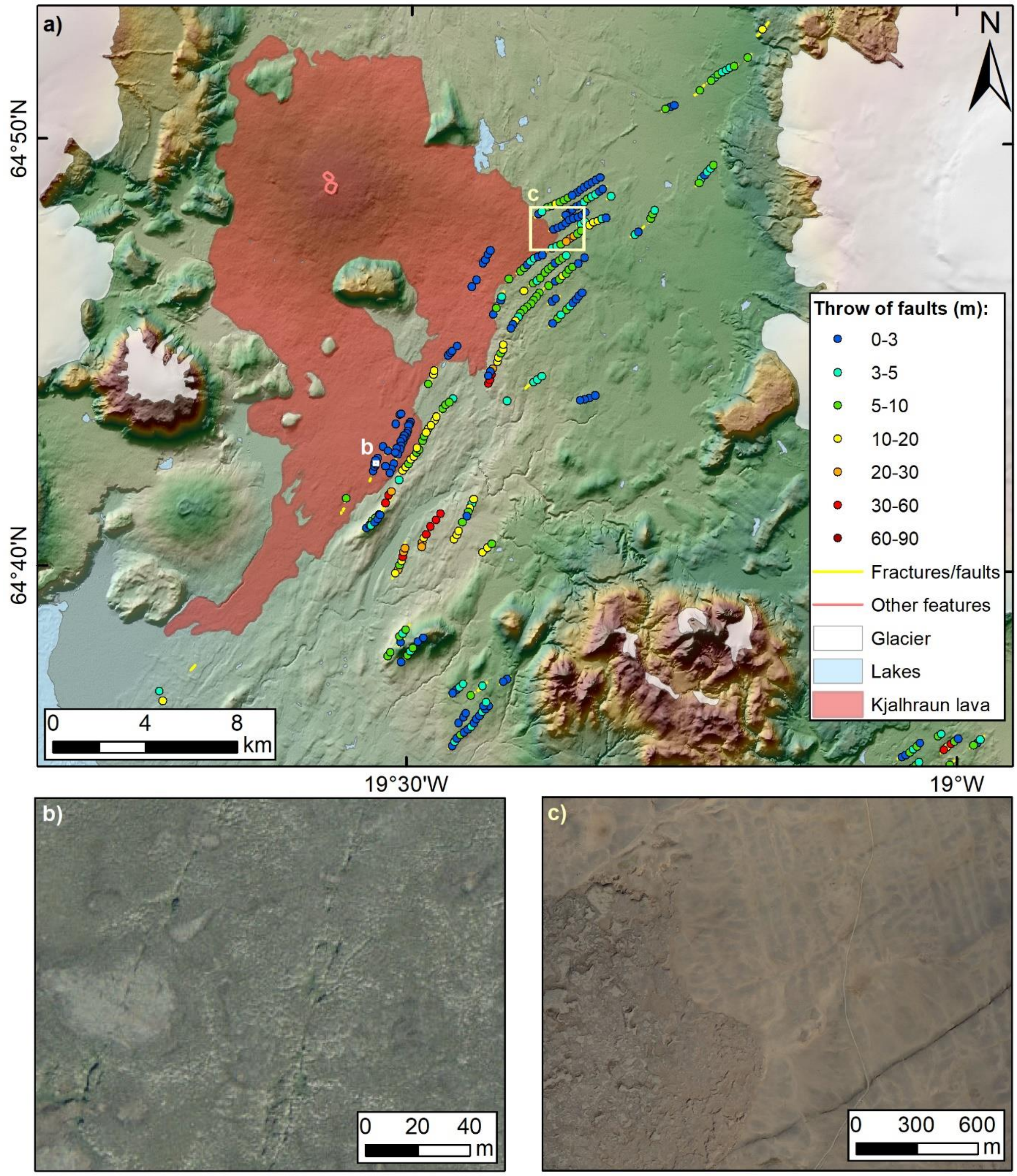



Fig. 6. a) Throw of faults in the western Hofsjökull fissure swarm. b) Aerial photograph showing fractures in the postglacial Kjalhraun lava. c) Faults at the boundary of the postglacial Kjalhraun lava and older formations, the location of the aerial photographs is shown in a). The aerial photographs are from Loftmyndir Corp. The extent of the Kjalhraun lava is from Sinton et al. (2005). ArcticDEM courtesy of the Polar Geospatial Center.

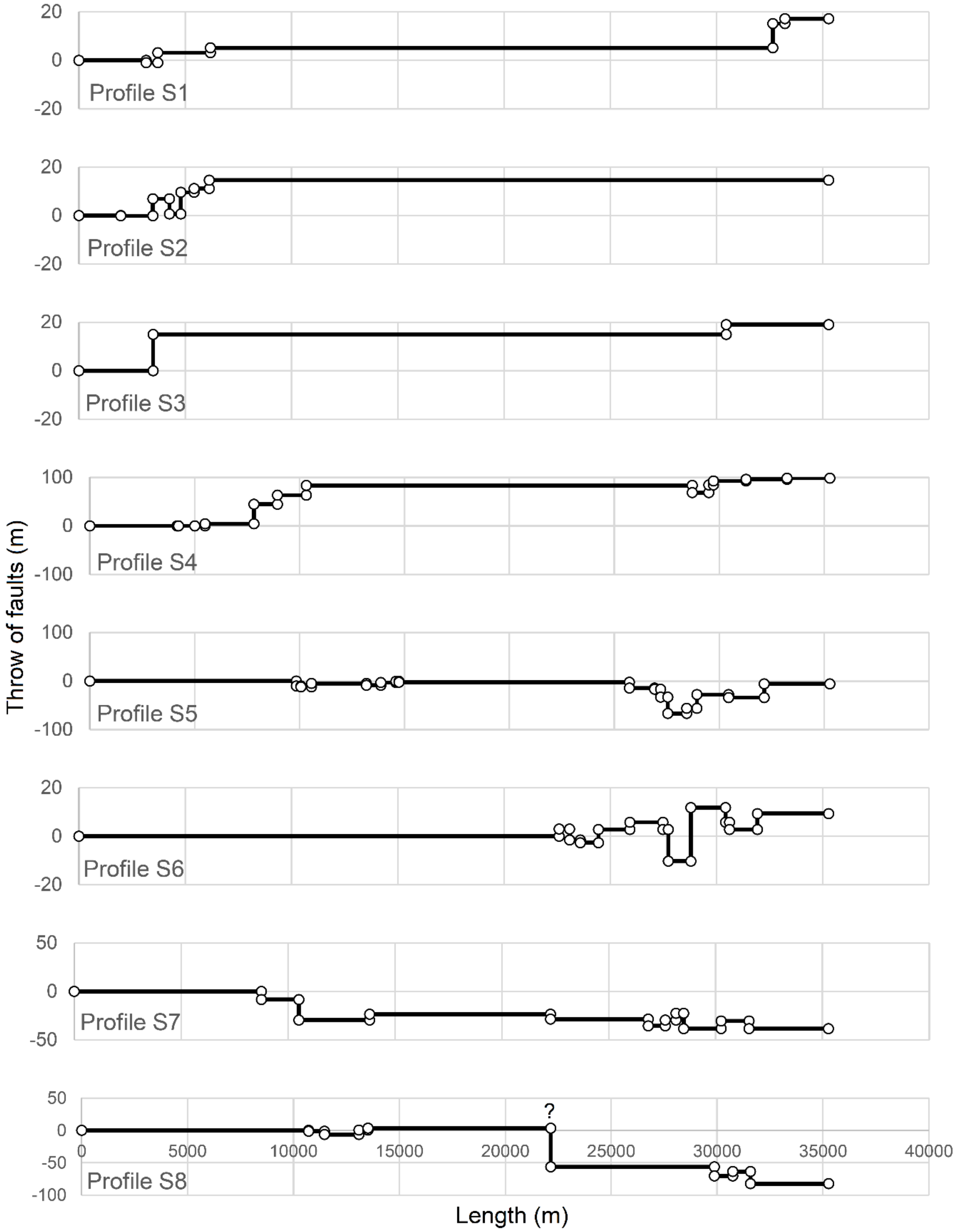



Fig. 7. Throw as a function of a distance along a profile across the southern Hofsjökull fissure swarms, showing offset of faults. Negative values indicate downthrow towards the east. The location of the profiles is shown in Fig. 3.

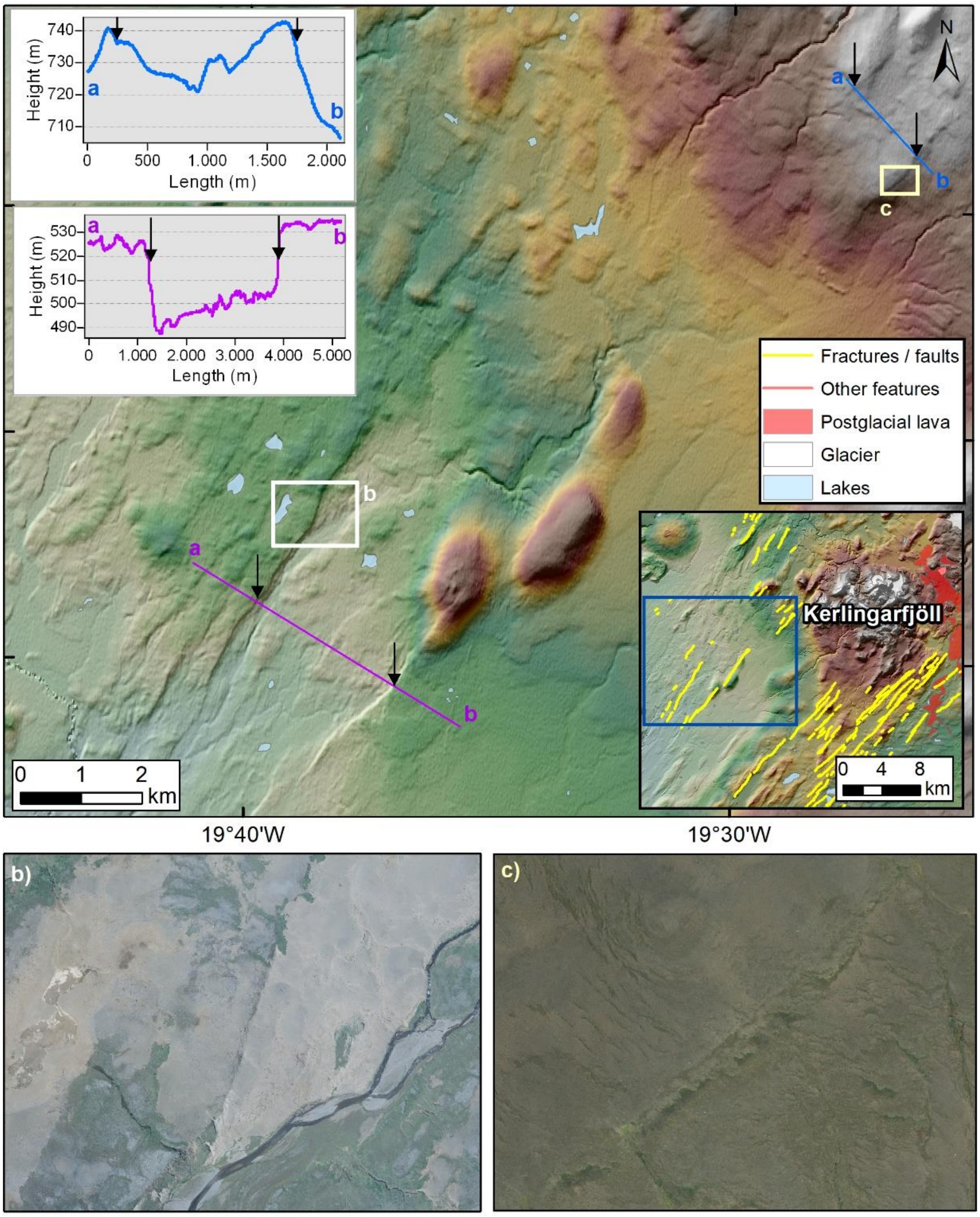



Fig. 8. a) The southwestern Hofsjökull fissure swarm. Inset graphs show profiles across different parts of the fissure swarm. ArcticDEM courtesy of the Polar Geospatial Center. Note the generally small throws of faults close to Kerlingarfjöll (blue profile), whereas the fault throws increase towards the south (e.g. purple profile). b) Aerial photograph from the Loftmyndir Corp. showing a fault in the southern part of the southwestern Hofsjökull fissure swarm, c) Aerial photograph showing a fault in the northern part of the fissure swarm. The locations of the aerial photographs are shown in a).

## 5.2. The southwestern Hofsjökull fissure swarm

This part of the Hofsjökull fissure swarm could be the southern part of the western fissure swarm, but it could also be a separate entity and will therefore be described separately.

The southwestern Hofsjökull fissure swarm is located to the west and south of the Kerlingarfjöll massif. Near Kerlingarfjöll, the throws of the faults are small (often less than 3.5 m). Towards the south, the throws increase significantly, and can sometimes be more than 30 m (Figs. 7 and 8). This fissure swarm has one clear graben which is about 3 km wide in the northern part (e.g. Fig. 8, purple profile), but gets narrower towards the south, where it is about 2 km wide. The faults in this fissure swarm trend towards the NE, with the most common trends between 30 and 50° N (Fig. 5).

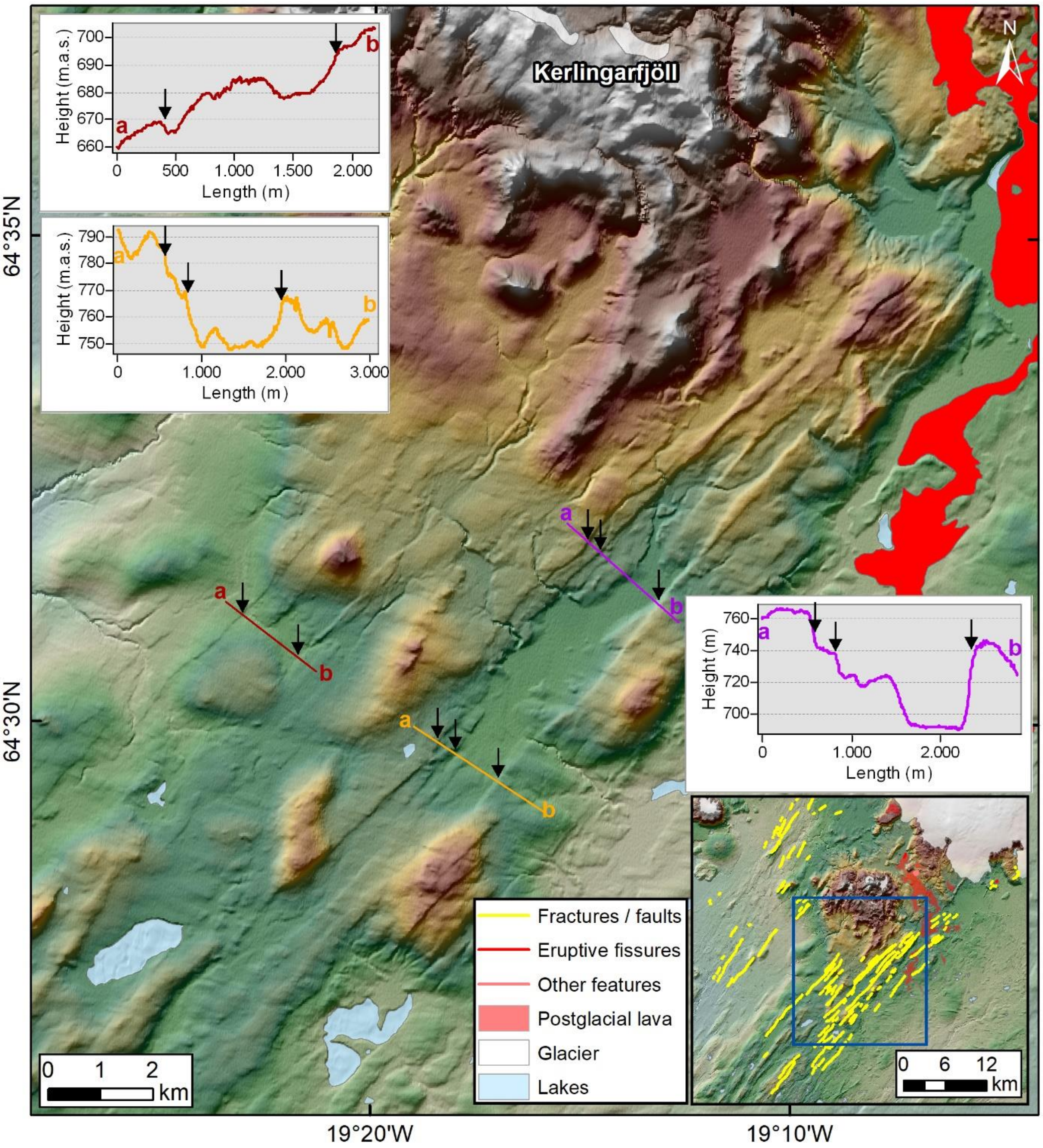



Fig. 9. The southern Hofsjökull fissure swarm. Inset graphs show profiles across different grabens in the fissure swarm. Outline of the postglacial lava is from Hjartarson et al. (2019). ArcticDEM courtesy of the Polar Geospatial Center.

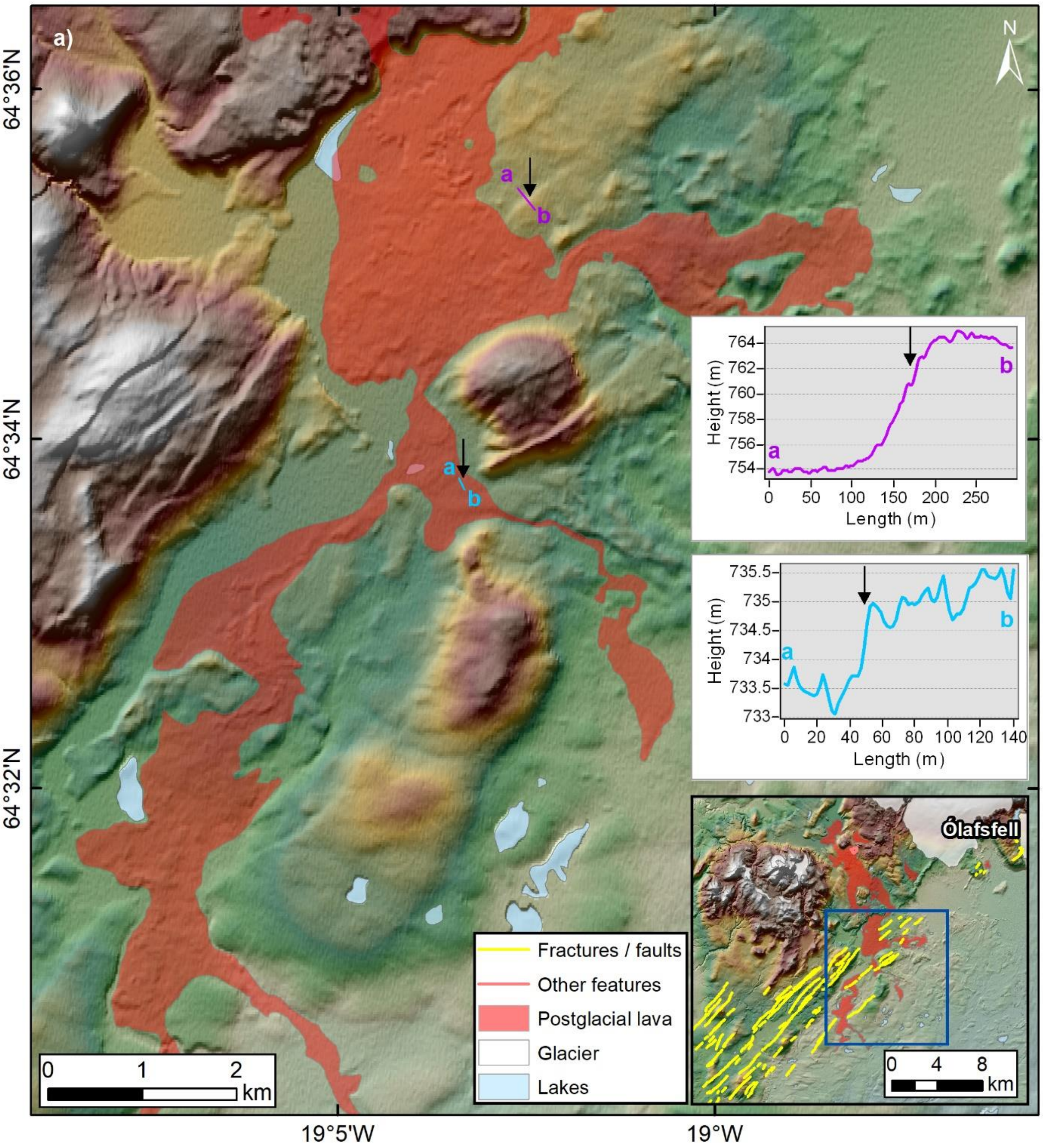



Fig. 10. The southern Hofsjökull fissure swarm. Here, the fissure swarm cuts the postglacial Illahraun lava. Inset graphs show profiles across different parts of the fissure swarm. The purple profile shows a fault with a throw of about 10 m, whereas the light-blue profile, which crosses a fault in the postglacial Illahraun lava, shows very little throw (~1.5 m). Outline of the postglacial lava is from Hjartarson et al. (2019). ArcticDEM courtesy of the Polar Geospatial Center.

## 5.3. The southern Hofsjökull fissure swarm:

The southern Hofsjökull fissure swarm is about 50 km long. Its southern end is slightly uncertain since it merges with the highly fractured Hreppar microplate. Since the Hofsjökull fissure swarms are characterized by grabens we define the southern boundary of the fissure swarm to be where the clear graben structures end. The fissure swarm is up to 9 km wide and consists of several nearly parallel grabens, which can be up to ~2 km wide (Figs. 9 and 10). In some instances, grabens can be found within other grabens. The northeastern end of this fissure swarm starts near the Ólafsfell mountain (Fig. 10), but the start of the southwestern end of it is more uncertain. An eruptive fissure (which formed the Illahraun lava) is found north of Kerlingarfjöll, and is a part of this fissure swarm, but no fractures could be found in the Kerlingarfjöll massif. Few clear fractures are found north of Kerlingarfjöll, although there are some indications of eroded WNW-ESE lineaments which could be old fractures. However, some fractures are found south of Kerlingarfjöll (Fig. 9, e.g., dark red profile). No sink holes were found in the southern Hofsjökull fissure swarm, indicating that the fissure swarm has not been active recently, and that all sink holes have been filled with sediments. This differs from fissure swarms at volcanic systems which are located closer or at the main plate boundary in Iceland. Open sink holes along faults in loose sediments can, as an example, be seen in the nearby Tungnafellsjökull fissure swarm, as well as in the Krafla fissure swarm (Björnsdóttir and Einarsson, 2013; Hjartardóttir et al., 2012).

Faults in the southern Hofsjökull fissure swarm generally trend towards the NE, most commonly around 40-50°N (Fig. 5). This is a similar trend as is seen in the fissure swarm to the west of it, the southwestern fissure swarm, although the southern fissure swarm has more faults trending more eastwards (60-80°N) than the southwestern fissure swarm (Fig. 5).

The throws of the boundary faults of the grabens in the southern Hofsjökull fissure swarm vary significantly (Figs. 7, 9 and 10). They are greatest in the main southern fissure swarm, where the throws of faults often reach 18-30 m (Figs. 11 and 12a). However, the throw of fractures just south of Kerlingarfjöll is much less, typically less than 10 m, and often less than 3.5 m (Fig. 11). This occurs even though these fractures are in surface formations of similar age as the fractures with the greater offsets to the east of them (Fig. 1c) (Hjartarson et al., 2019). The fractures in and around the postglacially formed Illahraun lava also often have little throws (1-2 m, Figs. 10-12b).

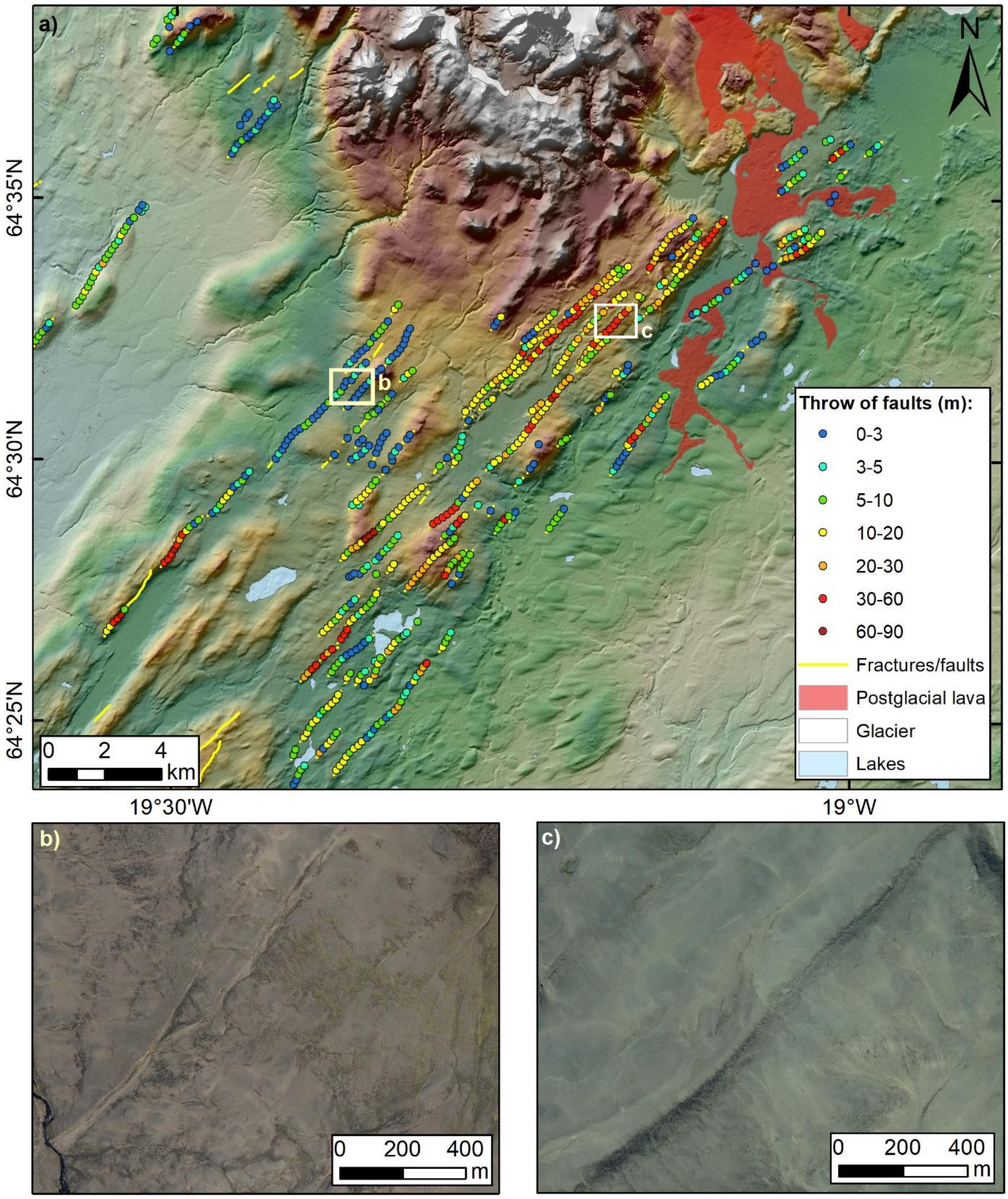



Fig. 11. a) Throws of faults in the southern Hofsjökull fissure swarm. Here, throws of faults are generally larger at lower altitudes, whereas few faults are found at the topographically high Kerlingarfjöll massif. Throws of faults are smaller directly south of Kerlingarfjöll, than of the faults that cross the area east of Kerlingarfjöll. b) and c) Aerial photographs of selected areas, locations shown in a). The aerial photographs are from Loftmyndir Corp. Outline of the

postglacial lava is from Hjartarson et al. (2019). ArcticDEM courtesy of the Polar Geospatial Center.

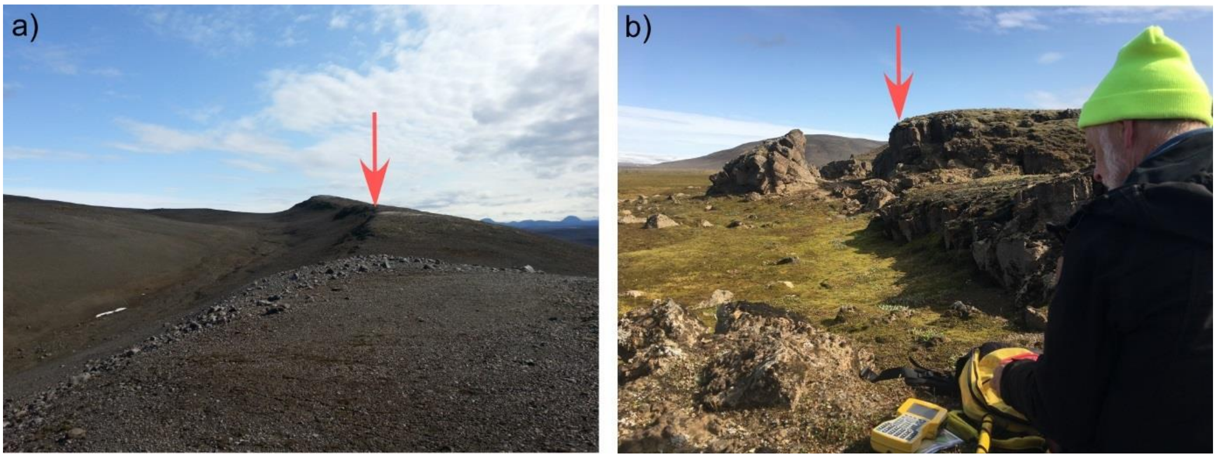



Fig. 12. Faults in the southern Hofsjökull fissure swarm. a) Fault in a hyaloclastite formation, with a throw of ~30 m. b) Fault in the postglacial Illahraun lava, with a throw of ~2 m. Páll Einarsson is sitting next to the Trimble Pathfinder ProXR GPS instrument.

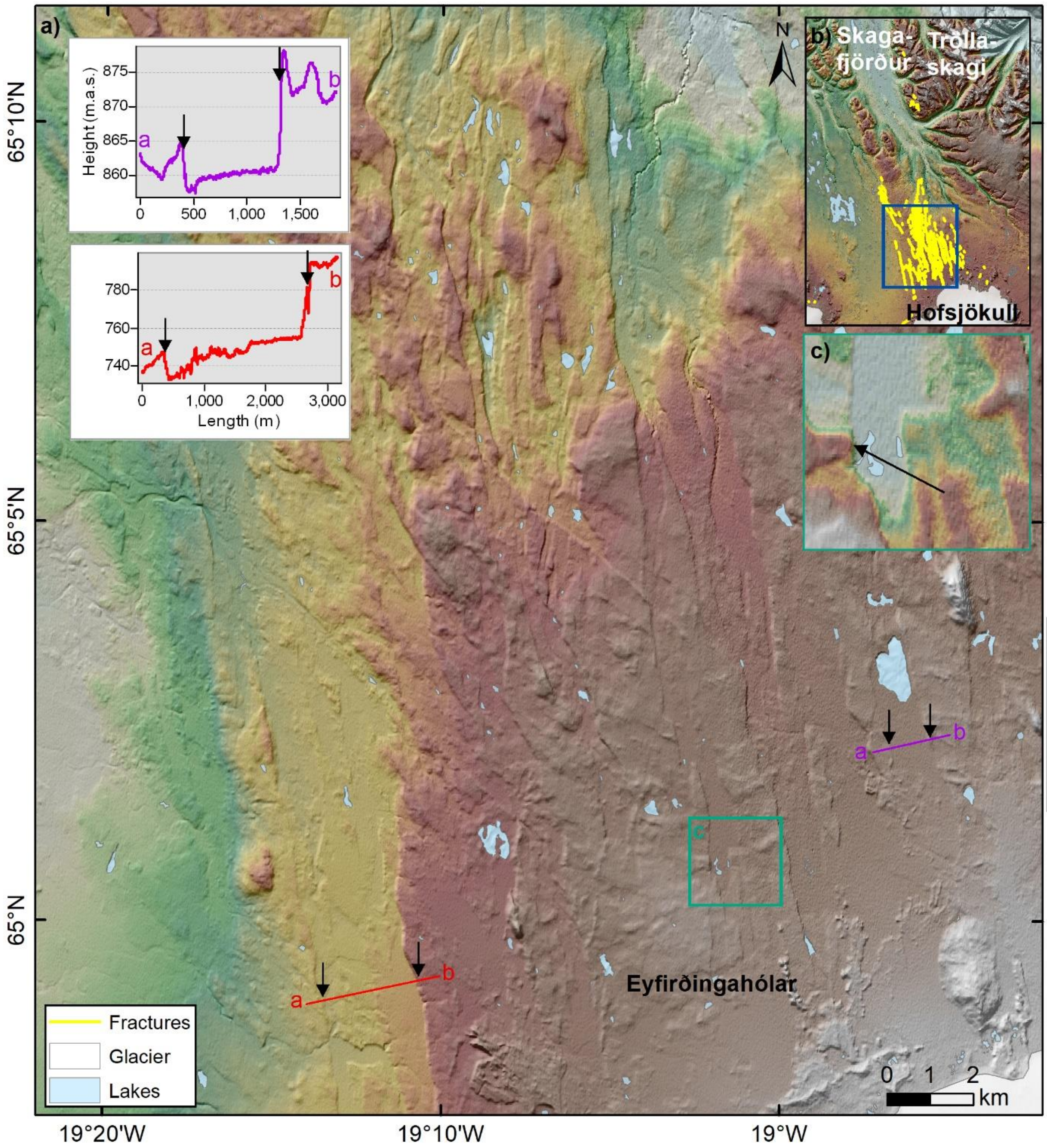



Fig. 13. a) The northern Hofsjökull fissure swarm consists of multiple grabens and other faults. b) The northern Hofsjökull fissure swarm. Blue frame indicates the location of a). c) Examples of faults cutting glacial moraines, indicating that the faults have been active in postglacial times. The location is shown in the green frame in a). Inset graphs show two examples of profiles across grabens, the profiles are marked in a).

### 5.4. The northern Hofsjökull fissure swarm:

The northern Hofsjökull fissure swarm extends at least 40 km north of the Hofsjökull volcano (Fig. 3). However, freshly looking fractures can be found farther to the north, in the Tröllaskagi area by the northern coast of Iceland (Fig. 13). These fractures might be a separate entity not related to the northern Hofsjökull fissure swarm; the Tröllaskagi fractures will therefore not be discussed further in this paper.

The overall orientation of the northern Hofsjökull fissure swarm is towards the north-northwest. The orientation of individual fractures there is, however, more varied than in the fissure swarms extending to the south and west of the Hofsjökull glacier (Figs. 3 and 5). Three fracture population orientations are prevalent: A north-northwesterly orientation, which prevails in the southern and middle part of the fissure swarm, a northwesterly orientation which intermingles with the north-northwesterly oriented faults, and a northerly orientation which is mostly found in the northernmost part of the fissure swarm (Fig. 3).

Throws of faults in the northern Hofsjökull fissure swarm varies significantly. Although the faults in the main part of the fissure swarm generally have throws of less than 30 m, some faults, especially in the western part, have larger offsets (Figs. 14 and 15). This applies particularly to the northwesterly oriented population of faults located in the northwesternmost part of this area. This fault population is overprinted by the more northerly oriented faults which extend towards the Skagafjörður valley (Figs. 3 and 13). The northwesterly oriented faults generally have larger offsets than the northerly oriented fault population, even though they are in surface formations of a similar age (Jóhannesson and Sæmundsson, 1998a). Profiles across the northern Hofsjökull fissure swarm show that faults in the northern part of it are mainly downthrown towards the west (Fig. 15). This trend continues somewhat in the profiles further to the south, but there, profiles showing small grabens become more prevalent.

No clear sink holes were found in the northern Hofsjökull fissure swarm, which suggests that the fissure swarm has not been active for a considerable time, despite the significant throw of faults (Figs. 14-17). In addition, a fault in its southern part, near Eyfirðingahólar, is covered with unbroken hyaloclastite (Figs. 13 and 16). The hyaloclastite is from the last part of the last glaciation (Hjartarson et al., 2019). This indicates that the fault has not been active since the subglacial eruption which formed the hyaloclastite occurred.

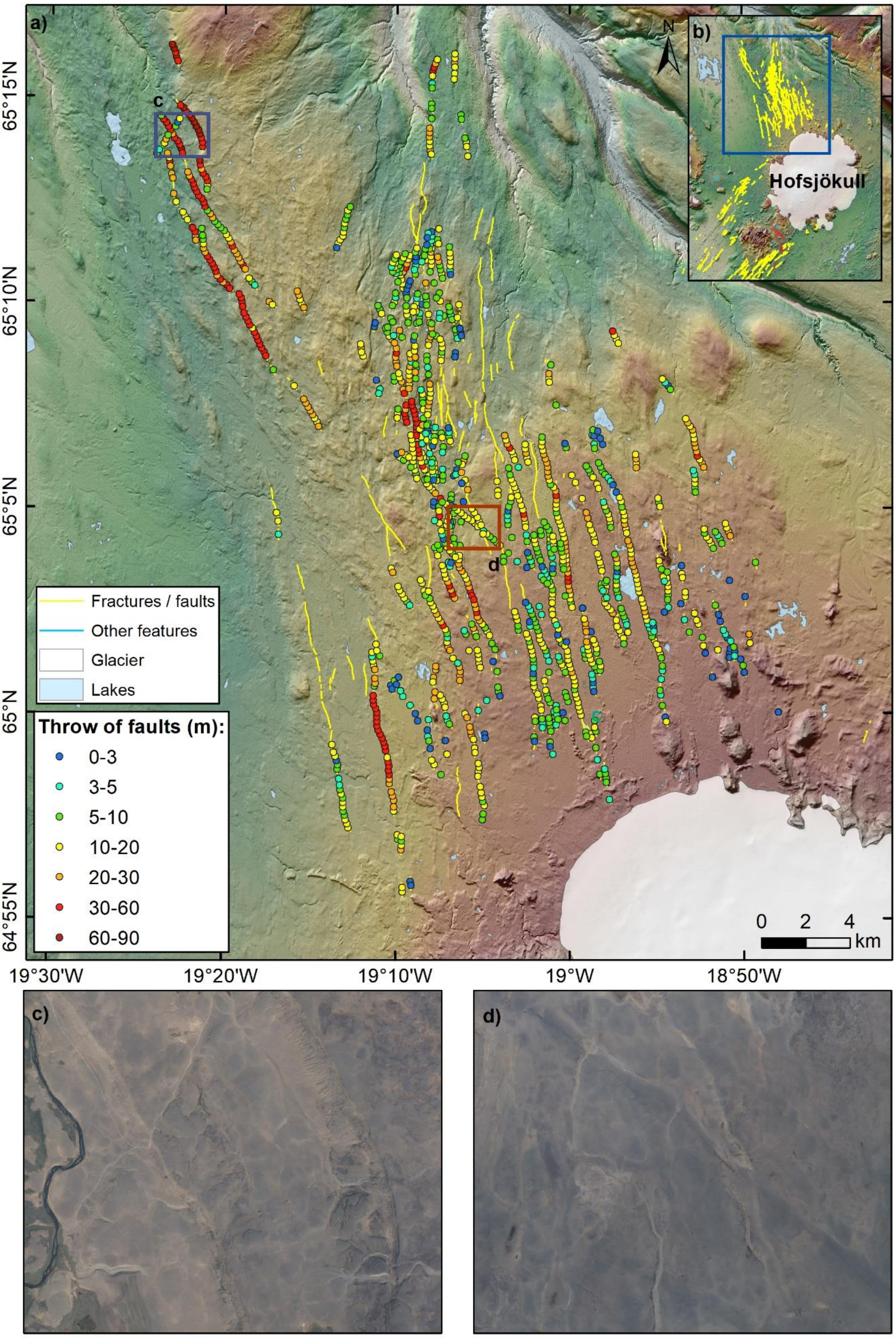

a)
b)
Hofsjökull
c
d
N
65°15'N
65°10'N
65°5'N
65°N
64°55'N
19°30'W
19°20'W
19°10'W
19°W
18°50'W
Fractures / faults
Other features
Glacier
Lakes
Throw of faults (m):
0-3
3-5
5-10
10-20
20-30
30-60
60-90
0 2 4
km
c)
d)

Fig. 14. a) Throw of faults in the northern Hofsjökull fissure swarm. Gaps in the measurements are due to gaps in the ArcticDEMs. b) An overview map of the northern Hofsjökull fissure swarm. c) An example of an aerial photograph showing faults, see a) for location. d) Another example of an aerial photograph showing faults, see a) for location.  The aerial photographs are from Loftmyndir Corp.

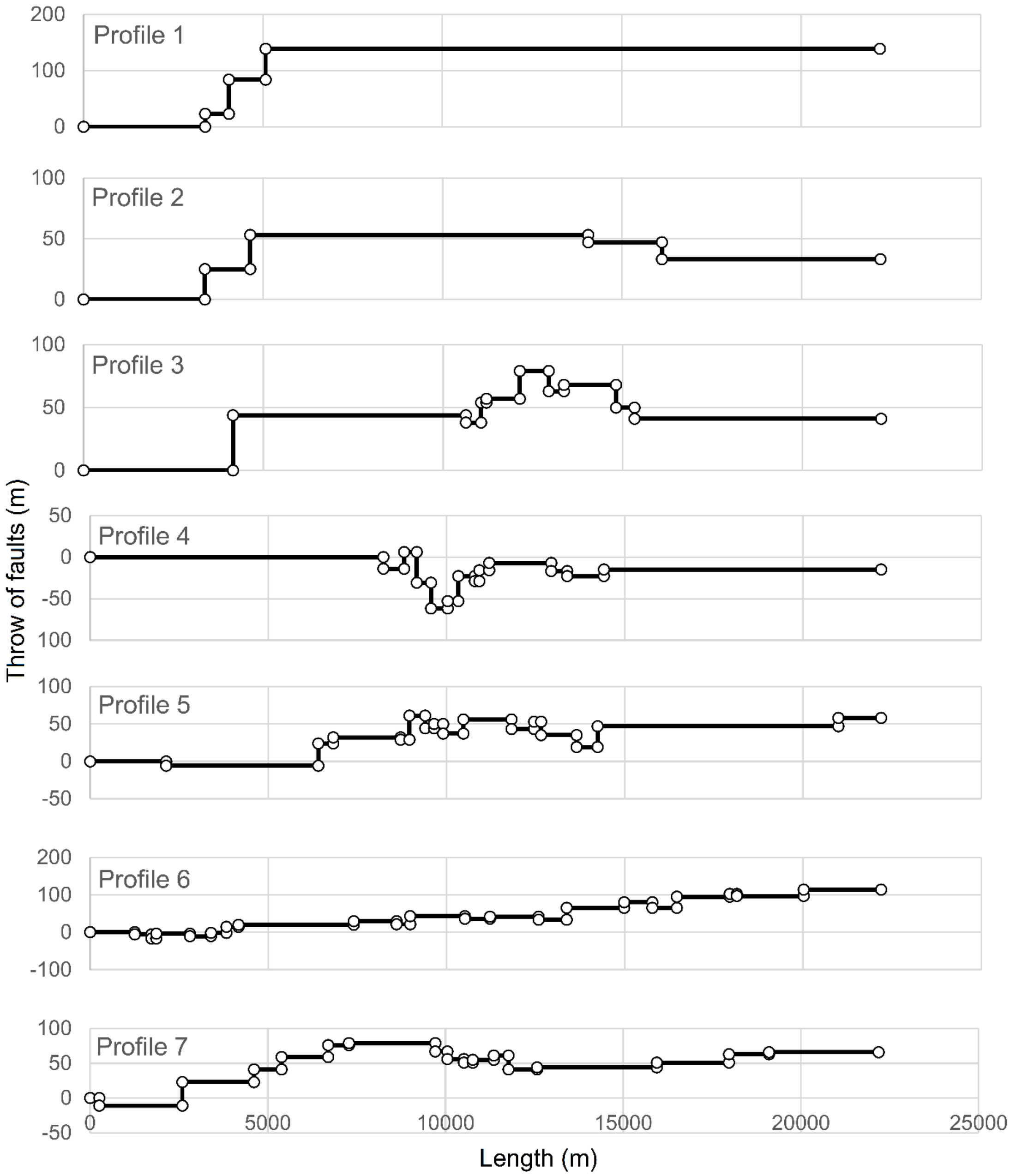
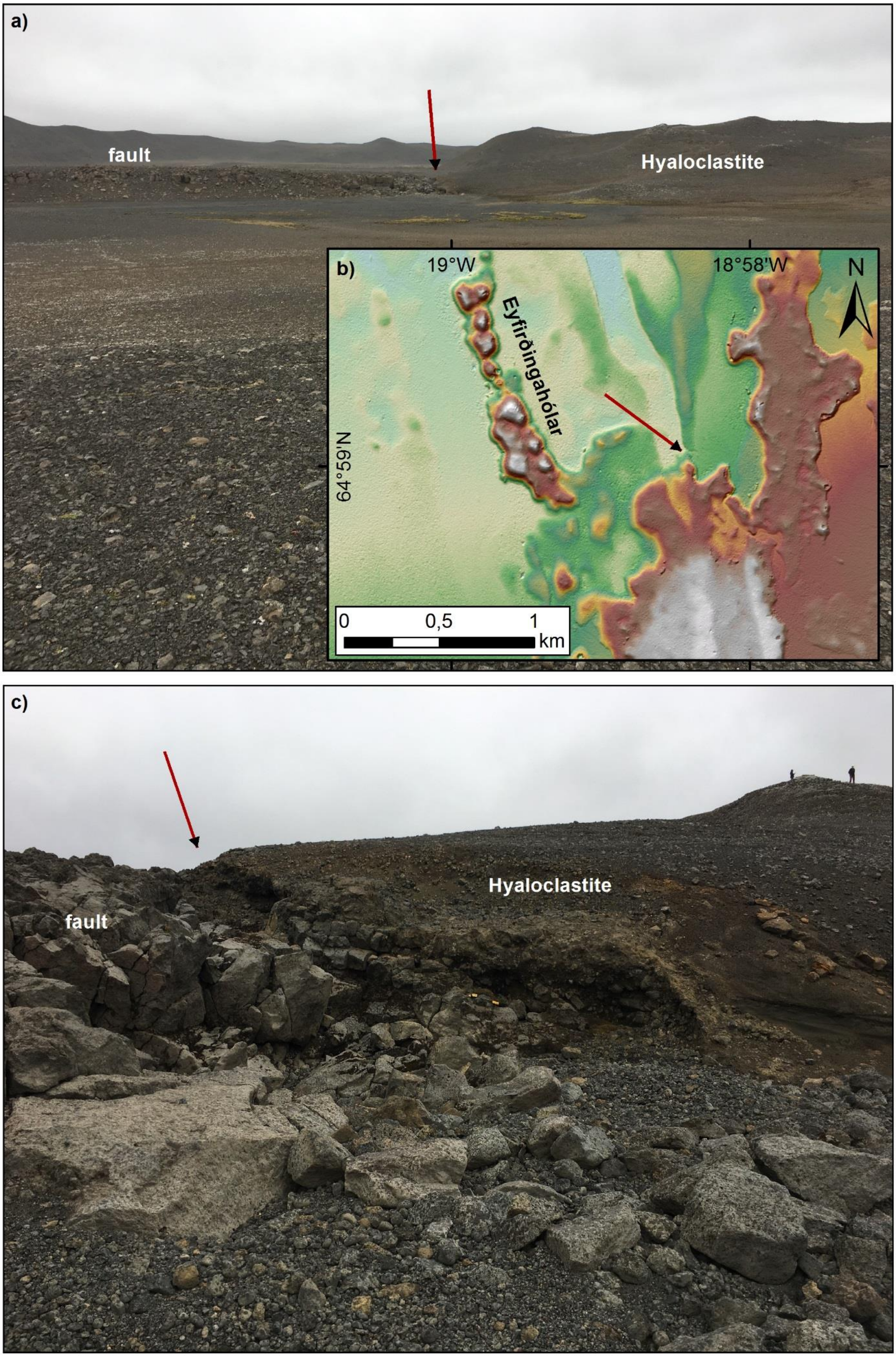



Fig. 15. Throw as a function of a distance along a profile across the northern Hofsjökull fissure swarms, showing offset of faults.  Negative values indicate downthrow towards the east. The location of the profiles is shown in Fig. 3.


a)
fault
Hyaloclastite
b)
19°W
18°58'W
N
Eyfirðingahólar
64°59'N
0
0,5
1
km
c)
fault
Hyaloclastite

413

Fig. 16. a) A fault near Eyfirðingahólar. This fault is covered by an unbroken hyaloclastite, implying that the fault has not moved after the formation of the hyaloclastite. b) The location of the fault. c) A closer look at the boundary between the fault and the hyaloclastite. ArcticDEM courtesy of the Polar Geospatial Center.

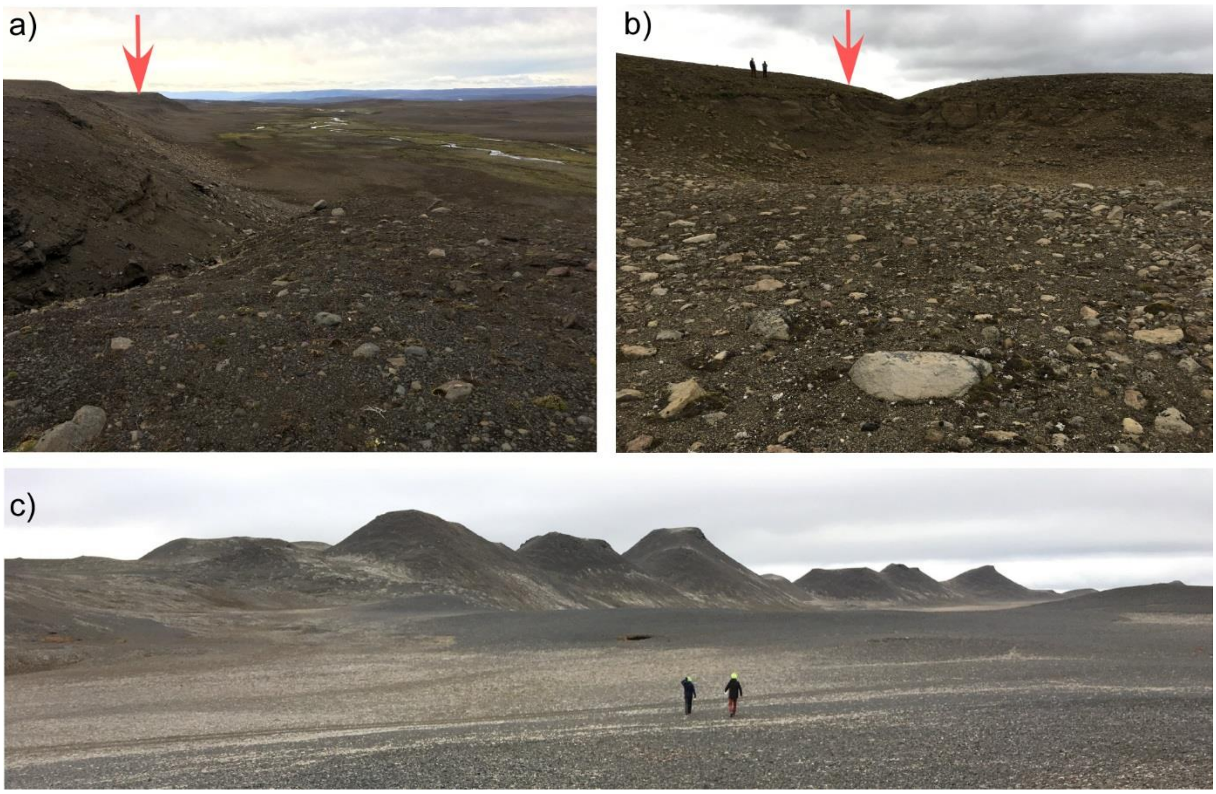



Fig. 17. Fieldwork in the northern Hofsjökull fissure swarm. a) Fault in the central part of the northern HFS. Red arrow points to the fault. b) View towards another fault in the northern HFS, for scale, see two persons left of the red arrow. c) The Eyfirðingahólar pillow lava mounds.

## 6. Discussion

The mapping and analyzing of the fissure swarms of the Hofsjökull volcanic system indicate that they are mostly composed of grabens of various widths and depths, as indicated by the difference in the throw of faults (Figs. 3, 4, 6-10, 13, 15). The northwestern part of the northern Hofsjökull fissure swarm has a different appearance. There, most faults have a dip direction towards the west, often with a large-scale throw, and trend more northwestward than the more northerly-oriented faults to the east of them (Figs. 3b, 14a and 15). They appear therefore to form a different fault population than the other faults in the northern Hofsjökull fissure swarm.

### *6.1. Local stress field of the Hofsjökull central volcano vs. the regional stress field*

Fissure swarms tend to radiate away from the Hofsjökull central volcano. This indicates that the Hofsjökull central volcano has a significant local stress field. This pattern is visible in the western Hofsjökull fissure swarm, where faults closest to the Hofsjökull central volcano bend more towards the northeast, while faults farther away have a more north-northeasterly orientation (Fig. 3). In addition, Holocene lava flows have been erupted not only north and south of the Hofsjökull central volcano, but also east and west of it (Hjartarson et al., 2019). This suggests that a local stress field of the Hofsjökull central volcano plays a significant role in this area, as it can cause the formation of a radial pattern of dike intrusions when $\sigma_3$ follows a circular trace around the magma source in central volcanoes (e.g. Anderson, 1951; Nakamura, 1977)

Sometimes, fissure swarms in Iceland cut central volcanoes without much deviation of fracture orientations. This can indicate that the local stress field of the central volcano was not significant when the fractures within the fissure swarms formed, or that the principal axes of the regional stress field and the local stress field were aligned. This applies as an example to the Fremrinámar and Þeistareykir central volcanoes in the Northern Volcanic Zone in Iceland (Fig. 1a) (Hjartardóttir et al., 2016c; Magnúsdóttir and Brandsdóttir, 2011; Tibaldi et al., 2020). The Krafla central volcano has some local stress field, but mostly, the fractures follow the regional stress field (Hjartardóttir et al., 2012). Two central volcanoes in the Northern Volcanic Zone show significant local stress field. These are the Askja central volcano (Hjartardóttir et al., 2009), and the Bárðarbunga central volcano, where a dike intrusion, which occurred in 2014, started by propagating away from the Bárðarbunga central volcano in a southeasterly direction, far from the north-northeasterly direction expected if it would be opening perpendicular to the plate spreading direction in the area (DeMets et al., 1994; Sigmundsson et al., 2015). As the dike propagated away from the central volcano, it changed its heading until its distal part aligned with the regional stress field (Hjartardóttir et al., 2016b; Sigmundsson et al., 2015). This suggests that some central volcanoes in Iceland have a significant local stress field, and that the strength of the local stress field varies between central volcanoes. In the case of Hofsjökull, its local stress field may be dominant because it is not on the main plate boundary, therefore divergent plate movements are small or non-existent in this area (Fig. 1). This local stress field may also be augmented by the close proximity of the Hofsjökull central volcano to the center of the Iceland hotspot, which is near the Bárðarbunga central volcano (Wolfe et al., 1997). It is also likely that strength of the local stress field of the central volcano can vary with time, depending on whether the magma source is inflating or not. Therefore, the relative contribution of the local stress field and the regional stress field can vary (e.g. Geshi, 2005; Magee et al., 2012). The eruptions on the east and west flanks of Hofsjökull could thus represent periods of a strong local stress field of the Hofsjökull central volcano, implying a significant inflation of the volcano at the time.

### *6.2. The orientation of fractures and faults in the northern Hofsjökull fissure swarm*

The northern Hofsjökull fissure swarm is not located on a clear plate boundary (Fig. 1). Its NNW-orientation is also far from the NNE orientation which would be expected if the fissure swarm would open perpendicular to the plate spreading between the Eurasian and the North American plates.

It is therefore not clear why the Hofsjökull fissure swarm is oriented towards the NNW. One possibility is that the orientation of the fissure swarm is caused by differences in the crustal thickness in this area. Measurements of seismic velocities show that an area of increased crustal thickness extends in the NNW direction from the center of the Iceland hotspot near the Bárðarbunga central volcano, extending into the area where the northern Hofsjökull fissure swarm is located (Fig. 1a) (Allen, 1999; Brandsdóttir and Menke, 2008; Menke, 1999). West of this area, the crustal thickness decreases significantly. The NNW oriented Hofsjökull fissure swarm is therefore nearly parallel with the area of increased crustal thickness, and with the boundary between the thicker and the thinner crust.

During deglaciations, crustal blocks of different thicknesses can respond differently to the unloading of the glaciers. Therefore, crustal uplift can occur at different rates, causing enhanced differential stresses in a zone oriented parallel with the boundaries of these crustal blocks, i.e. in the NNW orientation in this case. In the absence of the crustal stresses by the divergent plate boundary, these divergent stresses may become the governing factor in where dike injections from the Hofsjökull central volcano propagate, therefore creating and maintaining the NNW orientation of the northern Hofsjökull fissure swarm.

Similar arguments have also been used to explain the Kerlingar fault at the eastern boundary of the Northern Volcanic Zone, which has also been active during the Holocene (Hjartardóttir et al., 2010). According to this suggestion, such differences in crustal thickness can cause dominant stress fields in areas where little or no deformation takes place due to plate divergence. This could also explain why fractures in the Northern Hofsjökull fissure swarm became activated by the end of the last glaciation, in the beginning of the Holocene, but has not been active recently, as observed by the lack of sink holes in the area.

The differently oriented fault populations in the northern Hofsjökull fissure swarm; the northerly fault system and the northwesterly fault system, suggest that the stress field has changed significantly. It is unclear why this occurred, but this might be explained by a changing stress field as the glacier retreated farther inland during the last deglaciation. Such an interaction between the orientation of dyke intrusions and crustal stresses due to uplift of land during glacier retreat has been used to explain the anomalous orientation of a recent dike intrusion in the Northern Volcanic Zone during small-scale glacier retreats at present time (Hooper et al., 2011), and this could also play a large part during large-scale glacier retreats as occurred during the end of the last glaciation.

### *6.3. Activity of the Hofsjökull fissure swarms at the end of the last glaciation and during the Holocene*

Both the western and southern Hofsjökull fissure swarms include fractures and faults in Holocene lava flows. Therefore, it is clear that these fissure swarms have been active during postglacial times, the western fissure swarm sometime after the emplacement of the ~10.000 years old Kjalhraun lava, and the southern fissure swarm sometime after the emplacement of the 4500-7000 years old Illahraun lava (Eason et al., 2015; Hjartarson et al., 2019).

The vertical movements of faults in these postglacial lava flows are, however, rather small, around 1-2 m in both. Vertical fault movements during individual dike intrusions are often around 1-3 m (or more) (e.g. Hjartardóttir et al., 2016b; Saemundsson, 1992; Sigurdsson, 1980; Wright et al., 2006). Therefore, it is possible that these fissure swarms have had only one dike intrusion each since the emplacement of these postglacial lava flows, or that some of the dike intrusions caused little surface deformation. If more dike intrusions have occurred during this time period they would most likely have propagated shorter distances from the Hofsjökull central volcano, therefore not affecting the postglacial lava flows.

The postglacial lava flows north of Hofsjökull have not been fractured. They cover a very small part of the fissure swarm, and therefore, the fissure swarm may have been activated without causing fracturing in the postglacial lava flows. Other evidences also suggest that the northern fissure swarm has not been very active during the Holocene. Firstly, no sink holes are found along faults of the fissure swarm, indicating that all sink holes have been filled with sediments. Secondly, the unbroken hyaloclastite which covers the fault east of Eyfirðingahólar (Fig. 16), suggests that the fault has not been active after the emplacement of the hyaloclastite. No independent dating is available for the hyaloclastite, but the appearance of it suggests that it is from the last part of the last glaciation, since it hasn't been eroded (Hjartarson et al., 2019). The hyaloclastite formed under a glacier, but the fault not, which indicates that the extent of the glacier was only slightly larger than today. If the fault was activated during the magmatic event which formed the hyaloclastite, then that should have happened at the end of the last glaciation. The glacier extend was then only slightly larger than today, but soon retreated leaving little time to erode the fault.

Hyaloclastite from the end of the last glaciation is found across the entire northwestern boundary of the Hofsjökull glacier, and is found at up to 8 km distance from the glacier (Fig. 1c) (Hjartarson et al., 2019). This suggests that there was a significant volcanic activity in the Hofsjökull volcanic system at the end of the last glaciation. In addition, faults in the northern Hofsjökull fissure swarm appear not to have been eroded significantly by a glacier. Also, faults cut glacial end moraines formed by the retreating glacier (Kaldal and Víkingsson, 1990), showing that faulting has occurred after the glacier left the area (e.g. Fig. 13c). This pattern occurs on many different faults along the borders of different grabens. Therefore, it is likely that repeated dike intrusions occurred in the northern Hofsjökull fissure swarm at the end of the last glaciation or during the earliest part of Holocene, when glacier still covered the area closest to the current location of the Hofsjökull glacier. These repeated dike intrusions caused the tens of meters of throw along the many grabens which collectively define the northern Hofsjökull fissure swarm (e.g. Figs. 13 and 14). That would be in line with other evidences of increased volcanic activity in Iceland during that time period (e.g. Gudmundsson, 1986; Sigvaldason et al., 1992). Such an increase in magmatic activity, including eruptions and dike intrusions, can occur because of a rapid fall in pressure due to the deglaciation (Sigmundsson et al., 2010; Sigvaldason et al., 1992).

### 6.4. The lack of fractures and faults in the Kerlingarfjöll rhyolitic massif

Few fractures and faults were found in the rhyolitic Kerlingarfjöll massif, although fissure swarms extend far south both east and west of Kerlingarfjöll. The lack of fractures and faults just north of Kerlingarfjöll can be due to the proximity of the Hofsjökull glacier and sediments deposited by the glacier and its rivers. However, few fractures were also found in the Kerlingarfjöll massif itself as well as at the southern border of the Kerlingarfjöll rhyolitic massif, where the few faults which are found have small throws (Fig. 11). On the other hand, high density of fractures is found just east, west, and south of Kerlingarfjöll. Therefore, it appears that there is a "fissure swarm shadow" in the vicinity of the Kerlingarfjöll rhyolitic massif. This suggests that dike intrusions are hindered near Kerlingarfjöll. Either vertically fed dikes do not ascend high enough to cause surface deformation, or dikes fed horizontally from the Hofsjökull volcano do not penetrate through Kerlingarfjöll

Two processes might contribute to this "fissure swarm shadow":

1. *Basaltic magma may have a hard time penetrating the lower density rhyolitic layers close to the surface*

Such hindering of basaltic dike intrusions can occur due to density differences between the lower density rhyolitic material closer to the surface and higher density basaltic dikes or sills. Basaltic magma is trapped and ponds at the level of neutral buoyancy instead of protruding up to the surface. Such mechanism has been used to explain the lack of basaltic formations in Yellowstone (USA), and in the Torfajökull caldera (Iceland) (Dzurisin et al., 1994; Sæmundsson, 2011; Walker, 1974).

The basaltic hyaloclastite formations in and near Kerlingarfjöll nevertheless indicate that basaltic magma does in some cases reach the surface (Fig. 1c), our suggestions are therefore more indicative on how "difficult" it is for the basaltic magma to reach the surface. This suggestion could explain why there is a high-temperature geothermal area in Kerlingarfjöll, even though the surface formations there are rather old. No volcanic activity is known in the Holocene, the rhyolites are between ~68 and 350 ka of age, and the hyaloclastite formations are from the early part of the Weichselian (Flude et al., 2010; Hjartarson et al., 2019). Basaltic dike intrusions ponded under the rhyolitic massif, could cause uplift of the rhyolitic lava domes found in the area and lead to increased geothermal activity.

*2. The elevation of the Kerlingarfjöll rhyolitic massif*

The distance from the top of dikes to the surface can increase near topographic highs, which would cause fewer fractures and grabens at the higher topographic elevations. Such an inverse relationship between the number of fractures and elevation of topographic highs has been observed in monogenetic basaltic lava shields in Iceland (Hjartardóttir and Einarsson, 2015). Similarly, dike intrusions in Iceland have been observed to propagate to lower areas, where they become shallower and fissure eruptions eventually take place, as occurred during the Bárðarbunga dike intrusion in 2014 (Sigmundsson et al., 2015). The Kerlingarfjöll massif rises to about 500-600 m above its surroundings, and thus, dike intrusions can be diverted to either pond beneath the Kerlingarfjöll massif or propagate laterally at deeper levels towards the north or south, rather than propagating as shallow dikes under the massif. This can occur regardless of whether the dikes propagate directly up from the mantle, or laterally from the Hofsjökull central volcano.

6.5 Cumulative extension across the Hofsjökull fissure swarms

By calculating cumulative heave across each profile in Figs. 7 and 15, the dilatation across the fissure swarms can be assessed (Fig. 18). Here, a fault dip of 65°is assumed. In the northern Hofsjökull fissure swarm, the cumulative heave generally decreases with increasing distance northwards from the Hofsjökull central volcano (Fig. 18). The pattern is more complicated in the southern part (Fig. 18). There, the heave peaks in the middle part whereas it tapers both towards the north and south. The tapering in the northern part can at least partly be due to the profile crossing a glacier (Fig. 3). The southern and the northern Hofsjökull fissure swarms are in different tectonic regimes. While the northern Hofsjökull fissure swarm propagates into the North-American plate, the southern fissure swarms extend into the Hreppar microplate and are therefore in-between the Western and Eastern Volcanic Zones (Fig. 1). This could cause complicated patterns of extension across the southern Hofsjökull fissure swarms, as the dilatation across the fissure swarm could be associated not only with distance from the Hofsjökull central volcano, but also with the interplay between the Western and Eastern Volcanic Zones.

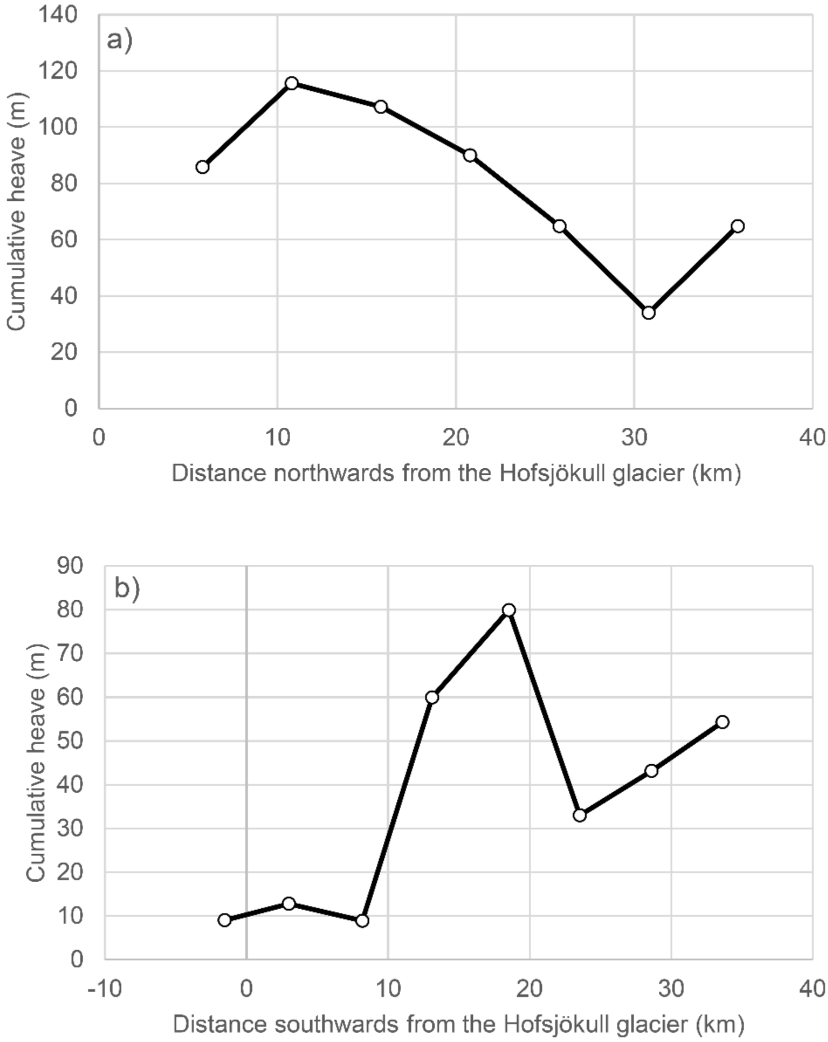



Fig. 18. The cumulative heave of faults with distance towards the north (a) and south (b) from the Hofsjökull glacier. The cumulative heave is calculated from the throw of faults in the profiles in Figs. 7 and 15, assuming that the faults have a dip of 65°.

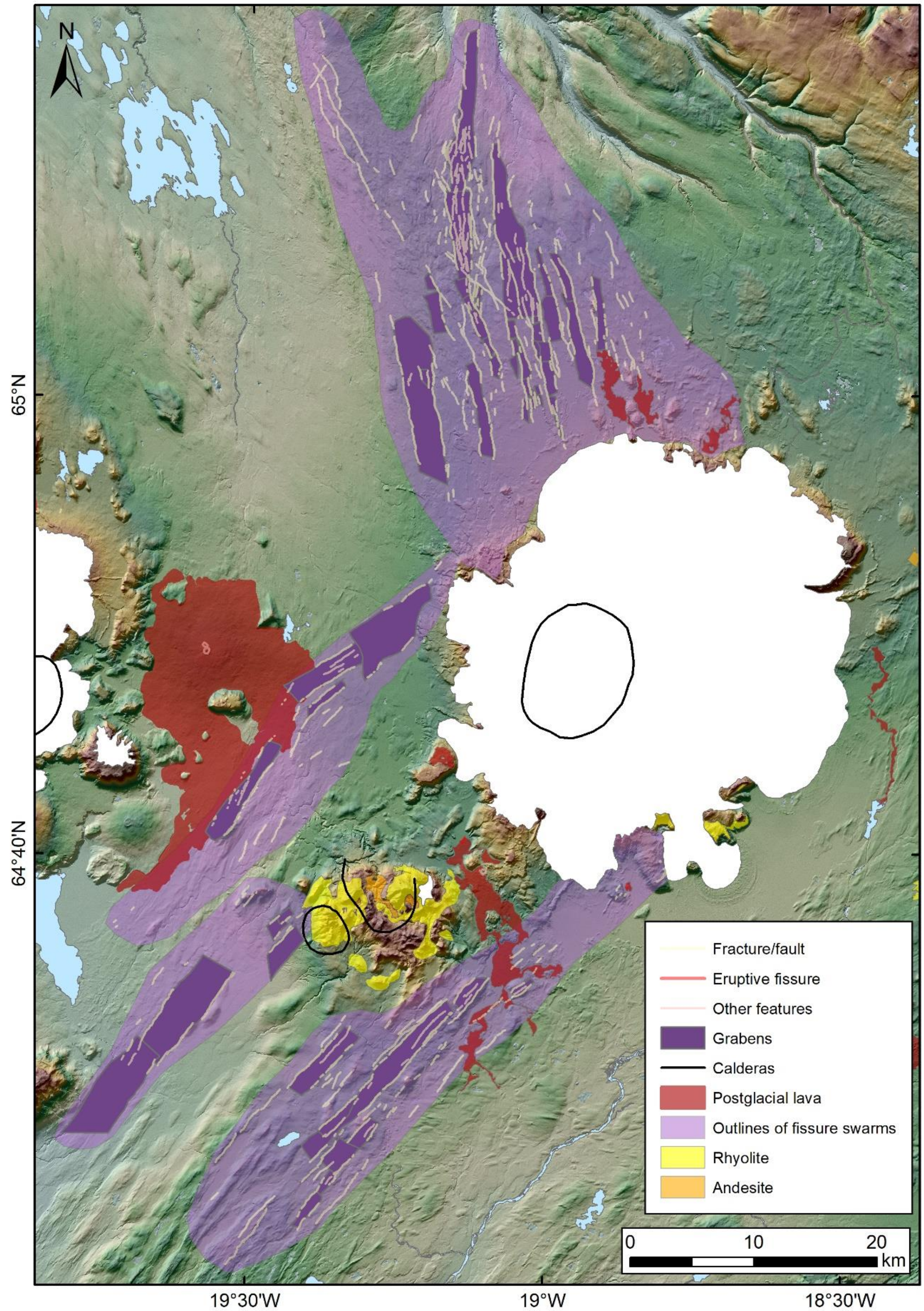



Fig. 19. The overall structure of the Hofsjökull volcanic system, including grabens, faults, and the outlines of the fissure swarms. Rhyolitic and andesitic formations were mapped by the Iceland Geosurvey (ÍSOR) (Hjartarson et al., 2019). Postglacial lava flows were mapped by ÍSOR and Sinton et al. (2005).

## Conclusions

Our mapping of the fissure swarms of the Hofsjökull volcanic system reveals three to four separate swarms emanating from the central volcano, each one consisting of one to several parallel grabens (Fig. 19). The graben subsidence ranges from a few meters to more than 30 m, and the width from less than one to four km. The length of the swarms exceeds 50 km, measured from the caldera of the volcano. We interpret the grabens as the result of intrusion of shallow dikes from the central part of the system into the crust on both sides of the Central Iceland plate boundary. No Holocene eruptions are known with a source more than 20 km from the caldera. The Hofsjökull fissure swarms show that spreading rates have significant effect on the morphology and activity of fissure swarms. The lack of sink holes and other clear indicatives of most recent movements in the Hofsjökull fissure swarms indicates that they have been less active than the fissure swarms where full spreading rates are taking place, as an example in the Northern Volcanic Zone, Iceland. Faults in the postglacial Illahraun and Kjalhraun lavas on the other hand indicate that the southern fissure swarms have been activated during postglacial times.

The northwesterly orientation of the northern Hofsjökull fissure swarm is far from being perpendicular to the current plate spreading direction, indicating that the current spreading direction cannot explain the orientation. We suggest that the northwesterly orientated faults were formed and/or reactivated due to differential movements of crustal blocks of different thicknesses during the last deglaciation.

The lack of faults in the Kerlingarfjöll rhyolitic massif (Fig. 19), indicates that dikes have not propagated to shallow levels in that area, although faults and grabens east, west and south of Kerlingarfjöll suggest shallow dike intrusions there. We suggest that the lack of shallow dike intrusions under Kerlingarfjöll is due to a density barrier. Higher density basaltic dikes become trapped under lower density rhyolite. The basaltic intrusions under Kerlingarfjöll would thus be a heat source for the high-temperature geothermal area in Kerlingarfjöll despite the lack of recent eruptions. Another possible explanation for the lack of faults in Kerlingarfjöll is that Kerlingarfjöll is a topographic high, the distance to the top of a propagating dike will thus increase under Kerlingarfjöll, unless the dike propagates to higher elevations, which is unlikely.

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