Bull Volcanol (2012) 74:143–162
DOI 10.1007/s00445-011-0496-6

RESEARCH ARTICLE

The Kverkfjöll fissure swarm and the eastern boundary of the Northern Volcanic Rift Zone, Iceland

Ásta Rut Hjartardóttir · Páll Einarsson

Received: 7 January 2011 / Accepted: 26 May 2011 / Published online: 14 June 2011

Abstract Rift zones at the divergent plate boundary in Iceland consist of central volcanoes with swarms of fractures and fissures extending away from them. Fissure swarms can display different characteristics, in accordance with their locations within the ~50-km-wide rift zones. To better discern the characteristics of fissure swarms, we mapped tectonic fractures and volcanic fissures within the Kverkfjöll volcanic system, which is located in the easternmost part of the Northern Volcanic Rift Zone (NVZ). To do this, we used aerial photographs and satellite images. We find that rifting structures such as tectonic fractures, Holocene volcanic fissures, and hyaloclastite ridges are unevenly distributed in the easternmost part of the NVZ. The Kverkfjöll fissure swarm extends 60 km north of the Kverkfjöll central volcano. Holocene volcanic fissures are only found within 20 km from the volcano. The Fjallgarðar area, extending north of the Kverkfjöll fissure swarm, is characterized by narrow hyaloclastite ridges indicating subglacial volcanism. We suggest that the lack of fractures and Holocene volcanic fissures there indicates decreasing activity towards the north in the easternmost part of the NVZ, due to increasing distance from the long-term spreading axis. We argue that arcuate hyaloclastite ridges at the eastern boundary of the Northern Volcanic Rift Zone are mainly formed during deglaciations, when three conditions may occur; firstly, eruption rate increases due to decompression of the mantle. Secondly, the high tensile stresses accumulated during glaciations due to lack of magma supply may be relieved as magma supply increases during deglaciations. Thirdly, faulting may occur during unloading due to differential movements between the thinner and younger Northern Volcanic Rift Zone crust and the thicker and older crust to the east of it.

Keywords Kverkfjöll volcano · Fissure swarm · Mid-Atlantic plate boundary · Iceland · Rift zone · Northern Volcanic Zone

Editorial responsibility: M. Manga

Á. R. Hjartardóttir · P. Einarsson (✉)
Institute of Earth Sciences, University of Iceland,
Askja, Sturlugata 7,
101 Reykjavík, Iceland
e-mail: palli@hi.is

Á. R. Hjartardóttir
e-mail: astahj@hi.is

Introduction

Crustal extension at divergent plate boundaries shows cyclic behavior, each cycle lasting from a few hundred to a thousand years (e.g., Buck et al. 2006; Foulger et al. 1992). This deformation cycle has been divided into three phases: inter-, co- and post-rifting (Sigmundsson 2006a). Co-rifting deformation occurs when magma intrudes fractures within fissure swarms to form dikes. Post-rifting refers to the time period after the rifting episode, when the movements around the fissure swarm are governed by viscous coupling between the crust and the mantle, while the inter-rifting period is characterized by elastic strain accumulation across the rift zone. The spreading between the Eurasian and the North American plates is about 2 cm/year (Sigmundsson 2006a). Subaerial rifting episodes at divergent plate boundaries have only been instrumentally recorded four times on Earth. Those were the Krafla rifting episode in 1975–1984 (e.g., Einarsson and Brandsdottir 1980; Tryggvason 1984), the Asal-Ghoubbet rifting episode in 1978 (e.g., Cattin et al. 2005; Vigny et al. 2007), the

Tanzania rifting in 2007 (e.g., Biggs et al. 2009; Calais et al. 2008), and the Afar, Ethiopia, rifting episode, which has been ongoing since 2005 (e.g., Ayele et al. 2009; Ebinger et al. 2008; Hamling et al. 2009; Rowland et al. 2007; Wright et al. 2006). Although these rifting events show common characteristics, their exact behavior varies. As an example, rifting events have occurred both with and without any activity in the nearby central volcanoes (e.g., Bjornsson et al. 1977; Calais et al. 2008; Wright et al. 2006). Magma may propagate horizontally away from a central volcano into a fissure swarm (e.g., Ayele et al. 2009; Einarsson and Brandsdottir 1980). Propagation vertically directly from the mantle has also been suggested (Gudmundsson 1995a). However, studies of rifting events are limited by the low number of cases that have been instrumentally recorded. Surface features, representing past rifting events, can give important information on the different processes that may cause or influence the formation of fissure swarms.

The Northern Volcanic Rift Zone (NVZ) marks the mid-Atlantic plate boundary in central and north Iceland (Fig. 1). It is up to 200 km long, extending from the center of the hotspot located beneath NW Vatnajökull glacier to the northern coast. The NVZ consists of 5–6 central volcanoes and their fissure swarms (Sæmundsson 1974). In this paper, we focus on the structure of the Kverkfjöll fissure swarm and the Fjallgarðar area, located north of the fissure swarm (Fig. 1). These features delineate the eastern margin of the NVZ.

We map Holocene fractures by using aerial photographs and satellite images from a ~3,300-km^2 study area. We compare our data with information on earthquakes from the Icelandic Meteorological Office and with information on surface formations mapped by Sigbjarnarson (1988, 1993, 1995) and Helgason (1987). We also compare our data with interferometric synthetic aperture radar (InSAR) images from the Upptyppingar area (Hooper et al. 2008b), where earthquake swarms and surface deformation were associated with a deep magma intrusion beneath the Kverkfjöll fissure swarm in 2007 and 2008.

Our main goals are to determine how the Kverkfjöll fissure swarm interacts with the Kverkfjöll central volcano and to find the relationship between earthquakes and the fissure swarm. We also want to establish the relationship between the Kverkfjöll fissure swarm and the hyaloclastite ridges in the Fjallgarðar area. Another goal is to investigate whether this fissure swarm, which is located at the eastern edge of the NVZ, is different from the central NVZ fissure swarms. We have done similar work on the Askja fissure swarm, which is located within central NVZ (Hjartardottir et al. 2009).

We find that Holocene volcanic fissures within the Kverkfjöll fissure swarm become fewer with increasing distance from the Kverkfjöll central volcano. We also speculate that the termination of the Kverkfjöll fissure swarm towards the north is caused by increased distance from the Kverkfjöll fissure swarm to the center of the long-term spreading axis. We suggest that the hyaloclastite ridges in the Fjallgarðar area, north of the Kverkfjöll fissure swarm, formed during deglaciations.

Regional setting

The Kverkfjöll fissure swarm, along with the hyaloclastite ridges in the Fjallgarðar area, delineates the easternmost part of the NVZ in Iceland (Fig. 1). Together, they extend about 120–145 km northward from the Kverkfjöll central volcano, while the subglacial southern part of the Kverkfjöll fissure swarm can be traced to about 10 km distance SW of the volcano (Björnsson and Einarsson 1990; Helgason 1987).

Most of the bedrock of the Kverkfjöll fissure swarm is pre-Holocene (formed more than 11,700 years ago). The pre-Holocene bedrock was eroded by the glacier which covered Iceland during the last glaciation 11,200 to 8,700 years ago (Ingólfsson et al. 2010; Kaldal and Víkingsson 1991; Sigbjarnarson 1988). The bedrock of the Kverkfjöll fissure swarm is mainly characterized by hyaloclastite formations and lava shields. Information on the age of these pre-Holocene formations is not available, although hyaloclastite formations indicate formation beneath a glacier (Kjartansson 1943), while lava shields are formed subaerially. Holocene volcanic fissures are known in the vicinity of the Kverkfjöll central volcano but are scarce within most of the fissure swarm. Hyaloclastite ridges are common within the vicinity of the Kverkfjöll central volcano (see sharp ridges in Fig. 2). These ridges are characterized by pillow lavas and hyaloclastites, with the latter increasingly prominent towards the north. These ridges are estimated to have formed below a glacier about 1.2–1.6 km thick in this area (Hoskuldsson et al. 2006).

The bedrock of the southern and middle Fjallgarðar area is characterized by three approximately parallel rows of hyaloclastite ridges (Vilmundardóttir 1997). The westernmost row, which consists of sharp and narrow hyaloclastite ridges, is considered to have formed during the last glaciation (Helgason 1987; Vilmundardóttir 1997). The two rows towards the east are much higher than the westernmost row of hyaloclastite ridges. Generally, units within each row of hyaloclastite ridges have been suggested to be of similar age, while the age of individual rows of hyaloclastite ridges is thought to increase eastward (Vilmundardóttir 1997). The distinction between the three rows becomes unclear in the northern part of the Fjallgarðar area, in the Dimmifjallgarður

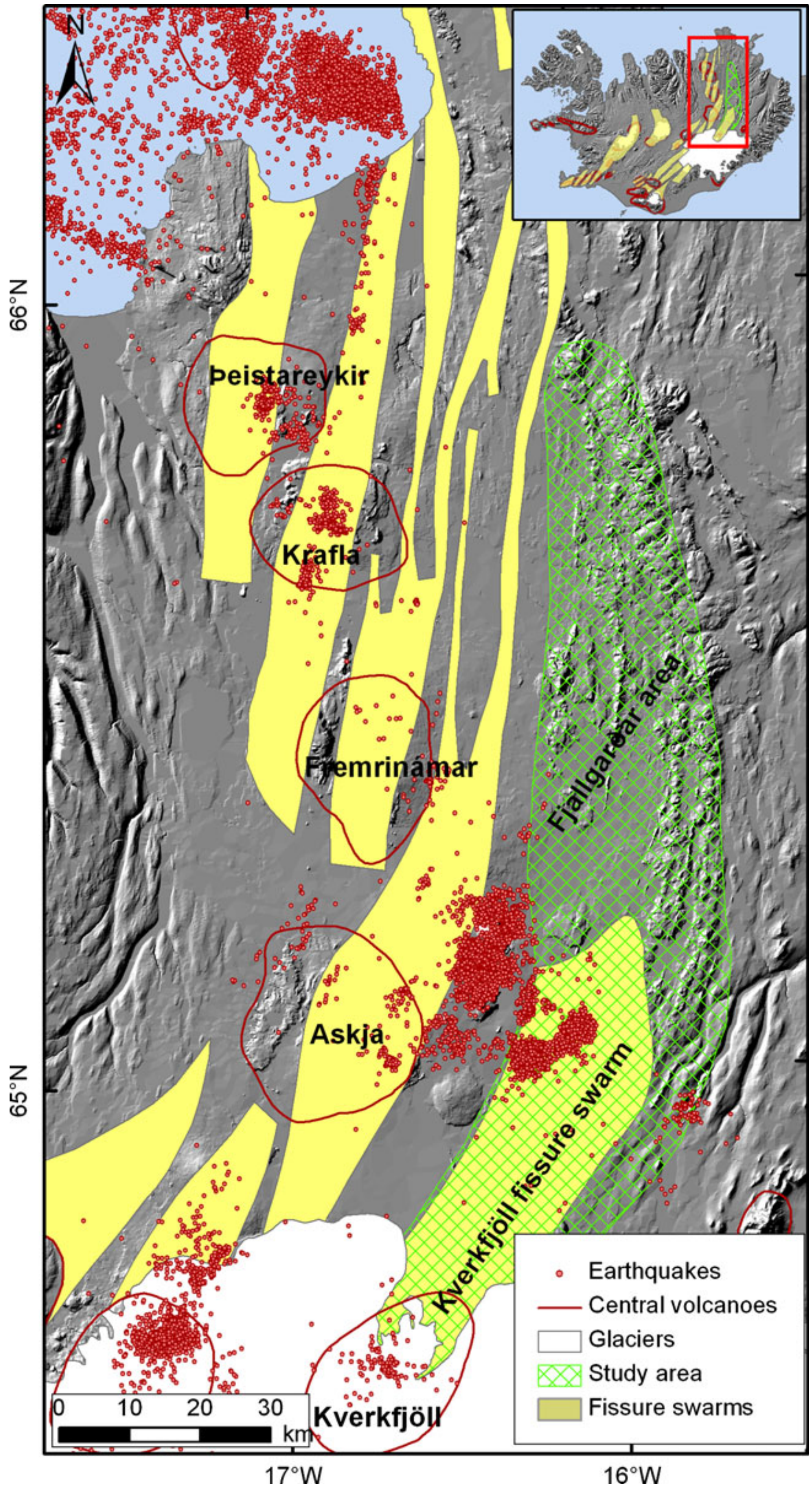


Fig. 1 The NVZ, Iceland. Delineations of the fissure swarms are from Einarsson and Sæmundsson (1987). Earthquake data for the time period of October 1991 to December 2009 are from the Icelandic Meteorological Office

mountains. There, the hyaloclastite/pillow lava formations are thought to be Upper Pleistocene (Jóhannesson and Sæmundsson 1998a).

The Kverkfjöll fissure swarm and the Fjallgarðar area have been eroded considerably, both because of glaciations and glacially originated floods. Catastrophic floods, originating from the northern part of the Vatnajökull glacier, flooded large areas in the Kverkfjöll fissure swarm and in the Fjallgarðar area in the Holocene. The floods, which likely took place in the period between

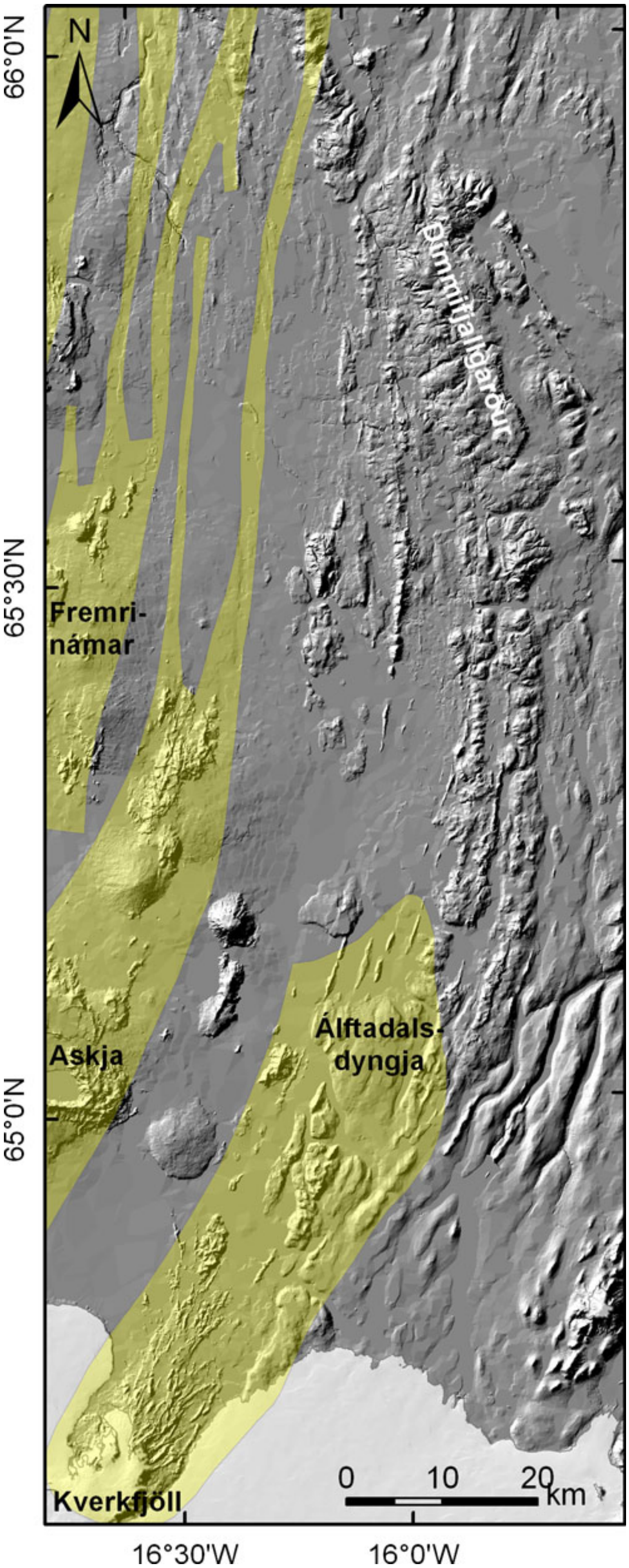


Fig. 2 The Kverkfjöll and Askja volcanic systems. Hyaloclastite ridges within the Kverkfjöll fissure swarm and the Fjallgarðar area are visible as sharp ridges and elongated mountains (such as the Dimmifjallgarður mountains) on the image. The *background* is from the National Land Survey of Iceland, and the delineations of the fissure swarms are from Einarsson and Sæmundsson (1987)

2,000 and 7,100 years BP, had a suggested discharge ranging between 0.2 and 1.0×10^6 m^3/s (Alho et al. 2005; Elíasson 1977; Helgason 1987; Sæmundsson 1973; Tómasson 1973; Waitt 2002).

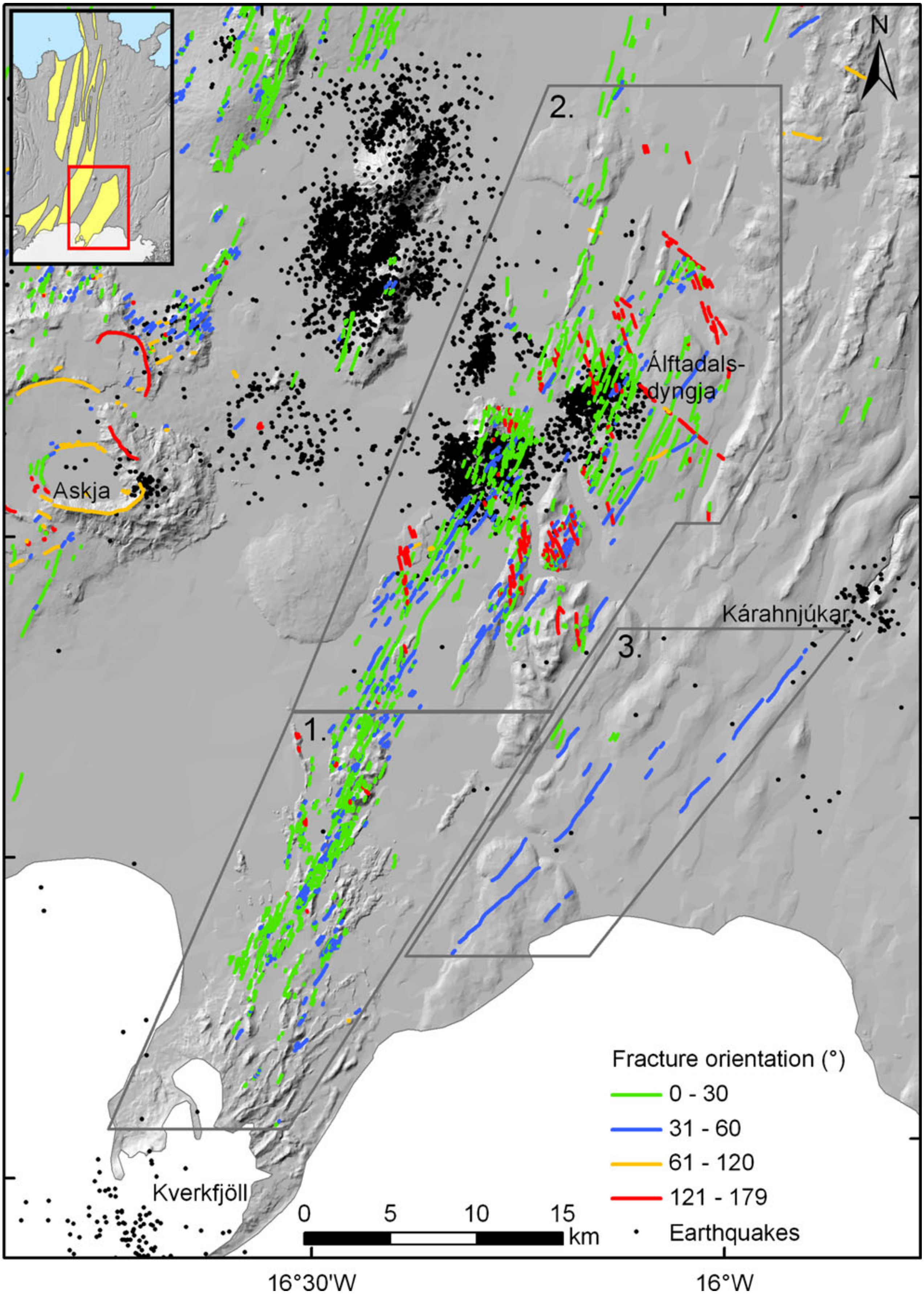
The two calderas of the Kverkfjöll central volcano are covered by a glacier. They are both elliptical in shape and about 8 km long and 5 km wide, although the orientation of their long axis is different. The long axis of the north caldera is NE–SW oriented, while it is NW–SE oriented in the south caldera (Thorarinsson et al. 1973). Considerable geothermal activity occurs in the Kverkfjöll central volcano itself. No clear evidence exists for eruptive activity there during historical times (Björnsson and Einarsson 1990; Friedman et al. 1972), even though Óladóttir (2009) estimated, based on tephrochronological studies, that about 70 prehistorical eruptions took place in the Kverkfjöll volcano during the last 6,500 years.

Generally, earthquakes in the area occur near the Kverkfjöll central volcano. However, in February 2007, a persistent earthquake swarm of ~14–22 km depth started about 40–50 km NNE of the central volcano, beneath the Kverkfjöll fissure swarm (Fig. 3) (Jakobsdottir et al. 2008; White et al. 2011). Inflation, centered below the Álftadalsdyngja lava shield, was detected by GPS geodetic measurements and InSAR images (Hooper et al. 2008a). This earthquake swarm came to a halt in the spring of 2008. Since then, a dense cluster of persistent earthquakes has been detected at about 6 km depth ~2 km north of Mt. Upptyppingar.

Methods

We mapped Holocene fractures and volcanic fissures within our study area both from aerial photographs and satellite images. The aerial photographs were contact images from Landmælingar Íslands (The National Land Survey of Iceland) and digital images from both Landmælingar Íslands and Loftmyndir Corp. These images were taken at ~6,000 and ~3,000 m altitude, respectively. We obtained satellite images both from SpotImage© and the ASTER archive. We consider it necessary to use satellite images as they often show large structures more clearly than the aerial photographs. Field trips were also made to various areas within or close to the fissure swarm for ground checking.

Fig. 3 Orientation of Holocene tectonic fractures and volcanic fissures within the Kverkfjöll fissure swarm. *Frame 1.* denotes the Kverkfjöll–Rani segment, *frame 2.* the Upptyppingar segment, and *frame 3.* the Kverkárnes subswarm. The earthquake data (from October 1991 to December 2009) are from the Icelandic Meteorological Office. Some of the earthquakes in the easternmost part of the map, in the Kárahnjúkar area, are due to man-made explosions ▶


N
2.
65°10'N
Álftadals-
dyngja
Askja
65°N
Kárahnjúkar
3.
1.
64°50'N
Fracture orientation (°)
0 - 30
31 - 60
61 - 120
121 - 179
64°40'N
Kverkfjöll
0 5 10 15
km
Earthquakes
16°30'W
16°W

To better constrain interpretations of the age of the fractures and fissures, we used the lava flow mapping by Sigbjarnarson (1988) and Helgason (1987). We also obtained information on earthquakes located in the area, from the Icelandic Meteorological Office, for comparison of their locations and the locations of tectonic features. The earthquake data covered the period from October 1991 to December 2009. To filter out poorly located earthquakes, we excluded earthquakes which were determined by a network which had an azimuthal gap of more than 150°.

Structural architecture

Overview

The eastern part of the Northern Volcanic Rift Zone forms a curved structure extending from the Kverkfjöll central volcano, almost to the north coast of Iceland (Fig. 1). It has been a matter of debate how much of this structure belongs to the Kverkfjöll volcanic system (e.g., Helgason 1987; Jóhannesson and Sæmundsson 1998b; Sæmundsson 1974). In an attempt to clarify this, we divide the area into segments according to its physiographic and tectonic style: Kverkfjöll–Rani segment, Kverkárnes subswarm, Upptyppingar segment, and the Fjallgarðar area (Figs. 1 and 3).

Based on our fracture mapping, the majority of visible fractures active in the Holocene are located within ~60 km of the Kverkfjöll central volcano (Figs. 3 and 4). However, the number of mapped fractures may be influenced by factors other than tectonics, such as the age of the fractured lava flows and erosion due to glaciers and glacially originated floods. As Holocene catastrophic floods have swept the area north of the Kverkfjöll fissure swarm, the exact extent of the Kverkfjöll fissure swarm towards the north is not clear.

Hyaloclastite ridges, the product of subglacial fissure eruptions (Kjartansson 1943), are common both near the Kverkfjöll central volcano and in the Fjallgarðar area. In both areas, the hyaloclastite ridges are narrow, with sharp features. The abundance of ridges is nevertheless much higher in the area close to the Kverkfjöll central volcano than in the Fjallgarðar area north of the fissure swarm. However, the area in between these two areas, the northern part of the Kverkfjöll fissure swarm, has very few hyaloclastite ridges.

The orientation of the KFS and the Fjallgarðar area follows the orientation of other fissure swarms at a similar latitude in the NVZ. This orientation gradually changes from south to north (Figs. 2 and 5). In the southern and middle part, the Kverkfjöll fissure swarm and the southern Fjallgarðar area are NNE oriented, while the northern Fjallgarðar area is more northerly oriented.

Fractures within the study area are tensional fractures and normal faults. We did not find any evidences of strike-slip faults, such as push-ups or en echelon tensional fractures (Einarsson 2010). However, that does not exclude the existence of such features, as many fractures in this area are situated in loose deposits.

Holocene volcanic fissures are common close to the Kverkfjöll central volcano, but are only found up to a distance of ~20 km NNE of the volcano. No clearly defined Holocene volcanic fissures are therefore found in large parts of the Kverkfjöll fissure swarm. This pattern is different from that of the Askja fissure swarm, where Holocene volcanic fissures are found all the way along the swarm (Hjartardottir et al. 2009).

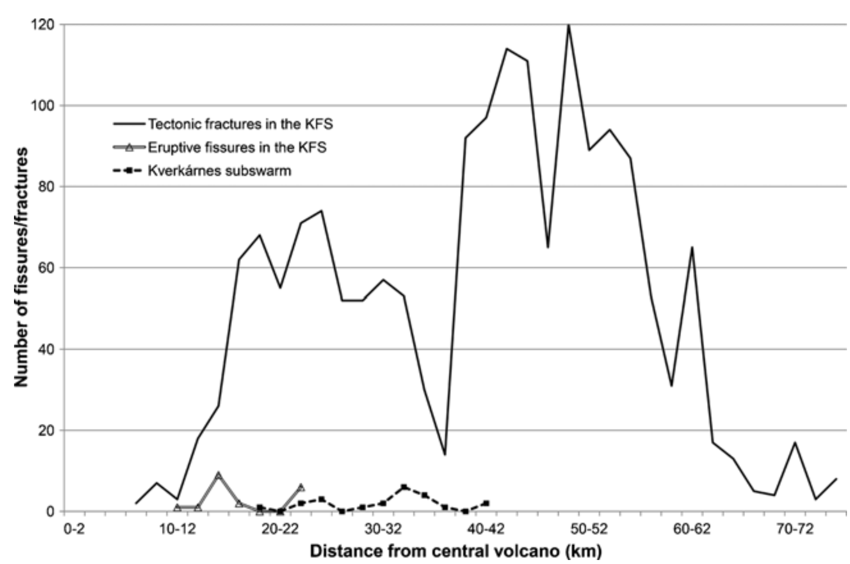


Fig. 4 The number of eruptive fissures and tectonic fractures with distance from the Kverkfjöll central volcano. The central volcano is covered with glacier. Therefore, no fractures were mapped in the immediate vicinity of the volcano. The number of fractures and fissures is calculated within 2-km-wide frames, which are parallel to the plate spreading vector in the area (DeMets et al. 1994). Note that the number of fractures may depend on the age of the lava flows or hyaloclastite units in which they are located

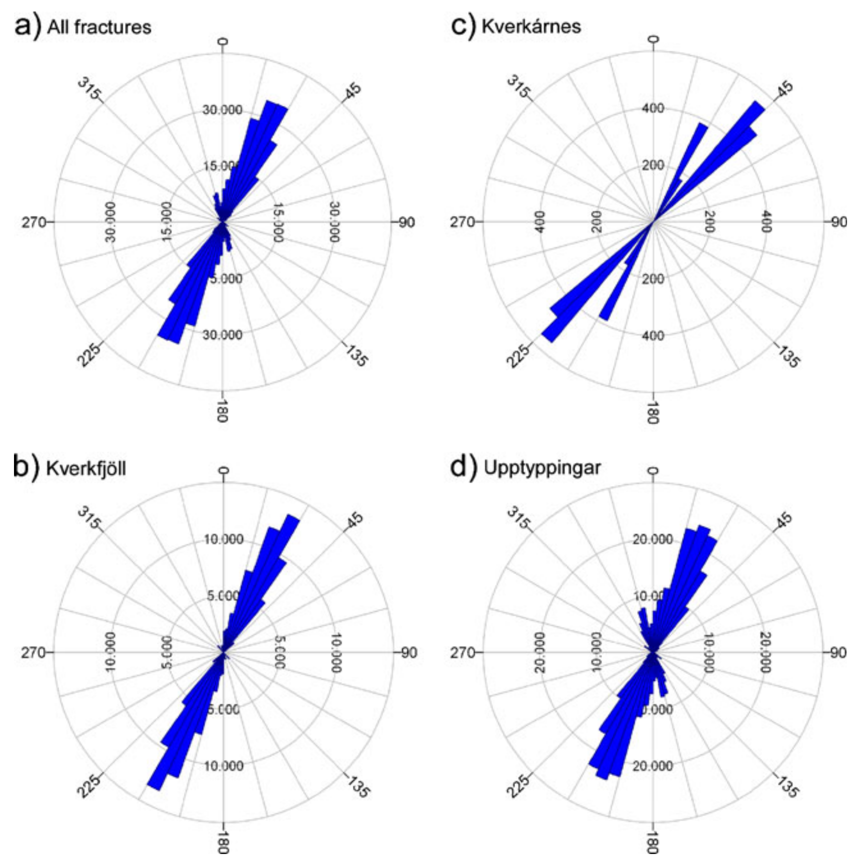


Fig. 5 **a** Orientations of fractures in the Kverkfjöll fissure swarm. *Numbers in rays* are the orientations in degrees. *Numbers in circles* represent the cumulative length (in meters) of fractures within each ray. *Rose diagrams* in (**b**), (**c**), and (**d**) represent the orientations of fractures in the Kverkfjöll–Rani segment, the Kverkárnes subswarm, and the Upptyppingar segment, respectively

Kverkfjöll–Rani segment

While the Kverkfjöll central volcano and the southern Kverkfjöll fissure swarm are covered by a glacier and therefore not observable, the area just north of the Kverkfjöll central volcano has been severely eroded due to propagation of the glacier as well as glacier-originated floods (e.g., Carrivick et al. 2004; Marren et al. 2009; Rushmer 2006). This must be taken into consideration when studying the fractures (or the lack of them) in the vicinity of the glacier.

The area immediately close to the Kverkfjöll central volcano is characterized by numerous hyaloclastite ridges, while fractures are scarce (Fig. 6). Hyaloclastite ridges and fractures in the western part trend more towards the NNE, while hyaloclastite ridges and fractures in the eastern part trend more towards the NE (Figs. 3 and 5b). The NNE-oriented features form a part of the Kverkfjöll fissure swarm, while the Kverkárnes subswarm is situated in the continuation of the NE-oriented features.

The number of fractures in the Kverkfjöll–Rani segment increases with distance from the Kverkfjöll central volcano. We found both normal faults and tensional fractures in this area. Although there are numerous faults in the area, this part of the fissure swarm is only about 5 km wide. The length of this part of the fissure swarm is about 30 km. However, the division between the Kverkfjöll–Rani segment and the Upptyppingar segment is only determined by changes in the width of the swarm. Holocene volcanic fissures are prominent in the Kverkfjöll–Rani segment, while they are absent in the Kverkárnes subswarm (Fig. 6).

The Kverkárnes subswarm

East of the Kverkfjöll fissure swarm, we find the Kverkárnes subswarm, a subtle but distinct fracture system which extends from Kverkfjöll via Kverkárnes to Mt. Kárahnjúkar (Fig. 7). In general, the Kverkárnes subswarm is about 30–40 km long and about 8 km wide (although the width varies considerably). Compared with the Kverkfjöll fissure swarm, the fractures within this subswarm are few but long. Many of the faults have vertical offset, although we cannot determine if that applies to all fractures in the area. Despite the few identified fractures, indications of Holocene activity within the subswarm have been observed in the field. Sæmundsson and Jóhannesson (2005) found evidence for Holocene movements on the “Sauðárdalur fault” which is located at the northern end of the Kverkárnes subswarm.

In Kverkárnes, sharp and long fractures are located in direct continuation of the NE-oriented hyaloclastite ridges

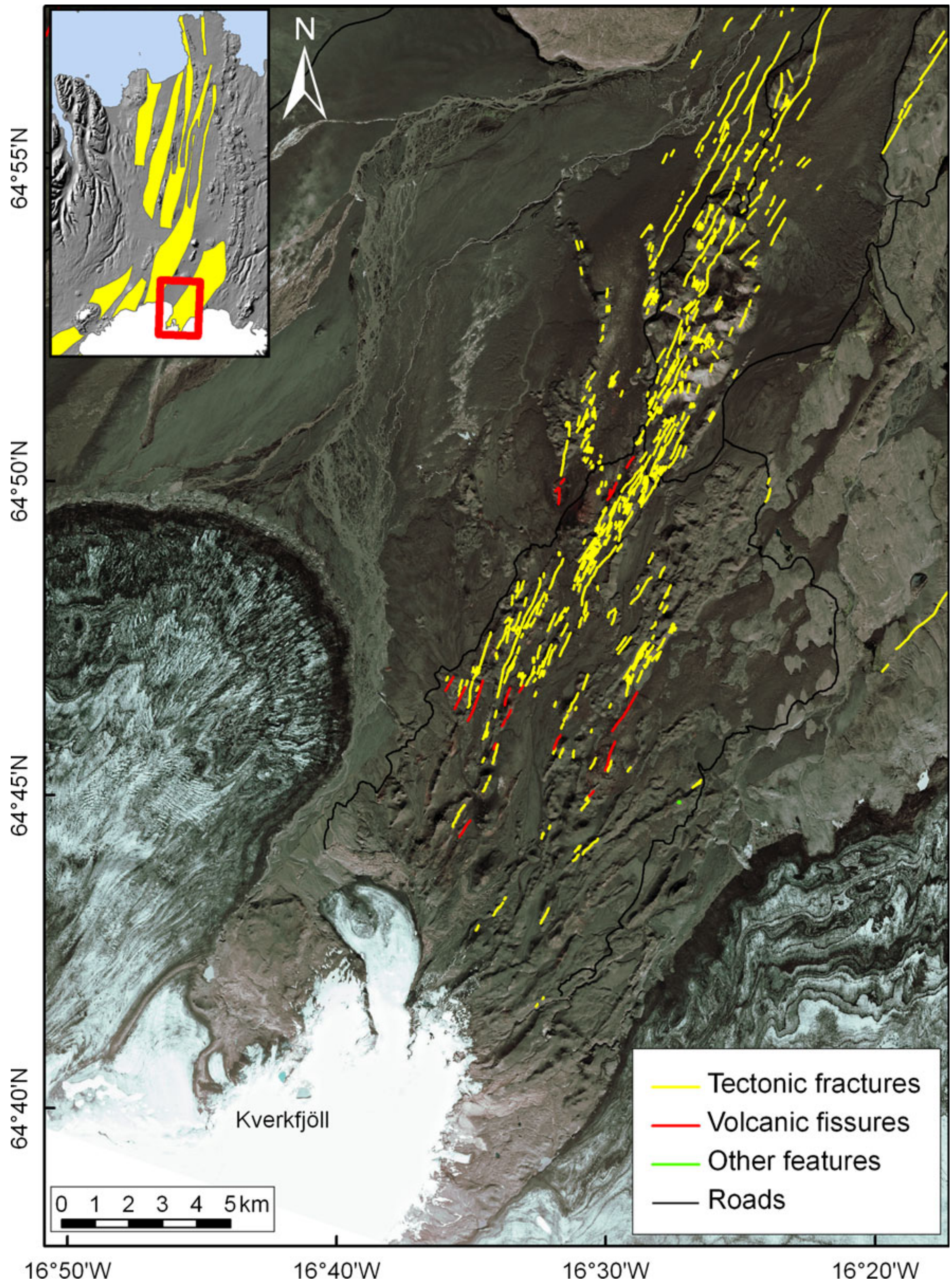


Fig. 6 The Kverkfjöll–Rani segment. The Kverkfjöll central volcano is located in the *SW corner* of the image. The satellite image is from SpotImage©

in Kverkfjöll (Fig. 3). The fractures in Kverkárnes, which generally have a NE orientation, are located in hyaloclastite/pillow lava units (Fig. 5c) (Sigbjarnarson 1988). We found no Holocene volcanic fissures within this fissure swarm, and the NE-oriented hyaloclastite ridges close to the Kverkfjöll central volcano were the only

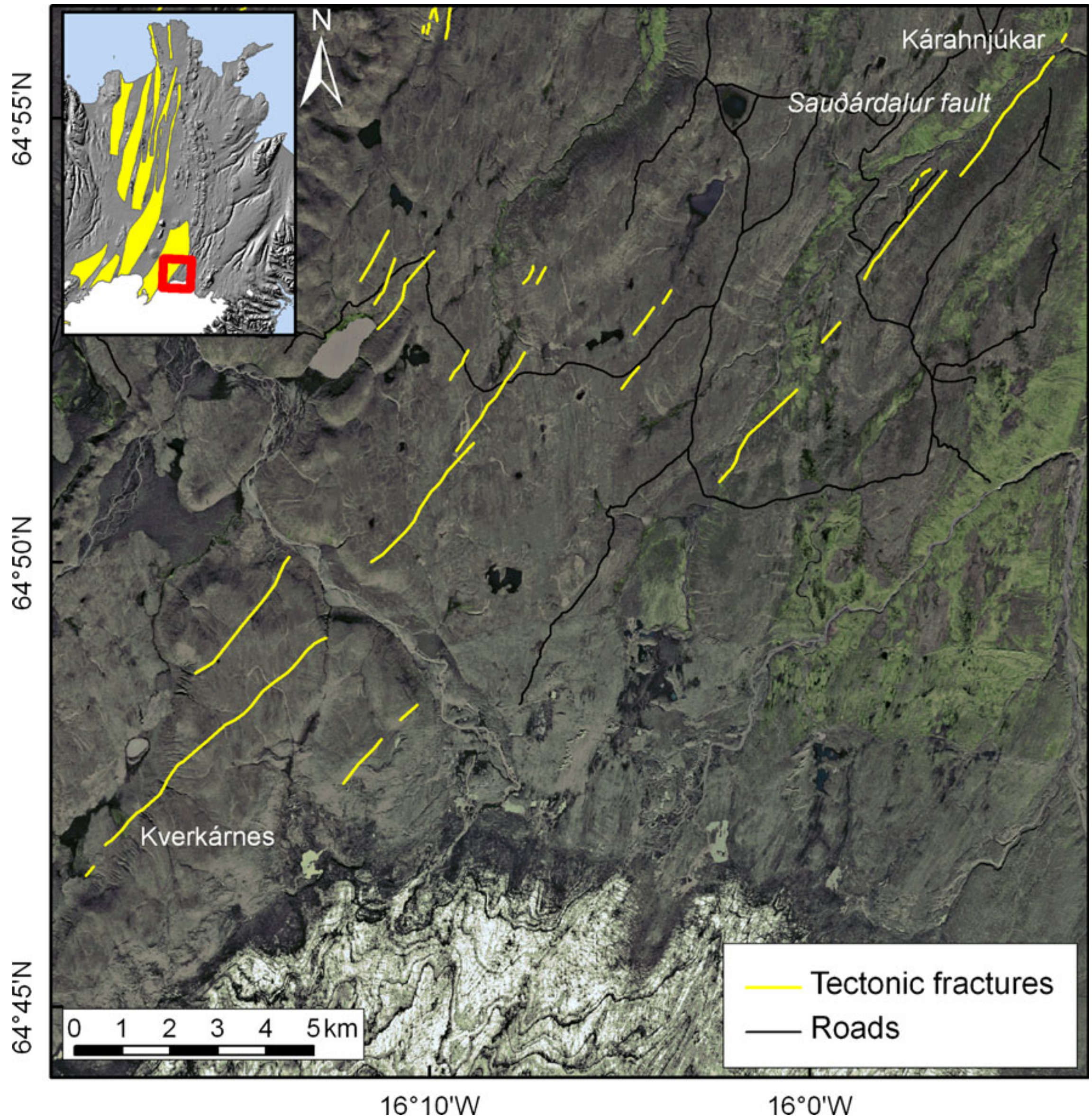


Fig. 7 The Kverkárnes subswarm. The satellite image is from SpotImage©

evidence we found for subglacial fissure eruptions within the Kverkárnes subswarm. This subswarm, therefore, is less active than the main fissure swarms within the NVZ.

The Upptyppingar segment

The Upptyppingar segment is about 10–15 km wide and about 30 km long. Fractures in this area have various orientations (Figs. 3 and 8). Most of them are oriented ~NNE, parallel with the fissure swarm (Fig. 5d). For example, Mt. Lónshnjúkur is characterized by the regular NNE orientation and NNW-oriented fractures. Fractures within the Álftadalsdyngja lava shield, however, have more diverse orientations. There, many of the fractures are NNE oriented, while NW, ENE, NNW, and WNW fractures are seen. On top of the Álftadalsdyngja lava shield, some of the WNW-oriented fractures together form a ~6.5-km-long lineament. The Upptyppingar area has many ~NNE to N trending fractures, and the same applies for the Krepputunguhraun lava. Generally, the orientation of fractures in the eastern part is therefore more heterogeneous than in the western part, where N- to NNE-oriented fractures are dominant.

The fractures in the area have a different appearance according to their location within older or younger lava formations. Fractures in the older formations are generally normal faults, while fractures within Holocene lava flows

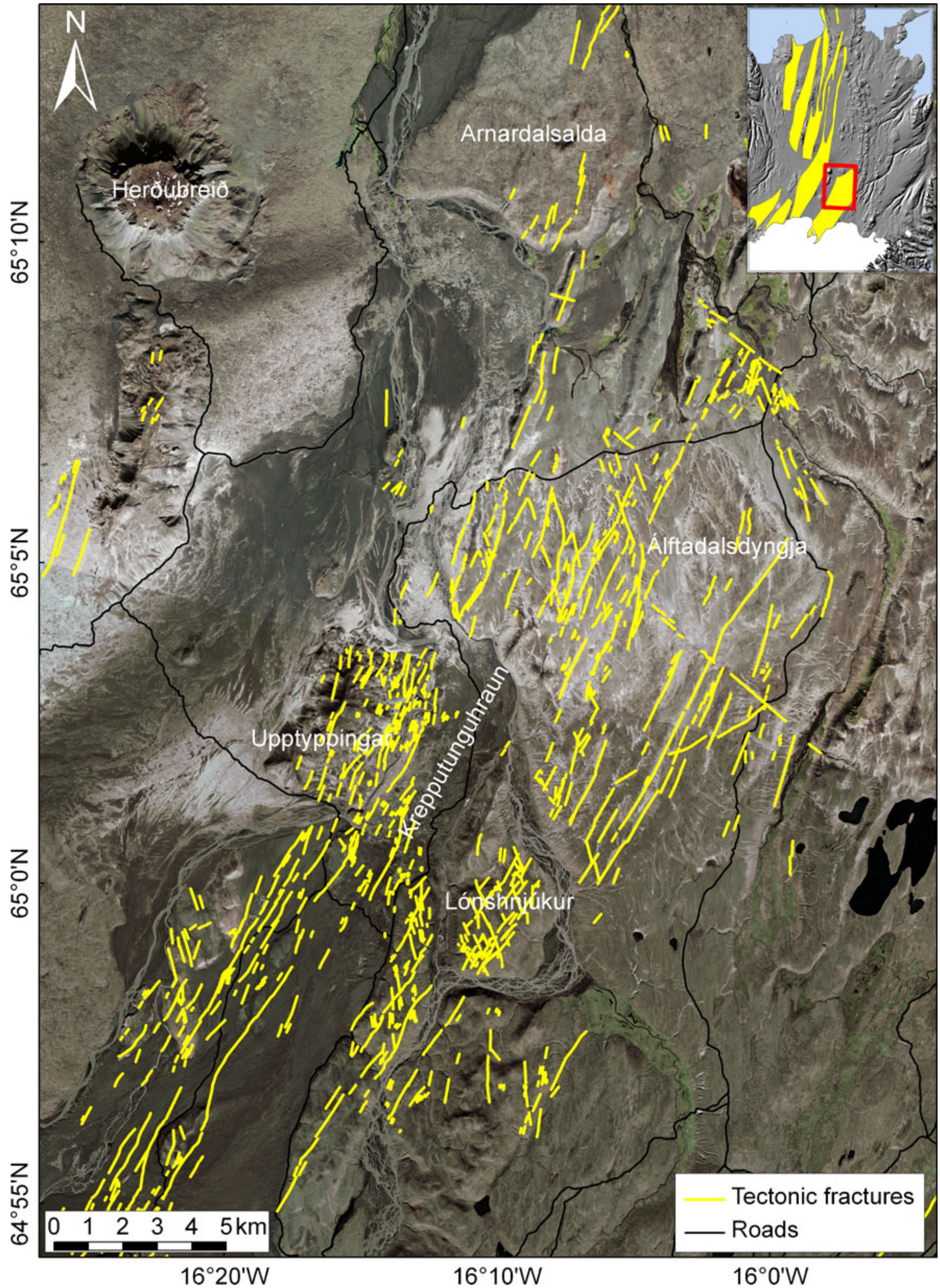


Fig. 8 Fractures in the Upptyppingar segment. No eruptive fissures were found in this area. The satellite image is from SpotImage©

are generally tensional fractures (Fig. 9a). There are also more heterogeneous fracture orientations in the older formations. Based on cross-cutting relationships and variable sharpness of the fractures, it can be inferred that the NNE-oriented fractures are younger than fractures of other orientations.

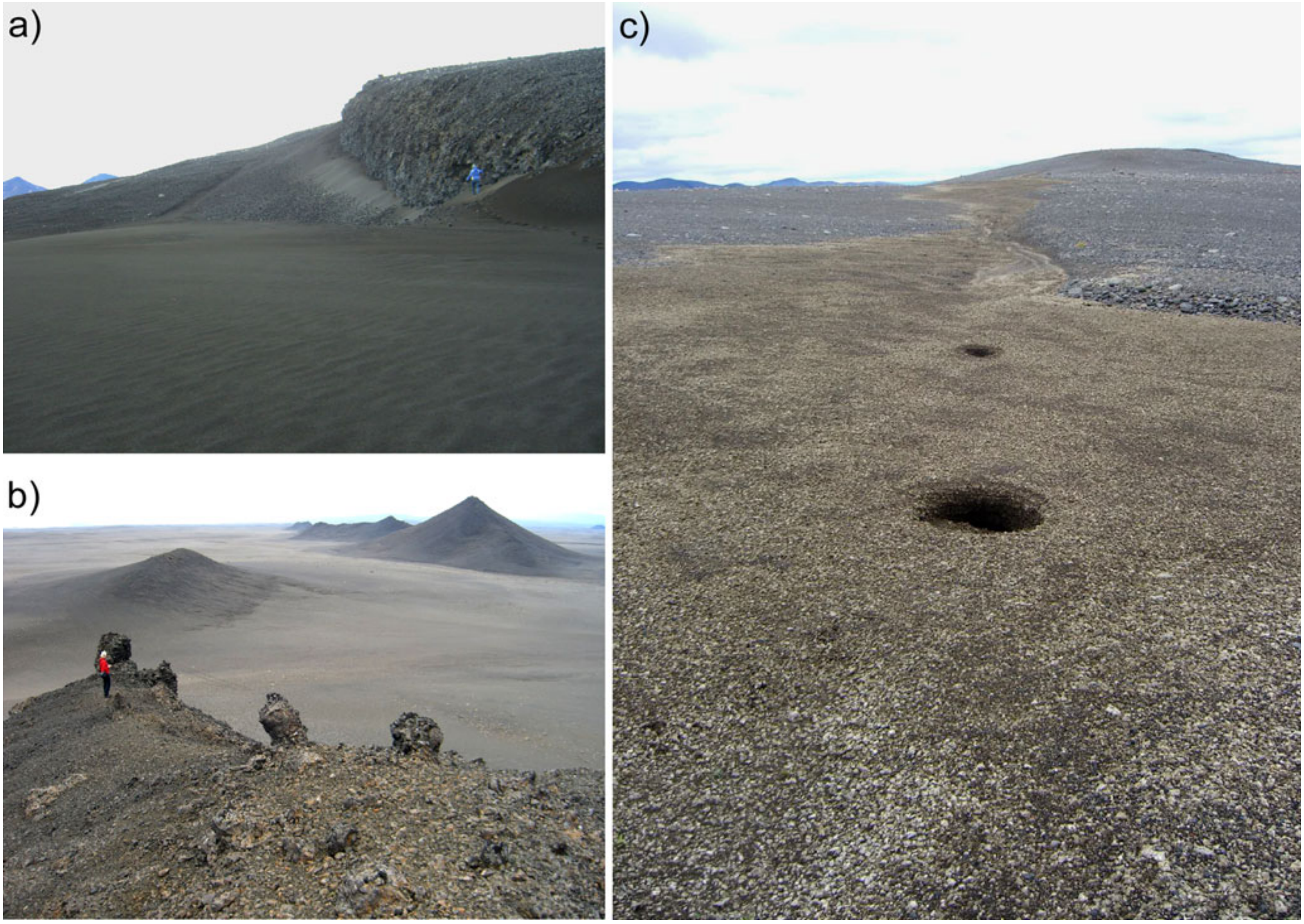


Fig. 9 **a** Normal fault south of Upptyppingar. **b** Hyaloclastite ridges with pillow lava on top in the southern Fjallgarðar area. **c** Normal fault with sinkholes southeast of Upptyppingar

Small amounts of scoria mark a volcanic fissure in the eastern part of the Arnardalsalda lava shield. This fissure has been suggested to be Holocene or from the end of the last glaciation (Helgason 1987; Sigbjarnarson 1988). However, we found tillite on top of the scoria, indicating that the volcanic fissure existed during the last glaciation. This suggests that the fissure is pre-Holocene. Vilmundardóttir (1997) reached a similar conclusion. The absence of Holocene volcanic fissures in the area is notable as the density of tectonic fractures there is high.

The Fjallgarðar area

This area is characterized both by long, narrow, and sharp hyaloclastite ridges and larger hyaloclastite mountains, while fractures are scarce compared with the Kverkfjöll fissure swarm (Figs. 1, 9b, 10, and 11). Near the Arnardalsalda lava shield, where the Holocene Kverkfjöll fissure swarm ends, the ridges are usually NNE oriented. They have therefore similar orientations as the most common orientation of the fractures within the Kverkfjöll fissure swarm and are also in the direct continuation of the fissure swarm (Figs. 2 and 10).

The majority of the few fractures in this area have similar orientations as the Kverkfjöll fissure swarm and the hyaloclastite ridges. Other orientations are, however, common, although none are prevalent. A large part of the southern Fjallgarðar area has been eroded and covered by sediments from Holocene catastrophic glacial floods, which may have covered surface fractures in the area (Helgason 1987). It is therefore possible that the number of fractures in Fjallgarðar area has been underestimated.

The northernmost part of the Fjallgarðar area contains the ~30-km-long Holocene Kerlingar fault (Fig. 11). Our field studies indicate that the fault has a throw down to the east (Hjartardóttir et al. 2010). The hyaloclastite mountains in which the Kerlingar fault is located are subparallel to the ~NNW-oriented fault. However, narrow rows of hyaloclastite ridges, less than 10 km west of the fault, are more northerly oriented. Therefore, the tectonic features in the

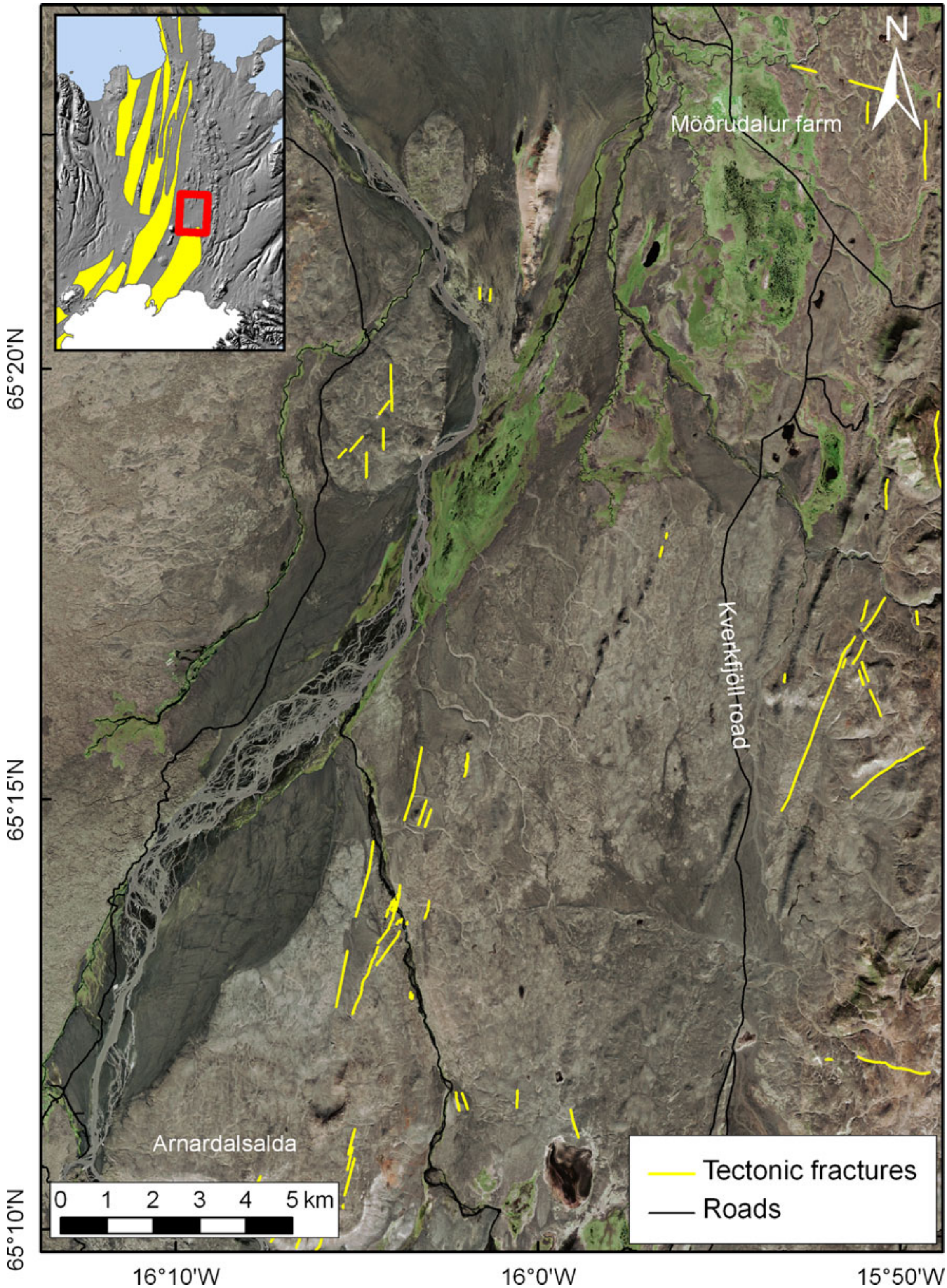


Fig. 10 The southern Fjallgarðar area. The satellite image is from SpotImage©

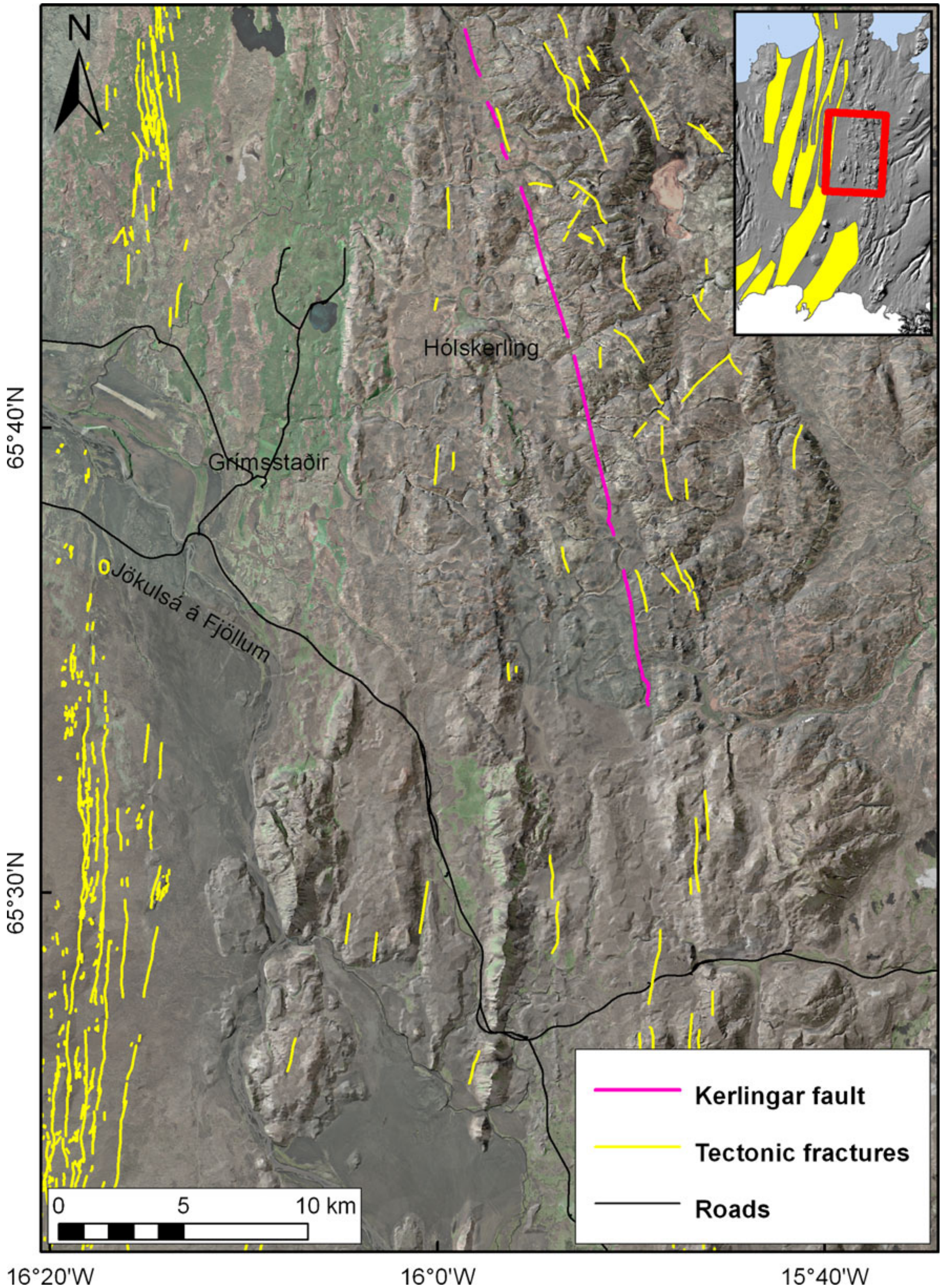


Fig. 11 The northern Fjallgarðar area. The satellite image is from SpotImage©

northern part of the Fjallgarðar area have a rather heterogeneous orientation.

Discussion

In this study, we mapped tectonic fractures and volcanic fissures within both the northern Kverkfjöll fissure swarm and the Fjallgarðar area. The Kverkfjöll fissure swarm also extends to the south from the Kverkfjöll central volcano. However, the southern Kverkfjöll fissure swarm is poorly known as it is subglacial. The southern fissure swarm may be influenced by the complicated tectonics observed beneath the NW Vatnajökull glacier. There, several volcanoes (i.e., Bárðarbunga, Grímsvötn, and Hamarinn) are situated in a relatively small area, compared with the lower density of volcanoes within other areas at the divergent plate boundary in Iceland. This highly volcanic area is considered to be the central area of the Iceland hotspot (e.g., Wolfe et al. 1997). A triple junction of the North American, Eurasian, and the Hreppar microplates has been suggested to be located in the same area (e.g., Einarsson 2008; La Femina et al. 2005), whereas Gudmundsson (1995b) prefers to regard the Hreppar microplate as a block between overlapping spreading centers.

The Kverkfjöll fissure swarm, located at the eastern boundary of the NVZ, differs from the central NVZ fissure swarms in some respects. The surface lava flows in the Kverkfjöll fissure swarm are older than the surface lava flows in central NVZ (Sigbjarnarson 1988). Also, the orientation of tectonic fractures is more heterogeneous in the Kverkfjöll fissure swarm than in central NVZ fissure swarms. This may highlight the difference between fissure swarms that are located in the center of rift zones and the fissure swarms that are located at the boundaries of rift zones.

Although the Kverkfjöll fissure swarm and the hyaloclastite ridges in the Fjallgarðar area are two distinct features, they form together an arc-shaped feature. This feature delineates the eastern part of the NVZ. Notably, such an arc-shaped area of hyaloclastite ridges is not found along the western boundary of the NVZ, making the structure of the NVZ asymmetric.

The orientation of fractures in the northernmost part of the Kverkfjöll fissure swarm

The majority of fractures in the Kverkfjöll fissure swarm are oriented N to NE, approximately perpendicular to the plate spreading vector (DeMets et al. 1994). However, there are numerous fractures with other orientations in the northernmost part of the fissure swarm, in the Upptyppingar segment (Figs. 3 and 5). We suggest three different reasons for these unusual fracture orientations:

1. The variable fracture orientations in this area occur as the Kverkfjöll fissure swarm ends here, i.e., numerous dikes stopped propagating in this area. The stress field in front of dikes favors the formation of strike-slip faults in a Y-shaped pattern (Rubin and Pollard 1988). This may cause a complex pattern of fractures in an area where a fissure swarm ends suddenly.
2. That strike-slip fractures form as extension decreases in this area. Strike-slip fractures could form in this area as there is much higher extension south of this area than north of it, as indicated by the number of Holocene fractures. In addition, this process could reactivate some of the Y-shaped fractures discussed in 1.
3. The local stress field of the Askja central volcano can extend to the northern part of the Kverkfjöll fissure swarm, as is currently the case (Pedersen et al. 2009), causing perturbations in the stress field of the fissure swarm. Inflation in Askja central volcano may cause compression within this part of the Kverkfjöll fissure swarm, preventing dikes to propagate farther along the Kverkfjöll fissure swarm. Deflation in the volcano on the other hand can cause high extension in the fissure swarm, which may cause a dike to loose its driving pressure necessary for farther propagation. Duffield et al. (1982) suggested a similar relationship between the Kilauea and Mauna Loa volcanoes in Hawaii. The variable stress field of the Askja central volcano might also trigger opening of fractures in the Kverkfjöll fissure swarm that were initially formed as strike-slip faults.

In general, some or even all of these three different processes may influence the fracture pattern at the northern end of the Kverkfjöll fissure swarm. Magma may have intruded (or possibly formed) some of these unusual fracture orientations. This occurred during the 2007–2008 Upptyppingar intrusion, which took place in the ductile part of the crust. These events will be discussed in more detail below.

Seismicity within the Kverkfjöll fissure swarm

Few earthquakes are detected in the Kverkfjöll fissure swarm, and no rifting episodes have occurred there in historic times. In general, few earthquakes are detected within fissure swarms between rifting events (Einarsson 1991). However, in 2007, an intense earthquake episode started near Mt. Upptyppingar and the Álftadalsdyngja lava shield (Figs. 3 and 8). This activity was accompanied by surface uplift and has been interpreted as an intrusion of an ENE striking dike beneath this area (Geirsson et al. 2009; Jakobsdottir et al. 2008; White et al. 2011).

These events are in many respects different from typical rifting events. The earthquakes associated with the earlier part of these events were, as an example, generally deeper than earthquakes that occurred in the Krafla rifting episode (~14–22 km deep and ~0–6 km deep, respectively), indicating that the dike was situated deeper in the crust than the dikes that were emplaced during the Krafla rifting episode (Brandsdottir and Einarsson 1979; Jakobsdottir et al. 2008; White et al. 2011). In the Krafla 1975–1984 and Askja 1875 rifting events, unrest was detected within the central volcanoes. However, no unrest has been detected in the Kverkfjöll central volcano during the current unrest in the Kverkfjöll fissure swarm. In general, this implies that unrest within fissure swarms can vary considerably.

Although the main intrusion seems to have occurred at 14–22 km depth, surface fracture movements were observed by InSAR images (Hooper et al. 2008b). In August 2007, we found fractures in this area with recent sinkholes, probably formed during these events (Fig. 9c). Interestingly, these movements were observed south of the seismically active area, indicating aseismic faulting. The fractures are located in the sedimented flood plains of the Jökulsá á Fjöllum glacial river. The InSAR images from Hooper et al. (2008b) indicated subsidence of a ~1.5-km-wide graben south of Mt. Upptyppingar.

Another interesting feature of the suggested dike is its orientation. It dips ~41–50° to the S, and its strike is ENE, that is, oblique to the Kverkfjöll fissure swarm (Jakobsdottir et al. 2008; White et al. 2011). There is only one detectable fault which has this orientation in the Álftadalsdyngja lava shield. This fault, which consists of several smaller fault segments, is located about 2–4 km south of the seismically active area. Earthquake fault plane solutions indicate that normal, reverse, and strike-slip faulting have taken place during these events (Jakobsdottir et al. 2008). Sometimes, different earthquakes occurring within a time frame of minutes and at the same location within the dike plane have had different fault plane solutions, flipping between normal and reverse faulting (White et al. 2011).

In general, we conclude that the Upptyppingar–Álftadalsdyngja events are not to be considered the type of activity that is responsible for the formation of the main fissure swarm. This is supported by the lack of concurrent activity in the Kverkfjöll central volcano, the unusual orientation of the dike, and that the earthquakes associated with these events were in the lower crust.

Are hyaloclastite ridges in the Fjallgarðar area a part of the Kverkfjöll fissure swarm?

The Kverkfjöll fissure swarm extends to the Arnardalsalda lava shield, with distinct fractures including tension fractures and normal faults (Figs. 3 and 8). North of this lava shield, in the Fjallgarðar area, fractures are uncommon, while sharp hyaloclastite ridges become prominent.

There may be two reasons for the apparent lack of fractures in the Fjallgarðar area:

1. The fractures are there, but sediments from Holocene catastrophic floods have erased their surface expression.
2. There are fewer fractures in these areas than in the Kverkfjöll fissure swarm.

As Holocene catastrophic floods have covered the southern part of the Fjallgarðar area (Helgason 1987), it is clear that the sediments have covered surface features. However, these floods did not cover the entire Fjallgarðar area. As an example, the interglacial Arnardalsalda lava shield has not been affected by these floods. However, the fracture density there is at least an order of magnitude lower than in the area to the south of it. Similarly, the catastrophic floods have not covered the north part of the Fjallgarðar area, which has also a low fracture density. This indicates that the fracture density diminishes abruptly north of the Álftadalsdyngja lava shield and that Holocene activity in the Kverkfjöll fissure swarm ends in this area, or its behavior changes significantly.

This sudden decrease in the number of fractures indicates decreasing activity of the Kverkfjöll fissure swarm northward from the Kverkfjöll central volcano. We suggest that this decreasing activity occurs as the distance from the Kverkfjöll fissure swarm to the center of the long-term spreading axis increases northwards from the Kverkfjöll central volcano. The spreading axis is here defined as the line that extends through the central volcanoes within the NVZ (Fig. 1). This long-term spreading axis has therefore been active since the NVZ became fully operative, about 4 million years ago (Sæmundsson 1974). On a shorter time scale, the location of the spreading axis along the NVZ is likely to change, as the spreading center may temporarily follow fissure swarms during and after rifting episodes in the swarms. Such episodes occur on an average with a 100- to 150-year interval in the NVZ (Bjornsson et al. 1977). Recent InSAR images indicate that the axis of maximum deformation today follows the south part of the Askja fissure swarm, crosses the Askja central volcano, and continues northward through Krafla and its northern fissure swarm (Pedersen et al. 2009). The trend through Krafla is likely to be the result of the 1975–1984 rifting episode in Krafla's fissure swarm. In a similar manner, it is likely that the axis crosses the northern part of the Askja fissure swarm because of the rifting episode there in 1875 (Sigurdsson and Sparks 1978). Despite the short-term deviations due to rifting episodes, the long-term axis should be on average located in the center of the NVZ, through the central volcanoes. If so, the distance from the axis to the Kverkfjöll fissure swarm increases towards the north, leading to less extension in the northern part of the fissure swarm. In the southernmost part, the distance from the center of the spreading axis to the southern part of the Kverkfjöll fissure swarm is ~30 km. This distance is ~40 km in the Fjallgarðar area (Fig. 1).

This could explain why the northern Kverkfjöll fissure swarm is shorter than most of the fissure swarms extending north from other central volcanoes in the Northern Volcanic Zone. Lateral propagation of dikes away from central volcanoes is controlled by both magma pressure and tectonic stresses at the dike tip (Buck et al. 2006). As less spreading would take place in the Fjallgarðar area than in the Kverkfjöll and Upptyppingar areas, as well as in other fissure swarms in the Northern Volcanic Rift Zone, unusually high magma pressure would be required to drive dikes into the Fjallgarðar area.

Active periods in the Fjallgarðar area

The Fjallgarðar area is characterized by hyaloclastite ridges, while fractures and interglacial lava flows are uncommon. The youngest ridges are estimated to have formed during the last glaciation, 10–100 thousand years ago (Vilmundardóttir 1997). As hyaloclastite ridges are formed by subglacial eruptions (Kjartansson 1943), this indicates that this area is mostly active during periods of glaciation. We suggest that the Fjallgarðar area mainly becomes active during deglaciations, as there are three special circumstances that may occur at the end of each glaciation:

1. Eruption rate is increased, due to decompression of the mantle.
2. The tensile tectonic stresses in the lithosphere may have become larger than during non-glaciated periods, as the strength of the lithosphere becomes higher due to a higher confining pressure (Sigmundsson 2006a, b). The tensile component of tectonic stresses can therefore grow higher before failure during glaciations.
3. The different response of the thinner NVZ crust and the thicker crust east of the NVZ to the unloading during deglaciation may cause differential movement and fracturing at the boundary between these two crustal blocks, as they have different density, thickness, Young's modulus, and subcrustal viscosity (Hjartardóttir et al. 2010).

The first point has been reported by various authors (e.g., Jellinek et al. 2004; Maclennan et al. 2002; Nowell et al. 2006; Singer et al. 2008). In the Askja central volcano, which is located ~20 km west of the Kverkfjöll fissure swarm, a 30-fold increase in lava production occurred during the beginning of the Holocene, compared with the current lava production in the area (Sigvaldason 2002; Sigvaldason et al. 1992). Therefore, we consider it likely that magma supply may have increased beneath the Kverkfjöll fissure swarm and the Fjallgarðar area during deglaciations.

Another point, which may contribute to increased volcanic activity in the Fjallgarðar area during deglaciations, is that tensile stresses in the crust may have become larger during glaciations. Crustal stresses are likely to build up to higher levels when magma supply is insufficient, as it may occur during glaciations. The stress required to initiate a slip on a normal fault at a 5-km depth without an involvement of magma is an order of magnitude higher than required for dike intrusion (Sigmundsson 2006b, and references therein). When deglaciation occurs, the combined effect of the highly stressed crust and increased magma supply may therefore cause activity in areas that otherwise remain inactive.

The third process which may explain the existence of the hyaloclastite ridges within the Fjallgarðar area is related to the fact that the crustal thickness increases from 20 km west of the area to 35 km east of the area (Staples et al. 1997). When deglaciations occur, the isostatic response of the thinner NVZ crust may be different from the response of the thicker crust to the east (Hjartardóttir et al. 2010). This causes differential movement in the area, which may facilitate formation of fractures, which magma intrudes to form dikes and fissure eruptions.

These three different processes may cause activity in the slowly dilating Fjallgarðar area during deglaciations, while the area remains inactive during other times (Fig. 12). The deglaciation may, in this sense, play a triggering role for rifting in the slow deformation cycle that occurs in the Fjallgarðar area. It is possible that the fractures in which magma intruded to form the hyaloclastite ridges in the Fjallgarðar area were initially formed as boundary faults at the early stages of the NVZ. Such faults have been observed in various rift zones, i.e., in the Rhine valley (e.g., Lopes Cardozo and Behrmann 2006) and in the Main Ethiopian Rift, East Africa (MER) (e.g., Corti 2009). In the MER, the boundary faults are thought to have formed at the early stages of the rift and have been mostly inactive for 2 Ma (Corti 2009). While surface load is a constant in the MER, it varies in the NVZ due to periods of glaciations. This may cause episodic activity of the boundary faults of the NVZ, while the MER faults remain mostly inactive.

The three different processes suggested here are conceptual ideas. To constrain them better, modeling (i.e., with Finite Element Modeling) is preferable.

Conclusions

Two zones of fractures extend north of the Kverkfjöll central volcano: the NNE-oriented Kverkfjöll fissure swarm and the NE-oriented Kverkárnes subswarm. The Kverkfjöll fissure swarm extends from the western part of the Kverkfjöll central volcano, while the Kverkárnes subswarm

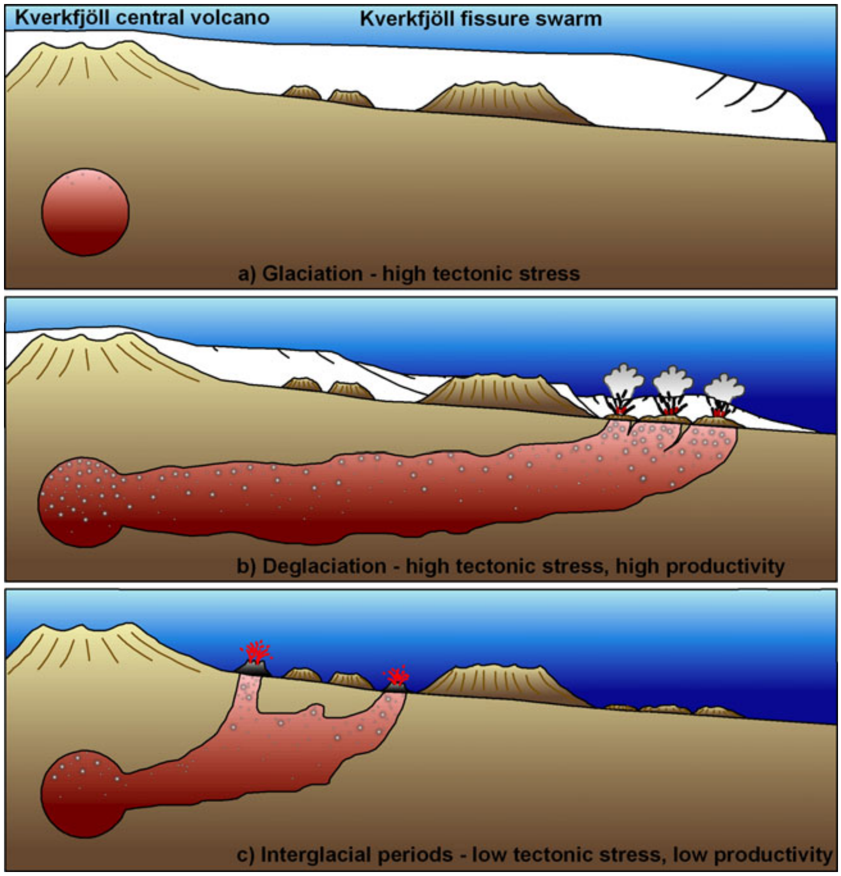


Fig. 12 Sketch of the suggested relationship between diking/magma productivity and glaciations in the Kverkfjöll fissure swarm. **a** During glaciation, there is less magma supply due to elevated overburden pressure. The less magma supply allows the tectonic component of the stress in the crust to rise to higher levels of tensile stresses (Sigmundsson 2006b). **b** During deglaciation, lowering overburden pressure of the mantle causes increased magma production. The high tensile stresses in the crust, accumulated during the glaciation, and the increased magma supply together form conditions favoring a propagation of a longer dike. Since the glacier is not completely gone, hyaloclastite/pillow lava ridges are formed. **c** During interglacial periods, there is more magma supply than during glaciation, as the mantle has less overburden pressure. Therefore, tensile stresses are relieved more frequently by dike intrusions. According to this, dikes should generally propagate shorter distances during interglacial periods than during deglaciations

extends from the eastern part of it. We found no Holocene volcanic fissures within the Kverkárnes subswarm.

The Kverkfjöll fissure swarm extends northwards from the Kverkfjöll central volcano to the Arnardalsalda lava shield. North of the lava shield, in the Fjallgarðar area, hyaloclastite ridges are common while fractures are few. The distance to the center of the current NVZ rift axis increases from about 30 km in the Kverkfjöll fissure swarm to ~40 km in the Fjallgarðar area (Fig. 1). We suggest that this increasing distance explains why the Kverkfjöll fissure swarm is more active than its continuation, the Fjallgarðar area.

We suggest that the Fjallgarðar area may become active during periods of rapid deglaciations, while remaining inactive during other times. This is due to three processes. Firstly, magmatic activity increases during deglaciations, due to decompression of the mantle. Secondly, the crust accumulates higher amounts of tectonic stresses during glaciations than during other times. During deglaciations, there is therefore both increased magma production and a favorable tectonic condition for magma propagation in the crust. The magma may therefore propagate farther into Kverkfjöll's fissure swarm during deglaciations than during other times. Thirdly, different crustal thicknesses in the area may lead to differential movements, forming fractures facilitating magma propagation.

NNE-oriented fractures are prominent in the Kverkfjöll fissure swarm. However, other orientations are common in the northernmost part of the fissure swarm. We suggest three reasons for this unusual variety of fracture orientations. These fractures may have formed as strike-slip fractures in front of dikes. They may be strike-slip faults formed due to differences in extension rates north and south of them, or they may have formed (or be reactivated) when the local stress field of the Askja central volcano extended to the Kverkfjöll fissure swarm.

Holocene volcanic fissures within the Kverkfjöll fissure swarm are located within 20 km distance from the Kverkfjöll central volcano. We have also found this pattern in the Askja fissure swarm, where eruptive fissures are most common in the vicinity of the volcano, while the number of tectonic fractures increases with distance from the volcano (Hjartardottir et al. 2009).

Our study of the Kverkfjöll fissure swarm supports the notion that the activity within individual fissure swarms is highly episodic on time scale of thousands of years. However, GPS measurements across the whole NVZ show that the plate spreading is constant with time (Arnadottir et al. 2008; Geirsson et al. 2010, 2006).

Acknowledgments We would like to express our gratitude to Gunnar B. Guðmundsson, who provided seismic data from the area, and to Bragi Benediktsson, farmer at Grímstunga, for his assistance during our field trip. Thanks are due to Haukur Jóhannesson and Kristján Sæmundsson who provided constructive suggestions. We would also like to thank the reviewers and editor of this paper: Simon Kattenhorn, Valerio Acocella, and Michael Manga for their valuable comments. This work was supported by the Icelandic Research Fund (Rannís) and the Eimskip Fund of the University of Iceland (Háskólasjóður Eimskipafélags Íslands).

References

Alho P, Russell AJ, Carrivick JL, Kayhko J (2005) Reconstruction of the largest Holocene jokulhlaup within Jokulsa a Fjollum, NE Iceland. Quat Sci Rev 24(22):2319–2334

Arnadottir T, Geirsson H, Jiang WP (2008) Crustal deformation in Iceland: plate spreading and earthquake deformation. Jökull 58:59–74

Ayele A, Keir D, Ebinger C, Wright TJ, Stuart GW, Buck WR, Jacques E, Ogubazghi G, Sholan J (2009) September 2005 mega-dike emplacement in the Manda-Harraro nascent oceanic rift (Afar depression). Geophys Res Lett 36:5. doi:10.1029/2009gl039605

Biggs J, Amelung F, Gourmelen N, Dixon TH, Kim SW (2009) InSAR observations of 2007 Tanzania rifting episode reveal mixed fault and dyke extension in an immature continental rift. Geophys J Int 179 (1):549–558. doi:10.1111/j.1365-246X.2009.04262.x

Björnsson H, Einarsson P (1990) Volcanoes beneath Vatnajökull, Iceland: evidence from radio echo-sounding, earthquakes and jökulhlaups. Jökull 40:147–168

Bjornsson A, Saemundsson K, Einarsson P, Tryggvason E, Gronvold K (1977) Current rifting episode in North Iceland. Nature 266:318–323

Brandsdottir B, Einarsson P (1979) Seismic activity associated with the September 1977 deflation of the Krafla central volcano in northeastern Iceland. J Volcanol Geotherm Res 6(3–4):197–212

Buck WR, Einarsson P, Brandsdottir B (2006) Tectonic stress and magma chamber size as controls on dike propagation: constraints from the 1975–1984 Krafla rifting episode. J Geophys Res-Solid Earth 111(B12):B12404. doi:10.1029/2005JB003879

Calais E, d'Oreye N, Albaric J, Deschamps A, Delvaux D, Deverchere J, Ebinger C, Ferdinand RW, Kervyn F, Macheyeki AS, Oyen A, Perrot J, Saria E, Smets B, Stamps DS, Wauthier C (2008) Strain accommodation by slow slip and dyking in a youthful continental rift, East Africa. Nature 456(7223):783–U767. doi:10.1038/nature07478

Carrivick JL, Russell AJ, Tweed FS (2004) Geomorphological evidence for jokulhlaups from Kverkfjoll volcano, Iceland. Geomorphology 63(1–2):81–102. doi:10.1016/j.geomorph.2004.03.006

Cattin R, Doubre C, de Chabalier J-B, King G, Vigny C, Avouac J-P, Ruegg J-C (2005) Numerical modelling of quaternary deformation and post-rifting displacement in the Asal-Ghoubbet rift (Djibouti, Africa). Earth Planet Sci Lett 239(3–4):352–367. doi:10.1016/j.epsl.2005.07.028

Corti G (2009) Continental rift evolution: From rift initiation to incipient break-up in the Main Ethiopian Rift, East Africa. Earth-Science Reviews 96(1–2):1–53. doi:10.1016/j.earscirev.2009.06.005

DeMets C, Gordon RG, Argus DF, Stein S (1994) Effect of recent revisions to the geomagnetic reversal time-scale on estimates of current plate motions. Geophys Res Lett 21(20):2191–2194

Duffield WA, Christiansen RL, Koyanagi RY, Peterson DW (1982) Storage, migration, and eruption of magma at Kilauea volcano, Hawaii, 1971–1972. J Volcanol Geotherm Res 13(3–4):273–307

Ebinger CJ, Keir D, Ayele A, Calais E, Wright TJ, Belachew M, Hammond JOS, Campbell E, Buck WR (2008) Capturing magma intrusion and faulting processes during continental rupture: seismicity of the Dabbahu (Afar) rift. Geophys J Int 174 (3):1138–1152. doi:10.1111/j.1365-246X.2008.03877.x

Einarsson P (1991) Earthquakes and present-day tectonism in Iceland. Tectonophysics 189(1–4):261–279

Einarsson P (2008) Plate boundaries, rifts and transforms in Iceland. Jökull 58:35–58

Einarsson P (2010) Mapping of Holocene surface ruptures in the South Iceland Seismic Zone. Jökull 60:117–134

Einarsson P, Brandsdottir B (1980) Seismological evidence for lateral magma intrusion during the July 1978 deflation of the Krafla volcano in NE Iceland. J Geophys 47(1–3):160–165

Einarsson P, Sæmundsson K (1987) Earthquake epicenters 1982–1985 and volcanic systems in Iceland (map). In: Sigfússon I (ed) Í hlutarins eðli, Festschrift for Þorbjörn Sigurgeirsson. Menningarsjóður, Reykjavík

Elíasson S (1977) Molar um Jökulsárhlaup og Ásbyrgi (in Icelandic). Náttúrufræðingurinn 47(3–4):160–179

Foulger GR, Jahn CH, Seeber G, Einarsson P, Julian BR, Heki K (1992) Post-rifting stress-relaxation at the divergent plate boundary in northeast Iceland. Nature 358(6386):488–490

Friedman JD, Williams RS, Thorarinsson S, Pálmason G (1972) Infrared emission from Kverkfjöll subglacial volcanic and geothermal area, Iceland. Jökull 22:27–43

Geirsson H, Arnadottir T, Volksen C, Jiang WP, Sturkell E, Villemin T, Einarsson P, Sigmundsson F, Stefansson R (2006) Current plate movements across the Mid-Atlantic Ridge determined from 5 years of continuous GPS measurements in Iceland. J Geophys Res-Solid Earth 111(B9):B09407. doi:10.1029/2005jb003717

Geirsson H, Jakobsdottir S, Gudmundsson GB, Roberts MJ, Decriem J (2009) A deep seated magmatic intrusion at Upptyppingar, Iceland, during 2007 and 2008. In: Bean CJ, Braiden AK, Lokmer I, Martini F, O'Brien GS (eds) The Volume Project, volcanoes: understanding subsurface mass movement. School Geol Sci, Univ College Dublin, Dublin, Ireland

Geirsson H, Arnadottir T, Hreinsdottir S, Decriem J, LaFemina PC, Jonsson S, Bennett RA, Metzger S, Holland A, Sturkell E, Villemin T, Volksen C, Sigmundsson F, Einarsson P, Roberts MJ, Sveinbjornsson H (2010) Overview of results from continuous GPS observations in Iceland from 1995 to 2010. Jökull 60:3–22

Gudmundsson A (1995a) Infrastructure and mechanics of volcanic systems in Iceland. J Volcanol Geotherm Res 64(1–2):1–22

Gudmundsson A (1995b) Ocean-ridge discontinuities in Iceland. J Geol Soc London 152:1011–1015

Hamling IJ, Ayele A, Bennati L, Calais E, Ebinger CJ, Keir D, Lewi E, Wright TJ, Yirgu G (2009) Geodetic observations of the

ongoing Dabbahu rifting episode: new dyke intrusions in 2006 and 2007. Geophys J Int 178(2):989–1003. doi:10.1111/j.1365-246X.2009.04163.x
Helgason J (1987) Jarðfræðirannsóknir á vatnasviði Jökulsár á Fjöllum við Möðrudal (in Icelandic). Orkustofnun, Reykjavík
Hjartardottir AR, Einarsson P, Sigurdsson H (2009) The fissure swarm of the Askja volcanic system along the divergent plate boundary of N Iceland. Bull Volcanol 71(9):961–975. doi:10.1007/s00445-009-0282-x
Hjartardóttir ÁR, Einarsson P, Brandsdóttir B (2010) The Kerlingar fault, Northeast Iceland: a Holocene normal fault east of the divergent plate boundary. Jökull 60:103–116
Hooper A, Ófeigsson B, Geirsson H, Sigmundsson F, Einarsson P, Sturkell E (2008a) Magma capturing in lower ductile crust: reawakening of Northern Iceland's divergent plate boundary. Eos Trans. AGU 89(53):Abstract V51D-2075
Hooper A, Ófeigsson B, Sigmundsson F, Geirsson H (2008b) Recent deep-seated magmatic activity and the 2008 M6.3 earthquake: applicability of ALOS/PALSAR in Iceland. In: ALOS Workshop. Rhodes, Greece, 3–7 November 2008
Hoskuldsson A, Sparks RSJ, Carroll MR (2006) Constraints on the dynamics of subglacial basalt eruptions from geological and geochemical observations at Kverkfjoll, NE-Iceland. Bull Volcanol 68(7–8):689–701. doi:10.1007/s00445-005-0043-4
Ingólfsson Ó, Norðdahl H, Schomacker A (2010) Deglaciation and Holocene glacial history of Iceland. In: Schomacker A, Krüger J, Kjær KH (eds) The Mýrdalsjökull ice cap, Iceland. glacial processes, sediments and landforms on an active volcano. Elsevier, Amsterdam, pp 51–68
Jakobsdottir SS, Roberts MJ, Gudmundsson GB, Geirsson H, Slunga R (2008) Earthquake swarms at Upptyppingar, North-East Iceland: a sign of magma intrusion? Stud Geophys Geod 52 (4):513–528
Jellinek AM, Manga M, Saar MO (2004) Did melting glaciers cause volcanic eruptions in eastern California? Probing the mechanics of dike formation. J Geophys Res-Solid Earth 109(B9):10. doi:10.1029/2004jb002978
Jóhannesson H, Sæmundsson K (1998a) Geological map of Iceland. Bedrock geology, Icelandic Inst Natur Hist, Reykjavík
Jóhannesson H, Sæmundsson K (1998b) Geological map of Iceland. Tectonics, Icelandic Inst Natur Hist, Reykjavík
Kaldal I, Víkingsson S (1991) Early Holocene deglaciation in Central Iceland. Jökull 40:51–66
Kjartansson G (1943) Geology of Árnessýsla (in Icelandic). In: Árnesingasaga I. pp 1–250
La Femina PC, Dixon TH, Malservisi R, Árnadóttir T, Sturkell E, Sigmundsson F, Einarsson P (2005) Geodetic GPS measurements in south Iceland: strain accumulation and partitioning in a propagating ridge system. J Geophys Res 110:B11405. doi:10.1029/2005JB003675
Lopes Cardozo GGO, Behrmann JH (2006) Kinematic analysis of the Upper Rhine Graben boundary fault system. J Struct Geol 28 (6):1028–1039. doi:10.1016/j.jsg.2006.03.010
Maclennan J, Jull M, McKenzie D, Slater L, Gronvold K (2002) The link between volcanism and deglaciation in Iceland. Geochem Geophys Geosyst 3(11):1062. doi:10.1029/2001gc000282
Marren PM, Russell AJ, Rushmer EL (2009) Sedimentology of a sandur formed by multiple jökulhlaups, Kverkfjöll, Iceland. Sed Geol 213(3–4):77–88
Nowell DAG, Jones MC, Pyle DM (2006) Episodic Quaternary volcanism in France and Germany. J Quat Sci 21(6):645–675. doi:10.1002/jqs.1005
Óladóttir BA (2009) Holocene eruption history and magmatic evolution of the subglacial Vatnajökull volcanoes, Grímsvötn, Bárdarbunga and Kverkfjöll, Iceland. Ph.D. thesis, Université Blaise Pascal, Clermont-Ferrand, France
Pedersen R, Sigmundsson F, Masterlark T (2009) Rheologic controls on inter-rifting deformation of the Northern Volcanic Zone, Iceland. Earth Planet Sci Lett 281(1–2):14–26. doi:10.1016/j.epsl.2009.02.003
Rowland JV, Baker E, Ebinger CJ, Keir D, Kidane T, Biggs J, Hayward N, Wright TJ (2007) Fault growth at a nascent slow-spreading ridge: 2005 Dabbahu rifting episode, Afar. Geophys J Int 171(3):1226–1246. doi:10.1111/j.1365-246X.2007.03584.x
Rubin AM, Pollard DD (1988) Dike-induced faulting in rift zones of Iceland and Afar. Geology 16(5):413–417
Rushmer EL (2006) Sedimentological and geomorphological impacts of the jokulhlaup (glacial outburst flood) in January 2002 at Kverkfjoll, Northern Iceland. Geog Ann Ser a Phys Geog 88A (1):43–53
Sæmundsson K (1973) Straumrákaðar klappir í kringum Ásbyrgi (in Icelandic). Náttúrufræðingurinn 43(1–2):52–60
Sæmundsson K (1974) Evolution of the axial rifting zone on Northern Iceland and the Tjörnes Fracture Zone. Geol Soc Am Bull 85:495–504
Sæmundsson K, Jóhannesson H (2005) Kárahnjúkar, notes on tectonics and geothermal activity and comments on "Assessment of the Hálslón Tectonic Activity" by Ágúst Guðmundsson (JFS) and Jóhann Helgason (EKRA). In: ÍSOR memorandum, 5. January 2005
Sigbjarnarson G (1988) Krepputunga og Brúardalir: lýsingar á korteiningum jarðfræðikorts (in Icelandic). Orkustofnun, Reykjavík, pp 1–44
Sigbjarnarson G (1993) Norðan Vatnajökuls: II Jarðlagaskipan og jarðfræðikort (in Icelandic). Náttúrufræðingurinn 63(3–4):201–217
Sigbjarnarson G (1995) Norðan Vatnajökuls: III. Eldstöðvar og hraun frá nútíma (in Icelandic). Náttúrufræðingurinn 65(3–4):199–212
Sigmundsson F (2006a) Iceland geodynamics. Crustal Deformation and Divergent Plate Tectonics, Praxis, Chichester, UK
Sigmundsson F (2006b) Magma does the splits. Nature 442 (7100):251–252
Sigurdsson H, Sparks SRJ (1978) Rifting episode in North Iceland in 1874–1875 and the eruptions of Askja and Sveinagja. Bull Volcanol 41(3):149–167
Sigvaldason GE (2002) Volcanic and tectonic processes coinciding with glaciation and crustal rebound: an early Holocene rhyolitic eruption in the Dyngjufjoll volcanic centre and the formation of the Askja caldera, north Iceland. Bull Volcanol 64(3–4):192–205
Sigvaldason GE, Annertz K, Nilsson M (1992) Effect of glacier loading deloading on volcanism - postglacial volcanic production-rate of the Dyngjufjoll area, central Iceland. Bull Volcanol 54(5):385–392
Singer BS, Jicha BR, Harper MA, Naranjo JA, Lara LE, Moreno-Roa H (2008) Eruptive history, geochronology, and magmatic evolution of the Puyehue-Cordon Caulle volcanic complex, Chile. Geol Soc Am Bull 120(5–6):599–618. doi:10.1130/1326276.1
Staples RK, White RS, Brandsdottir B, Menke W, Maguire PKH, McBride JH (1997) Faroe-Iceland Ridge Experiment 1. Crustal structure of northeastern Iceland. J Geophys Res-Solid Earth 102 (B4):7849–7866
Thorarinsson S, Sæmundsson K, Williams RS (1973) ERTS-1 image of Vatnajökull: analysis of glaciological, structural, and volcanic features. Jökull 23:7–17
Tómasson H (1973) Hamfarahlaup í Jökulsá á Fjöllum (in Icelandic). Náttúrufræðingurinn 43(1–2):12–34
Tryggvason E (1984) Widening of the Krafla fissure swarm during the 1975–1981 volcano-tectonic episode. Bull Volcanol 47(1):47–69. doi:10.1007/bf01960540
Vigny C, de Chabalier JB, Ruegg JC, Huchon P, Feigl KL, Cattin R, Asfaw L, Kanbari K (2007) Twenty-five years of geodetic measurements along the Tadjoura-Asal rift system, Djibouti, East Africa. J Geophys Res-Solid Earth 112(B6):B06410. doi:10.1029/2004jb003230

Vilmundardóttir EG (1997) Berggrunnskort af Möðrudalsfjallgörðum og nágrenni (in Icelandic). Orkustofnun, Reykjavík

Waitt RB (2002) Great Holocene floods along Jökulsá á Fjöllum, north Iceland. In: Martini PI, Baker VR, Garzon G (eds) Flood and megaflood processes and deposits: recent and ancient examples. Special Publications of the International Association of Sedimentologists, Oxford, pp 37–51

White RS, Drew J, Martens HR, Key J, Soosalu H, Jakobsdóttir SS (2011) Dynamics of dyke intrusion in the mid-crust of Iceland. Earth Planet Sci Lett 304(3–4):300–312. doi:10.1016/j.epsl.2011.02.038

Wolfe CJ, Bjarnason IT, VanDecar JC, Solomon SC (1997) Seismic structure of the Iceland mantle plume. Nature 385 (6613):245–247

Wright TJ, Ebinger C, Biggs J, Ayele A, Yirgu G, Keir D, Stork A (2006) Magma-maintained rift segmentation at continental rupture in the 2005 Afar dyking episode. Nature 442 (7100):291–294. doi:10.1038/nature04978