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RESEARCH ARTICLE

The Krafla fissure swarm, Iceland, and its formation by rifting events

Ásta Rut Hjartardóttir · Páll Einarsson · Emma Bramham · Tim J. Wright

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Abstract Fissure swarms at divergent plate boundaries are activated in rifting events, during which intense fracturing occurs in the fissure swarm accompanied by intrusion of magma to form dikes that sometimes lead to eruptions. To study the evolution of fissure swarms and the behaviour of rifting events, detailed mapping was carried out on fractures and eruptive fissures within the Krafla fissure swarm (KFS). Fracture densities of dated lava flows ranging from 10,000 years BP to ~30 years old were studied, and the fracture pattern was compared with data on the historical Mývatn rifting episode (1724–1729) and the instrumentally recorded Krafla rifting episode (1975–1984). Additionally, the interaction of transform faults and fissure swarms was studied by analysing the influence of the Húsavík transform faults on the KFS. During the historical rifting episodes, eruptions on the fissure swarm occurred within ~7 km from the Krafla central volcano, although faults and fractures were formed or activated at up to 60–70 km distance. This is consistent with earlier rifting patterns, as Holocene eruptive fissures within the KFS are most common closer to the central volcano. Most fractures within the central Krafla caldera are parallel to the overall orientation of the fissure swarm. This suggests that the regional stress field is governing in the Krafla central volcano, while the local stress field of the volcano is generally weak. A sudden widening of the graben in the northern KFS and a local maximum of fracture density at the junction of the KFS and the extrapolation of the Húsavík transform fault zone indicates possible buried continuation of the Húsavík transform fault zone which extends to the KFS. Eruptive fissures are found farther away from the Krafla central volcano in the southern KFS than in the northern KFS. This is either due to an additional magma source in the southern KFS (the Heiðarsporður volcanic system) or caused by the Húsavík transform faults, transferring some of the plate extension in the northern part. Fracture density within particular lava flow fields increases with field age, indicating that repeated rifting events have occurred in the fissure swarm during the last 10,000 years BP. The fracture density in the KFS is also generally higher closer to the Krafla central volcano than at the ends of the fissure swarm. This suggests that rifting events are more common in the parts of the fissure swarm closer to the Krafla central volcano.

Keywords Iceland · Krafla volcano · Rift zone · Rifting · Fissure swarm · Northern Volcanic Zone

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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

E. Bramham · T. J. Wright
School of Earth and Environment, University of Leeds,
Leeds LS2 9JT W Yorkshire, UK

Introduction

Divergent plate boundaries are characterised by rift zones and defined by swarms of faults, open fractures, eruptive fissures and central volcanoes. During the last decades, it has become increasingly evident that swarms of fissures are active in rifting episodes (Wright et al. 2012). During such episodes, magma may repeatedly over a time period of months or years intrude fractures within the fissure swarm to form dikes, which sometimes leads to fissure eruptions. Each such intrusion is termed 'rifting event'. Fissure swarms are formed during rifting events. Nevertheless, opinions differ on whether dike intrusions cause the fracturing, or whether the dikes passively fill opening fractures (e.g.

Guðmundsson 1995; Sigmundsson 2006). Rifting episodes have been observed both in continental crust (e.g. Abdallah et al. 1979; Wright et al. 2006; Rowland et al. 2007; Calais et al. 2008; Baer and Hamiel 2010; Ebinger et al. 2010; Wright et al. 2012) and at mid-oceanic ridges (e.g. Björnsson et al. 1977; Sigurðsson and Sparks 1978; Fox et al. 1995; Dziak et al. 2004; Tolstoy et al. 2006; Dziak et al. 2007). Rifting episodes have even been observed in fissure swarms unrelated to divergent plate boundaries, where rifting is caused by destabilised flanks of volcanic edifices (e.g. Tilling and Dvorak 1993).

Despite these studies, the longer time history of rifting episodes in fissure swarms is less known due to scarce data. The Krafla fissure swarm (KFS) at the plate boundary in Northern Iceland is an ideal area to study this aspect of rifting because historical records are available for the past few hundred years (Fig. 1). The KFS is also both easily accessible and not heavily vegetated, which makes detailed fracture mapping from aerial photographs possible. In this paper, we present a detailed map of the fissure swarm, fractures and eruptive fissures in the KFS. Mapping was carried out using aerial photographs backed up by field validation when necessary. Our mapping covers two historical rifting episodes of KFS from the years of 1724–1729 and 1975–1984 (e.g. Sæmundsson 1730; Björnsson et al. 1977; Einarsson 1991a), and events of the previous ~10,000 years BP as deduced from geological maps (Sæmundsson 1991; Jóhannesson and Sæmundsson 1998).

We analysed the structure of the KFS to understand rifting episodes and how fissure swarms form during periods of thousands of years. The study had mainly three purposes. Firstly, to study how rifting episodes affect the various segments of the fissure swarm with emphasis on those distal and proximal to the Krafla central volcano. This is achieved by analysing the structural pattern of fractures and eruptive fissures. Secondly, to examine influence of the transform faults on the fissure swarm, and thirdly to study how the fracture density of lava flows in the fissure swarm has changed with time over the last ~10,000 years BP due to recurring rifting episodes.

Tectonic framework of the Krafla fissure swarm

The KFS and the Krafla central volcano constitute the Krafla volcanic system. It is one of five volcanic systems within the Northern Volcanic Zone (NVZ) in Iceland (Fig. 1). At the NVZ, the plate boundary diverges at a rate of ~2 cm/year, calculated from the plate velocity model of DeMets et al. (1994). The northern sector of the NVZ intersects the Tjörnes Fracture Zone, which comprises two to three strike-slip zones that link up with the submarine Kolbeinsey ridge to the north (Sæmundsson 1974; Einarsson and Sæmundsson 1987; Einarsson 1991a).

The Krafla central volcano features a ~8-km-wide caldera, formed in an eruption ~100,000 years ago (Sæmundsson 1991). Since its formation, the caldera has widened about 2 km in east–west direction due to plate spreading (Sæmundsson 1991). The Krafla volcano is primarily basaltic, but silicic deposits are found in the vicinity of the caldera (e.g. Sæmundsson 1991; Jónasson 1994). Below the caldera, a WNW–ESE stretching S-wave shadow zones indicate a magma chamber of irregular form. The top of the chamber is situated at about 3 km depth, while the bottom of it is probably at less than 7 km depth (Einarsson 1978). Analysis of ground deformation shows that deeper magma reservoirs are also present (Tryggvason 1986). Such a complex of magma chambers or reservoirs is also supported by studies of Grönvold et al. (2008) which show that magma erupted during the Krafla rifting episode in 1975–1984 came from different magma reservoirs.

The KFS extends about 50 km towards the north and about 40 km towards the south from the Krafla central volcano (Fig. 2). The fissure swarm is mostly situated in the post-glacial lava flows emplaced since ~10,000 years BP. Fractures within the swarm are mostly oriented N to NNE. The maximum width and throw of individual fractures detected by Opheim and Guðmundsson (1989) were 40 and 42 m, respectively. A separate swarm, the Heiðarsporður fissure swarm, has been suggested to be located in the SE part of the KFS (Fig. 2) (Sæmundsson 1974).

Two periods of intense eruptive activity have occurred during the Holocene (Sæmundsson 1991). The former period occurred during the latest part of the Pleistocene and at the beginning of the Holocene, while the latter, currently ongoing, period started at about 2,600–2,800 years BP. In between these events, there was a hiatus, which was interrupted by only one short eruption period which took place at about 5,000 years BP (Sæmundsson 1991). The eruptive activity during these periods has been thought to be a part of rifting episodes (Sæmundsson 1991).

The segment of the KFS south of the central volcano is covered by numerous lava flows emplaced since 3,000 years BP, although the southernmost part is covered by glacial deposits. However, the northern KFS is mostly located within the 10,000 years BP Stóravíti lava shield (Sæmundsson 1973, 1991; Mattsson and Höskuldsson 2011).

Two rifting episodes have occurred on the KFS in historical times (i.e. the last 1,140 years): the 1724–1729 'Mývatn rifting episode' and the instrumentally recorded 1975–1984 'Krafla rifting episode'. During both episodes, periods of intense earthquake activity and fault movements (often accommodating graben subsidence) occurred within the fissure swarm. The rifting was accompanied by fissure eruptions (Sæmundsson 1730, 1991; Einarsson 1991a). Prehistoric Holocene rifting episodes are thought to have caused the eruptions of the Grænavatnsbruni, Hólseldar, Hverfjallseldar,

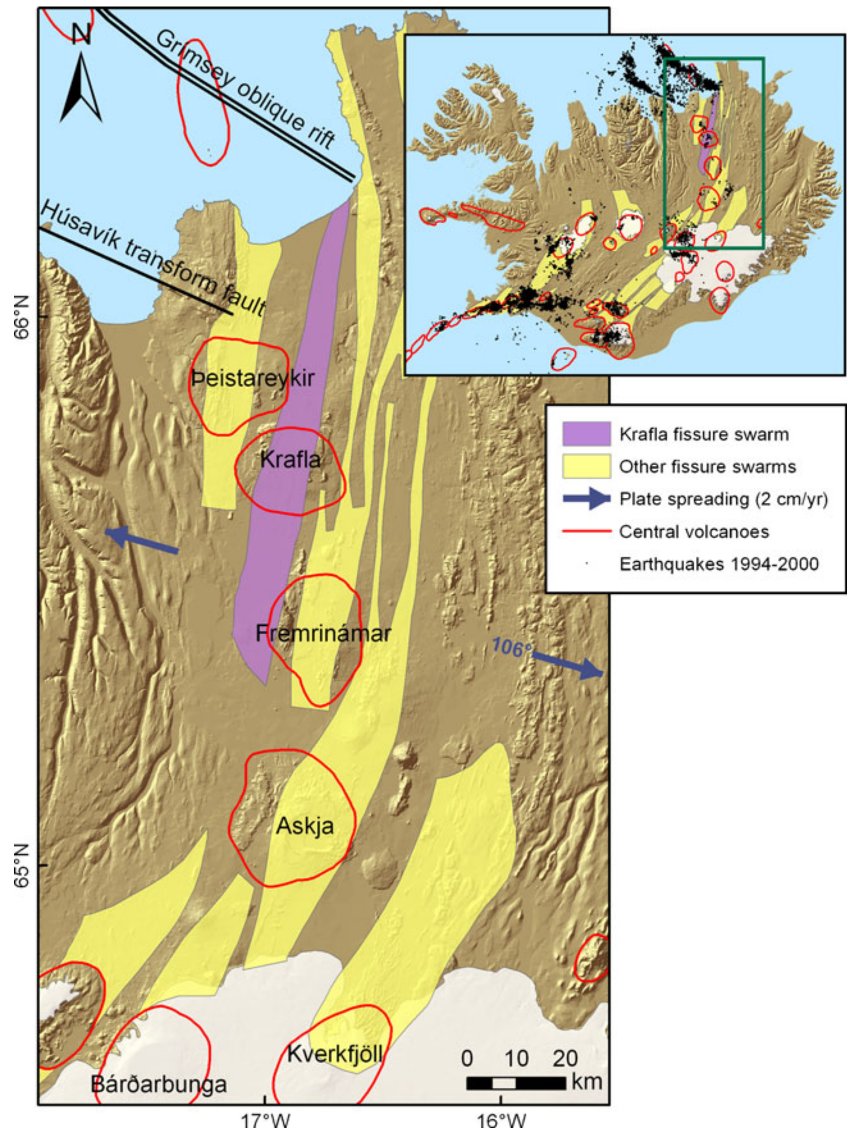

Fig. 1 The KFS and the Northern Volcanic Zone. *Green frame* in inserted figure shows the location of the Northern Volcanic Zone in Iceland. The outlines of fissure swarms and central volcanoes are from Einarsson and Sæmundsson (1987), the plate spreading direction of 106° (*blue arrows*) is calculated from DeMets et al. (1994). Cartographic data from the National Land Survey of Iceland

Hraungarðar and Younger Laxá lava flow fields, while the Stóravíti, Gjástykkisbunga and Older Laxá lava flow fields are parts of lava shields (Table 1) (Sæmundsson 1991).

The Northern Volcanic Zone connects with the offshore Tjörnes Fracture Zone, which consists of three WNW-oriented transform faulted areas: the Húsavík transform fault (or the Húsavík–Flatey fault), the Grímsey oblique rift and the Dalvík zone (e.g. Sæmundsson 1974; Guðmundsson 2007; Bergerat and Angelier 2008; Einarsson 2008; Stefánsson et al. 2008). The Húsavík transform fault and the Grímsey oblique rift extend near the KFS (Fig. 1).

Methods

To study the Holocene deformation pattern of the KFS, we mapped fractures (i.e. faults and fissures), eruptive fissures, as well as craters and individual scoria cones within the KFS (Fig. 2). The mapping was done from digital aerial photographs covering the entire area and from field observations of areas of special interest in order to verify whether lineaments on the aerial photographs were actual fractures. The resulting map (Fig. 2) was then compared with other data of deformation in the area.

The aerial photographs were obtained from Loftmyndir Inc. The photographs have a resolution of 0.5–1 m/pixel. In addition, we used aerial photographs from Samsýn Inc. for comparison, as well as satellite images from the US/Japan ASTER project (Advanced Spaceborne Thermal Emission and Reflection radiometer), as those give information on the overall structure of the area. These images have a resolution of 0.5 and 15 m/pixels, respectively. Aerial photographs taken before the Krafla rifting episode were not included. We use located earthquakes from the 1975–1984 Krafla rifting episode to show that the northern KFS was more influenced by this rifting episode than the southern KFS.

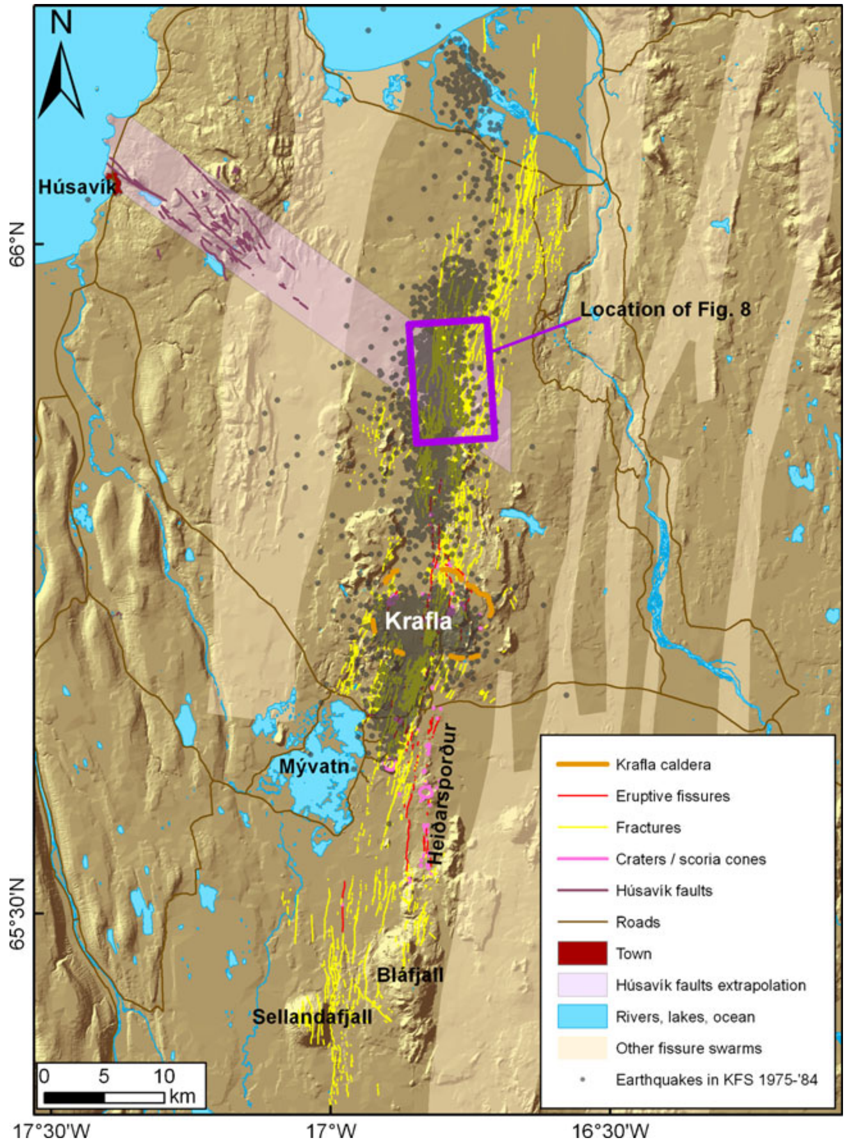

Fig. 2 Fractures and eruptive fissures in the KFS, and the Húsavík transform faults, as interpreted from aerial photographs. Earthquake data, indicating what parts of the KFS were activated during the Krafla rifting episode (1975–1984), is from Buck et al. (2006). The offset between the earthquakes and the fissure swarm in the north part may be real, but could also be caused by uncertainties in the earthquake locations. Also note that all the data from this episode have not been processed yet. The cartographic data are from the National Land Survey of Iceland

To avoid poorly located earthquakes, only earthquakes determined by a network with an azimuthal gap of less than 180° were included. The uncertainty in the relative horizontal location of the earthquake data from the Krafla rifting episode is about 1 km, while the uncertainties in the absolute locations are somewhat higher. It must be emphasized that the Krafla earthquake data are not uniform. Parts of the data set have not been fully analysed yet. This is particularly true for the two largest rifting events: December 1975–March 1976 and January 1978.

A digital elevation model (DEM) was used to study a graben structure in the northern part of the KFS. The DEM was created from LiDAR data acquired over two survey periods. The first survey was flown on 7 August 2007, and the second was flown on 5 September 2008. Both surveys were performed by the Airborne Research and Survey Facilities (ARSF) of the Natural Environment Council of Britain, using Optech's ALTM 3033 (Airborne Laser Terrain Mapper) that was flown with the aircraft ARSF-Dornier 228-101. The best estimate RMS calculated for the survey was calculated to be 0.068 m Eastings, 0.055 m Northings and 0.119 m for the elevation.

The ArcGIS software was used for the mapping of fractures, eruptive fissures and other features such as craters and scoria cones. To calculate fracture density, we used the Line Density tool in the ArcGIS Toolbox. The tool calculates line densities by dividing cumulative line lengths within a given search circle by the area of the circle. The defined search circle in this study has a radius of 0.5 km. From this, a raster file is created with the outcome of the calculations in each pixel, which in this study has a resolution of 0.5 km. From this, a maximum fracture density was found in each of 2-km-wide grids which were arranged along the fissure swarm, and oriented parallel with the plate-spreading vector, as calculated from DeMets et al. (1994). The fracture density was calculated for fracture populations in different lava flows, which have

Table 1 The lava flows that were used for comparison of fracture densities within differently dated lava flows

Lava flow(s)	Number	Age
Krafla rifting episode	1	~30 years
Mývatn rifting episode	2	~280 years
Younger Laxá lava flow	3	~2,200 years BP
Grænavatnsbruni lava flow	4	~2,200 years BP
Hólseldar lava flow	5	~2,350 years BP
Hverfjallseldar lava flow	6	~2,800 years BP
Older Laxá lava flow	7	~3,800 years BP
Hraungarðar lava flow	8	~8,000–10,000 years BP
Stóraviti lava flow	9	~10,000 years BP
Gjástykkisbunga lava flow	10	~10,000 years BP

The information about the ages of the lava flows are from Þórarinsson (1979), Sæmundsson (1991) and Höskuldsson et al. (2010). The numbers refer to the numbering of lava flows in Figs. 4, 5, 6, 10, 11 and 13

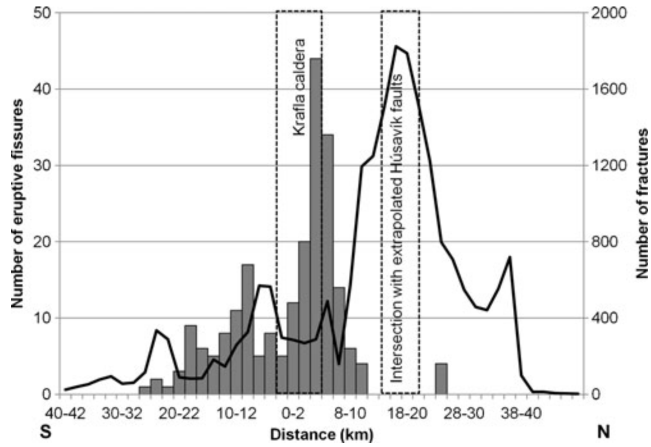

Fig. 3 Number density of fractures (or fracture segments; *black line*) and eruptive fissures (*grey columns*) in cross-swarm distance bins away north and south from the centre of the Krafla caldera. The position of the caldera is indicated by the *black dashed line* in centre of graph. The inferred intersection with extrapolated Húsavík faults is also indicated

been dated by tephrochronology (Þórarinsson 1979; Sæmundsson 1991).

Due to the detailed mapping, many fractures are mapped as multiple fracture segments, even though these fracture segments represent the same fracture at depth. Similarly, individual eruptive fissures are mapped separately, although some of them formed during the same eruption. This explains the discrepancy between the number of eruptive fissures mapped here (~150) and the number of Holocene eruptions in the same area (<50) as illustrated by Sæmundsson (1991).

Results

The KFS has been intensively deformed during post-glacial times. This is indicated by the 20,211 mapped fractures (or fracture segments) and eruptive fissures of which 85 % are situated in post-glacial lava flow fields (Jóhannesson and Sæmundsson 1998). Most of the remaining fractures and eruptive fissures (15 %) are situated in loose sediments, hyaloclastite or in interglacial lava flows and show evidence of post-glacial activity, specifically, sharp edges indicating that they have not been eroded by a glacier.

The number density of eruptive fissures in the fissure swarm is greatest in the vicinity of the central volcano, while there are few eruptive fissures towards the terminus of the fissure swarm. Similarly, the number density of fractures increases towards the central volcano, although this pattern is somewhat masked by the young lava flow fields closest to the central volcano (Figs. 3 and 4).

The northern Krafla fissure swarm

The northern KFS extends northwards from the northern rim of the Krafla caldera. It is characterised by a 'branched' pattern, especially in the vicinity of the central volcano (Figs. 5 and 6). This pattern is formed by fracture segments striking dominantly N–S, parallel to the rift, and a few fractures that have a NW or NE strike (Figs. 5, 6 and 7). About 17 km north of the Krafla caldera, the graben with which many of the fractures are associated widens suddenly (Figs. 1 and 8). The LiDAR data indicate that the N–S-oriented fractures generally have significant vertical offset, while the offset along fractures with other orientations is less. The fractures with other orientations are situated at overlap zones, connecting between the N–S-oriented faults which are spread over larger areas as the graben widens (Fig. 8).

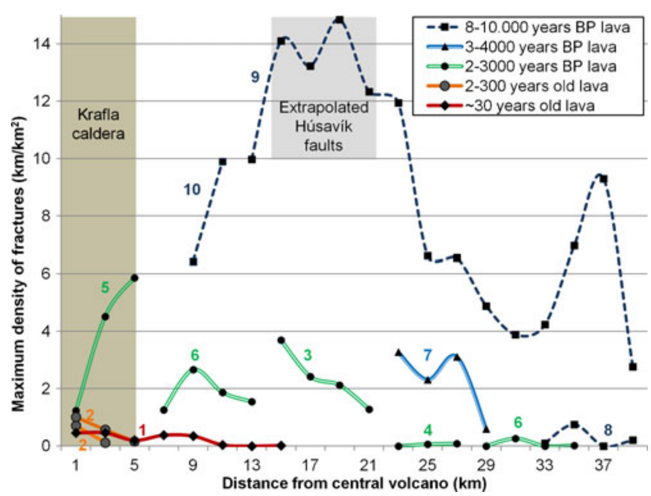

Fig. 4 Fracture densities within differently aged lava flow fields, denoted by numbers (Table 1). The area of the Krafla caldera is *shaded brown* and shows the portion of individual lava flow fields that are confined to the caldera. The inferred junction of the northern KFS with the extrapolated Húsavík faults (Fig. 2) is shown as a *grey shaded area*

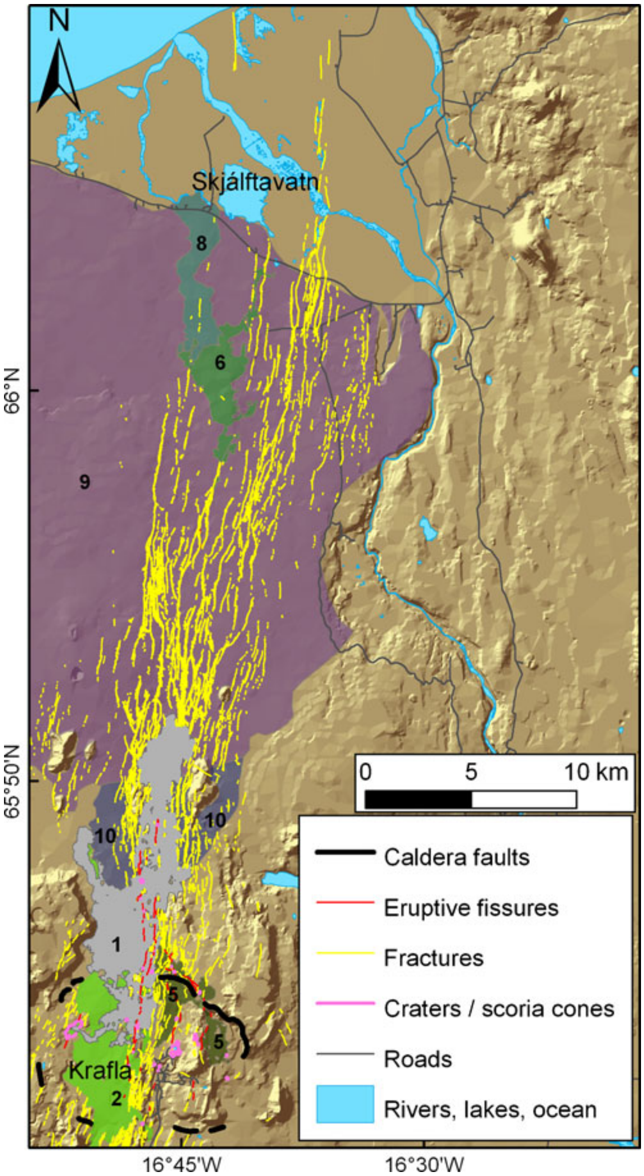

Fig. 5 Map of the northern KFS, where numbers denote individual lava flow fields (Table 1). The cartographic data is from the National Land Survey of Iceland, information on the extend of the lava flows is from Sæmundsson (1977, 1991) and Elíasson (1979)

Fractures within the northern KFS are of two different origins. Firstly, there are long faults with vertical offsets of several meters (Fig. 9). Those faults are likely boundary faults of grabens, as faults with an opposite throw are usually situated at the other site of a subsided land strip. Secondly, there are shorter tension fractures, situated both on the floors of the grabens (Fig. 9), as well as along the margins of the northern KFS, where there are no grabens.

The vast majority of fractures within the northern KFS are located in the ~10,000 years BP Stóravíti lava flow (Fig. 5) (Sæmundsson 1991). There, the fracture density is generally higher closer to the central volcano than farther away from it. Nevertheless, the fracture density varies greatly, from 3 km to more than 14 km cumulative length of fractures over each square kilometre (Fig. 4). Notably, the maximum density of fractures in the 10,000 years BP lava flow occurs in the previously mentioned area where there is a sudden widening of a graben and where the extrapolated Húsavík faults meet the KFS. The ~30-year-old lava flow fields of the Krafla rifting episode also extend onto the northern KFS (Fig. 5). Compared with the 10,000 years BP Stóravíti lava flow, the 30-year-old lava flows have a much lower fracture density (Fig. 4 and Table 1).

The vertical deformation that took place during one of the Krafla rifting events was measured by levelling (Sigurðsson 1980). Comparison of this deformation with the fracture pattern indicates that there are far fewer fractures on the western boundary of the subsided area than on the eastern boundary, and that the western boundary of both the subsidence and the fissure swarm coincide (Fig. 10). This is not the case for the eastern boundary of the subsidence, as numerous fractures are present east of it, extending to the Ásbyrgi canyon (Fig. 10). During a field trip, it was observed that most of the fractures close to Ásbyrgi are small fractures with no vertical offset. Therefore, they are not a part of the subsided graben to the west of them.

Eruptive fissures in the northern KFS are few, only 0.4 % of the total number of eruptive fissures and fracture segments (Fig. 5). Most of the eruptive fissures are located in the vicinity of the central volcano (Fig. 3). These include several eruptive fissures active during the Krafla rifting episode. No eruptive fissures are found where the extrapolated Húsavík faults intersect the KFS (Fig. 3). However, a few eruptive fissures are found farther to the north and are typically short or less than 200 m. We did not detect eruptive fissures within the northernmost Hverfjallseldar and Hraungarðar lava flow fields, although there are two small eruptive fissures situated about 2 km south of the northernmost Hverfjallseldar lava flow (Fig. 5 and Table 1).

The southern Krafla fissure swarm

Here, we define the southern KFS as the set of all the fractures and eruptive fissures extending south from the southern margin of the Krafla caldera, including the Heiðarsporður volcanic system (Sæmundsson 1974).

The southern KFS differs from the northern KFS in its fracture pattern. The southern KFS does not feature the 'branched' fracture pattern that characterises the northern KFS (Fig. 6). Instead, most of the fractures within the southern KFS are sub-parallel and exhibit a N to NNE orientation (Figs. 6 and 11). The most common fracture azimuths in the southern KFS range from 5 to 20°, i.e. over

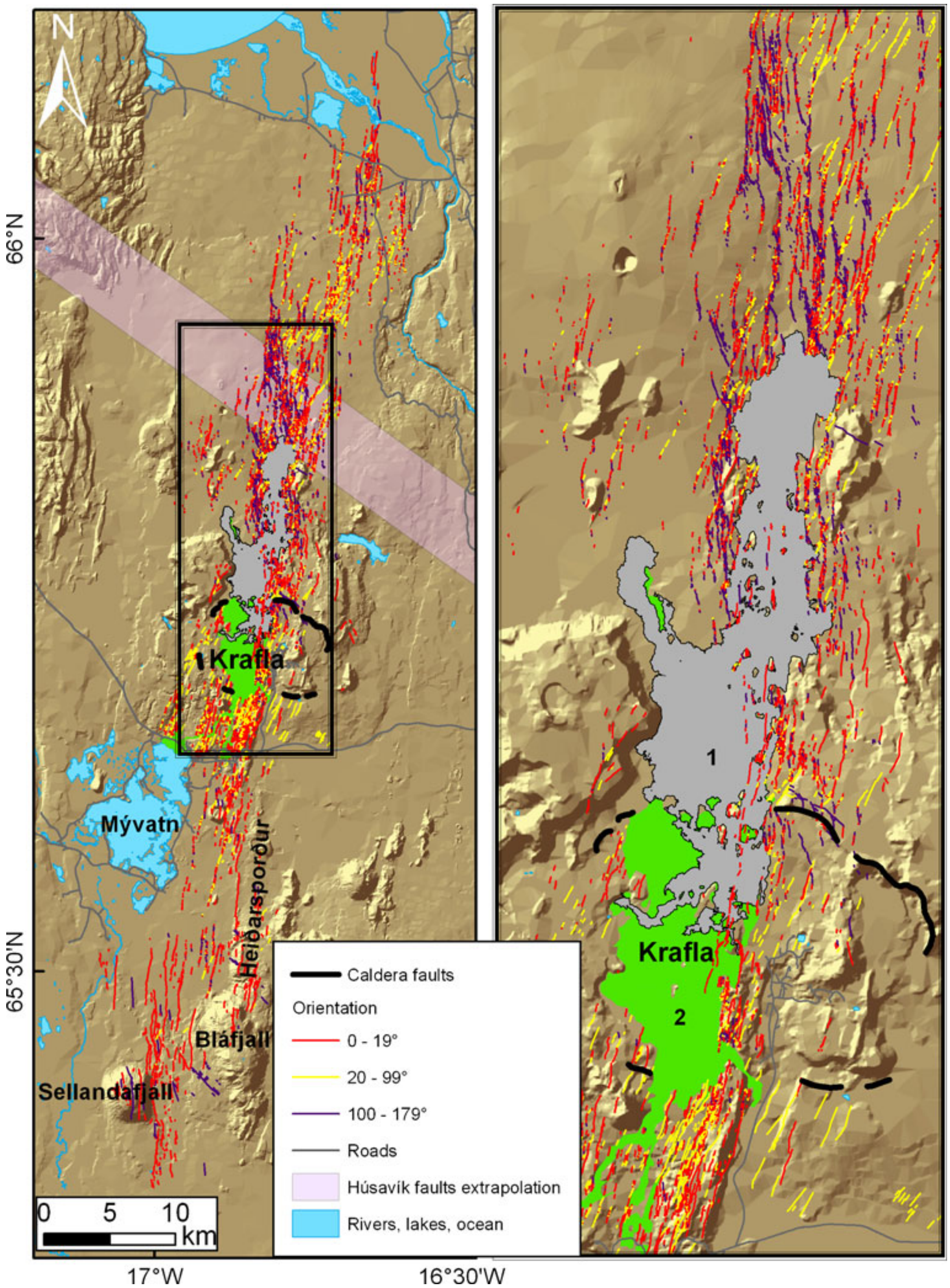

Fig. 6 Orientation of fractures and eruptive fissures within the KFS. *Black box* in the left-hand image outlines the extent of the right-hand image. The cartographic data are from the National Land Survey of Iceland

a wider range than the fractures in the northern KFS. In addition, the range of the azimuth of fractures within the southern sector exhibits a skewed distribution and thus contrasting the near-perfect normal distribution within the northern KFS (Fig. 7). There are several fractures with an azimuth of 135–140° located in the southernmost domain of the KFS (Figs. 6 and 7). These fractures are situated in loose glacial deposits. Their appearance is different from other fractures within the southern KFS, as they show evidence of having been modified by erosion.

Fracture densities in the ~2,000–4,000 years BP lava flows in the southern KFS are lower than fracture densities of the 10,000 years BP Stóravíti lava flow in the northern KFS, but considerably higher than the fracture densities of lava flow fields younger than ~300 years old (Figs. 4, 11 and Table 1).

Eruptive fissures in the southern KFS are found up to 30 km from the Krafla central volcano. Generally, they become fewer with distance from the central volcano. This is different from the northern KFS, where eruptive fissures are most abundant at less than 10 km distance from the volcano (Fig. 3).

The NW-oriented fractures in the southernmost part of the southern KFS are in some aspects different from the regular N to NNE-oriented fissures in the fissure swarm

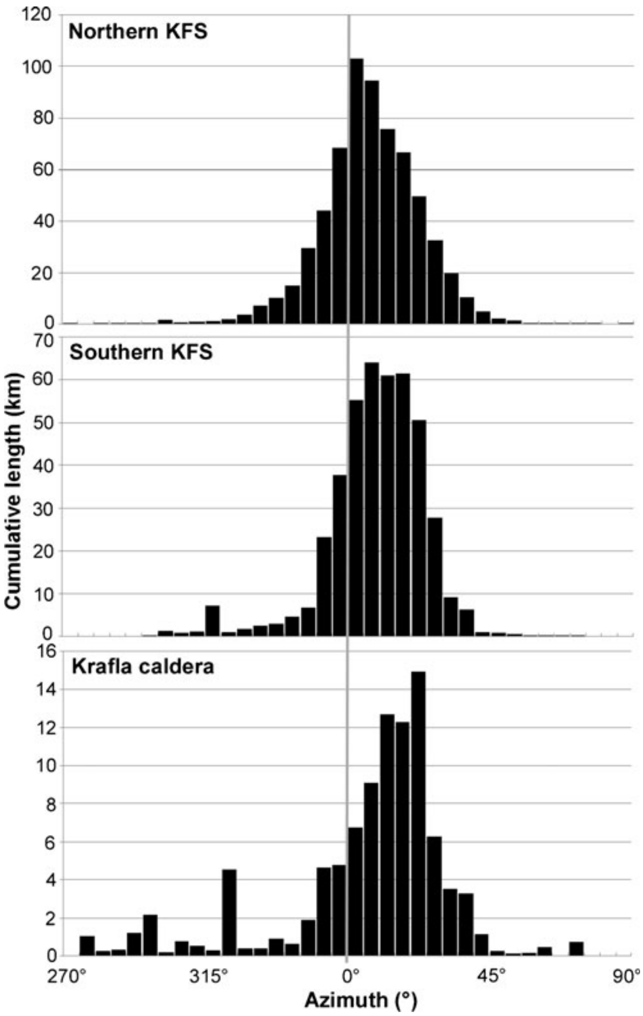

Fig. 7 Cumulative length of fractures relative to their orientations in the northern KFS, southern KFS and in the Krafla caldera. Orientations are given in 5° bins

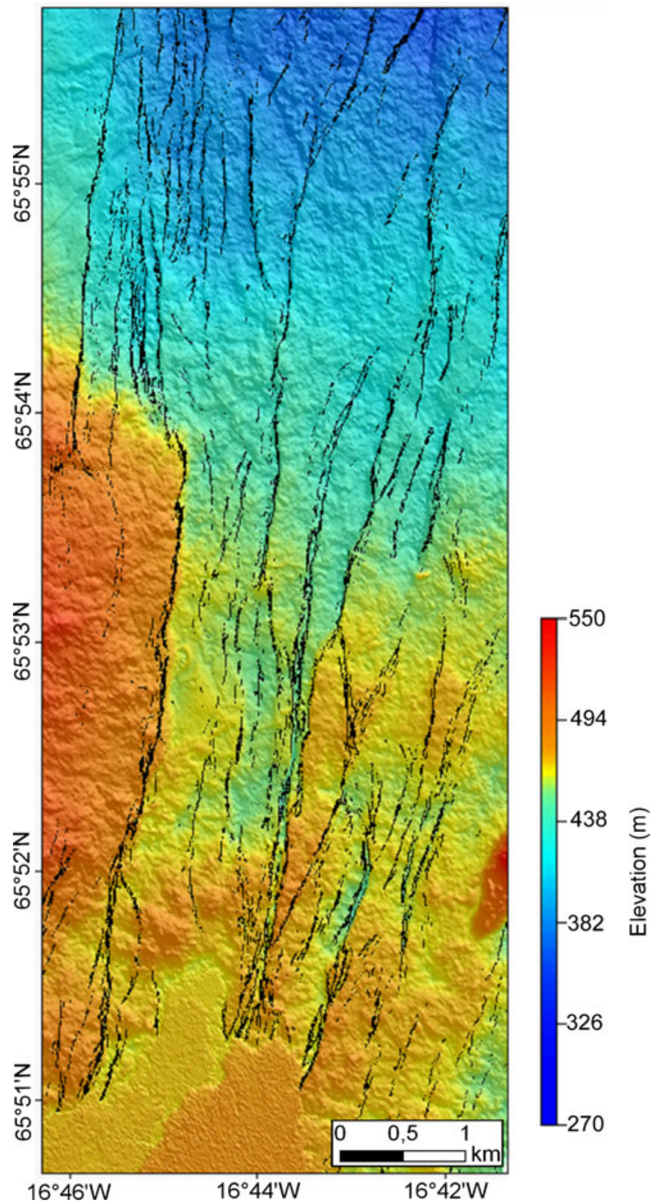

Fig. 8 The graben extending along the northern KFS as seen by LiDAR data and fractures in the area (*black lines*). See Fig. 2 for location

(Fig. 6). Especially, the NW-oriented fractures are eroded. The NW-oriented fractures do therefore seem to belong to a different fracture population than the regular N to NNE-oriented fractures. There was also evidence of recent fracture movements in the southernmost part of the fissure swarm, as a fault offset can be seen in the eastern scree slope of Mount Sellandafjall (Fig. 12). As the scree slope is highly mobile, this fault offset cannot be very old. In addition to this fracture, we found numerous other fractures in the same area indicating young age. These cluster in an elongated swarm, about 1–1.5-km wide, which extends along and north of the eastern slope of Mt. Sellandafjall. All these fractures are either located in the Sellandafjall scree slope or in loose glacial deposits.

The Krafla caldera

The Krafla caldera is to a large extent filled by lava and hyaloclastite, and the caldera rim is only exposed in a few places. The area of the caldera is characterised by faults delineating the caldera rim and by two swarms of fractures that extend through the caldera (Sæmundsson 1991).

The main fissure swarm extends through the centre of the caldera, while the other, less pronounced swarm is situated in the westernmost part of the caldera (Figs. 2 and 13). The majority of fractures within both these fissure swarms are aligned parallel to the NNE-oriented KFS. However, there are deviations in the northern part of the central swarm, near the northern caldera rim, where fractures with NW and NE orientations are present (Fig. 13). In addition, there are several eruptive fissures with a WNW orientation (i.e. parallel to the

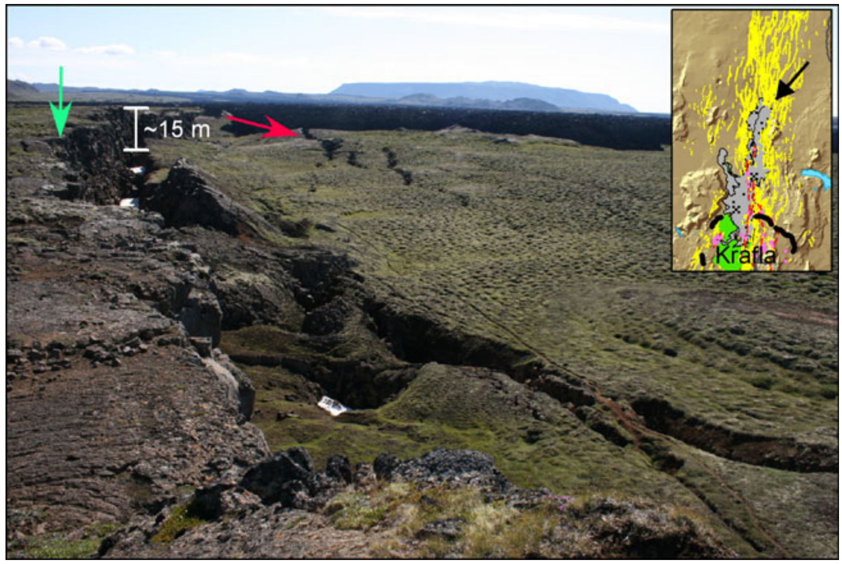

Fig. 9 The northern KFS with tension fractures (*red arrow*) and a graben bounding fault (*green arrow*), *white coloured number* indicates vertical offset of the fault. *Black arrow* in inserted map shows the view and location of the photo

caldera rim) in the same area. These fractures are intercalated with NNE-oriented fractures. Although fractures within the Krafla caldera strike generally parallel to the fractures in the KFS, the distribution of fracture orientations within the Krafla caldera varies more than the distribution within the KFS and is more irregular (Fig. 7). Within the Krafla caldera, the Krafla rifting episode took place in the central swarm. Eruptive fissures from that period are parallel to the KFS.

Fracture densities of near-equal age lava flow fields are generally higher in the central volcano (i.e. within the caldera) than in the fissure swarms (Fig. 4). Low fracture density was nevertheless measured in the 2,000–3,000 years BP lava field (number 5 in Table 1) in the central part of the caldera. However, that data point may underestimate the fracture density, as the aerial extent of the lava flow in that area is low.

Discussion

The distribution of eruptive fissures along the KFS

Eruptive fissures are unevenly distributed along the KFS and show two distinct patterns. Firstly, eruptive fissures extend farther into the southern KFS than the northern KFS. In the northern KFS, no eruptive fissures are found beyond the intersection with the continuation of the Húsavík faults (Fig. 3). Secondly, the number of eruptive fissures is highest close to the Krafla central volcano and decreases with distance from it (Fig. 3).

We suggest two possible reasons for the different pattern of eruptive fissures in the southern and northern segments of the fissure swarm:

(a) That there is an additional deep magma source south of the Krafla central volcano.

(b) That the KFS is intersected by the Húsavík transform fault leading to reduced extension in the fissure swarm to the north.

The southernmost eruptive fissures (situated at a distance of 10–25 km from the Krafla caldera), have all been assigned to the Heiðarsporður volcanic system instead of the Krafla volcanic system, based on chemical analysis (Sæmundsson 1974, 1991; Jónasson 2005). This indicates that the Heiðarsporður volcanic system shares a fissure swarm with the Krafla central volcano. Regarding the second point, the Húsavík transform fault must lessen the extension of the part of the KFS which is located north of the Húsavík fault, which may cause less eruptive activity there. We conclude that both the additional deep magma source in the southern KFS and the effect of the Húsavík transform fault may explain why there are more eruptive fissures in the southern KFS than in the northern KFS.

The majority of eruptive fissures associated with the Krafla volcanic system are found less than ~10–30 km from the central volcano, while farther away the fissure swarm is mostly defined by non-eruptive fractures. This is in agreement with the historical rifting episodes in the KFS, when eruptive activity only reached about 6–7 km distance from the central volcano into the fissure swarm, while deformation of fractures was detected at a distance of tens of kilometres (Sæmundsson 1730; Einarsson 1991b; Buck et al. 2006). A similar pattern has been observed in the ongoing rifting episode in the Dabbahu–Manda Hararo fissure swarm in Afar, Ethiopia, as three out of the four eruptions that have occurred to date during the episode have taken place less than ~10 km from the magma reservoir (Ebinger et al. 2010; Wright et al. 2012). This is also in accordance with the Askja fissure swarm, where the majority of eruptive fissures are located close to the central volcano (Hjartardóttir

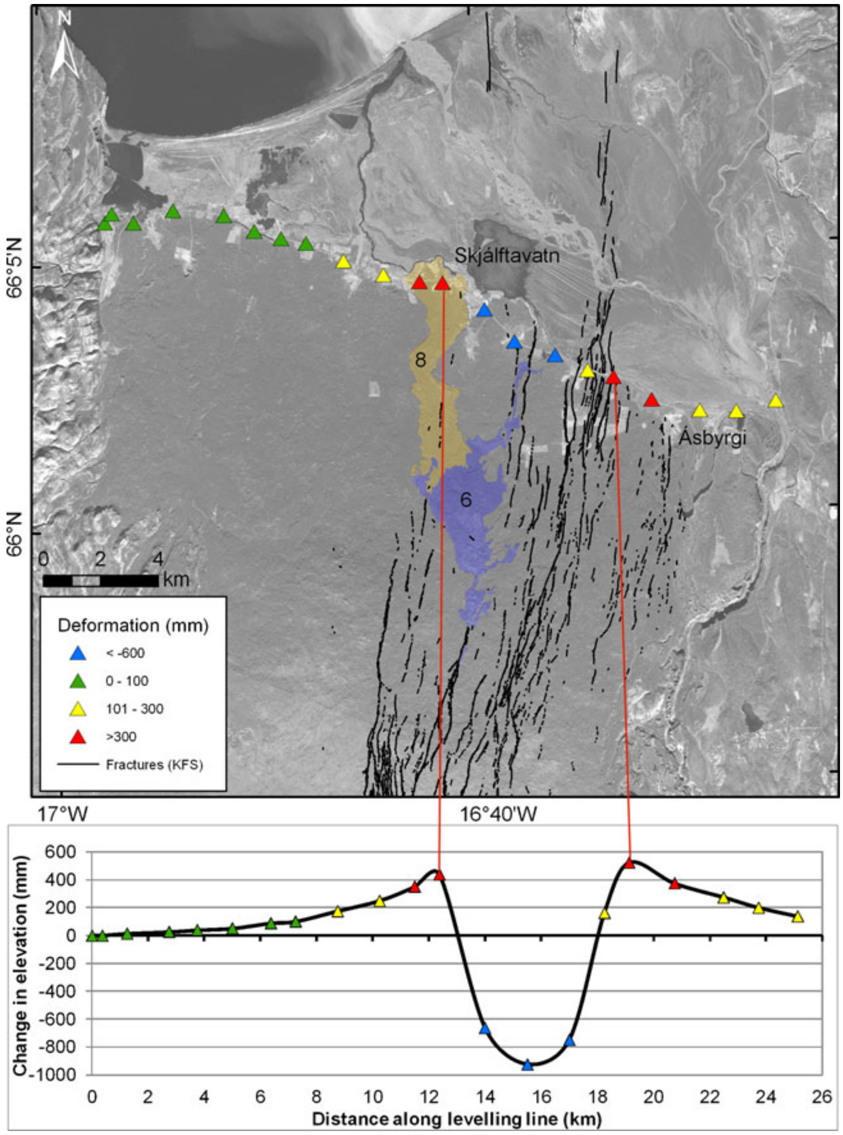

Fig. 10 The deformation that took place during a rifting event in the northernmost part of the KFS in January 1978. *Numbers* denote lava flows (Table 1). The graph is from Sigurðsson (1980)

et al. 2009). Instrumentally recorded rifting episodes may shed light on how this pattern forms. In both the Krafla rifting episode (1975–1984) and in the currently ongoing Afar rifting episode in Ethiopia, which started in 2005, the first dike propagated the longest distance (Einarsson 1991a; Hamling et al. 2009; Ebinger et al. 2010). During the Krafla rifting episode, subsequent dikes propagated shorter and shorter distances as time passed. Eventually, eruptions close to the central volcanoes became common (Einarsson 1991a).

A model by Buck et al. (2006) offers one way to explain this pattern. Those authors inferred that magma propagated laterally away from the central volcano into the fissure swarm. The dike is thought to propagate while enough driving pressure, defined as the difference between the magma pressure and the tectonic stress at the dike tip, exists. When the extensional stresses in the fissure swarm that have accumulated during non-rifting periods have been relieved due to the dike intrusions, extrusion of magma becomes prominent in the vicinity of the central volcano. This is consistent with observations both during the Krafla and the Dabbahu (Ethiopia) rifting episodes, when seismicity concentrated nearer to the central volcanoes at the later stages of the episodes (Einarsson 1991b; Wright et al. 2012). Therefore, the decrease of eruptive fissures with distance from the central volcano may be a general pattern, representing the gradual release of accumulated tectonic stresses.

Another possible explanation of the decreasing number of eruptive fissures with distance from the central volcano is that the dikes propagate vertically to the surface from magma reservoirs beneath the Krafla volcanic system (Guðmundsson 1995). This may explain why magmas from different sources were erupted simultaneously within and outside the Krafla caldera during the Krafla rifting episode (Grönvold et al. 2008). However, it remains unclear how a magma propagating from >20 km depth and a magma propagating from 3 to 7 km depth can start to erupt

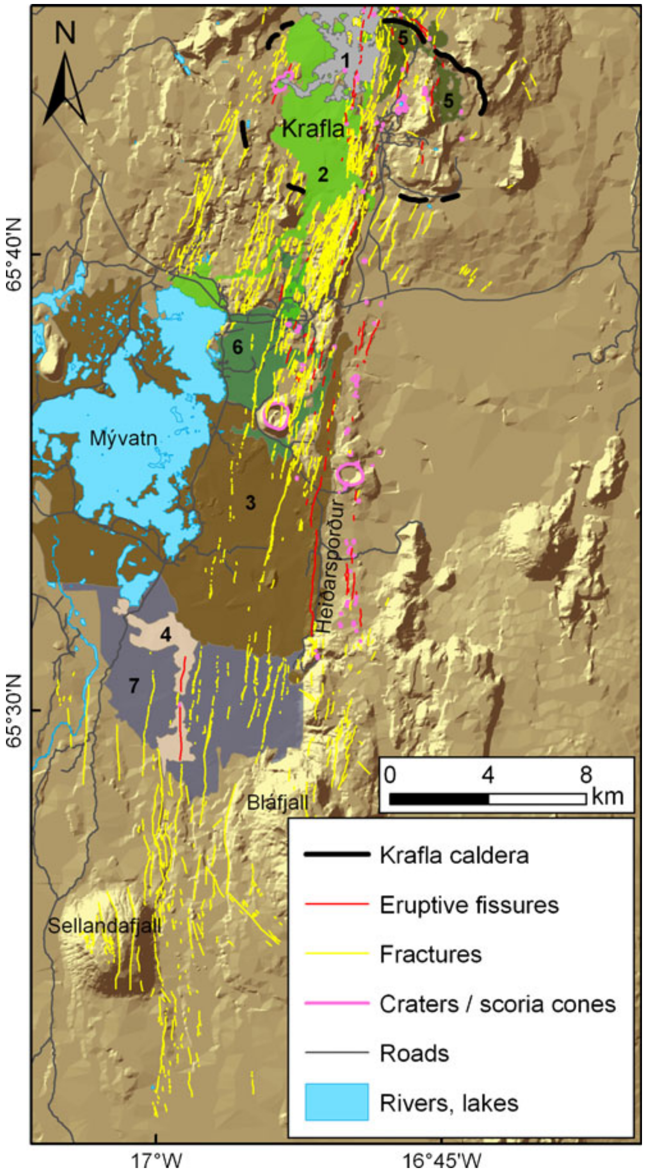

Fig. 11 The southern KFS. *Numbers* denote lava flows (Table 1). The cartographic data is from the National Land Survey of Iceland. Information on the extend of the lava flows is from Sæmundsson (1991), Þórarinsson (1951) and Höskuldsson et al. (2010)

simultaneously and in close proximity to each other (Einarsson 1978; Tryggvason 1986).

In general, it is known that dikes can both propagate laterally and vertically. Magnetic fabric studies have, as an example, shown that a dike in East Iceland propagated laterally, but with a slight upward motion (Eriksson et al. 2011). However, the deep dike intrusion in the Kverkfjöll fissure swarm in 2007 and 2008 most likely propagated vertically, as the intrusion occurred without any unrest in the Kverkfjöll central volcano, and without any significant horizontal propagation of earthquakes (e.g. Jakobsdóttir et al. 2008; Hooper et al. 2011; White et al. 2011).

The influence of transform faults on the KFS

Two transform zones either intersect the northern KFS or are located in the vicinity of it (Fig. 1). The Grímsey oblique rift (GOR) extends from the northern end of the KFS to the dilatational part of the Mid-Atlantic Ridge to the north. It was activated during the first event of the Krafla rifting episode, when the rifting event was followed by a 6.5-Ms strike-slip earthquake on the GOR (Einarsson 1987, 1991b).

The Húsavík transform fault extends to the Þeistareykir fissure swarm (Fig. 1) (e.g. Guðmundsson et al. 1993; Garcia and Dhont 2005; Magnúsdóttir and Brandsdóttir 2011). It has remained unclear whether the Húsavík transform fault extends east of the Þeistareykir fissure swarm, although changes in the trend of the fissure swarms in the NVZ might indicate a buried transverse structure (Sæmundsson 1974). There are four points of evidence that suggest that a subsurface continuation of the transform fault exists beneath the KFS. Firstly, there is an age difference of lava formations south and north of the continuation of the Húsavík transform fault, as volcanism in the part of the NVZ which is south of the extrapolated transform fault has been continuous for about 4 Ma, while it has only been continuous for about 1 Ma north of the fault (Sæmundsson 1974). Secondly, the graben that extends along the KFS suddenly gets wider in this area. The widening follows a NW-oriented structure, which may be a part of the Húsavík transform fault (Figs. 1 and 8). Thirdly, earthquakes during one of the rifting events temporarily propagated away from the fissure swarm, towards the continuation of the Húsavík fault, possibly suggesting a subsurface continuation of the fault (Einarsson 1991b). Fourthly, the extrapolation of the Húsavík transform faulted zone coincides with the highest density of fractures in the KFS (Fig. 4), and also with a lack of eruptive fissures there (Fig. 3). Such a continuation may also explain the peculiar 'branched' fracture pattern seen in the northern KFS, as an example where the fissure swarm meets the NW-oriented structure mentioned before. This 'branched' pattern, which is found in a wider area situated in the continuation of the Húsavík fault, cannot be found in the southern KFS.

Assuming that a subsurface continuation of the Húsavík transform fault is located beneath the KFS, it may have caused the widening of the KFS. As the widths of grabens have been suggested to indicate the depth to the top of underlying dikes (Rubin 1992), the increased width of the graben in the KFS indicates that the depth to the top of dikes generally increases towards the north in this area. We suggest that the increased depth is caused by less extension within the KFS north of the Húsavík transform fault than south of it, as the Húsavík transform fault takes up some of

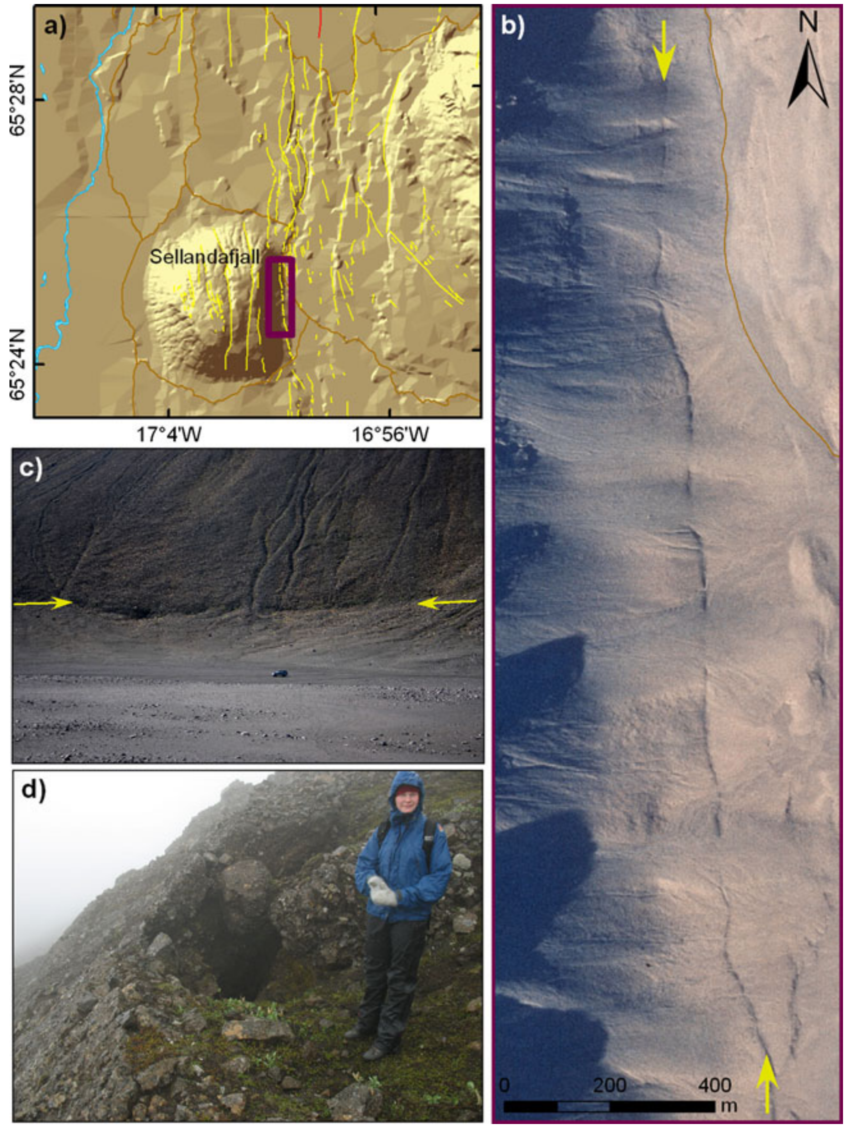

Fig. 12 A fault in the scree slopes of Mt. Sellandafjall (see location in Fig. 11). **a** The location of the fault (*purple* frame outlines frame **b**). **b** Aerial photograph showing the fault in the scree slopes, the photograph is from Loftmyndir©. **c** *Yellow arrows* pointing at the fault, see car for scale. **d** A part of the fault that is open

the extension. This may occur as the crust north of the Húsavík transform fault should be colder and less ductile than the crust south of it because of less frequent propagation of dikes to that area, and as that part of the NVZ is about 3 Ma younger than the part south of the Húsavík fault (Sæmundsson 1974). Therefore, the strength of the uppermost part of the crust is higher there than in the crust south of the transform fault. If a dike propagates vertically to the surface, this may stop the propagation at deeper levels north of the Húsavík fault than south of it. If it propagates horizontally from the Krafla central volcano, this may cause only the lower part of the dike to continue its propagation northwards.

Fracture densities with respect to the ages of lava flows

Fracture densities depend on the age of the surface lava flow which the fractures are located in. Older Holocene lava flows within the KFS have higher fracture densities than younger lava flows (Fig. 4). This indicates that the fissure swarms are formed during several rifting episodes over a long time period. This also suggests that the same parts of fissure swarms are deformed numerous times, as repeated deformation in the same area is the most likely process to explain why the oldest lava flows have the highest fracture density. In general, fracture densities of similarly aged lava flows decrease with distance from the central volcano (Fig. 4). This is consistent with studies of extinct and eroded volcanic systems in Eastern Iceland. There, numbers of dikes at similar elevation are generally higher closer to the central volcanoes than farther away, while the fraction and thickness of dikes increases with depth in the lava pile (e.g. Walker 1958, 1960; Helgason and Zentilli 1985; Paquet et al. 2007). It has been suggested that such dike swarms are the subsurface representation of surface fissure swarms, such as the KFS (Böðvarsson and Walker 1964). If propagation of dikes at shallow depths causes intensive surface

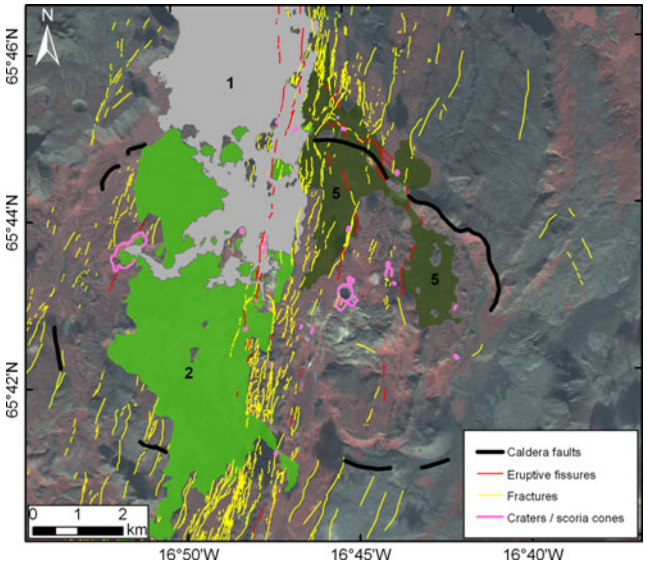

Fig. 13 Eruptive fissures and fractures in the Krafla caldera. *Numbers* denote lava flows (Table 1). Satellite image from SpotImage©

fracturing, the lower fracture density farther away from the Krafla central volcano can be taken to indicate that fewer shallow dikes have been emplaced there than closer to the central volcano, at least during the Holocene.

Historical rifting episodes in the KFS

The two historically documented rifting episodes within the KFS, the Krafla rifting episode (1975–1984) and the Mývatn rifting episode (1724–1729), activated different parts of the KFS. The Krafla rifting episode activated mostly the northern KFS (Fig. 2), while the Mývatn rifting episode activated mostly the southern KFS (Sæmundsson 1991; Einarsson 1991a; Buck et al. 2006). However, together they activated most of, or even the entire KFS.

During the Krafla rifting episode, the fissures that erupted within the central volcano were parallel to the N to NNE orientation of the KFS (Fig. 5). Assuming that the orientation of fractures and eruptive fissures represent the stress field in the area during their formation (Nakamura 1977), this suggests that the regional stress field of the plate boundary was the governing stress field in the Krafla central volcano during the fissure eruptions. This pattern also applies to prehistorical rifting episodes, as fractures and eruptive fissures within the Krafla central volcano are generally parallel to the fissure swarm, although fracture orientations there are more irregular than within the fissure swarm (Fig. 7). The local stress field of the Krafla central volcano was therefore weak or not existing at all during the Krafla rifting episode. This is, however, not always the case within the Northern Volcanic Zone. As an example, the fissure that erupted in the Askja central volcano in 1961 was situated at a caldera boundary, and was not parallel with the fissure swarm (Þórarinsson and Sigvaldason 1962). In general, the Askja central volcano shows higher diversity in fracture orientations than the Krafla central volcano (Hjartardóttir et al. 2009), indicating that while the local stress field is the governing stress field in the Askja central volcano, the regional stress field governs in the Krafla central volcano.

Although fracture movements were reported at up to ~30 km distance south of the Krafla volcano during the Mývatn Fires (Sæmundsson 1730), the exact distance is not clear since the southernmost part of the KFS was not inhabited. However, we found evidence for recent fracture movements in Mt. Sellandafjall, about 36 km south of the Krafla volcano (Fig. 12). This fracture is a part of a narrow area of sharp fractures within the loose glacially deposited material. Although we cannot exclude subtle fracture movements during other periods, we suggest that this narrow zone was activated during the Mývatn fires since it is the last time considerable fracture movements are known to have occurred in this area.

Conclusions

1. Fractures and eruptive fissures in the KFS usually strike N to NNE. Similar pattern emerges in the Krafla central volcano, although fracture orientations vary slightly more there than elsewhere in the Krafla volcanic system.
2. The Húsavík transform faulted zone appears to influence the KFS. At their intersection, the central graben of the KFS widens suddenly, and the maximum fracture density in the KFS is accordingly found in this area. In addition, earthquakes during one of the Krafla rifting events temporarily migrated away from the KFS and towards the Húsavík faults, suggesting a subsurface continuation of the transform faulted zone.
3. Eruptive fissures within the KFS are most common close to the Krafla central volcano and get gradually fewer with distance from the volcano. This pattern was also seen during the two historically accounted Krafla rifting episodes. A model by Buck et al. (2006) explains this pattern. According to the model, eruptions during a rifting episode generally occur closer to the central volcano, when earlier dikes in the episode have relieved accumulated extensional stresses in the fissure swarm.
4. Eruptive fissures can be found farther from the Krafla central volcano in the southern KFS than in the northern KFS. We suggest two explanations for this. Firstly, the Húsavik transform fault takes up a part of the extension of the northern KFS, which may cause less eruptive activity there. Secondly, there may be an additional

volcanic system (Heiðarsporður) south of the Krafla central volcano, as previously suggested by Sæmundsson (1974), providing an additional magma source in the southern KFS.

5. Indications of recent fracture movements are found in the scree slope of Mt. Sellandafjall in the southernmost part of the KFS. We suggest these occurred during the Mývatn fires (1724–1729).
6. Fracture densities in the KFS increase with age of the lava flows. This suggests repeated rifting episodes in the KFS since ~10,000 years BP, causing progressively higher fracture density with time.
7. Fracture densities of similarly aged lava flows in the KFS are generally higher closer to the Krafla central volcano than farther away in the fissure swarm. As fissure swarms are thought to be activated during dike intrusions, this suggests that dike intrusions occur more often in the parts of the fissure swarm that are closer to the central volcano.
8. Although some variations of fracture orientations are found within the Krafla central volcano, most fractures and eruptive fissures within the central volcano are parallel to the fissure swarm, including the fissures that erupted within the Krafla caldera during the Krafla rifting episode. This suggests that the regional stress field related to the divergent plate boundary governs in the Krafla central volcano, while the local stress field of the volcano is generally weak.

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