Fissure swarms of the Northern Volcanic Rift Zone, Iceland

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Faculty of Earth Sciences
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Abstract

The Northern Volcanic Rift Zone, Iceland, is a ~200 km long segment of the Mid-Atlantic plate boundary, where the North American and the Eurasian plates are diverging. The rift zone consists of about 5-6 volcanic systems with central volcanoes and fissure swarms, in addition to the Tungnafellsjökull Volcanic System at the border of the rift zone. The volcanic systems are the locus of eruptive activity in the Northern Volcanic Rift Zone. The central volcanoes consist of elevated massifs, high temperature geothermal areas, calderas and silicic formations. Fissure swarms with eruptive fissures and high density of fractures extend in opposite directions from the central volcanoes. In the Northern Volcanic Rift Zone, the fissure swarms are between 0.5 and 15 km wide and between 30 and ~125 km long. In this study, fractures and eruptive fissures within the fissure swarms of the Northern Volcanic Rift Zone were mapped in detail from aerial photographs. The results of the study indicate that eruptions are less common at the distal parts of the fissure swarms than closer to the central volcanoes. The proximal parts of the fissure swarms also generally show higher fracture density, even when the effect of the age of the lava flows has been taken into account. Older lava flows in the Krafla and Askja Fissure Swarms have usually higher fracture densities, suggesting repeated dike intrusions into the same parts of the fissure swarms during Postglacial times. Fractures in the fissure swarms of the Northern Volcanic Rift Zone are characteristically oriented towards north or NNE, i.e. more or less perpendicular to the spreading direction. However, deviations from this pattern occur in certain areas. These areas include the caldera volcanoes in the Northern Volcanic Rift Zone, Krafla and Askja, where some fractures and eruptive fissures are concentric to, or radiate from the calderas. Second example involves east-west oriented fractures and eruptive fissures near the Vatnajökull glacier, and third example eroded WNW-oriented fractures that can be found intermittently, cutting across the Northern Volcanic Rift Zone, from the north end of the Kverkfjöll Fissure Swarm to the south end of the Krafla Fissure Swarm. Other examples involve the previously known WNW oriented transform zones north of Iceland that connect with the Northern Volcanic Rift Zone. The transform zones influence the fissure swarms, although surface fractures that belong to them are not visible, except in the Þeistareykir Fissure Swarm. The number of fractures peaks and a graben widens to the north at the intersection of the Húsavík Transform Zone and the Krafla Fissure Swarm, indicating a buried continuation of the transform zone beneath the fissure swarm. Several fractures at the intersection of the Grímsey Oblique Rift and the Fremrinámar Fissure Swarm are WNW-oriented, as opposed to the general N to NNE oriented fissure swarms, suggesting an onshore continuation of the transform zone.

Ágrip (abstract in Icelandic)

Norðurgosbeltið er hluti af flekaskilum Atlantshafshryggjarins, þar sem Evrasíuflekann og Norður-Ameríkuflekann rekur í sundur. Gosbeltið samanstendur af 5-6 eldstöðvakerfum, sem hvert inniheldur megineldstöð og sprungusveima. Auk þeirra liggur eldstöðvakerfi Tungnafellsjökuls í jaðri gosbeltisins. Eldvirkni í Norðurgosbeltinu á sér stað innan eldstöðvakerfanna. Þar sem megineldstöðvar finnast liggur landslag yfirleitt hátt, ásamt því að þar finnast háhitasvæði, öskjur og/eða súrar myndanir. Innan sprungusveima má finna gossprungur, og þéttleiki sprungna er þar mikill. Sprungusveimarnir liggja í gagnstæða átt út frá megineldstöðvunum. Innan Norðurgosbeltisins eru sprungusveimarnir á milli 0,5 og 15 km breiðir, og milli 30 og ~125 km langir. Í þessari rannsókn voru sprungur og gossprungur innan Norðurgosbeltisins kortlagðar með mikilli nákvæmni eftir loftmyndum. Niðurstöður rannsóknarinnar gefa til kynna að eldgos innan sprungusveima Norðurgosbeltisins séu algengari nær megineldstöðvunum heldur en fjær. Þéttleiki sprungna innan sprungusveima er yfirleitt mestur næst megineldstöðvunum, jafnvel þegar tekið hefur verið tillit til aldurs yfirborðshraunlaganna sem sprungurnar liggja í. Þéttleiki sprungna í eldri hraunum innan sprungusveima Kröflu og Öskju er yfirleitt meiri en í yngri hraunum, sem gefur til kynna að gangainnskot sem átt hafa sér stað eftir að ísaldarjökla leysti hafi ítrekað farið í sömu hluta sprungusveimanna. Sprungur innan sprungusveima Norðurgosbeltisins stefna jafnan til norðurs eða til norð-norðausturs, meira og minna hornrétt á flekarekið. Þó má finna undantekningar á vissum svæðum. Sumar sprungur og gossprungur nærri öskjum Norðurgosbeltisins (í Öskju og Kröflu) hringa sig um öskjurnar eða eru geislalægar út frá þeim í stað þess að fylgja hefðbundinni sprungustefnu Norðurgosbeltisins. Þá má finna sprungur og gossprungur nærri Vatnajökli sem stefna í austur-vestur, og einnig má sjá ummerki um rofnar sprungur með vest-norðvestur stefnu á belti sem teygir sig frá nyrsta hluta sprungusveims Kverkfjalla til syðsta hluta Kröflusprungusveimsins. Auk þessara dæma má finna sprungur innan Norðurgosbeltisins með vest-norðvestlæga stefnu þar sem Norðurgosbeltið og þverbrotabeltin fyrir norðan land mætast, en slík þverbrotabelti geta einnig haft önnur áhrif á sprungusveimana. Til að mynda er hámarksþéttleiki sprungna í sprungusveim Kröflu á móts við Húsavíkurmisgengið, og þar víkkar einnig sigdalurinn til norðurs í sprungusveimnum. Þetta bendir til að Húsavíkurmisgengið nái að sprungusveim Kröflu, þótt yfirborðssprungur misgengisins sjáist ekki. Sömuleiðis má finna ummerki um Grímseyjarbrotabeltið á landi, þar sem sprungur með VNV stefnu finnast í framhaldi þess, innan þess hluta sprungusveims Fremrináma sem liggur í Öxarfirði. Stefna þessi stangast á við hina hefðbundnu norður til norð-norðaustur sprungustefnu í sprungusveimunum.

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Abbreviations

ALTM	Airborne Laser Terrain Mapper
ARSF	Airborne Research and Survey Facilities
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CIVZ	Central Iceland Volcanic Zone
DEM	Digital Elevation Model
DZ	Dalvík Zone
EFB	Eastern Fjords Block
EVZ	Eastern Volcanic Zone
FIRE	Faroe-Iceland Ridge Experiment
GIS	Geographic Information Systems
GOR	Grímsey Oblique Rift
HF	Húsavík-Flatey Fault
InSAR	Interferometric Synthetic Aperture Radar
LiDAR	Light Detection and Ranging
KFS	Krafla Fissure Swarm
MER	Main Ethiopian Rift
NVZ	Northern Volcanic Rift Zone
RMS	Root Mean Square
RPOR	Reykjanes Peninsula Oblique Rift
SISZ	South Iceland Seismic Zone
SPOT	Systéme Pour l'Observation de la Terre
TFZ	Tjörnes Fracture Zone
WVZ	Western Volcanic Zone

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Last but not least, I'd like to thank my friends and family for their support during my PhD studies and my family for introducing me to the fascinating world of volcanoes and nature in Iceland. Their support is greatly valued.

1 Introduction

This thesis constitutes the results of studies of fissure swarms within the Northern Volcanic Rift Zone, Iceland. This was done by mapping in detail fractures and eruptive fissures in the area by using aerial photographs, satellite images and ground-checking. The main focus was on the fissure swarms of the Kverkfjöll, Bárðarbunga, Fremrinámar and Krafla volcanic systems, as well as on the northern part of the Askja Volcanic System, and on the southern part of the Þeistareykir Volcanic System. Data on the southern part of the Askja Fissure Swarm, acquired during the M.Sc. studies of the candidate (Ásta Rut Hjartardóttir), and data from the mapping of the northern part of the Þeistareykir Fissure Swarm by Sigríður Magnúsdóttir and Bryndís Brandsdóttir, and the Tungnafellsjökull Fissure Swarm, by Þórhildur Björnsdóttir and Páll Einarsson, were also included (Magnúsdóttir and Brandsdóttir 2011; Björnsdóttir 2012). In total, these databases consist of 46,611 eruptive fissures, fractures and fracture segments. The data therefore consist of detailed information of fractures and eruptive fissures of all of the fissure swarms that form the Northern Volcanic Rift Zone. While working on the project, an unusual fault was rediscovered at the border of the Northern Volcanic Rift Zone, the "Kerlingar Fault". To describe the fault, an additional paper was written.

The thesis consists of four papers and introductory chapters. Three of the papers are already published in peer-reviewed journals; two in the Bulletin of Volcanology, and one in Jökull, while the fourth paper will be submitted to a Geological Society of London Special Publication issue on "Magmatic Rifting and Active Volcanism". The published papers are reprinted with the kind permission of Springer Science and Business Media, and the Jökull publication:

Paper 1: *Hjartardóttir, Á.R.,* Einarsson, P., and Brandsdóttir, B. (2010). The Kerlingar fault, Northeast Iceland: A Holocene normal fault east of the divergent plate boundary. Jökull 60, 103-116.

Paper 2: *Hjartardóttir, Á.R.,* and Einarsson, P. (2012). The Kverkfjöll fissure swarm and the eastern boundary of the Northern Volcanic Rift Zone, Iceland. Bulletin of Volcanology 74(1), 143-162. DOI: 10.1007/s00445-011-0496-6

Paper 3: *Hjartardóttir, Á.R.,* Einarsson, P., Bramham, E., and Wright, T.J. (2012). The Krafla fissure swarm, Iceland, and its formation by rifting events. Bulletin of Volcanology 74(9), 2139-2153. DOI: 10.1007/s00445-012-0659-0

Paper 4: *Hjartardóttir, Á.R.,* Einarsson, P., Magnúsdóttir, S., Björnsdóttir, Þ. and Brandsdóttir, B. Fracture systems of the Northern Volcanic Rift Zone, Iceland – An onshore part of the Mid-Atlantic plate boundary. Will be submitted to the Geological Society of London Special Publication issue on "Magmatic Rifting and Active Volcanism".

1.1 Background

Iceland is situated at the Mid-Atlantic plate boundary, at a location where the Eurasian and the North American plates spread apart at a rate of ~2 cm/yr (Figure 1) (DeMets et al. 1994; Sella et al. 2002; Árnadóttir et al. 2009). Most of the Mid-Atlantic plate boundary is situated beneath sea-level, and is characterized by a ridge with a wide central rift valley (Heezen 1960). However, a marked change occurs close to Iceland. The central valley becomes much less prominent, the ridge becomes smoother and shallower, seismicity along the plate boundary diminishes, and linear magnetic stripes become different (Vogt 1971; Francis 1973; Fleischer 1974; Vogt 1974; Einarsson 1986). This change is thought to occur due to increased magma supply from the Iceland hotspot, which has a centre below the west part of Vatnajökull (Vogt 1971; Wolfe et al. 1997; Gaherty 2001). Rifted depressions, as seen on the Mid-Atlantic ridge, characterize slow spreading (<3.5 cm/yr) divergent plate boundaries, while elevated volcanic edifices characterize fast spreading (>5 cm/yr) divergent plate boundaries (Mutter and Karson 1992). The structure of the divergent plate boundary in Iceland is in this sense more similar to fast spreading, than slow spreading divergent plate boundaries.

Volcanic systems, consisting of fissure swarms and central volcanoes, are the main structural units of the divergent plate boundary in Iceland. The fissure swarms are areas with high density of both faults and open fractures. They remain inactive for tens to thousands of years, until a rifting episode occurs, when a dike intrudes the fissure swarm. Then, the fissure swarm deforms significantly and fracturing as well as intensive earthquake activity occurs (e.g. Björnsson et al. 1977; Sigmundsson 2006; Ebinger et al. 2010; Wright et al. 2012). Fractures that form during such episodes are mainly normal faults, although reverse faults can also be found locally (Khodayar and Einarsson 2004; Guðmundsson et al. 2008).

Such events can pose significant threat to both constructions, such as roads, houses, water pipes and electric lines which cross the fissure swarm, as well as to human lives due to eruptions and climate change. These eruptions may be small-scale, such as those that occurred during the Krafla rifting episode in 1975-1984 and in Sveinagjá in 1875 (Sigurðsson and Sparks 1978b; Sæmundsson 1991), or large-scale, such as the fissure eruptions of Eldgjá (934-940 A.D.) and Laki (1783-1784 A.D.) (Larsen 2000; Thordarson et al. 2003; Thordarson and Larsen 2007). Increased understanding of the structure and behaviour of fissure swarms is thus important for a better preparedness for rifting events, which inevitably will occur in the future.

Recent rifting episodes, both in Iceland and in East Africa, have been monitored by seismic and geodetic techniques (i.e. Einarsson and Brandsdóttir 1980; Tryggvason 1984; Vigny et al. 2007; Calais et al. 2008; Hamling et al. 2009; Ebinger et al. 2010; Wright et al. 2012). They have shown that rifting events have certain characteristics. During rifting events, earthquakes often migrate horizontally along the fissure swarms, whilst a graben subsides above the propagating dike (Wright et al. 2012). When repeated rifting events have occurred, such as in Krafla and Dabbahu (Ethiopia), dikes generally become shorter with each rifting event, and during the end of the rifting episode, eruptions become common close to the centre of the system (Einarsson 1991b; Ebinger et al. 2010). The monitored rifting episodes have given invaluable information about the formation and activation of fissure swarms. Nevertheless, rifting episodes occur seldom on-land, and therefore they have only been instrumentally observed a few times.

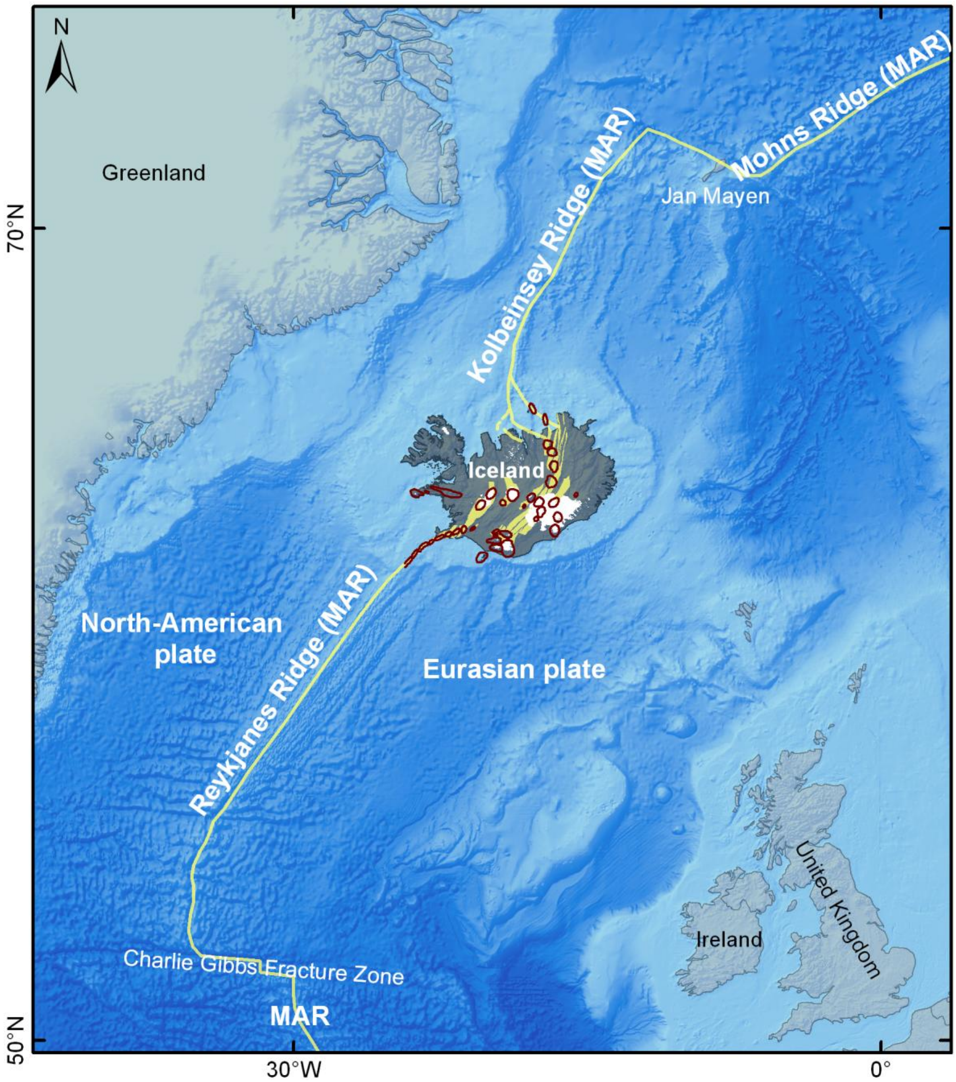

Figure 1 The Mid-Atlantic plate boundary. Red circles denote central volcanoes in Iceland, yellow areas fissure swarms in Iceland, and yellow lines the Mid-Atlantic Ridge (MAR) (Einarsson and Sæmundsson 1987; Einarsson 2008). Bathymetric data from the British Oceanographic Data Centre (BODC 2009).

Many issues regarding the formation and activation of fissure swarms also remain unresolved. It is unclear when and under what conditions rifting episodes occur, and why some fissure swarms have a thousand years period of alternating lower and higher activity, indicating that strain is neither equally distributed with regards to time or location within rift zones (Sigmundsson 2006). It is also unclear how rifting episodes evolve with time, and it is still debated whether the magma that feeds the dikes during these episodes propagates horizontally away from a magma chamber or vertically from the mantle (e.g. Einarsson and Brandsdóttir 1980; Guðmundsson 1995; Keir et al. 2009; Wright et al. 2012).

Several studies have been done in Iceland where fractures within fissure swarms are mapped (e.g. Guðmundsson 1987; Clifton and Schlische 2003; Clifton and Kattenhorn 2006; Hjartardóttir et al. 2009; Magnúsdóttir and Brandsdóttir 2011; Björnsdóttir and Einarsson, submitted 2012). Nevertheless, many fissure swarms and rift zones, including the Northern Volcanic Rift Zone, have not been mapped homogeneously in detail before. By detailed mapping of fissure swarms and rift zones, increased knowledge is gained on their exact locations, eruption locations, orientation of stress fields at the times of unrest, on their interaction with transform zones etc.

1.2 Research aims

The main purposes of this project were as follows:

1. To map in detail fractures and eruptive fissures within fissure swarms in the Northern Volcanic Zone (NVZ) in Iceland. The aim was to make a homogeneous digital database of fractures within the NVZ using the ArcInfo software.

2. To find out how fissure swarms interact with central volcanoes in the NVZ.

3. To find the relationship between earthquakes and fissure swarms in the NVZ.

4. To compare deformation detected within the NVZ and the fissure swarms.

5. To see how the NVZ and its associated fissure swarms connect with the Tjörnes Fracture Zone.

6. To confirm to what extent the results from the M.Sc. thesis of Ásta Rut Hjartardóttir (2008) on the Askja central volcano apply to other volcanic systems.

Studies like this can be hard to undertake, except where divergent plate boundaries are found on land, i.e. only in Iceland and in East Africa. The Northern Volcanic Rift Zone is an ideal area for this study, as it is easily accessible and sparsely vegetated and as it is the only rift zone in North Iceland, which minimizes complications. The Northern Volcanic Rift Zone resembles rift zones at some other divergent plate boundaries, such as the Main Ethiopian Rift and in the Afar area (e.g. Ebinger et al. 2010; Kurz et al. 2007). Results from this study may therefore contribute to better understanding of rift zones within those areas too.

1.3 Study area

The NVZ extends northwards from the Vatnajökull glacier to the northern coast of Iceland (Figure 2). In the south part, the plate boundary continues below the glacier and continues southwards as the Eastern Volcanic Zone. In the north part, the NVZ is linked with the offshore Kolbeinsey Ridge by the Tjörnes Fracture Zone, which consists of the Dalvík, Húsavík and Grímsey strike-slip faulted areas (Sæmundsson 1974; Einarsson 1976; Sæmundsson 1978; Einarsson and Sæmundsson 1987).

The NVZ started to form more than 12 million years ago (Jancin et al. 1985). It consists of several central volcanoes and fissure swarms that extend in opposite directions from them (Sæmundsson 1978). An arcuate shaped row of tindars (also termed hyaloclastite ridges) delineate the eastern boundary of the NVZ, while such features are not found at the western boundary.

Deformation along the NVZ occurs predominantly during rifting episodes (Björnsson et al. 1977; Sigurðsson and Sparks 1978a; Einarsson 1991a). At other times, deformation there mainly takes part within the central volcanoes, although a slow subsidence may be measured in the fissure swarms, especially those where rifting episodes have recently taken place (Pedersen et al. 2009). Earthquake activity in the NVZ reflects this pattern. During non-rifting periods, earthquakes usually take place within central volcanoes or at distinct places in the rift zone, often not within the fissure swarms (Einarsson 1991a). During rifting episodes, this pattern changes dramatically, as intensive earthquake activity is felt and measured both within the central volcanoes as well as in distinct parts of the fissure swarm associated with the volcano (e.g. Brandsdóttir and Einarsson 1979; Einarsson and Brandsdóttir 1980; Buck et al. 2006). In accordance with this, both visual observations and direct measurements indicate considerable subsidence along parts of the active fissure swarm (Sigurðsson 1980; Tryggvason 1994).

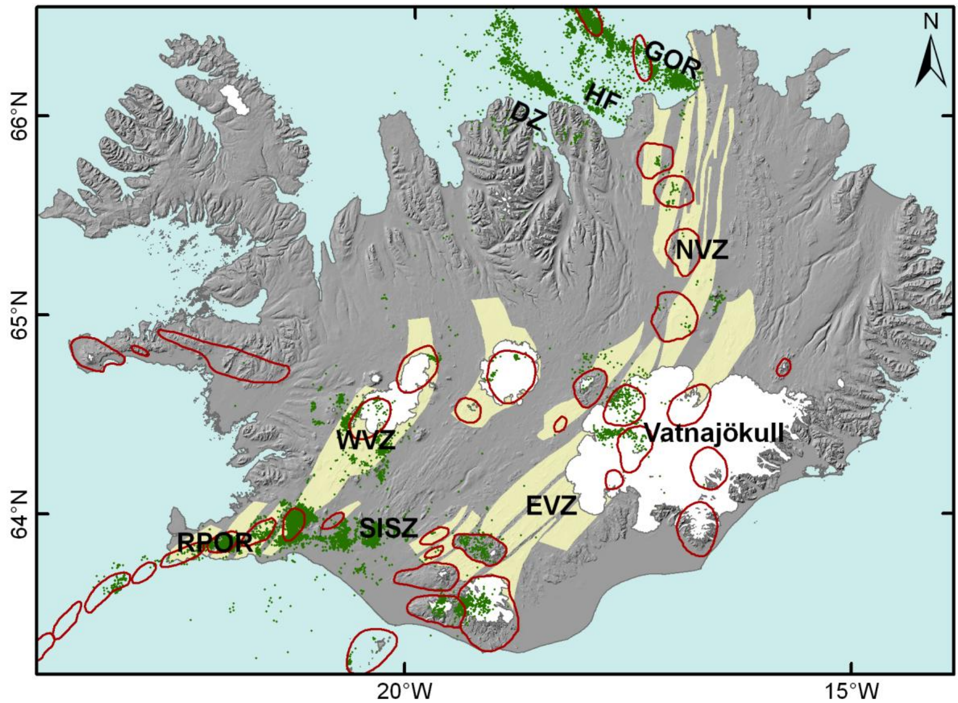

Figure 2 Volcanic systems (red), earthquakes (green) and fissure swarms (yellow) in Iceland (Einarsson and Sæmundsson 1987). RPOR=Reykjanes Peninsula Oblique Rift, SISZ= South Iceland Seismic Zone, WVZ= Western Volcanic Zone, EVZ= Eastern Volcanic Zone, NVZ= Northern Volcanic Rift Zone, DZ=Dalvík Zone, HF= Húsavík-Flatey Fault, GOR= Grímsey Oblique Rift. Earthquake data (1994-2000) from the Icelandic Meteorological Office. Cartographic data are from the National Land Survey of Iceland.

2 Methods

Fractures, eruptive fissures and scoria cones/craters were mapped from aerial photographs, covering the entire area. Satellite images were also used for a more comprehensive view, and field trips were made to the area to resolve uncertainties.

2.1 Aerial photographs

The aerial photographs were acquired from two different sources, from the National Land Survey of Iceland (Landmælingar Íslands) and from Aerial Photographs inc. (Loftmyndir ehf.).

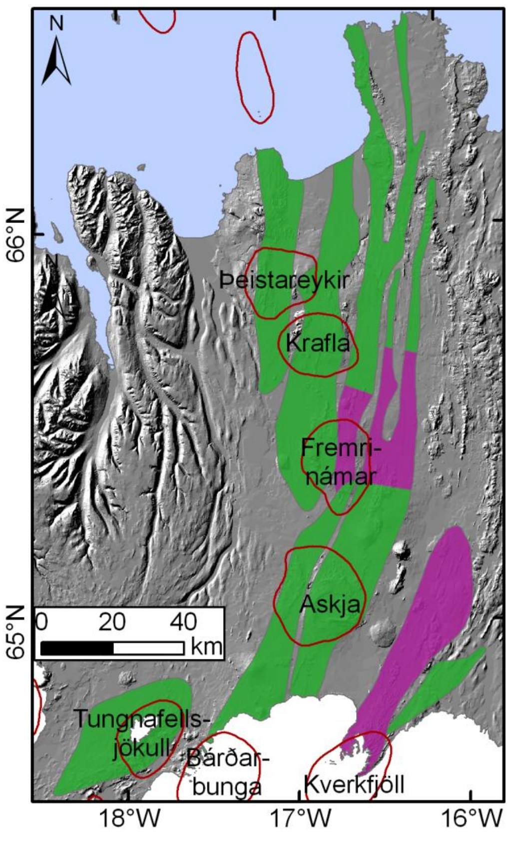

Figure 3 Outlines of the mapped fissure swarms within the Northern Volcanic Rift Zone. Areas mapped from aerial photographs from Loftmyndir ehf. are marked in green colour, purple areas were mapped from aerial photographs from the National Land Survey of Iceland. Central volcanoes are shown as red circles (Einarsson and Sæmundsson 1987), the cartographic data are from the National Land Survey of Iceland

At the beginning of the PhD project, and during the M.Sc. project, which covered the Askja Fissure Swarm (Hjartardóttir 2008; Hjartardóttir et al. 2009), contact aerial photographs from the National Land Survey of Iceland were used (Figure 3). These images were taken at an altitude of ~6000 m. Fractures, eruptive fissures and scoria cones/craters were drawn on top of these images, which were then scanned to digitize them. After that, the images were rectified, and the features mapped in the ArcMap software (Figure 4). By doing this, a detailed database with the features was made, which can be used for further investigations, as the features have co-ordinates which can be referred to. The Kverkfjöll Fissure Swarm and parts of the Askja and Fremrinámar fissure swarms were mapped from these contact aerial photographs (Figure 3).

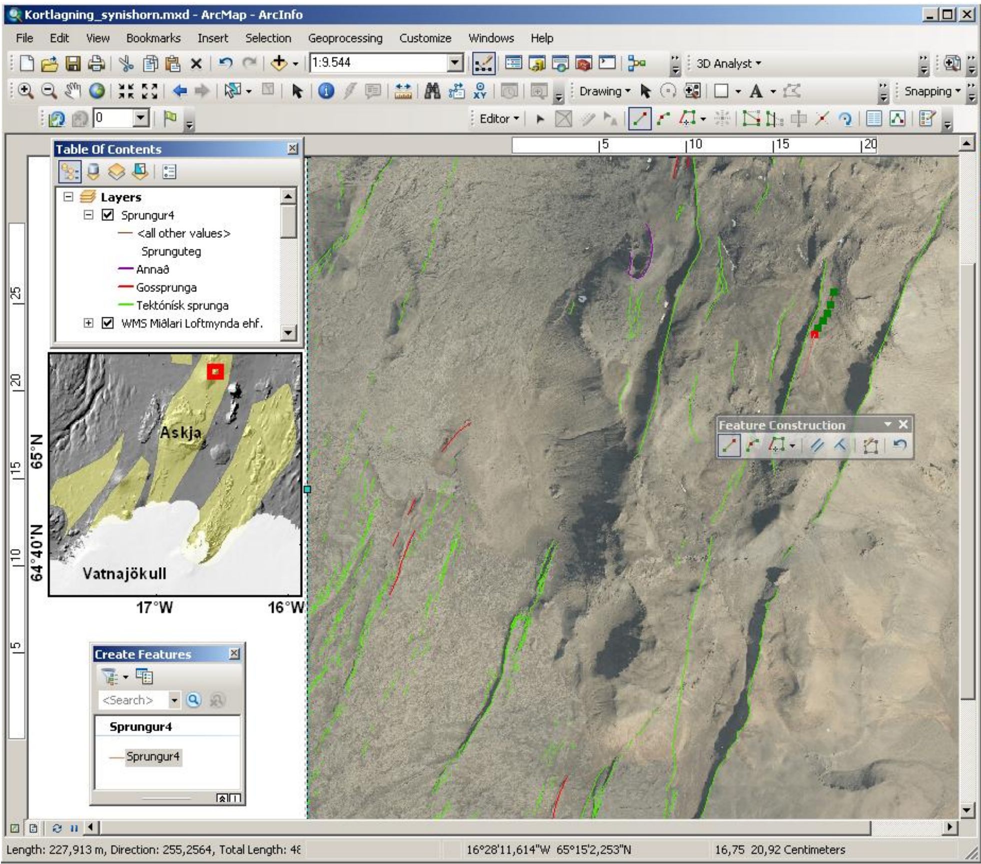

Figure 4 Mapping of fractures with the ArcMap® software. Green lines denote fractures, red lines eruptive fissures. Green and red boxes indicate where mapping is in process. The aerial photograph of Mt. Eggert in the Askja Fissure Swarm is from Loftmyndir ehf. Thick, red box in smaller image to the left denotes the location of Mt. Eggert in the aerial photograph.

During the PhD project, University of Iceland got an access to digital aerial photographs from Aerial Photographs inc. (Loftmyndir ehf.). These photographs were already rectified, which saved considerable work. Therefore, the rest of the fissure swarms were mapped from these photographs. Parts of the Askja Fissure Swarm were also mapped again with the digital aerial photographs. The accuracy of fracture locations is considerably higher when using these photographs than by using the contact images (less than 10 m vs. less than 100 m respectively). However, the contact images allow stereoscopic view, whereas the others do not. The resolution of the aerial photographs of Loftmyndir ehf. is generally 0.5 m/pixel. However, their quality varies as their contrast and light is different.

2.2 Satellite images

Satellite images from the US/Japan ASTER project, and from SPOTimage (SPOT5 images) were used to get a better overview of structures. However, these images were only used for large scale overview. Therefore, few features were mapped based on these images. Nevertheless, these images give important information on large structures, especially ASTER images taken when thin snow covers the ground and the sun is at low angle. Then, features can be quite easily seen that can otherwise be hard to spot.

2.3 Field trips

Several field trips have been undertaken since the beginning of the PhD project in 2009. During those field trips, various areas were investigated both to resolve whether lineaments of unknown origin are fractures or not, and to get a comprehensive view of the fractures and eruptive fissures in the area.

2.4 Processing of the fracture data

To study how fracture pattern changes with distance from the central volcanoes within the NVZ, each of the fissure swarms was divided into 2 km wide strips, oriented parallel with the plate spreading direction in the area (106°, calculated from DeMets et al. (1994)) (Figure 5). By doing this, changes that occur along the fissure swarm were studied.

Rose diagrams, made from the RockWorks software and colouring of fractures according to their orientations in the ArcMap software, were used to study fracture orientations within the NVZ.

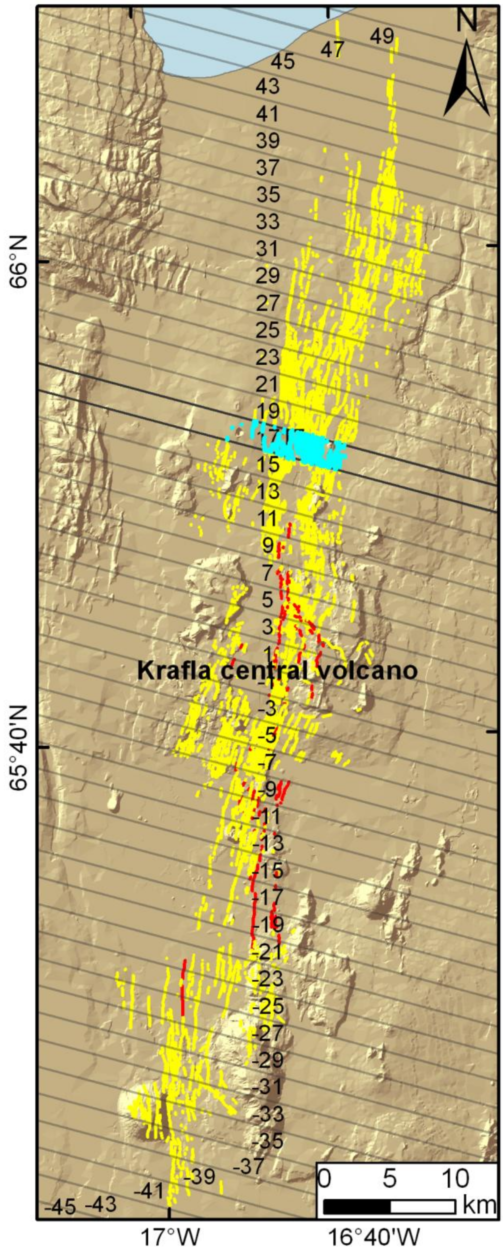

Figure 5 Subsectors dividing the Krafla Fissure Swarm according to distance from the central volcano, numbers denote the distances (in kilometers) to the central volcano, negative numbers towards the south, positive numbers towards the north. Division lines are parallel to plate spreading vector. Yellow lines are fractures, red lines eruptive fissures. Fracture structures within each subsector were investigated to look at how fracture pattern changes with distance from the central volcano, blue colored fractures denote one such selection. Cartographic data from the National Land Survey of Iceland.

3 Summary of papers

3.1 Paper 1

Hjartardóttir, Á.R., Einarsson, P., Brandsdóttir, B. (2010). The Kerlingar fault, Northeast Iceland: A Holocene normal fault east of the divergent plate boundary. Jökull 60, 103-116.

This study focused on the Kerlingar Fault at the eastern boundary of the NVZ (Figure 6). The purpose was to study its extent, potential seismic hazards related to it and to come up with ideas about its origin.

The Kerlingar Fault is all together about 30 km long (Figure 7). It has an eastward-dipping throw of 2-9 m and is situated in glacial deposits. However, it forms a sharp offset in these deposits, indicating Postglacial activity. The fault is unique amongst the Postglacial faults of the NVZ in the sense that it does not appear to be a part of any fissure swarm or transfer fault zone. It is situated at the eastern boundary of the NVZ and oriented obliquely to the otherwise parallel fissure swarms at the same latitude. Other fractures with similar orientation can also be found close to the Kerlingar Fault, although there are no evidences that they have been active during Postglacial times (Figure 7). As the fissure swarms are nearly perpendicular to the plate spreading vector as calculated from DeMets et al. (1994), the Kerlingar Fault is therefore oriented obliquely to it. Nevertheless, the Kerlingar Fault is parallel with the line of central volcanoes in the NVZ and with the boundary between the NVZ and the crustal block east of it, the Eastern Fjords Block (Figure 6). This boundary is defined from an arcuate row of tindars. This indicates different origin of the Kerlingar Fault and the arcuate rows of tindars than of the faults situated within the fissure swarms of the NVZ.

To estimate hazards related to this fault, a seismic moment was calculated. Assuming that the entire length of the fault ruptured in one event, that the fault has a dip of 60° and that it ruptured to a depth of 7 km, it is estimated that this fault could generate an earthquake with a maximum magnitude of M_W 6.7. During the approximately 40 years of seismic measurements in Iceland, earthquake activity has nevertheless not been detected in the vicinity of the Kerlingar Fault (Einarsson 1989; Einarsson 1991a; Jakobsdóttir 2008). This indicates that the earthquake activity in the area is limited in time.

In the paper, three possible scenarios on how the fault was formed are described:

1. That the fault is a part of the Kverkfjöll Fissure Swarm and that it was formed and/or reactivated during a typical rifting event, i.e. in a similar manner as fractures within the fissure swarms. This idea has some disadvantages. The Kverkfjöll Fissure Swarm, as defined by Postglacial fractures, ends ~50 km south of the Kerlingar Fault. In addition, the fault is not ~perpendicular to the plate spreading vector as fissure swarms and faults within them usually are. Therefore, the Kerlingar Fault seems to be a boundary feature and not related to fissure swarms.

2. That the fault formed due to stress transfer in relation to the Húsavík Transform Zone. This is thought to be unlikely since there aren't any indications that the Húsavík Transform Zone extends through the NVZ to the Kerlingar Fault, and there are no signs of sudden, abrupt changes in fracture orientations near the Kerlingar Fault which could be due to a buried transform fault.

3. That the fault is formed and/or reactivated due to unloading of the crust during deglaciation, as the hotter and less viscous crust of the NVZ should react differently to unloading than the colder, more viscous and thicker crust east of the rift zone (Sigmundsson 2006). This could occur as these two unlike crustal types have different density, effective Young's modulus and viscosity. The fault may thus be a part of the arcuate row of tindars at the eastern boundary of the NVZ, the tindars being formed by subglacial eruptions through faults of similar origin as the Kerlingar Fault. This explanation could explain the location and orientation of the Kerlingar Fault, as it is then related to the boundary of the NVZ and not to the fissure swarms.

To resolve the origin of the fault, further studies and modelling is necessary. The Kerlingar Fault indicates, however, that it is likely that faults exist in the NVZ that are not associated with fissure swarms. The Kerlingar Fault is the most prominent of them, and may pose seismic risk to the area.

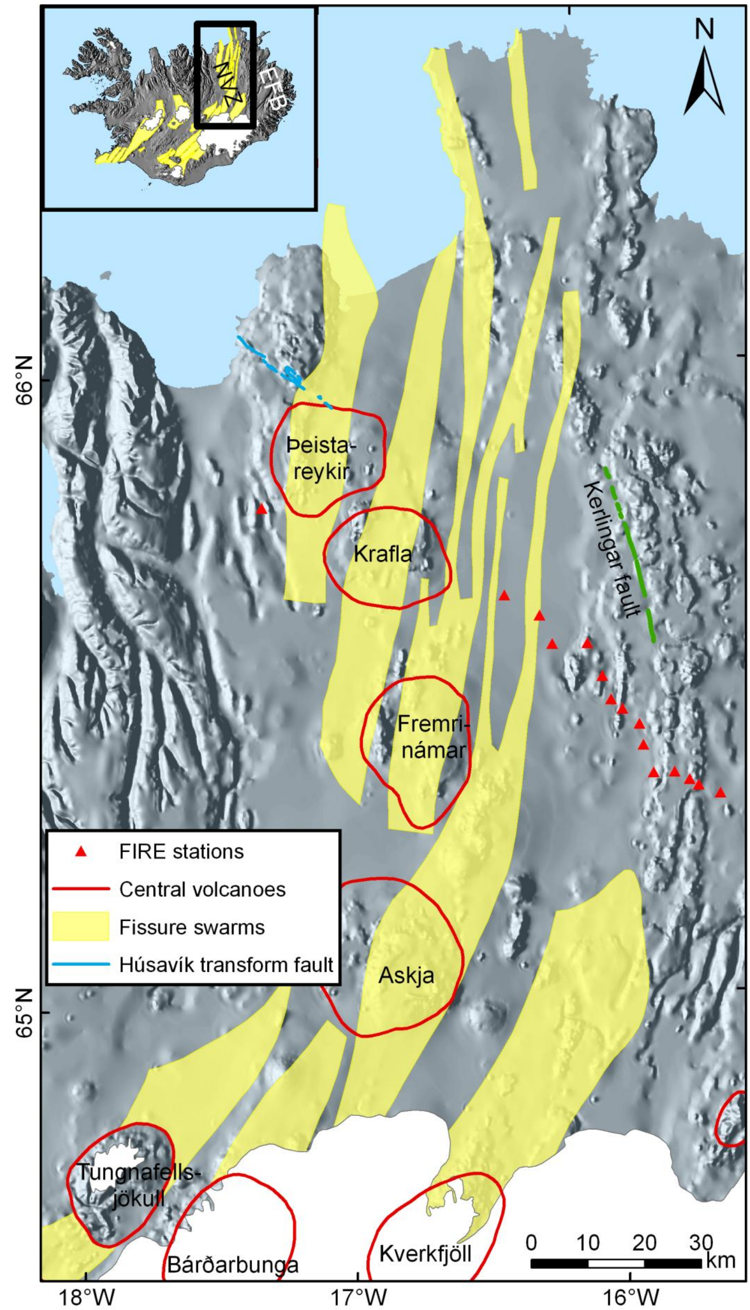

Figure 6 The NVZ, the Kerlingar Fault and the Húsavík transform fault. Image from Hjartardóttir et al. (2010). Information on fissure swarms and central volcanoes from Einarsson and Sæmundsson (1987). In the smaller image, NVZ denotes the Northern Volcanic Rift Zone, and the EFB the Eastern Fjords Block. The topographic higher area between the Kerlingar Fault and the Kverkfjöll Fissure Swarm is an arcuate row of the Fjallgarðar tindars.

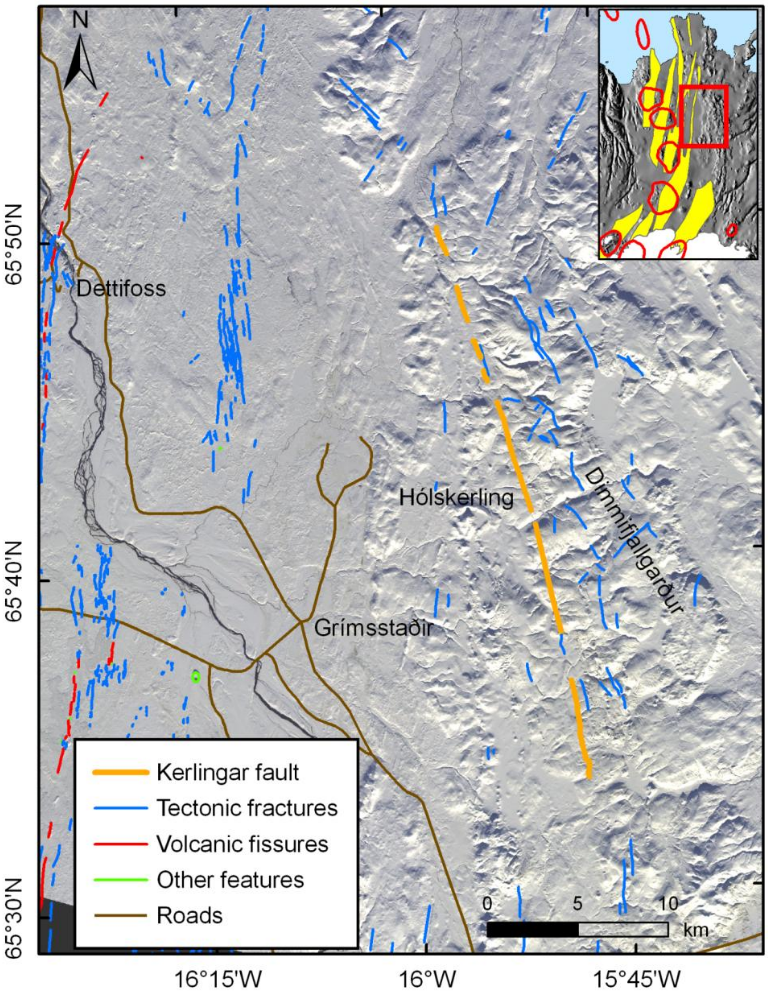

Figure 7 The Kerlingar Fault and other fractures and volcanic fissures situated near the fault. Image from Hjartardóttir et al. (2010). Yellow areas in the smaller image denote fissure swarms, red circles denote central volcanoes (Einarsson and Sæmundsson 1987), background image from the US/Japan ASTER project.

3.2 Paper 2

Hjartardóttir, Á.R. and Einarsson, P. (2012). The Kverkfjöll fissure swarm and the eastern boundary of the Northern Volcanic Rift Zone, Iceland. Bulletin of Volcanology 74(1), 143-162. DOI 10.1007/s00445-011-0496-6

The aim of this paper was to study the relationship between the Kverkfjöll Fissure Swarm and the tindars that extend north of it, find how the fissure swarm interacts with the Kverkfjöll Central Volcano and to find the relationship between the fissure swarm and earthquakes in the area.

The Kverkfjöll Fissure Swarm is about 60 km long, as defined by high density of Postglacial fractures. Eruptive fissures are nevertheless only found at distances less than ~20 km from the Kverkfjöll Central Volcano. The Fjallgarðar area north of the Kverkfjöll Fissure Swarm is characterized by an elongate row of tindars, generally considered to be the results of subglacial fissure eruptions (Kjartansson 1943). In addition to these features, the Kverkárnes subswarm is situated east of the Kverkfjöll Fissure Swarm (Figure 8). Together, the Kverkfjöll Fissure Swarm, the Kverkárnes subswarm and the Fjallgarðar tindars delineate the eastern boundary of the NVZ.

The lack of Postglacial fractures and lavas north of the Kverkfjöll Fissure Swarm, while subglacially-formed tindars are common there, indicates that there is a decrease in rifting activity towards the north along the eastern boundary of the NVZ. In the paper, this is suggested to be due to increasing distance to the long-term spreading axis of the NVZ. Activity in the northern part seems to occur mainly during periods when glaciers cover the area, as indicated by the existence of the tindars. It is suggested that these tindars are mainly formed during periods of deglaciations. Then, several different conditions may play together to create unusually favourable situations for activity along the boundary. Firstly, the decompression of the mantle causes increased magma supply and therefore raises the eruption rate. Secondly, high tensile stresses in the crust, accumulated during the magma-deprived glaciations periods may provide unusually open pathway for the increased magma supply to be erupted. Thirdly, this may occur specifically at the boundary between the NVZ and the older and thicker crust to the east of it, as the uplift rates of these different crustal types may differ, causing differential movements at their boundaries that may lead to the formation of faults there. The increased magma supply might then seek a pathway through these boundary faults, forming the tindars. Such a retreat of volcanic activity towards the Kverkfjöll Central Volcano has also been suggested by Carrivick et al. (2009).

Large parts of the study area are generally almost or completely seismically inactive, although exceptions do occur. Throughout the 40 years time span of seismic monitoring in the area, the highest activity has generally been located near the Kverkfjöll Central Volcano. In 2007-2008, intense earthquake activity took place in and below the northern part of the Kverkfjöll Fissure Swarm at Upptyppingar (Jakobsdóttir et al. 2008; White et al. 2011). This activity, which was accompanied by crustal uplift, is thought to be caused by a dike intrusion in the lower crust. The dike has a strike almost east and a dip of ~41-50°, and was most probably fed from below (Jakobsdóttir et al. 2008; Geirsson et al. 2009; White et al. 2011). Deformation took place along few fractures in the area during these events (Hooper et al. 2008).

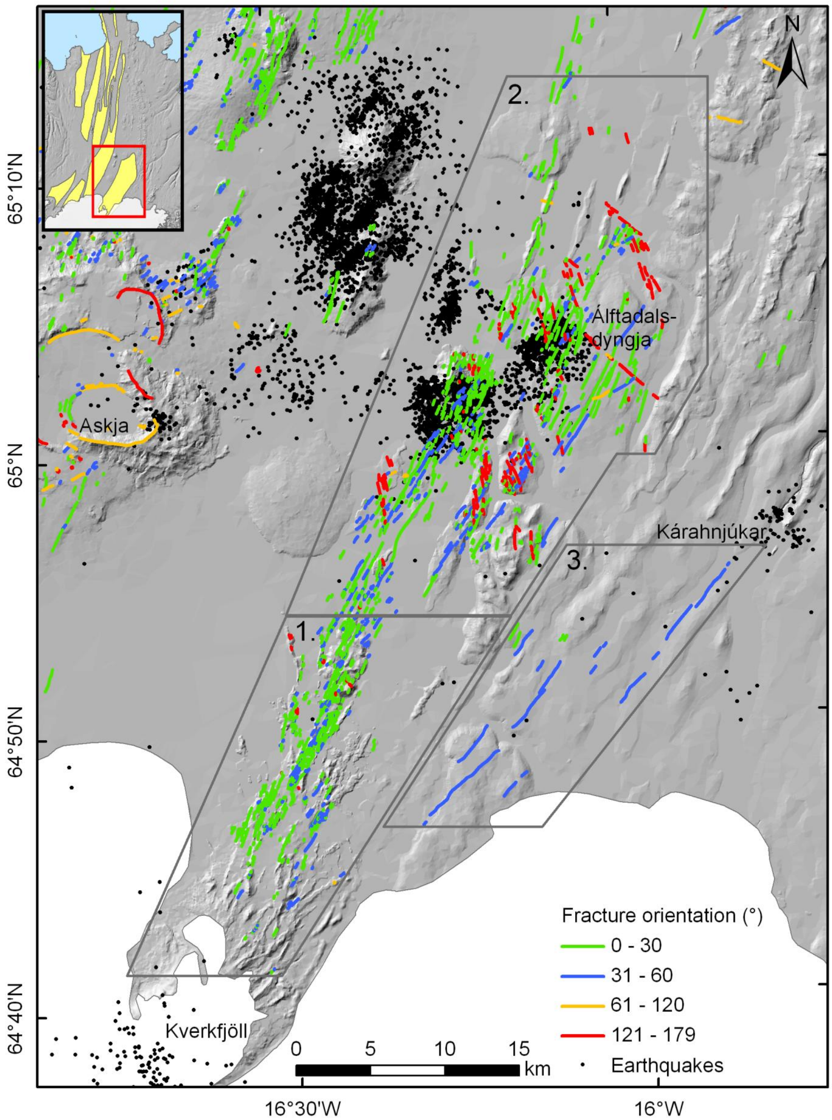

Figure 8 The orientation of fractures within the Kverkfjöll Fissure Swarm (frames 1 and 2) and the Kverkárnes subswarm (frame 3). Image from Hjartardóttir and Einarsson (2012). Earthquake data from October 1991 to December 2009 are from the Icelandic Meteorological Office. Earthquake near Kárahnjúkar are mostly due to explosions made during the construction of the Kárahnjúkar dam.

The eastern boundary of the NVZ is therefore an ideal area to study the interaction between fissure swarms and boundary faults. There is still considerable work to be done in the area. As an example, it would be valuable to have more precise dating of the tindars. Such data could provide information on the behaviour of the eastern boundary, and even give clues that would help understand the existence of the few faults situated in the area, such as the Kerlingar Fault.

3.3 Paper 3

Hjartardóttir, Á.R., Einarsson, P., Bramham, E. and Wright, T.J. (2012). The Krafla fissure swarm, Iceland and its formation by rifting events. Bulletin of Volcanology 74 (9), 2139-2153. DOI 10.1007/s00445-012-0659-0

The Krafla Fissure Swarm is to date the only fissure swarm in Iceland where rifting events have been instrumentally monitored. The monitored events, occurring between the years of 1975 and 1984, along with historical records of the 1724-1729 rifting episode there give valuable information on the formation and reactivation of fissure swarms (e.g. Björnsson et al. 1977; Einarsson 1991b). In this paper, the patterns of fractures and eruptive fissures within the Krafla Fissure Swarm are compared with known fracture patterns which occurred during these rifting episodes. The aim is also to study the relationship between the Krafla Fissure Swarm and the Krafla Caldera and to see whether the Húsavík Transform Zone influences the Krafla Fissure Swarm and in what way (Figure 9).

Together, the two last Krafla rifting episodes have activated the entire Krafla Fissure Swarm. While the 1975-1984 episode mainly activated the northern fissure swarm, historical accounts (Sæmundsson 1907) indicate that the 1724-1729 episode impacted the southern Krafla Fissure Swarm. During these periods, several rifting events occurred, characterized by intense seismic activity, deformation, fracturing and in some instances fissure eruptions.

Eruptions which took place during the last two rifting episodes within the Krafla Fissure Swarm took place at distances less than 7 km from the Krafla Caldera, while fracturing of the fissure swarm occurred at distances up to 60-70 km from the caldera. This is similar to former rifting patterns, as seen by mapping and studying the fractures and eruptive fissures in the fissure swarm. Eruptive fissures in the Krafla Fissure Swarm are most dense near the central volcano, although they can be found at up to ~30 km distances from the Krafla Central Volcano.

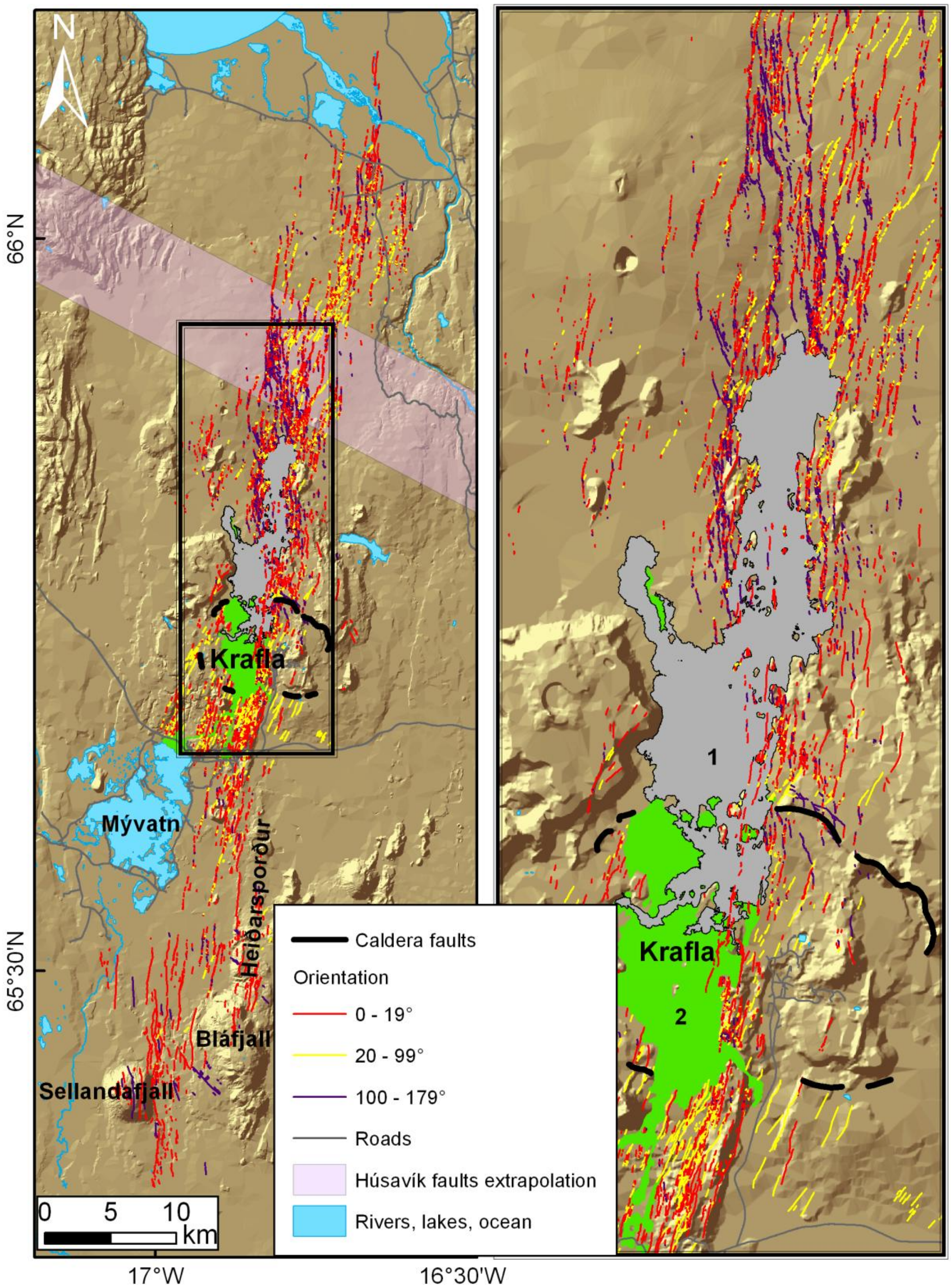

Figure 9 Orientation of fractures and eruptive fissures within the Krafla Fissure Swarm. Modified image from Hjartardóttir et al. (2012). Black box in the left-hand image outlines the extent of the right-hand image. Lava flows from last two rifting episodes in the fissure swarm (1724-1729 and 1975-1984) are also shown as green and gray areas respectively (Sæmundsson 1991). The cartographic data are from the National Land Survey of Iceland.

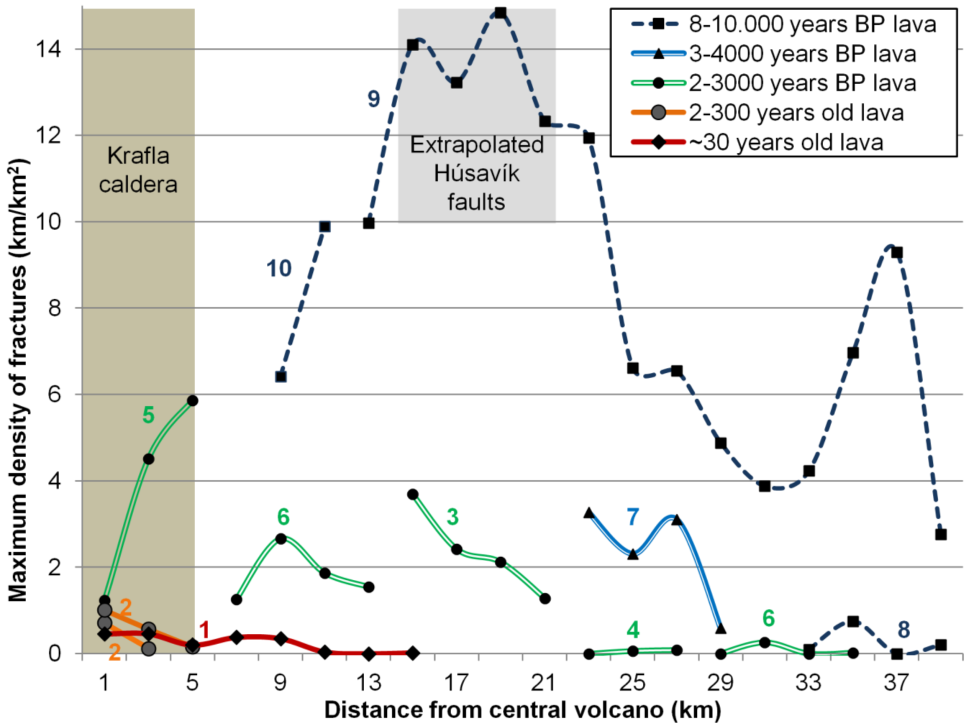

Figure 10 Fracture densities in differently aged lava flows, shown as cumulative length of fractures (km) within a square kilometer. The values on the graph show maximum value found in each two km wide subsector (see Figure 5). The image is from Hjartardóttir et al. (2012). Numbers denote the lava flows (see 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 Krafla Fissure Swarm with the extrapolated Húsavík Transform Fault is shown as grey shaded area.

The total length of the Krafla Fissure Swarm is about 100 km; with ~50 km belonging to the northern Krafla Fissure Swarm, ~40 km to the southern Krafla Fissure Swarm and the rest belonging to the Krafla Caldera. In the southern part, the fractures within the fissure swarm are generally nearly parallel to each other, while more irregular fracture orientations are prevalent in the northern Krafla Fissure Swarm, especially in direct continuation of the Húsavík Transform Fault. However, the closest surface expression of the Húsavík Transform Fault is found 10 km west of the Krafla Fissure Swarm, in the Þeistareykir Fissure Swarm. Nevertheless, there are both irregular fracture orientations as well as higher fracture densities in the part of the Krafla Fissure Swarm that is in direct continuation of the Húsavík Transform Fault. It is suggested that there is a buried continuation of the Húsavík Transform Fault that extends to the Krafla Fissure Swarm.

The density of fractures within the fissure swarm depends on the age of the surface lava flow that they cut (Figure 10, Table 1). Generally, the oldest lava flows have the highest fracture density, while lava flows less than few hundred years of age have very low fracture density. Similarly-aged lava flows in the fissure swarm have tendency to be more fractured close to the central volcano (Figure 10).

Lava flow(s)	Number	Age
Krafla rifting episode	1	~30 years
Mývatn rifting episode	2	~280 years
Younger Laxá lava flow	3	~2200 years BP
Grænavatnsbruni lava flow	4	~2200 years BP
Hólseldar lava flow	5	~2350 years BP
Hverfjallseldar lava flow	6	~2800 years BP
Older Laxá lava flow	7	~3800 years BP
Hraungarðar lava flow	8	~8000-10,000 years BP
Stóravíti lava flow	9	~10,000 years BP
Gjástykkisbunga lava flow	10	~10,000 years BP

Table 1 Ages of lava flows that are cut by the Krafla Fissure Swarm (Þórarinsson 1979; Sæmundsson 1991; Höskuldsson et al. 2010). The table is from Hjartardóttir et al. (2012).

3.4 Paper 4

Hjartardóttir, Á.R., Einarsson, P, Magnúsdóttir, S., Björnsdóttir, Þ. and Brandsdóttir, B. Fracture systems of the Northern Volcanic Rift Zone, Iceland – an onshore part of the Mid-Atlantic plate boundary. Submitted to the Journal of the Geological Society of London.

This paper presents an overall map of all the fracture systems of the NVZ, their extent and geometrical relationships. Almost all the fractures are arranged within fissure swarms that belong to the 5-6 volcanic systems in the rift zone. The fissure swarms are ~0.5-15 km wide and ~30-125 km long and are arranged sub-parallel to each other and the zone itself. The aim of the paper is to study their orientations, their densities according to the age of the surface lava flows and distance from the central volcanoes, as well as to study the relationship between earthquakes and fissure swarms in the area.

Fractures and eruptive fissures in the fissure swarms of the NVZ are generally subparallel to each other, with a N to NNE orientation. Nevertheless, several exceptions exist from this pattern. Close to central volcanoes, fracture orientations are more irregular. Often, fractures and eruptive fissures radiate away from the calderas of the central volcanoes, or are concentric around them. Irregular fracture orientations can also been seen at the junction between fissure swarms and the two strike-slip faulted areas adjacent to the NVZ; the Húsavík Transform Fault and the Grímsey Oblique Rift. This pattern is more prominent near the Húsavík Transform Fault. Fractures with a similar orientation as the faults of the strike-slip faulted areas can also be found in several areas in the NVZ, especially in an area which stretches across the NVZ north of the Askja Central Volcano. Close to the Vatnajökull glacier, another deviation of fracture orientations can be seen. This is the only area in the NVZ where E-W oriented Postglacial eruptive fissures can be found that are not part of caldera boundaries. Hooper et al. (2011) suggested that the E-W oriented fissures were formed when the regional plate spreading stress field had been relieved due to regular N to NNE oriented dike intrusions, and that a remnant stress field, due to deglaciation, caused the formation of the E-W oriented fissures. It may also be noted that the E-W oriented fractures and eruptive fissures are situated close to the E-W oriented Central Iceland Volcanic Zone (CIVZ) (Figure 11), although fractures within that zone generally have a northerly orientation.

During rifting events, when dike intrusions occur, intensive earthquake activity occurs along the active fissure swarm. However, the fissure swarms of the NVZ are almost seismically inactive between rifting events (Figure 11). In a similar manner, InSAR images indicate that the only deformation found within the fissure swarms during the non-rifting period of 1993 to 1998 was a small subsidence within the fissure swarms that had the most recent rifting episodes (Pedersen et al. 2009). Together, this indicates that little deformation occurs on fissure swarms during non-rifting periods, which supports the notion that fissure swarms form and are reactivated in diking events.

Eruptive fissures are most common within a distance of 20-30 km from the central volcanoes, while they are scarce at the distal parts of the fissure swarm where the fissure swarms are generally only characterized by non-eruptive fractures (Figure 12). This shows that activity of fissure swarms is highest close to central volcanoes and gradually decreases with distance from them.

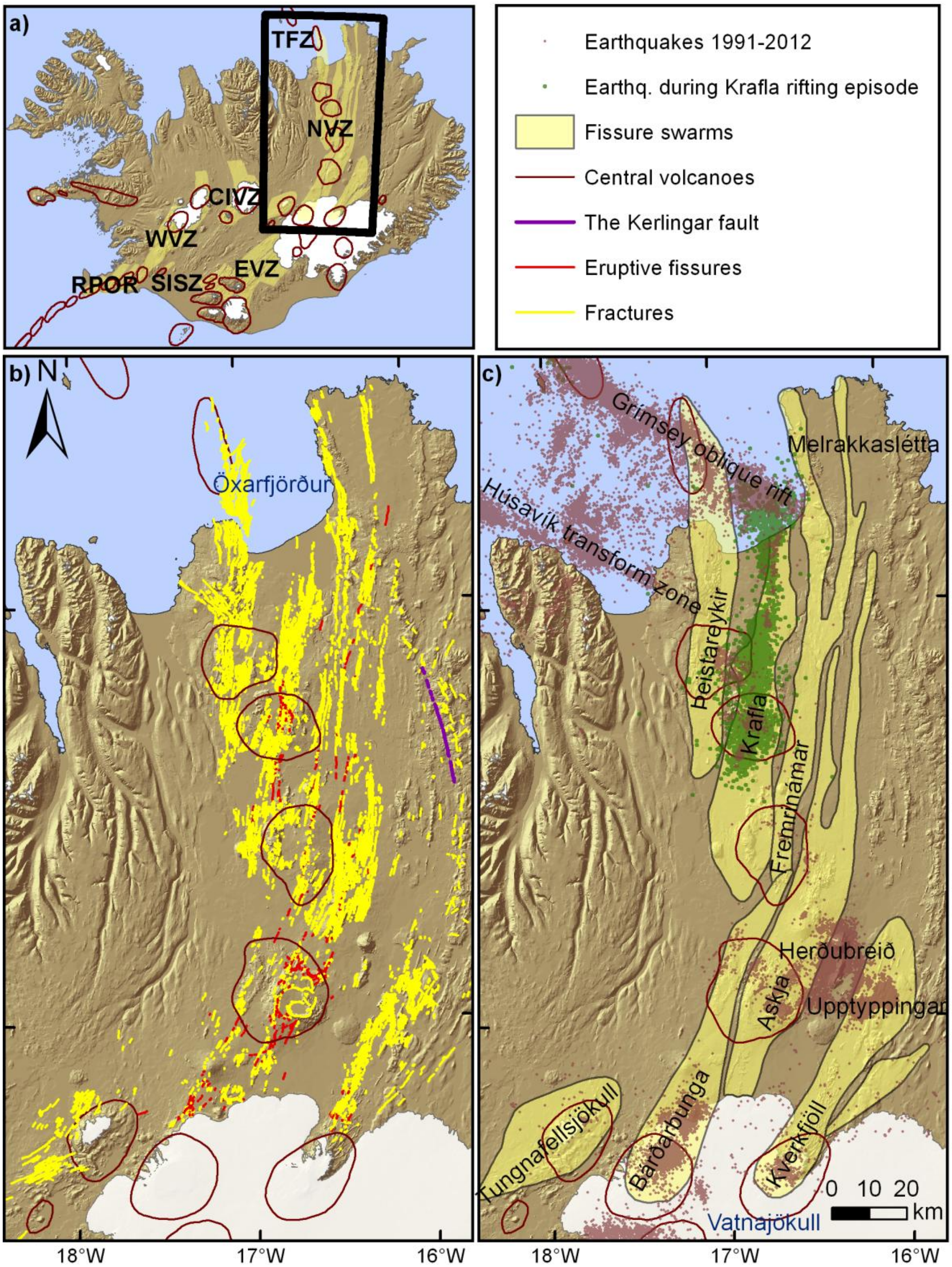

Figure 11 Fractures and eruptive fissures within the NVZ. Image from Hjartardóttir et al. (in prep.). Information on central volcanoes is from Einarsson and Sæmundsson (1987). Information on earthquakes during the Krafla rifting episode was acquired from Buck et al. (2006), earthquakes between the years of 1991 and 2011 are from the Icelandic Meteorological Office.

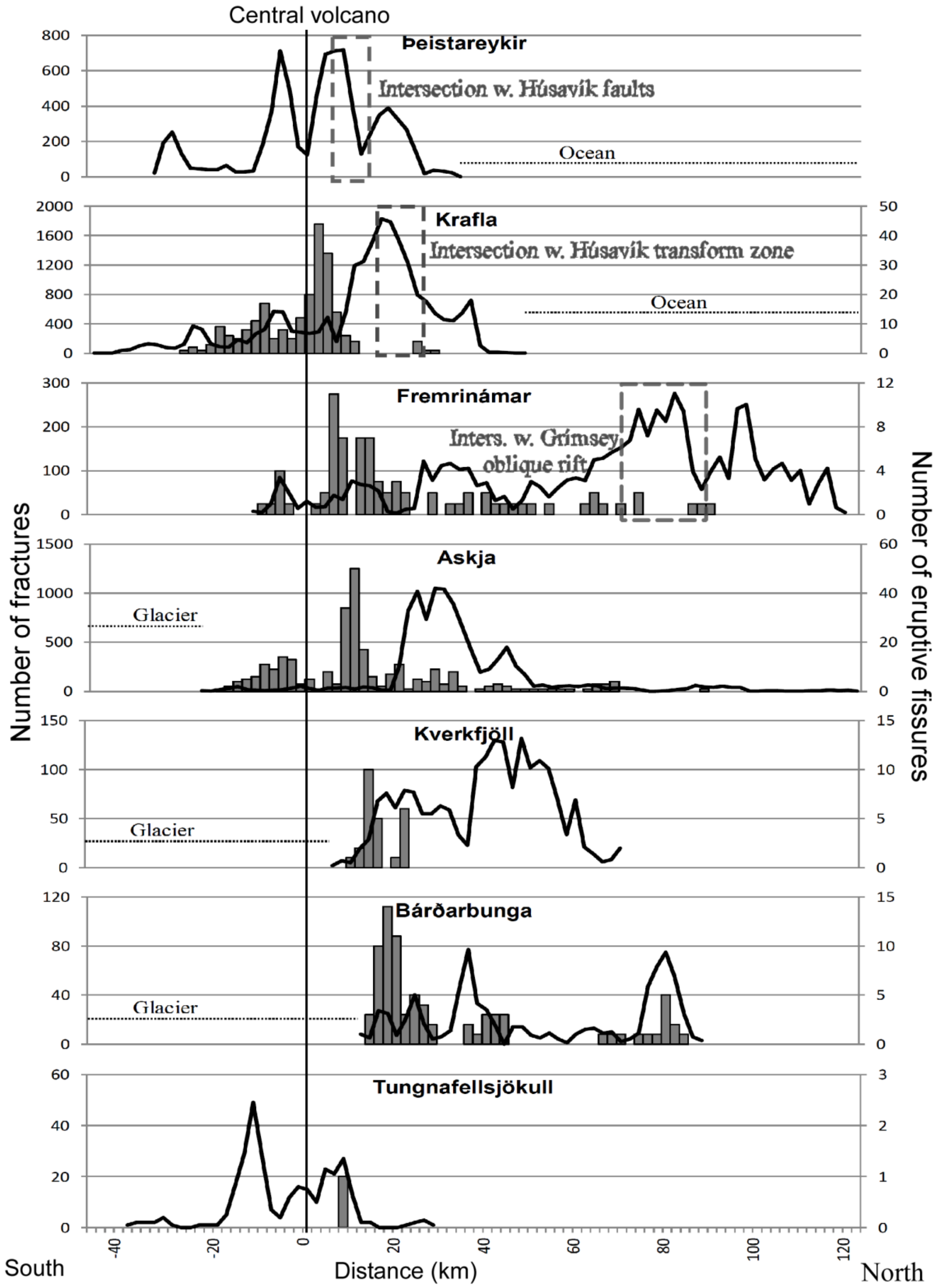

Figure 12 The number of fractures (lines) and eruptive fissures (columns) versus distance from the central volcanoes in the Northern Volcanic Rift Zone. Image from Hjartardóttir et al. (in prep.). Dashed boxes indicate where the extrapolated intersections with the Grímsey Oblique Rift and the Húsavík Transform Zone are.

4 Main conclusions

1. The NVZ is a ~50 km wide and ~200 km long part of the Mid-Atlantic plate boundary. It consists of several central volcanoes, and fissure swarms extending in north- and southerly directions from them.

2. The central volcanoes are, as previously known, the locus of concentrated activity within the fissure swarms. Density of eruptive fissures and fractures in the fissure swarms of the NVZ is generally greatest within ~20-30 km distance from the central volcanoes, the density gradually decreases with distance from the central volcano.

3. Density of fractures depends on the age of the surface lava flows, showing how fissure swarms form gradually on a time scale of thousands of years.

4. Most fractures in the NVZ are oriented ~perpendicular to the spreading vector, indicating that the spreading controls their orientation. Exceptions from this pattern occur mainly in these circumstances:

    a. Close to the only calderas in the NVZ, in the stress domains of their underlying magma chambers; Askja and Krafla calderas, where some fractures and eruptive fissures are either concentric around the calderas or radiate away from them.

    b. Close to the NW part of Vatnajökull, where several fractures and eruptive fissures have E-W orientation.

    c. WNW-oriented faults, found in central NVZ. Possibly related to an almost inactive transform zone.

5. At the junctions of transform zones and fissure swarms the fissure swarm‘s fracture density is higher than elsewhere, and fracture orientations are more irregular. This occurs where the Grímsey Oblique Rift connects with the NVZ, and where Þeistareykir and Krafla Fissure Swarms connect with the Húsavík Transform Zone.

6. Comparison of fissure swarms, earthquakes and deformation indicate that the fissure swarms are mostly inactive during inter-rifting periods. Intense deformation and earthquake activity occurs during rifting events.

7. The eastern boundary of the NVZ is characterized by the Fjallgarðar area, which has elongated rows of tindars. The Kerlingar Fault is a 30 km long Postglacial feature situated at the northern part of the Fjallgarðar area. It is suggested that this area is

mainly activated during deglaciations, due to increased magma supply, and release of high tensile stresses accumulated during glaciations.

8. The Fjallgarðar area has an arcuate shape, rather than being perpendicular to the spreading vector. The Postglacial Kerlingar Fault is also not oriented perpendicular to the spreading vector, as it has an arcuate NNW orientation. It is suggested that the orientation of the Fjallgarðar area and the Kerlingar Fault is controlled by their location at the boundary between the NVZ and the EFB, due to differential movements between these crustal blocks during deglaciations. This occurs as these crustal blocks have different thickness, Youngs modulus, density and viscosity. The differential vertical movements may have activated the Kerlingar Fault during the beginning of Postglacial times.

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Paper 1

Hjartardóttir, Á.R., Einarsson, P. and Brandsdóttir, B. (2010). The Kerlingar fault, Northeast Iceland: A Holocene normal fault east of the divergent plate boundary. Jökull 60, 103-116.

Reviewed research article

The Kerlingar fault, Northeast Iceland: A Holocene normal fault east of the divergent plate boundary

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Abstract — *The Kerlingar fault is a ∼30 km long fault located at the boundary between the Northern Volcanic Rift Zone, and the Tertiary Eastern Fjords Block in Iceland. The fault has a throw of 2–9 m down to the east and is most likely a normal fault. It probably ruptured in several earthquakes over extended time, but assuming it ruptured in one event it would have a magnitude of about* M_w*=6.7. The Kerlingar fault forms a sharp offset in a flat moraine, showing that the fault was active in the Holocene. Several characteristics of the fault are different from that of the presently active fissure swarms of the NVZ. It is unusually long, straight and continuous, and it is parallel with the boundary between the NVZ and EFB not perpendicular to the plate spreading. We consider three possible explanations for the existence of the fault. It may be formed in a rifting event, by stress transfer in relation to the Húsavík transform, or by a stress field caused by rapid crustal unloading during the last deglaciation. We favour the third explanation but note that the other two cannot be excluded. Differential movements at the NVZ-EFB boundary during deglaciations can occur as the two crustal blocks have different density, Young's modulus, thickness, and subcrustal viscosity. They therefore respond differently to the unloading. This may explain why the fault is parallel with the NVZ-EFB boundary and not with the Holocene fissure swarms in the NVZ. Other faults at the NVZ-EFB boundary may be formed in a similar manner. Magma may have intruded some of them to form the distinct arcuate pattern of hyaloclastite ridges at the boundary between the NVZ and the EFB. Future model calculations could constrain better the effects this process has on the formation of faults.*

INTRODUCTION

The Northern Volcanic Rift Zone (NVZ) marks the mid-Atlantic plate boundary in Northern Iceland (e.g. Einarsson, 2008). This zone is ∼40 km wide, with 5–6 active volcanic systems. The outer flanks of the NVZ are asymmetric with respect to the plate boundary. A 30 km wide zone on the flank east of the neovolcanic zone is characterized by hyaloclastite ridges, indicating subglacial basaltic fissure eruptions (Kjartansson 1943; Sæmundsson 1974), while Holocene volcanism is absent. Vilmundardóttir (1997) has assigned these ridges late Pleistocene age based on their appearance. No corresponding zone is found on the west side of the plate boundary. Although the majority of Holocene fractures in the area are situated within the neovolcanic zone, there are exceptions. In this paper, we present the results of our survey on one of the notable exceptions, the Holocene Kerlingar fault (Figure 1). We find that the fault is not a part of the Holocene fissure swarm of any of the 5–6 volcanic systems, and that while it has a different orientation than the fissure swarms at this latitude, it is parallel both with the line of central volcanoes in the NVZ, and with the boundary of the NVZ with the Eastern Fjords block (EFB). Therefore, we suggest that the

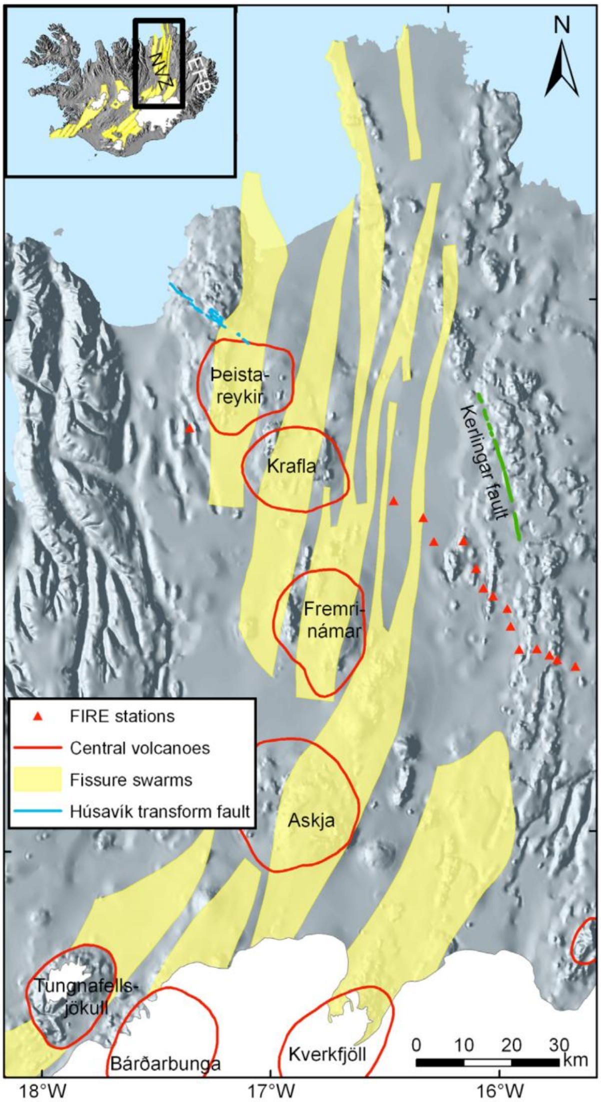

Figure 1. The Northern Volcanic Rift Zone (NVZ), Iceland. The Kerlingar fault is denoted as a green lineament at the eastern boundary. EFB in the index map denotes the Eastern Fjords block. The eastern FIRE seismic stations (Staples *et al.*,1997) are denoted as red triangles. Information on fissure swarms from Einarsson and Sæmundsson (1987). – *Norðurgosbeltið (NVZ) og Austurland (EFB). Græna línan við austurbrún gosbeltisins táknar Kerlingamisgengið. Rauðir þríhyrningar sýna hluta skjálftastöðva FIRE verkefnisins (Staples et al. 1997). Upplýsingar um sprungusveima eru frá Páli Einarssyni og Kristjáni Sæmundssyni (1987).*

fault is related to processes that affected the zone as a whole rather than more localized rifting events of individual fissure swarms. We point out that the location of the fault coincides with a rapid change in crustal thickness (Figure 2) (Staples *et al.* 1997). Thus, the areas west and east of the fault may have reacted differently to crustal load changes in the Pleistocene and in the beginning of the Holocene.

METHODS

We mapped the Kerlingar fault and its surroundings from SPOT and ASTER satellite images, and from aerial photographs. We obtained the SPOT images from the National Land Survey of Iceland (Landmælingar), the ASTER images from the US/Japan ASTER project, and the aerial photographs from Aerial Photographs corp. (Loftmyndir ehf.). The images have different resolutions: the SPOT images have a resolution of 10 m/pixel, the ASTER images 15 m/pixel and the aerial photographs 0.5 m/pixel. Although the satellite images have less resolution than the aerial photographs, they are useful as they show different aspects of the geological structures than the aerial photographs (i.e. different solar angle and different contrast). As an example, the Kerlingar fault is particularly well delineated on some of the ASTER satellite images, especially those taken under winter condition and low sun angle (e.g. October 11th 2003, Figure 3).

A 4.3 km long section of the fault was investigated in the field, mainly to ascertain the sense of faulting and to estimate vertical offset of some of the fault segments. Transects across the fault were measured in a few places by GPS-instruments.

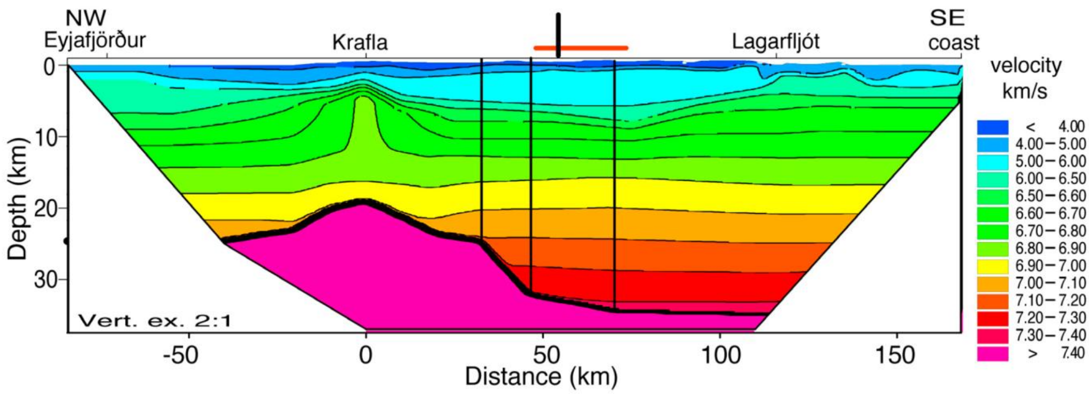

Figure 2. Best fit P-wave velocity model by Staples *et al.* (1997) along the FIRE seismic array line. A part of this line is shown in Figure 1. Thin black lines mark abrupt changes in crustal thickness at the NVZ-EFB boundary. A vertical black line 55 km east of Krafla indicates the approximate location of the Kerlingar fault, whereas the horizontal red line spans a 30 km wide arcuate area of hyaloclastite ridges at the NVZ-EFB boundary. – *Jarðlagasnið eftir bylgjubrotsmælilínu FIRE verkefnisins samkvæmt Staples et al. (1997). Staðsetning hluta þversniðsins er sýnd á 1. mynd. Svarta línan bendir á hvar Kerlingamisgengið sker þversniðið, rauða línan þar fyrir neðan spannar móbergshryggina á austurmörkum Norðurgosbeltisins.*

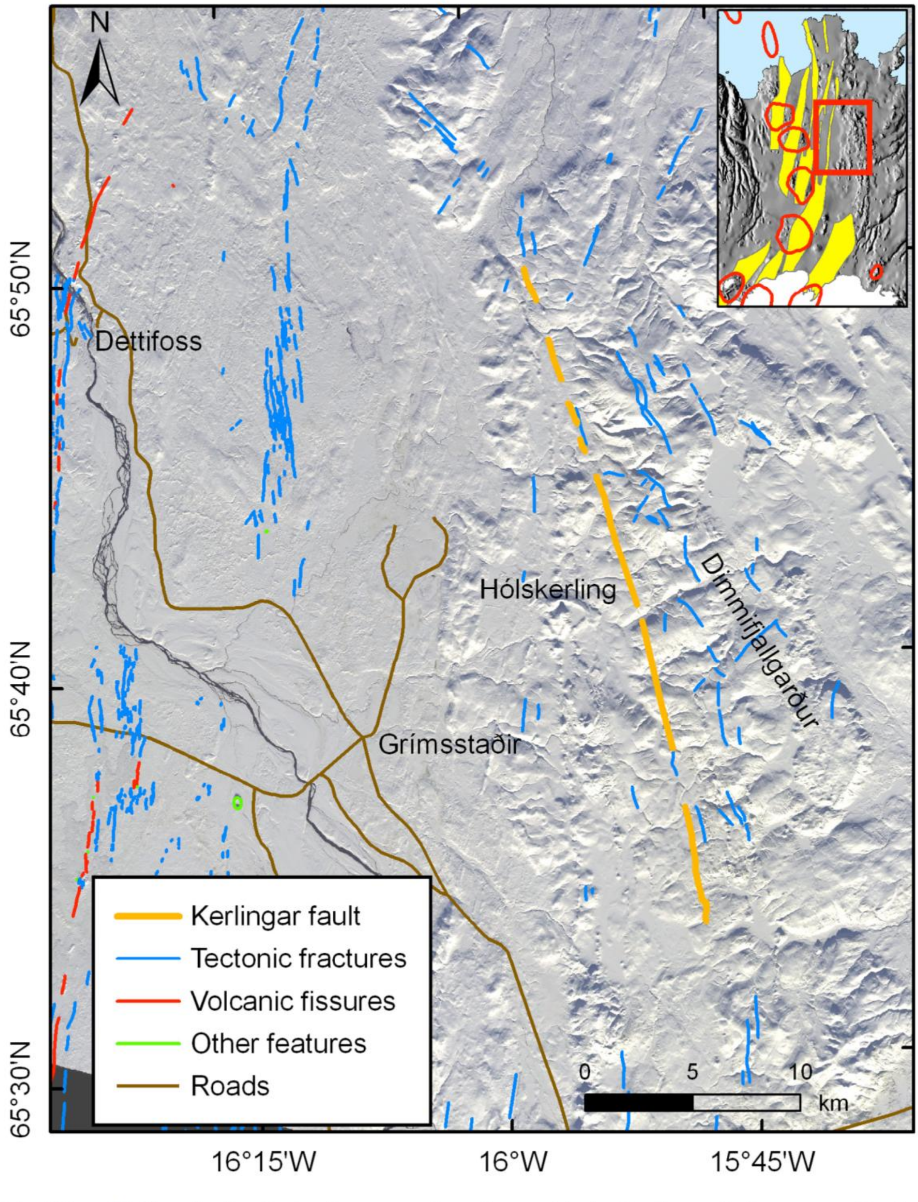

Figure 3. The Dimmifjallgarður hyaloclastite mountains, along with the Kerlingar fault on a satellite image from the US/Japan ASTER project. Fractures at the westernmost part of the map belong to the Askja fissure swarm (Figure 1). – *ASTER gervitunglamynd, frá 11. október 2003 af Dimmafjallgarði, ásamt Kerlingamisgenginu. Sprungur vestast á kortinu eru hluti sprungusveims Öskju í Dyngjufjöllum (sjá 1. mynd).*

RESULTS

The fault region

The Kerlingar fault is located within the Dimmifjallgarður mountains, a series of arcuate hyaloclastite ridges along the NVZ-EFB boundary (Figure 1), (Helgason 1987; Sæmundsson 1977; Vilmundardóttir 1997). Various structures related to tectonic activity are present in this region. However, due to the complexity of the area, we have only mapped the most prominent features. The fractures which we mapped are of various sizes, sharpness and orientations (Figure 3). Many of these fractures, including the Kerlingar fault, form a structural pattern which is oriented parallel with the EFB-NVZ boundary. However, no Holocene volcanic fissures have been mapped in the area close to the Kerlingar fault.

Fault orientation

The Kerlingar fault is oriented NNW-SSE; therefore, it is not parallel with fractures in the NVZ fissure swarms at this latitude, which are generally N or NNE oriented (i.e. $\sim$perpendicular to the 106° plate spreading vector (DeMets *et al.* 1994)) (Figure 1). The fault is, however, parallel with the line of central volcanoes that extends along the axis of the NVZ: Fremrinámar, Krafla, and Þeistareykir (Figure 1). Although the Kerlingar fault has a general NNW orientation, it curves along its length from a NNW orientation at its southern end to a NW orientation at its northern end. Generally, the strike of different fault segments ranges from 350° in the south, to 336° in the north.

Fault dip and vertical offset

Our field observations show that the eastern side of the Kerlingar fault is downthrown. Assuming a normal fault, this indicates that the fault is east-dipping, i.e. it dips away from the NVZ (Figures 4–8). This is not obvious everywhere, particularly where the fault cuts westward sloping surfaces. The throw of the fault varies along the fault. Our field measurements ranged from 2 to 9 m in vertical offset. As can be seen from Figure 7, snow accumulates and stays longer in some parts of the fault. The meltwater from this snow may erode the fault scarp, which makes precise measurements of vertical offset due to fault movements difficult. Therefore, 9 m may be an overestimate, at least in terms of Holocene movements.

Fault length

The Kerlingar fault is at least 30 km long, interrupted by a few E-W oriented gullies. It may even extend further, if we assume that the NW oriented fractures north of the Kerlingar fault are a part of the fault. The Kerlingar fault is therefore an unusually long feature, compared with faults within the fissure swarms of the NVZ. As a comparison, the majority of fractures within the Askja fissure swarm are less than 1 km long (Hjartardottir *et al.* 2009).

Earthquakes

Although some faults (including the Kerlingar fault) have been previously identified in the Dimmifjallgarður mountains (Sæmundsson 1977), earthquakes have not been detected there by seismograph networks that have been in operation in the area since 1974 (Einarsson 1989; Einarsson 1991; Jakobsdóttir 2008). This indicates that the activity of the area is not steady-state. Although it is more likely that the fault ruptured in several smaller earthquakes, we calculate the maximum size of an earthquake, assuming that the total length of the fault ruptured in one event. The seismic moment is calculated according to:

$$M_0 = \mu \underline{u} F \qquad (1)$$

We assume that the shear modulus (μ) is 10 GPa and the mean displacement ($\underline{u}$) is 4 m. The area of the fault (F) is calculated assuming that the fault has a dip of 60°, that the length of the rupture is 30 km and that the rupture reaches 7 km depth, i.e. the approximate bottom of the seismogenic crust (Einarsson *et al.* 1977; Soosalu *et al.* 2010). The moment magnitude is calculated according to:

$$M_w = 2/3 \log M_0 - 6.0 \qquad (2)$$

From this, we conclude that the fault could have generated an earthquake of moment magnitude up to $M_w \approx 6.7$. If we increase the depth of the fault to 10 km, we get an earthquake of magnitude $M_w \approx 6.8$.

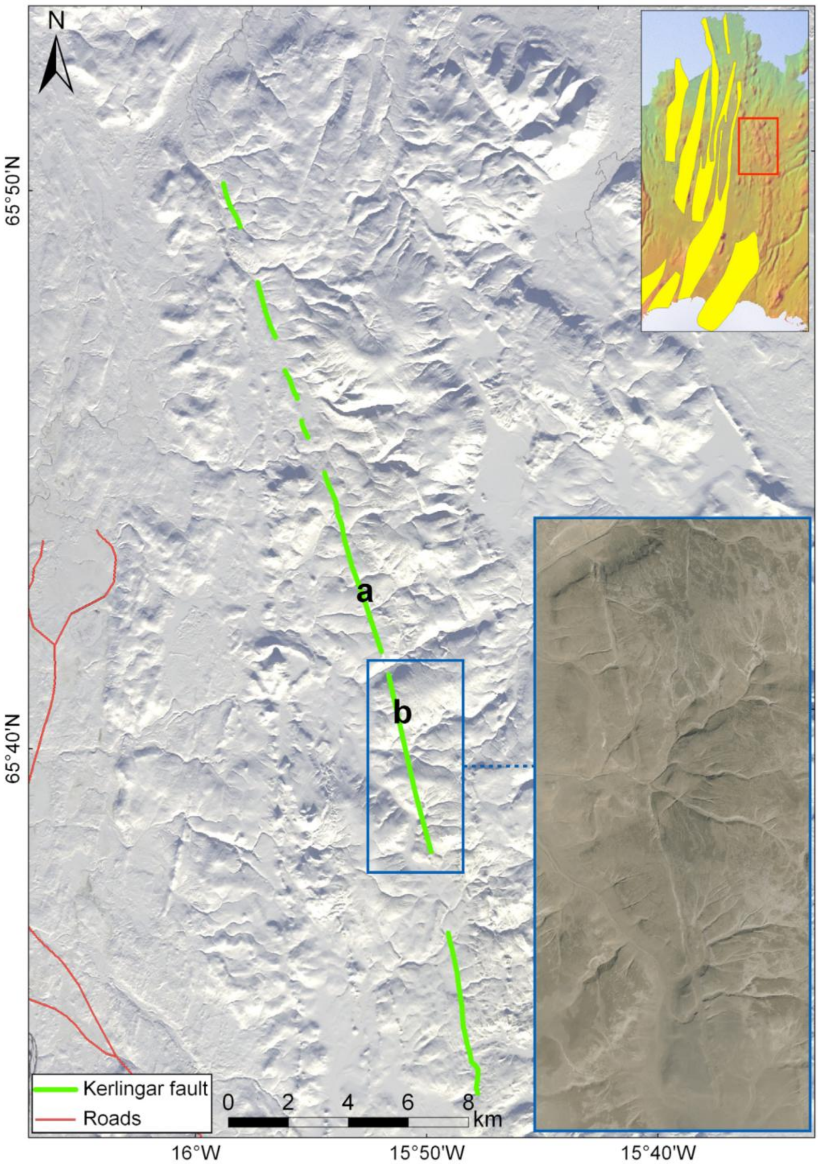

Figure 4. The Kerlingar fault (green) on a satellite image from the US/Japan ASTER project. The lower right inset shows a zoom-in on a fault segment on an aerial photograph from Loftmyndir corp. "a" denotes the location of the parallel sections in Figure 6 and "b" the location of the cross-section in Figure 5. – *Kerlingamisgengið (grænt). Í bakgrunni er ASTER gervitunglamynd. "a" sýnir staðsetningu samsíða sniðanna á 6. mynd og "b" staðsetningu þversniðsins á 5. mynd . Í bláa rammanum má finna nærmynd af einu sprungustykkinu.*

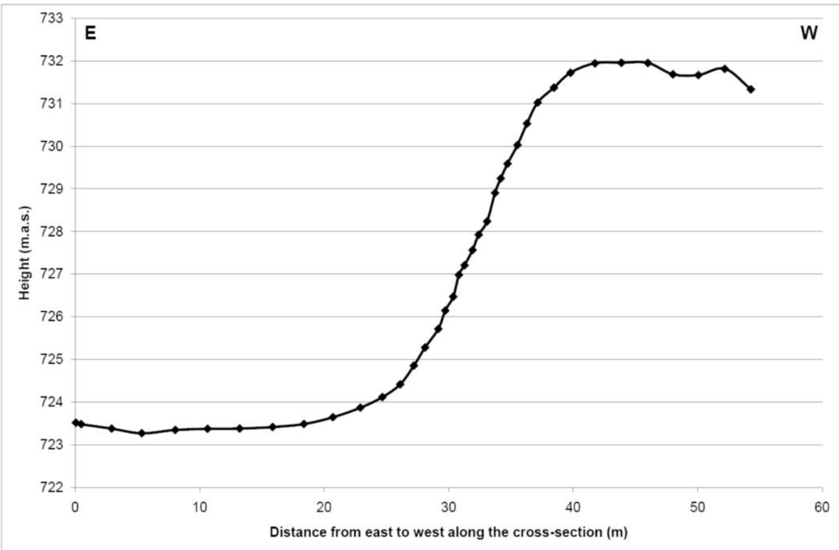

Figure 5. Cross-section of the Kerlingar fault scarp (see Figure 4). – *Þversnið af Kerlingamisgenginu.*

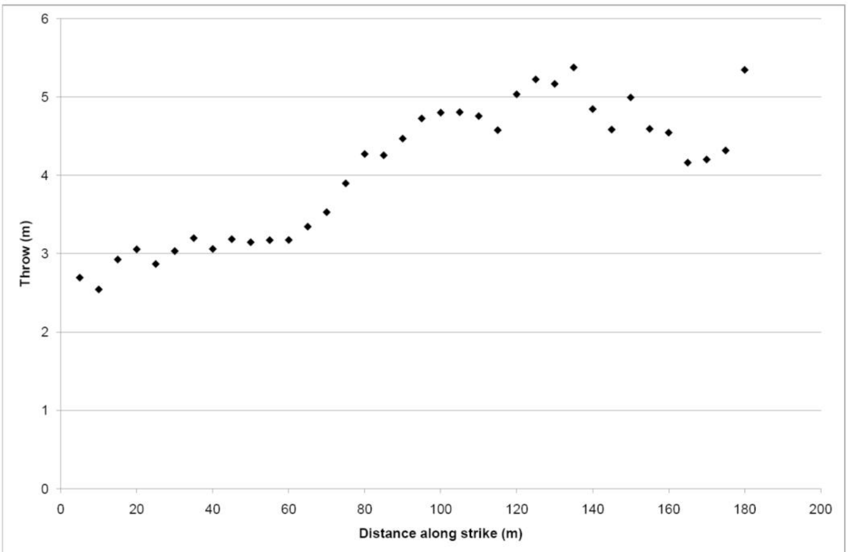

Figure 6. Throw along a section of the Kerlingar fault (see location in Figure 4). – *Lóðrétt færsla á hluta Kerlingarmisgengisins. Staðsetning sniðanna er sýnd á 4. mynd.*

Figure 7. The Kerlingar fault, visible as a depression filled with snow. View towards the south. – *Snjóskaflar sýna staðsetningu Kerlingamisgengisins vel. Horft til suðurs.*

DISCUSSION

We have mapped and conducted field studies of the Kerlingar fault to get a better constraint on its origin. The Kerlingar fault is, in many respects, different from the vast majority of fractures within the NVZ. The fault is unusually long and has a throw down to the east, although it is located in the easternmost part of the NVZ. Rift zones are usually manifested as gentle graben structures with boundary faults dipping inward. In addition, the fault strikes obliquely to the fissure swarms of the NVZ at this latitude, although it is both parallel with the line of central volcanoes in the NVZ, which includes Fremrinámar, Krafla, and Þeistareykir, and with the NVZ-EFB boundary. The fault is located within an area of hyaloclastite ridges, which extends along the boundary between the NVZ and the EFB (Figure 1). There, several faults have similar orientation as the Kerlingar fault. These unusual attributes of the Kerlingar fault might indicate that the fault was formed and/or reactivated by processes which affect the NVZ area as a whole.

Sense of faulting

The rift zones of Iceland are predominantly made up of normal faults. Some structures previously suggested to be due to thrust faulting have turned out to be of local origin (Khodayar and Einarsson 2004). In general, intraplate earthquakes in young (10–20 m.y.) crust (such as the Icelandic crust) are caused by normal faulting, while thrust faulting is predominant in older crust (e.g. Sykes and Sbar 1974). Indeed, the Kerlingar fault has characteristics which may indicate that it is a normal fault, as it is continuous, as opposed to the segmented and sinuous fault structure that often characterizes thrust faults.

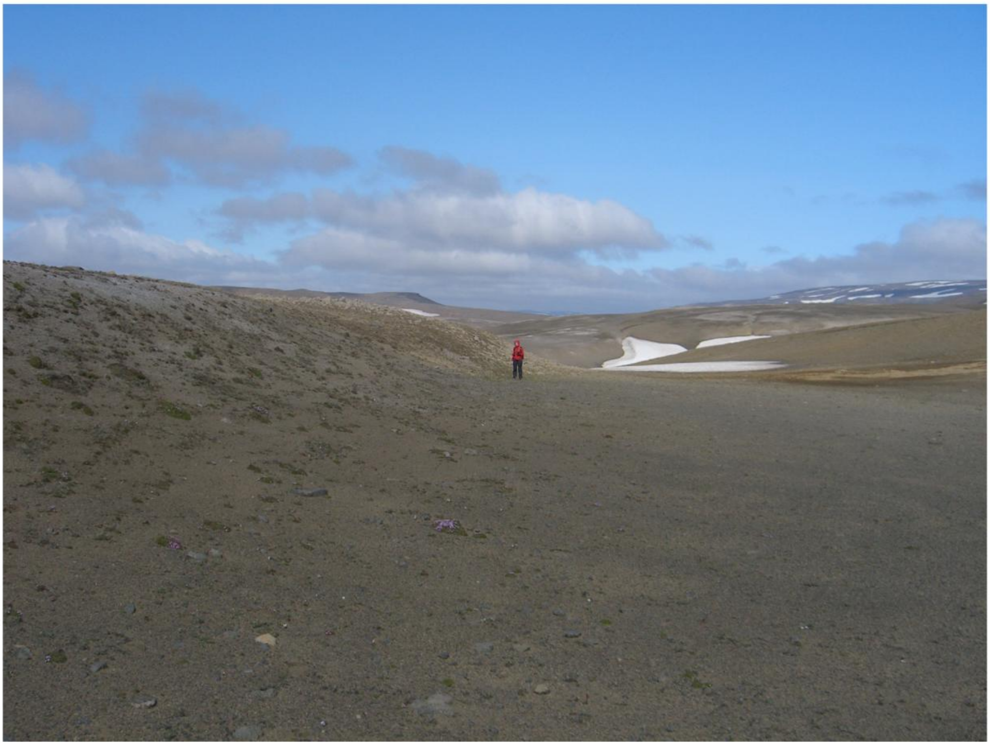

Figure 8. A segment of the Kerlingar fault. View towards the north. – *Hluti af Kerlingamisgenginu. Horft til norðurs.*

The Kerlingar fault – a Holocene feature

Several faults are found outside or at the margins of the NVZ in the Dimmifjallgarður area (Figure 3). The majority of them have been assumed to be pre-Holocene because of their eroded appearance and large distance from the axis of the rift zone. A notable exception is the Kerlingar fault. It has a sharp topographic expression and can be traced on satellite images for tens of kilometers with few interruptions. Our field investigation revealed a sharp step in a moraine, delineating a part of the fault (Figures 8 and 9). This indicates that the Kerlingar fault has been active at some time during the Holocene, as a glacier would have eroded this feature if it was older. It is unlikely that drainage of a snow melt would cause the sharp step in the moraine, as the moraine is for the most part not located in a slope, where meltwater could carry away sediments from the fault scarp. Holocene activity of other faults in the Dimmifjallgarður area cannot be excluded, but this needs to be investigated further. As discussed before, the Kerlingar fault is parallel with the NVZ-EFB boundary, and is not perpendicular to the plate spreading vector (DeMets *et al.* 1994). Normal faults, such as the Kerlingar fault, are stress indicators, i.e. probably have a strike perpendicular to the least principal stress axis. The Holocene activity of the fault therefore indicates that it is either formed before a change occurred in the crustal stress field at the beginning of the Holocene, or it is related to processes unrelated to the plate movements that generate the present crustal stress field.

Figure 9. A part of the Kerlingar fault, viewed towards the west. Yellow dashed lines denote the top and bottom of the fault scarp. The mountaintop is Mt. Hólskerling. – *Horft í vesturátt að Kerlingamisgenginu. Efri og neðri mörk misgengisins eru táknuð með brotnum gulum línum. Fjallstindurinn í baksýn kallast Hólskerling.*

The formation of the fault

We consider three possible explanations for the existence of the Kerlingar fault:

1) That the fault was formed in a rifting event related to its location at the end of the Möðrudalur area, which is in the continuation of the Kverkfjöll fissure swarm.

2) That the fault was formed by stress transfer in relation to the activity of the Húsavík transform fault (Figure 1).

3) That the fault formed or was reactivated by isostatic response due to rapid crustal deloading during the last deglaciation.

The first point is supported by the location of the fault in the continuation of the Kverkfjöll fissure swarm, if we assume that the hyaloclastite formations that form an arc-shaped continuation of the Kverkfjöll fissure swarm are a part of the fissure swarm (Figure 1). However, the fissure swarm (as indicated by high density of tectonic fractures active in the Holocene), ends ~50 km south of the area, while the Kerlingar fault area is mostly characterized by hyaloclastite ridges, indicating subglacial Pleistocene fissure eruptions (Kjartansson 1943). During the Holocene, this area has therefore experienced few or no rifting events. Also, the fault is not oriented parallel with the most recent, sharp and narrow hyaloclastite ridges in the area, which are parallel with the NVZ fissure swarms to the west. This suggests that the fault was not formed in a typical rifting event.

Regarding the second point, the Kerlingar fault is in the direct continuation of the Húsavík transform fault (Figure 1), and it has been shown that the orientation of fractures in fissure swarms can change abruptly where a fissure swarm intersects with a transform fault (Gudmundsson *et al.* 1993). In a similar manner, the unusual NW orientation of the Kerlingar fault could be associated with the Húsavík transform fault. However, we consider such a link unlikely in the case of the Kerlingar fault, mainly for two reasons. Firstly, for this mechanism to be true, we would have to assume that the Húsavík fault extends all the way to the

Kerlingar fault. That is unlikely since the easternmost visible part of the Húsavík fault is located 65 km west of the Kerlingar fault. Secondly, the change in orientation of fractures in the area should happen abruptly where the fractures and the Húsavík transform fault meet. That is not the case in the area near the Kerlingar fault. There, the change of orientation is gradual along the border of the rift zone, suggesting even more regional-scale processes.

In the third point, it is suggested that the Kerlingar fault was formed (or reactivated) due to a landrise during the last deglaciation. This can occur as the hotter and less viscous NVZ should react differently to unloading due to deglaciation than the colder, thicker and more viscous EFB block.

The reaction to unloading is both elastic and viscous, partly instantaneous and partly extending over a period of time. Physical properties, i.e. elastic constants, viscosity and density, may differ between the NVZ and the EFB, increasing differential stress and inducing faulting between the NVZ and the EFB.

a) Effective Young's modulus

Sudden pressure change at the surface leads to instantaneous elastic reaction of the crust which depends on the effective Young's modulus, which again is inversely dependent on crustal thickness. The elastic rebound of the crust happens relatively fast during deglaciation. Variation in Young's modulus should lead to higher uplift of the EFB than the NVZ (on the order of few tens of centimeters). If this effect was the only effect to cause the formation of the Kerlingar fault, the fault should therefore have a throw towards the west and not towards the east as observed. Therefore, this effect cannot be the only cause of formation of the Kerlingar fault.

b) Effective viscosity

Lower viscosity material responds more rapidly to deloading than higher viscosity material with a linear relation between crustal relaxation time and viscosity (e.g. Cathles 1975). Assuming that the lower crustal and uppermost mantle viscosity beneath the volcanic zones of Iceland is lower than beneath older, Tertiary areas, the NVZ crust should rebound faster than the EFB during deglaciations. As variable response rates may generate differential stress field across the NVZ-EFB boundary during deglaciations, the Kerlingar fault may thus be a remnant of faster rebound of the NVZ crust than the thicker, more viscous EFB crust. Viscous crustal relaxation occurs more slowly and remains over a longer time period than the elastic rebound of the crust. As an example, a region with lower crustal viscosity of 1.5×10^{19} Pa s, has a relaxation time of 1000 years (Sigmundsson 2006), while the relaxation time is only 500 years if the viscosity is lowered to 0.75×10^{19} Pa s. Therefore, a slight difference in the viscosity can cause significantly different relaxation times.

c) Density difference – buoyancy effects

As the uppermost mantle below the NVZ has a lower density (3170 kg/m^3) than beneath the EFB (3240 kg/m^3) (Staples *et al.* 1997), the isostatic uplift of the NVZ during deglaciations should be higher than the uplift of the EFB. Using these mantle densities, an ice density of 920 kg/m^3, a 1500 m thick glacier and a simple isostatic uplift equation;

$$u = h_{ice} \times \rho_{ice}/\rho_{mantle}$$

the uplift of the NVZ is close to 435 m and the uplift of the EFB 426 m, which implies a 9 m excess uplift of the NVZ with respect to the EFB.

In addition, flexure at the rift zone margin can cause a different stress field there than in the center (i.e. Clifton and Kattenhorn 2006). However, marginal flexure should generate faults with a throw down to the west in this area. Therefore, that process cannot explain the existence of the Kerlingar fault, which has a throw down to the east.

A differential stress field, produced at the boundary between the NVZ and the EFB during deglaciations (or glaciations), could explain why the Kerlingar fault is located at the boundary of the NVZ and the EFB, and why it is parallel to the boundary and not parallel to the fissure swarms in the central NVZ. The differential stress field could form faults in two different ways: either directly, without the involvement of magma, or indirectly, by producing a stress field which governs the orientation of dike propagations in the area during deglaciations. Therefore, dike intrusions could play a part in the scenario, even though the stress field would be governed by the differential movements caused by the deglaciation. The Kerlingar fault displays characteristics which may indicate that the fault was formed without the involvement of magma; it is long (∼30 km) and continuous, as opposed to the sinuous and discontinuous normal faults characteristic of dike-induced rifts. This indicates that the stress field causing the formation of the Kerlingar fault extended over a large area. We consider it likely that numerous other faults at the boundary between the NVZ and the EFB formed in a similar manner, and that magma intruded some of them, either vertically from the mantle, or horizontally from the Kverkfjöll central volcano. This process could have formed the distinct arcuate pattern of hyaloclastite ridges seen at the boundary between the NVZ and the EFB, in the continuation of the Kverkfjöll fissure swarm (Figure 1).

Differential movements, as suggested here, would have been confined to this area and not applicable to other flank zones of the Icelandic rift. In particular, this does not apply to the southernmost part of the NVZ-EFB boundary, as no marked difference in crustal thickness exists there (e.g. Allen *et al.* 2002; Brandsdóttir and Menke 2008; Darbyshire *et al.* 1998). Variations in crustal thickness along the margin of the NVZ could also explain why the distinct arcuate pattern of hyaloclastite ridges seen at the NVZ-EFB boundary does not extend all the way to the Kverkfjöll central volcano (Figure 1).

It has been proposed that stress changes during deglaciations have caused the formation of faults in continental settings, such as in Fennoscandia (e.g. Muir Wood 1989). These are thrust faults, consistent with horizontal compression in the old, continental crust (Sykes and Sbar 1974; Wu *et al.* 1999). However, the reaction of the NVZ-EFB crust to deloading should be different. Crustal extension is expected in the much younger crust (Árnadóttir *et al.* 2009; Sykes and Sbar 1974).

In this paper, we have presented an overview on the processes that may cause differential movements at the NVZ-EFB boundary. For a more detailed study, modeling of these deloading effects (i.e. with Finite Element Modelling) is preferable.

CONCLUSIONS

1. The Kerlingar fault is a 30 km long normal fault located on the eastern boundary of the Northern Volcanic Rift Zone, Iceland. It is a gently curved NNW-oriented feature. The fault is located within and parallel with hyaloclastite ridges which form an arcuate pattern along the boundary of the NVZ and the EFB.

2. The fault has some notable features: a. It is unusually long and continuous, compared with fractures and normal faults within the NVZ. b. It has a throw down to the east, although it is located at the eastern boundary of the NVZ. c. It is not parallel with the fissure swarms in the NVZ at this latitude, although it is parallel with hyaloclastite ridges at the NVZ-EFB boundary, as well as with several other faults at the same boundary.

3. Although no earthquakes have been instrumentally detected in the area, the sharpness and continuity of the fault indicate that it has been active in the Holocene. The fault has most likely been active in many earthquakes but assuming it ruptured in only one event, its magnitude would have been close to M_w=6.7.

4. The offset of fault segments we observed in the field was in the range 2–9 m. The higher number might be an overestimate because of erosion due to snow melting.

5. We found a sharp offset in a moraine formation in a part of the Kerlingar fault, which shows that the fault has been active since the Pleistocene glacier disappeared from the area.

6. Considering three possible explanations for the formation of the Kerlingar fault, we conclude that the most likely process is differential movements due to deglaciation, isostatic rebound and variations in crustal buoancy. Lower viscosity of the lower crust and uppermost mantle induces faster rebound within the NVZ and buoyancy generates higher uplift of the NVZ than the adjacent EFB, explaining why the Kerlingar fault is situated at the NVZ-EFB boundary, why it is parallel with the boundary, and why it is so long and continuous. Other faults on the NVZ-EFB boundary may be formed in a similar manner. Magma may have intruded some of them, forming the arcuate pattern of hyaloclastite ridges at the NVZ-EFB boundary.

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ÁGRIP

Flekaskilin milli Norður-Ameríkuflekans og Evrasíuflekans á Norðurlandi markast af Norðurgosbeltinu. Það samanstendur af 5–6 eldstöðvakerfum, megineldstöðvum og sprungusveimum sem liggja út frá þeim. Á austurjaðri gosbeltisins tekur við belti af móbergshryggjum, stundum nefnt Fjallgarðar, sem myndar sveig um jaðarinn. Á því svæði finnast engin ummerki um eldvirkni frá nútíma. Hryggirnir eru myndaðir í gosum á jökulskeiðum og meginhluti sprungna þar er eldri en frá nútíma (10–12.000 ár). Eitt misgengi stingur þar nokkuð í stúf sökum þess hve fersklegt það er. Það er að minnsta kosti 30 km langt og liggur skammt austan við Hólskerlingu og Grímsstaðakerlingu, tvö áberandi móbergsfell í Fjallgörðunum. Viljum við kenna misgengið við fellin og kalla Kerlingamisgengið. Misgengið myndar 2–9 m háan stall og er sennilega siggengi. Austurveggur þess hefur sigið. Stallurinn kemur vel fram í flatri jökulurð sem sýnir að misgengið hefur verið virkt á nútíma, þ.e. síðan jökla leysti á svæðinu. Misgengið er þó að ýmsu leyti ólíkt þeim misgengjum sem liggja nær miðbiki Norðurgosbeltisins og tengjast eldstöðvakerfum þess. Kerlingamisgengið er í austurjaðri gosbeltisins og ekki í neinum sýnilegum tengslum við þá sprungusveima sem hafa verið virkir á nútíma. Auk þess er það óvanalega langt, beint og samfellt, og samsíða austurmörkum Norðurgosbeltisins, en ekki hornrétt á flekarekið eins og misgengi sprungusveimanna.

Ástæður þess að Kerlingamisgengið myndaðist eru óljósar. Við bendum á þrjár mögulegar ástæður. Misgengið gæti hafa myndast 1) í gliðnunaratburði, 2) vegna spennusviðsbreytinga í tengslum við Húsavíkurmisgengið eða 3) vegna tímabundins spennusviðs í lok ísalda þegar jökulfargi var létt af jarðskorpunni. Þrátt fyrir að okkur þyki þriðja skýringin líklegust, þá bendum við á að hinar tvær eru ekki útilokaðar.

Kerlingamisgengið liggur á eystri mörkum Norðurgosbeltisins þar sem breyting verður á jarðskorpuþykkt. Vestan þess er jarðskorpan um 20 km þykk en austan þess tekur við mun þykkari skorpa, allt að 35 km þykk. Eðlismassi og seigja möttulsins undir þessum svæðum er líka mismunandi. Eðlisfræðilegir eiginleikar svæðanna eru því ólíkir og þau bregðast við með ólíkum hætti þegar snöggar fargbreytingar verða, til dæmis í lok jökulskeiða. Þegar jökull hverfur af svæðinu rís jarðskorpan og hraði rissins ræðst af seigju undirlagsins. Möttullinn undir gosbeltinu hefur lægri seigju og eðlismassa en möttullinn austan þess. Þar rís því skorpan hraðar. Heildarrisið verður einnig meira vegna þess að möttulefnið hefur lægri eðlismassa þar en austan misgengisins. Þetta getur valdið mismunahreyfingum á mörkum þessara svæða og myndað misgengi eins og Kerlingamisgengið. Þetta ferli gæti einnig útskýrt af hverju Kerlingamisgengið er samsíða mörkum Norðurgosbeltisins en ekki hornrétt á flekarekið eins og flest önnur misgengi í Norðurgosbeltinu. Hugsanlegt er að önnur misgengi austan Norðurgosbeltisins hafi myndast á þennan hátt. Kvika gæti jafnvel hafa komist inn í sum þeirra, gosið og myndað þannig það bogalaga mynstur af móbergshryggjum sem sést svo vel í Fjallgörðunum austan Norðurgosbeltisins. Áhugavert væri að nota líkanreikninga til að kanna áhrif fargléttingar jökuls á myndun misgengja. Líklegt verður að telja að Kerlingamisgengið hafi myndast í mörgum minni háttar jarðskjálftum á löngu tímabili. Meta má hámarksstærð slíkra jarðskjálfta með því að gera ráð fyrir að öll færslan hafi orðið í einum skjálfta. Þá fæst vægisstærðin 6.7 (M_w).

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Paper 2

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RESEARCH ARTICLE

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

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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

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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

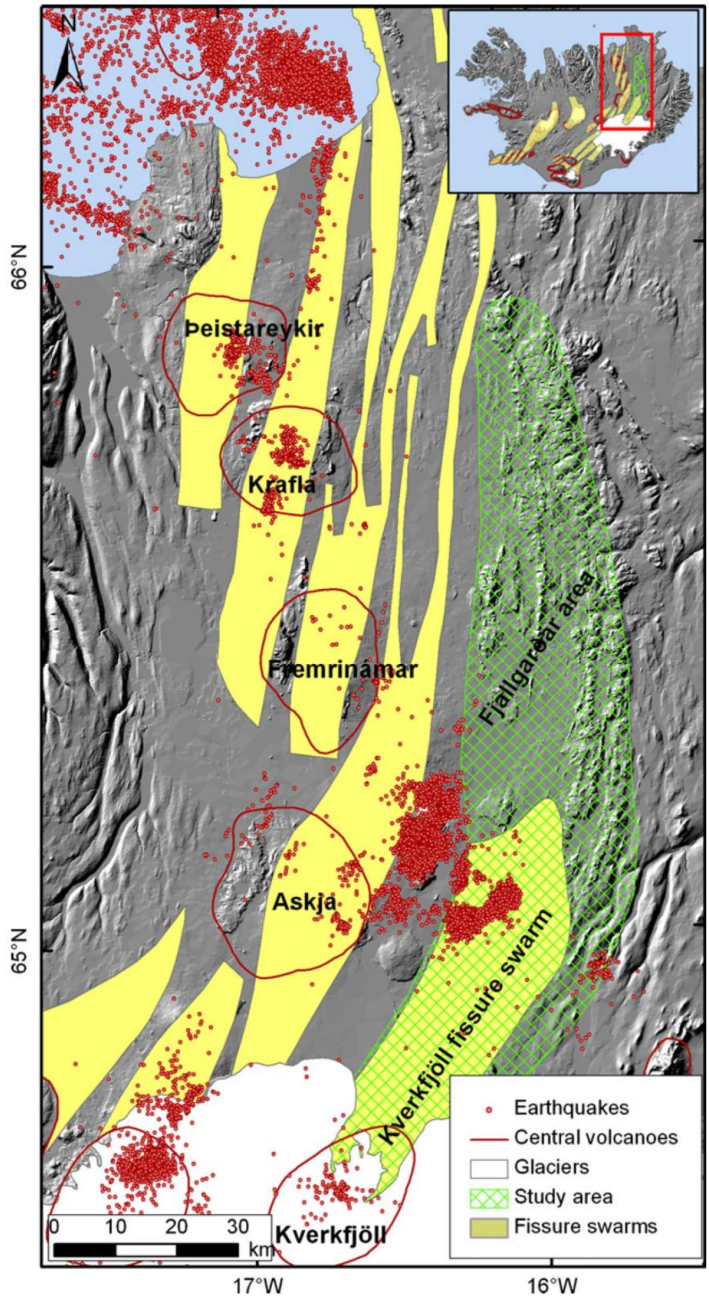


Fig. 1 The NVZ, Iceland. Delineations of the fissure swarms are from Einarsson and Sæmundsson (1987). Earthquake data for the time period of October 1991 to December 2009 are from the Icelandic Meteorological Office

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

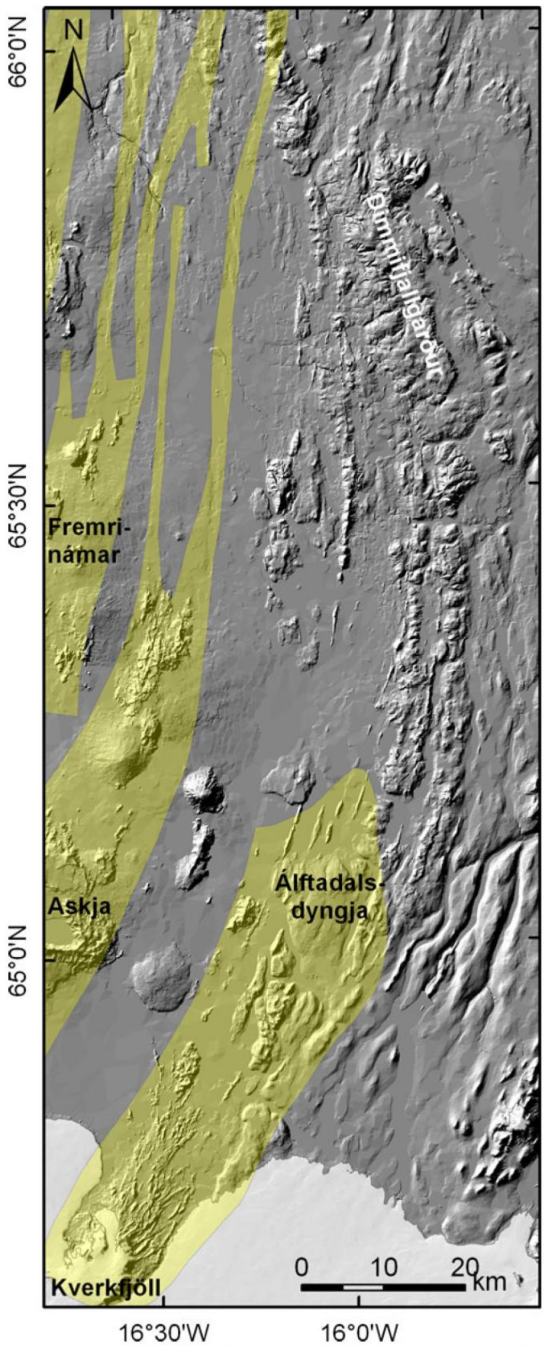


Fig. 2 The Kverkfjöll and Askja volcanic systems. Hyaloclastite ridges within the Kverkfjöll fissure swarm and the Fjallgarðar area are visible as sharp ridges and elongated mountains (such as the Dimmifjallgarður mountains) on the image. The *background* is from the National Land Survey of Iceland,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

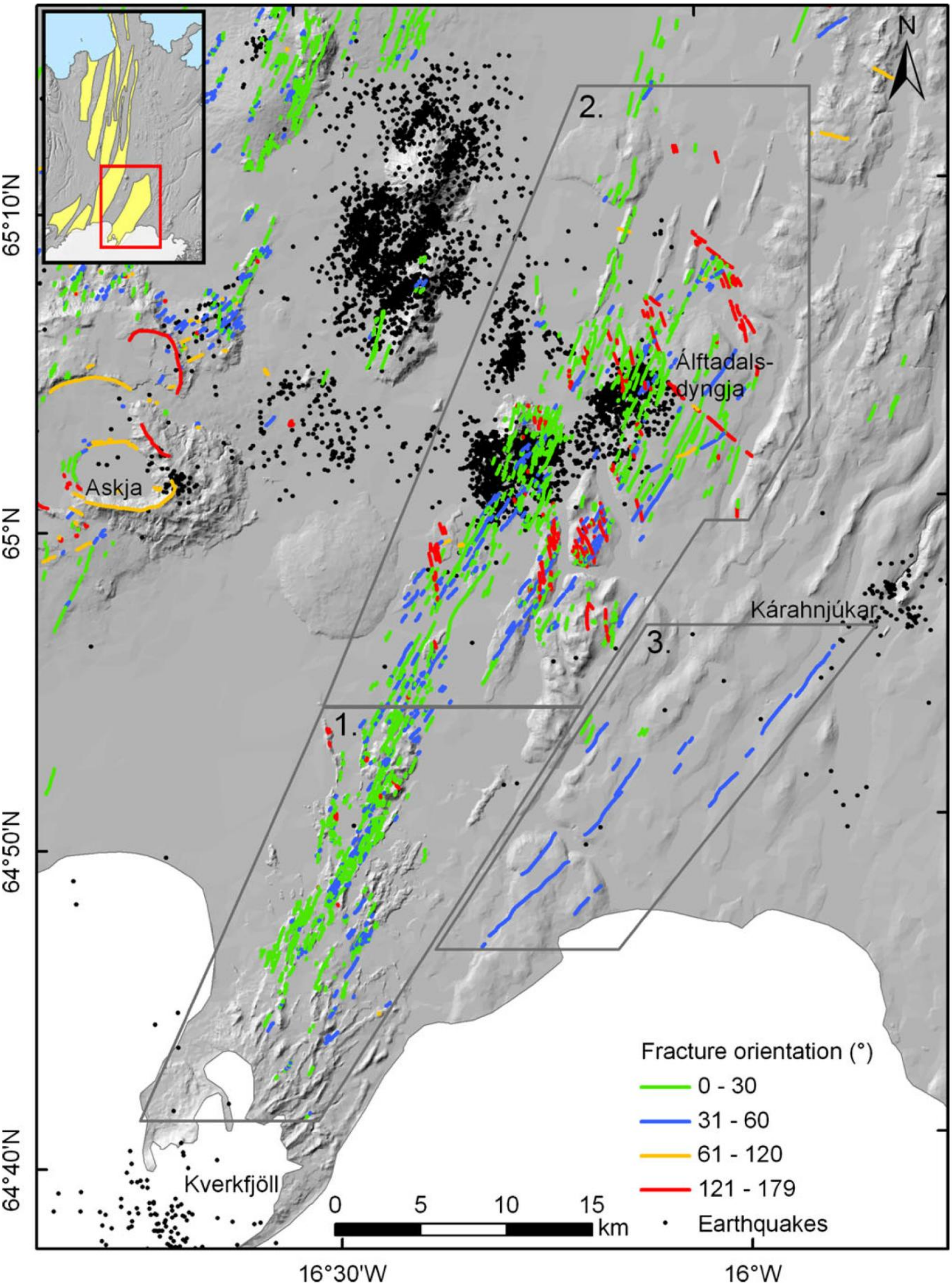
The two calderas of the Kverkfjöll central volcano are covered by a glacier. They are both elliptical in shape and about 8 km long and 5 km wide, although the orientation of their long axis is different. The long axis of the north caldera is NE–SW oriented, while it is NW–SE oriented in the south caldera (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.
1.
3.
Álftadals-
dyngja
Askja
Kárahnjúkar
Kverkfjöll
65°10'N
65°N
64°50'N
64°40'N
16°30'W
16°W
0 5 10 15 km
Fracture orientation (°)
0 - 30
31 - 60
61 - 120
121 - 179
Earthquakes

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).

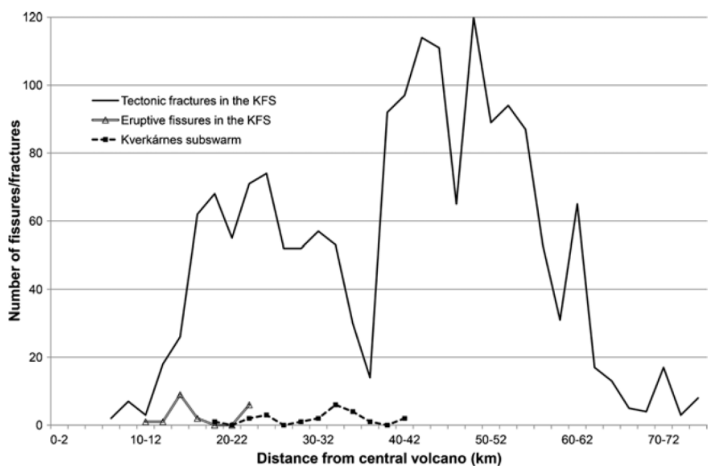


Fig. 4 The number of eruptive fissures and tectonic fractures with distance from the Kverkfjöll central volcano. The central volcano is covered with glacier. Therefore, no fractures were mapped in the immediate vicinity of the volcano. The number of fractures and fissures is calculated within 2-km-wide 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

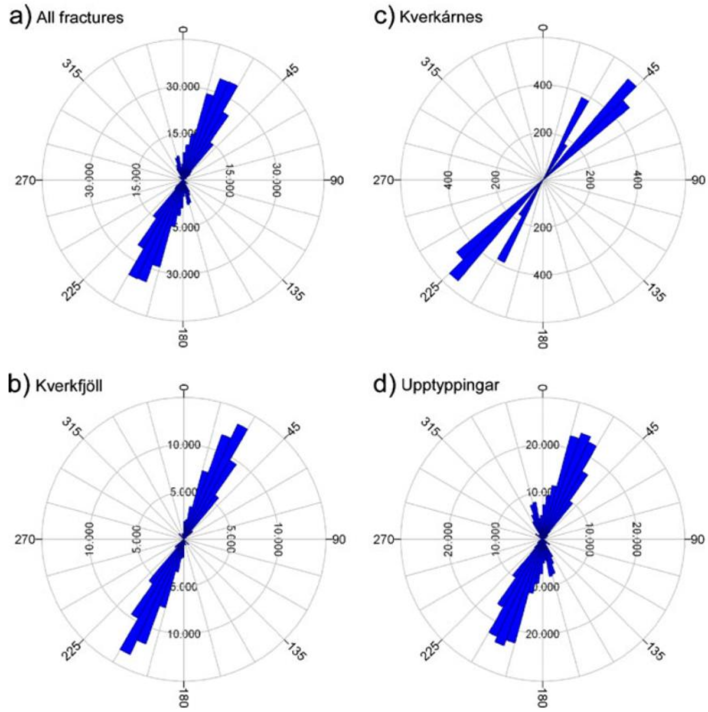


Fig. 5 **a** Orientations of fractures in the Kverkfjöll fissure swarm. *Numbers in rays* are the orientations in degrees. *Numbers in circles* represent the cumulative length (in meters) of fractures within each ray. *Rose diagrams* in (**b**), (**c**), and (**d**) represent the orientations of fractures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

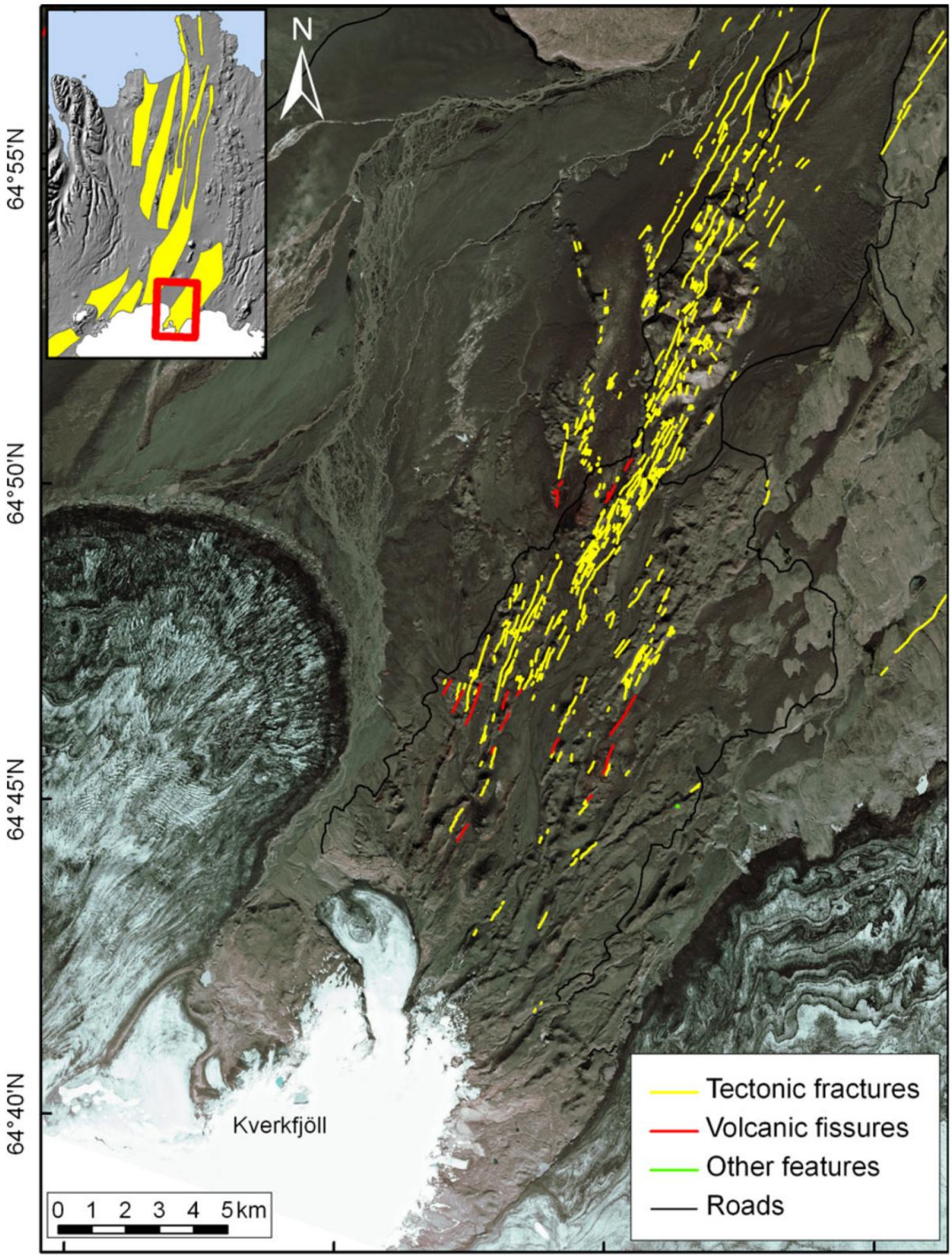


Fig. 6 The Kverkfjöll–Rani segment. The Kverkfjöll central volcano is located in the *SW corner* of the image. The satellite image is from SpotImage©

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

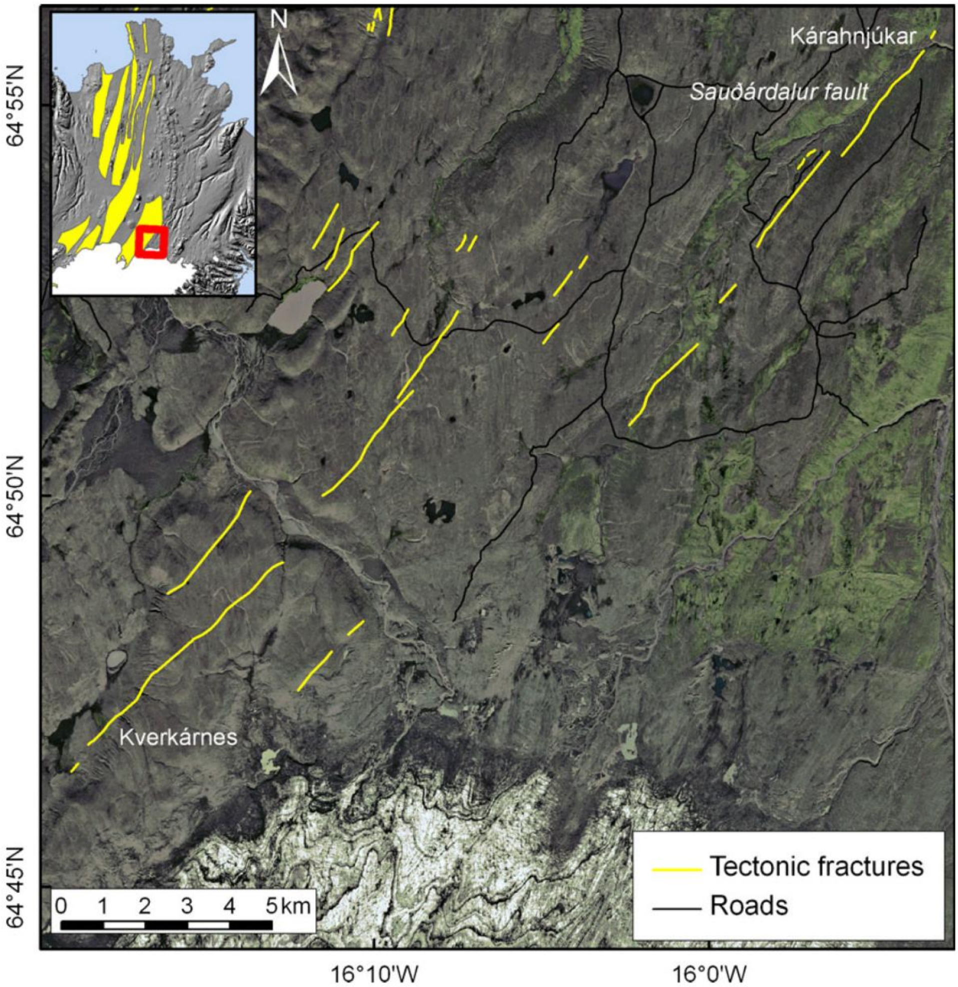


Fig. 7 The Kverkárnes subswarm. The satellite image is from SpotImage©

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

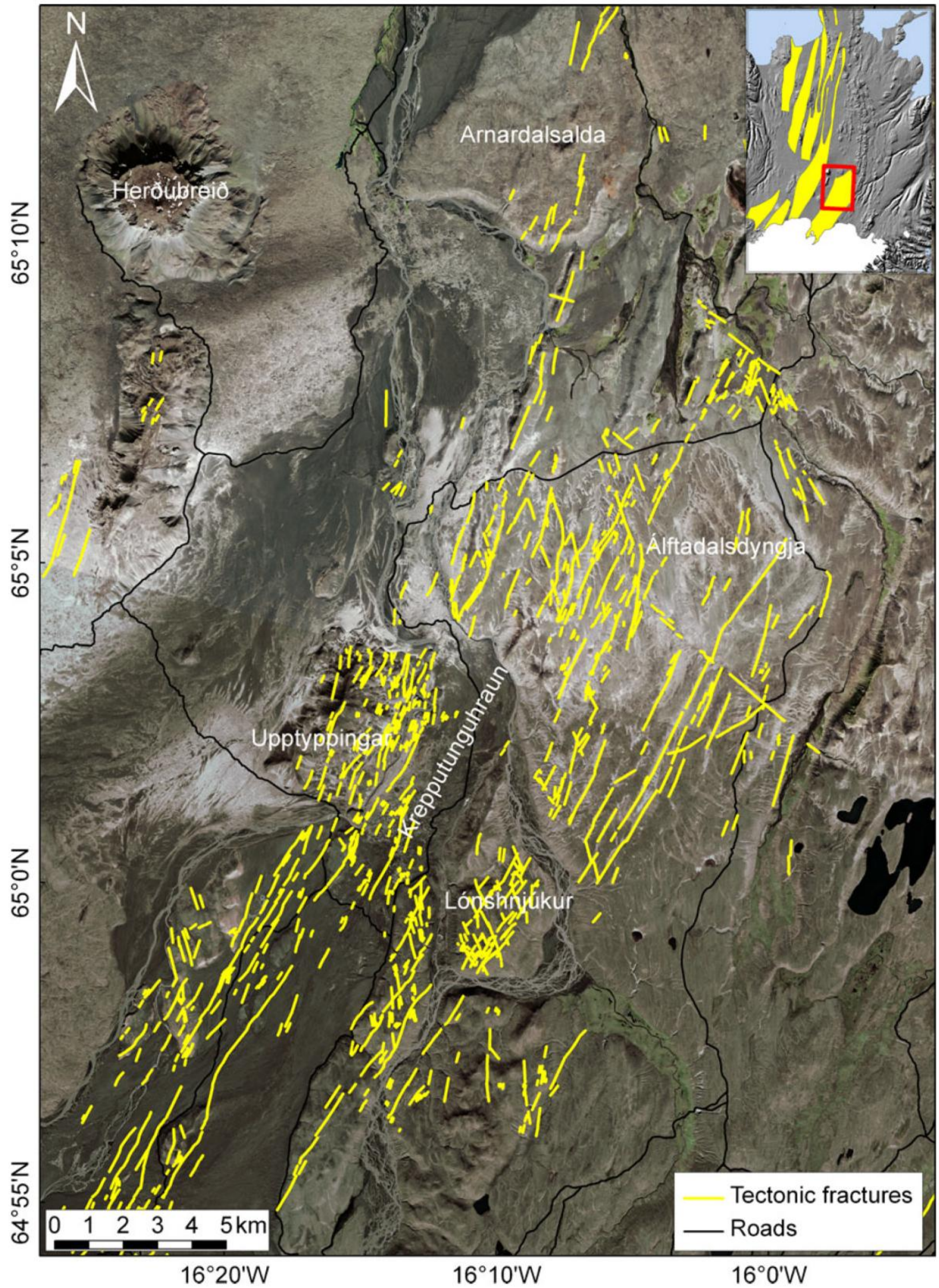


Fig. 8 Fractures in the Upptyppingar segment. No eruptive fissures were found in this area. The satellite image is from SpotImage©

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.

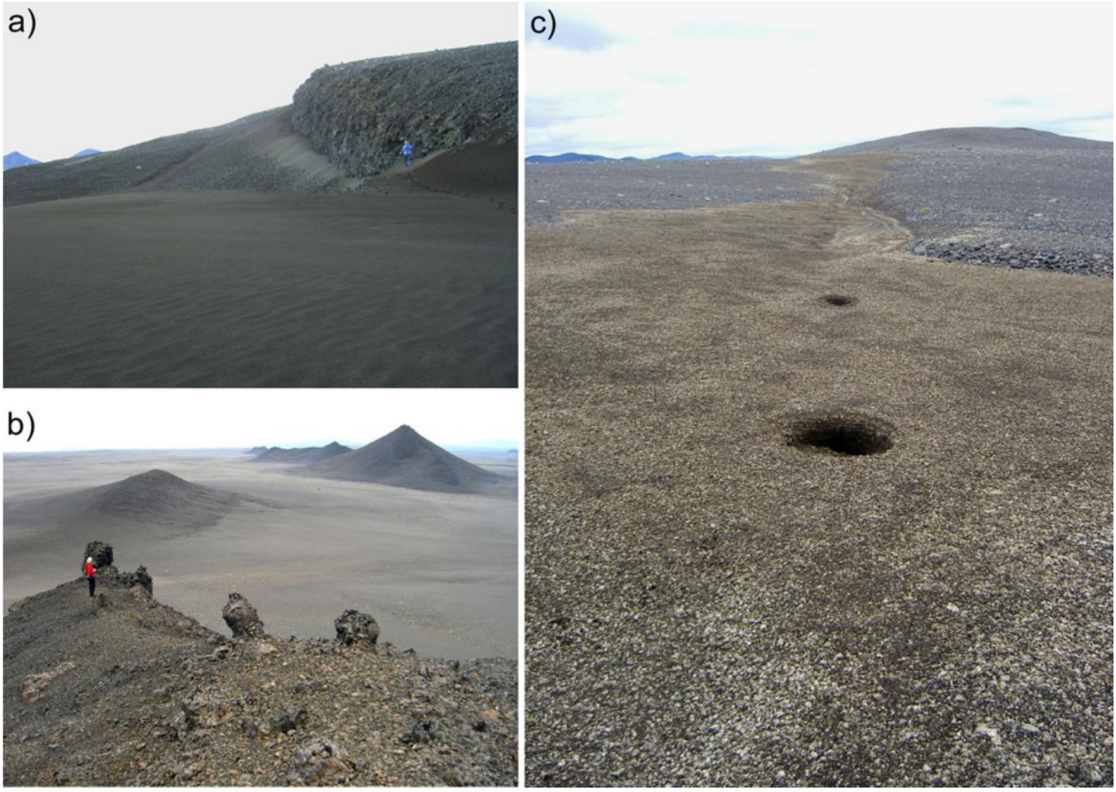


Fig. 9 **a** Normal fault south of Upptyppingar. **b** Hyaloclastite ridges with pillow lava on top in the southern Fjallgarðar area. **c** Normal fault with sinkholes southeast of Upptyppingar

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

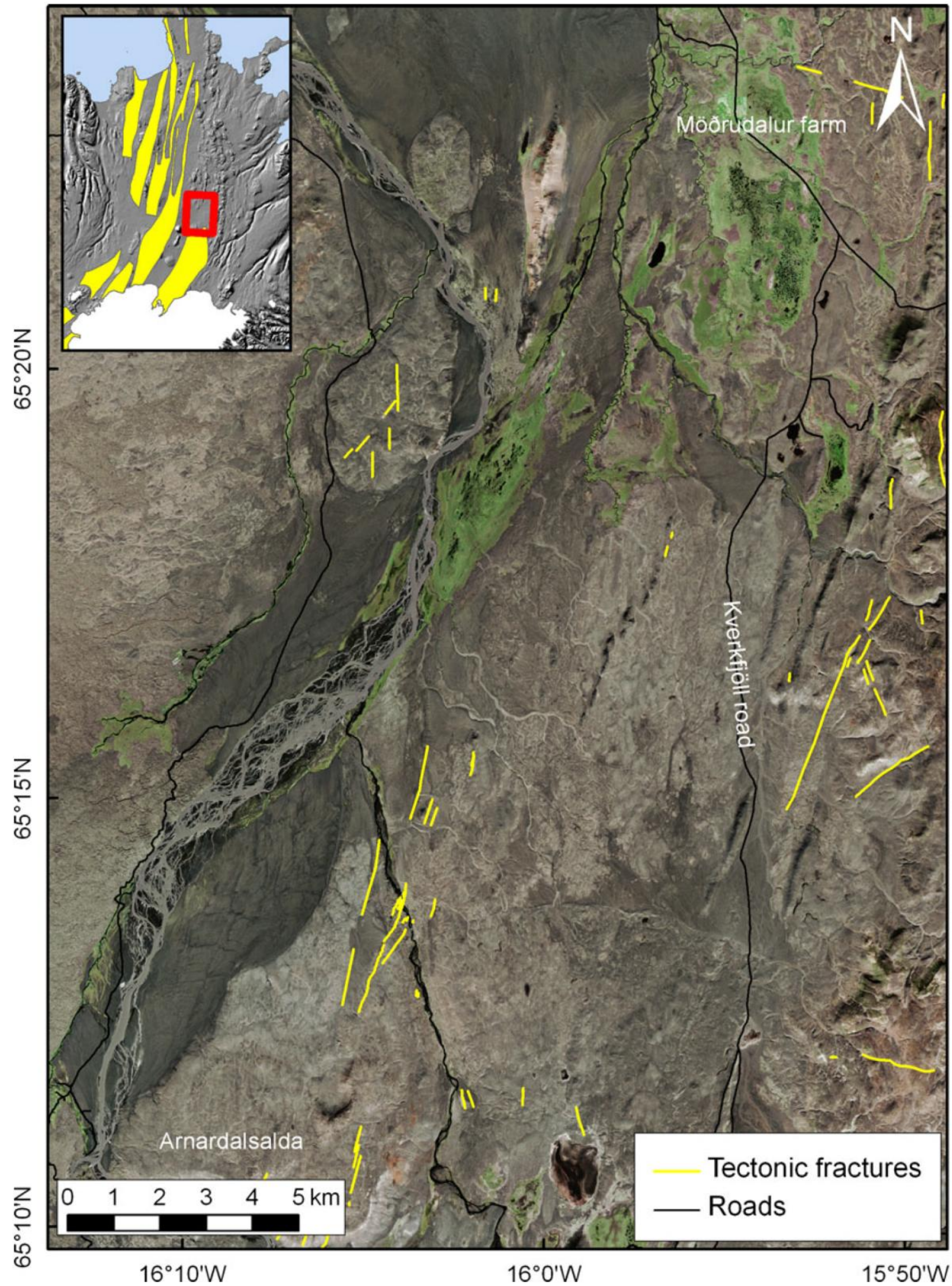


Fig. 10 The southern Fjallgarðar area. The satellite image is from SpotImage©

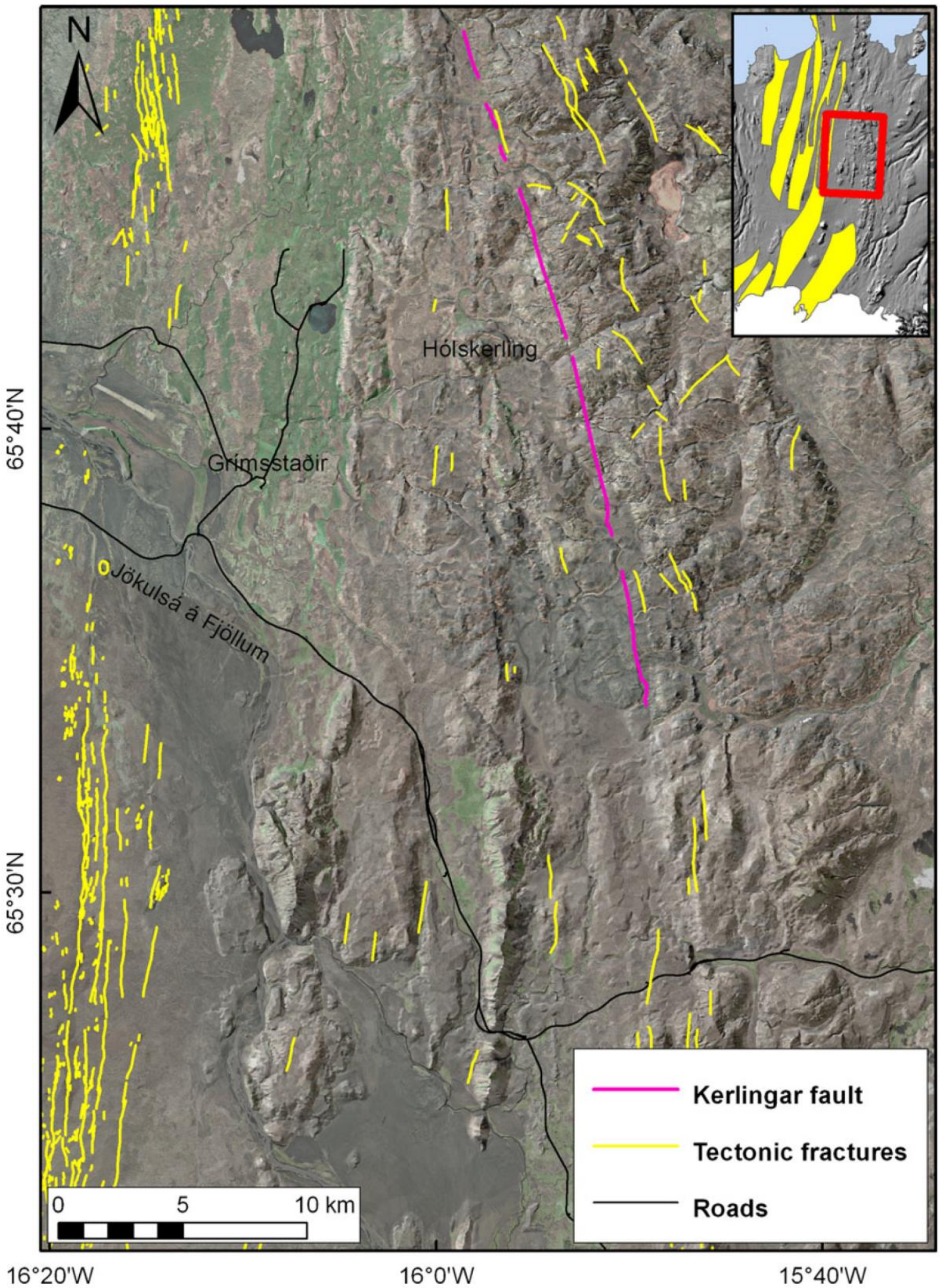


Fig. 11 The northern Fjallgarðar area. The satellite image is from SpotImage©

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

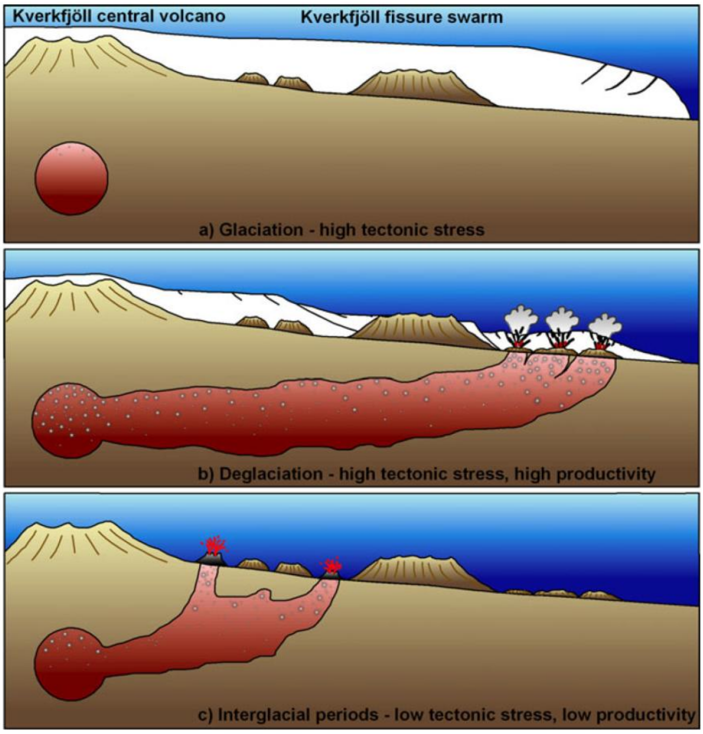


Fig. 12 Sketch of the suggested relationship between diking/magma productivity and glaciations in the Kverkfjöll fissure swarm. **a** During glaciation, there is less magma supply due to elevated overburden pressure. The less magma supply allows the tectonic component of the stress in the crust to rise 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).

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Paper 3

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RESEARCH ARTICLE

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

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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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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,

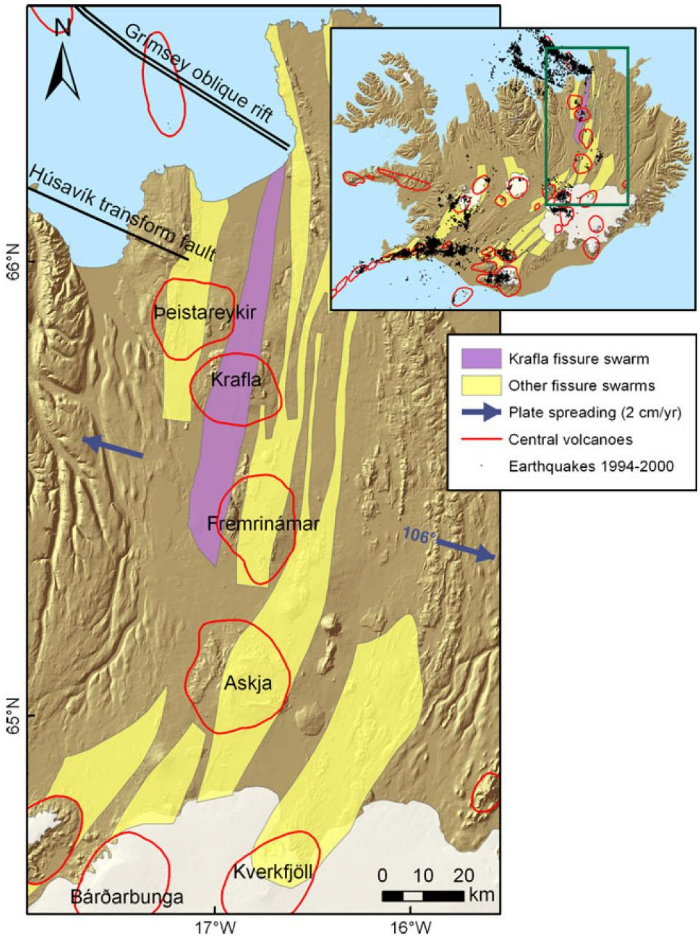

Fig. 1 The KFS and the Northern Volcanic Zone. *Green frame* in inserted figure shows the location of the Northern Volcanic Zone in Iceland. The outlines of fissure swarms and central volcanoes are from Einarsson and Sæmundsson (1987), the plate spreading direction of 106° (*blue arrows*) is calculated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

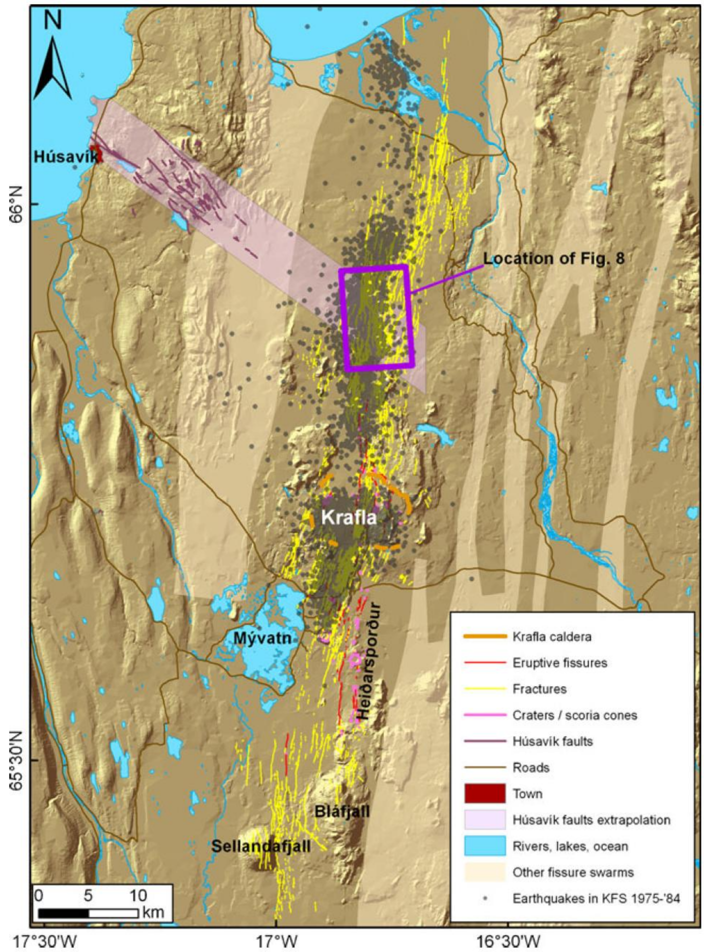

Fig. 2 Fractures and eruptive fissures in the KFS, and the Húsavík transform faults, as interpreted from aerial photographs. Earthquake data, indicating what parts of the KFS were activated during the Krafla rifting episode (1975–1984), is from Buck et al. (2006). The offset between the earthquakes and 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

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).

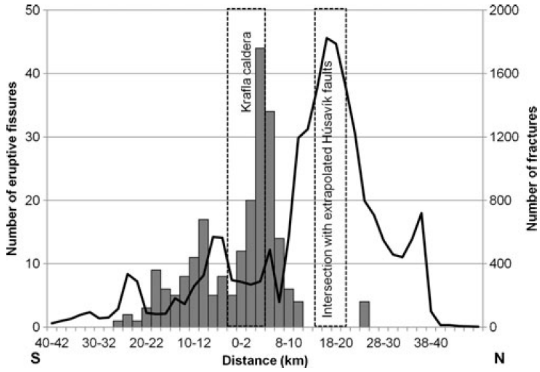

Fig. 3 Number density of fractures (or fracture segments; *black line*) and eruptive fissures (*grey columns*) in cross-swarm distance bins away north and south from the centre of the Krafla caldera. The position of the caldera is indicated by the *black dashed line* in centre of graph. The inferred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

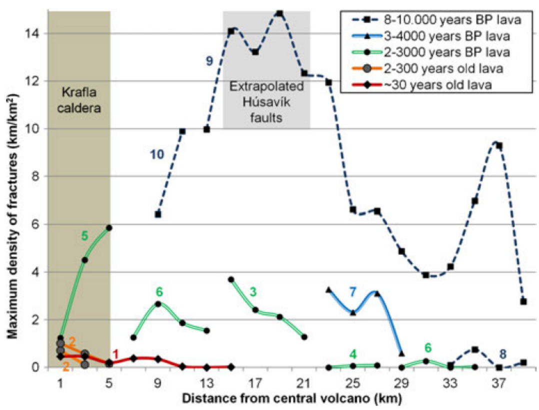

Fig. 4 Fracture densities within differently aged lava flow fields, denoted by numbers (Table 1). The area of the Krafla caldera is *shaded brown* and shows the portion of individual lava flow fields that are confined to the caldera. The inferred junction of the northern KFS with the extrapolated Húsavík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

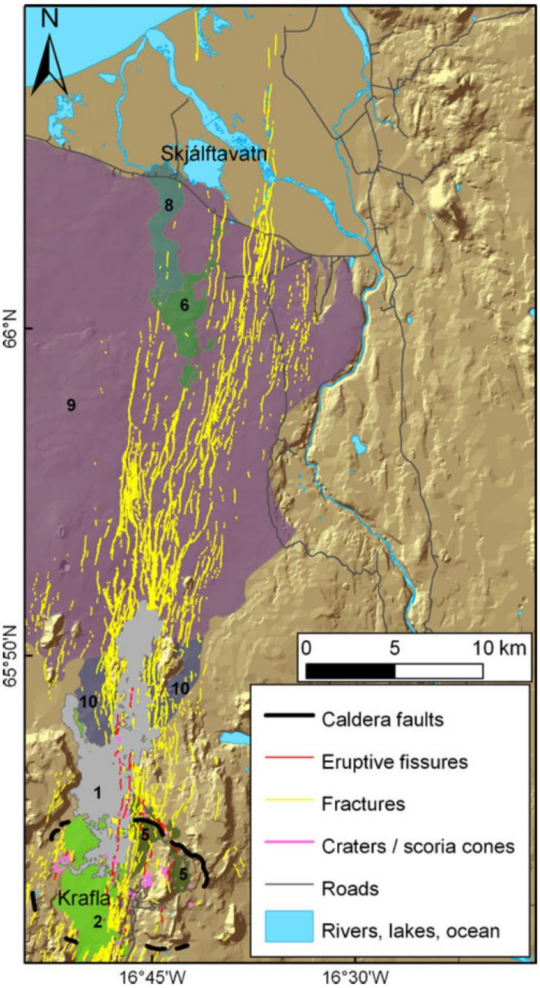

Fig. 5 Map of the northern KFS, where numbers denote individual lava flow fields (Table 1). The cartographic data is from the National Land Survey of Iceland, information on the extend of the lava flows is from Sæmundsson (1977, 1991) and Elíasson (1979)

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

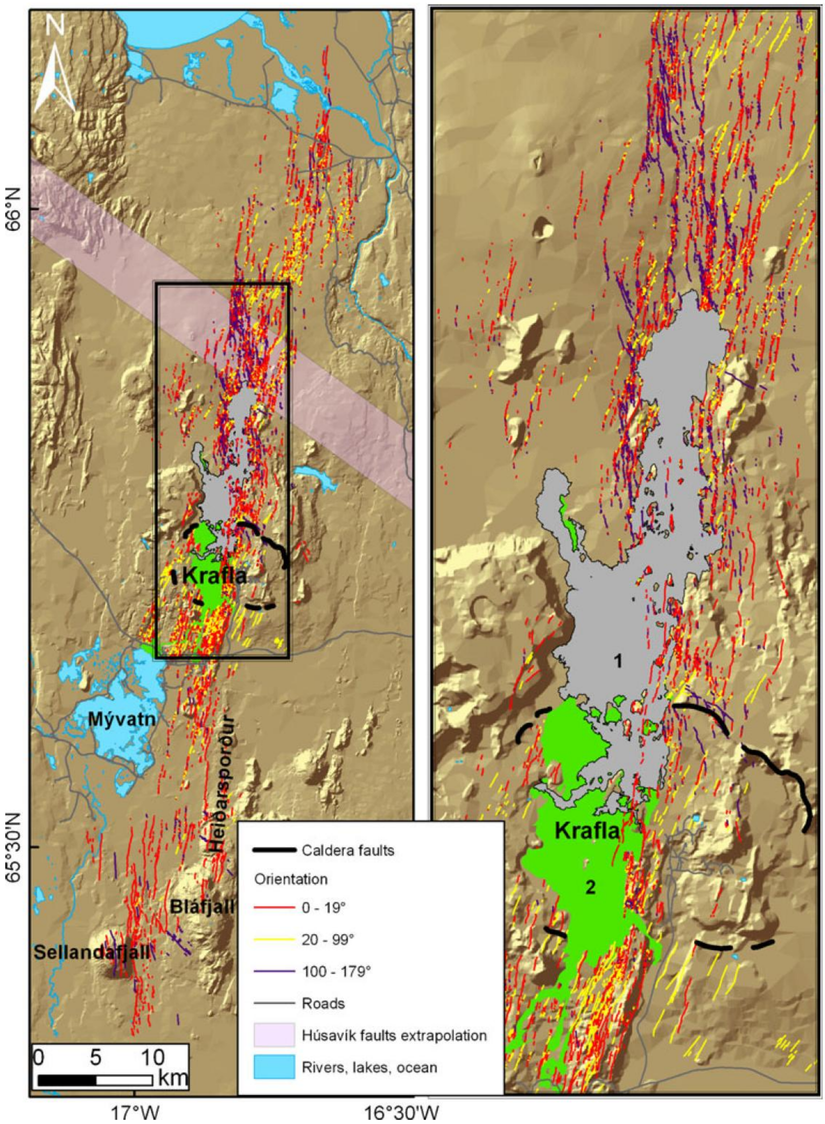

Fig. 6 Orientation of fractures and eruptive fissures within the KFS. *Black box* in the left-hand image outlines the extent of the right-hand image. The cartographic data are from the National Land Survey of Iceland

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

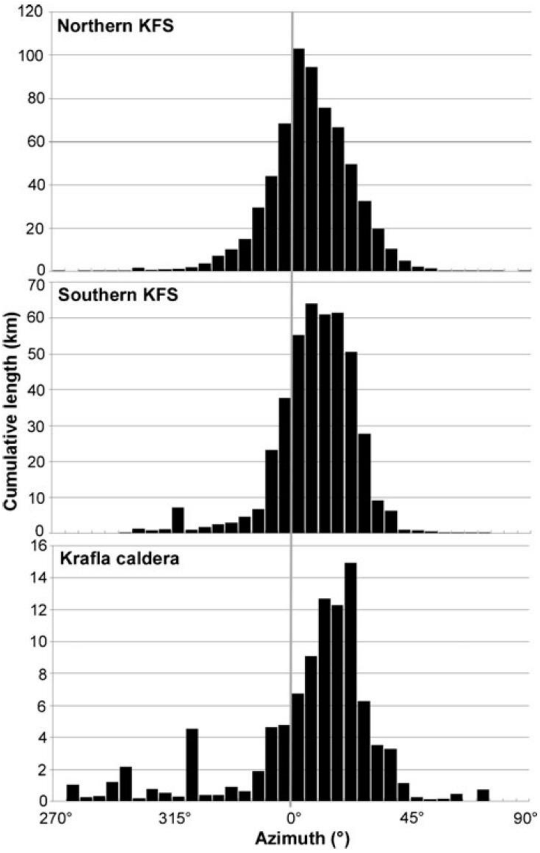

Fig. 7 Cumulative length of fractures relative to their orientations in the northern KFS, southern KFS and in the Krafla caldera. Orientations are given in 5° bins

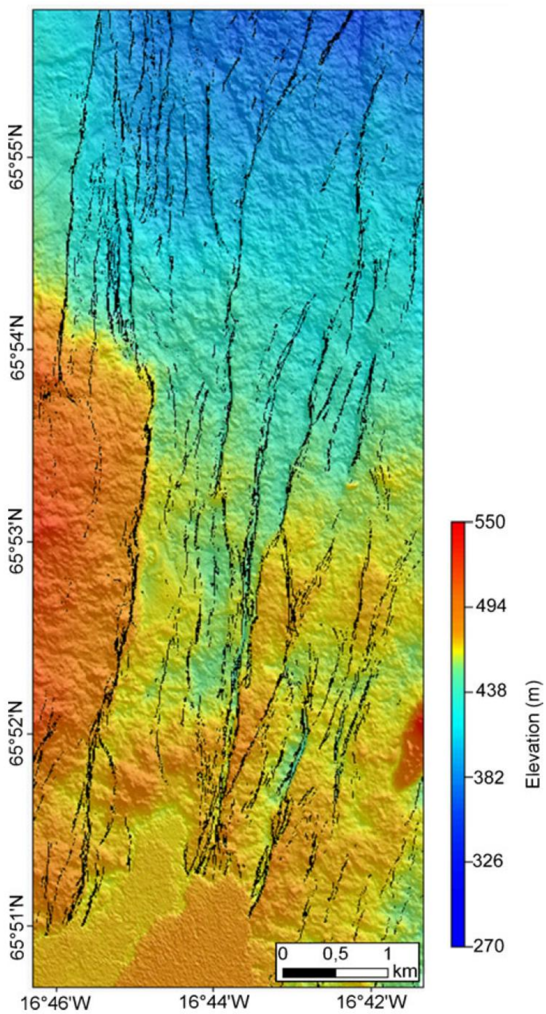

Fig. 8 The graben extending along the northern KFS as seen by LiDAR data and fractures in the area (*black lines*). See Fig. 2 for location

(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

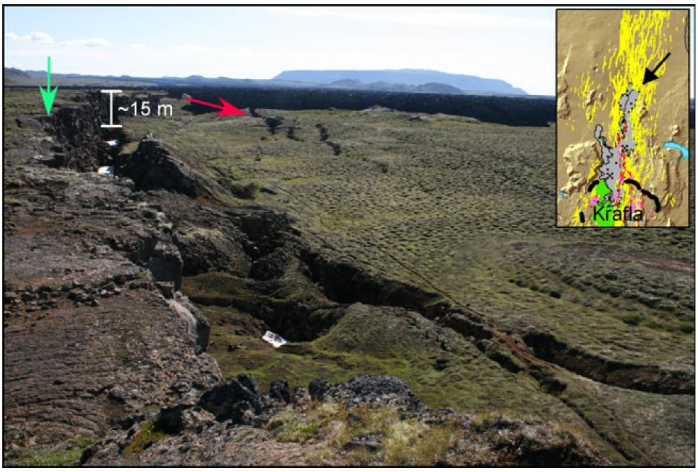

Fig. 9 The northern KFS with tension fractures (*red arrow*) and a graben bounding fault (*green arrow*), *white coloured number* indicates vertical offset of the fault. *Black arrow* in inserted map shows the view and location of the photo

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

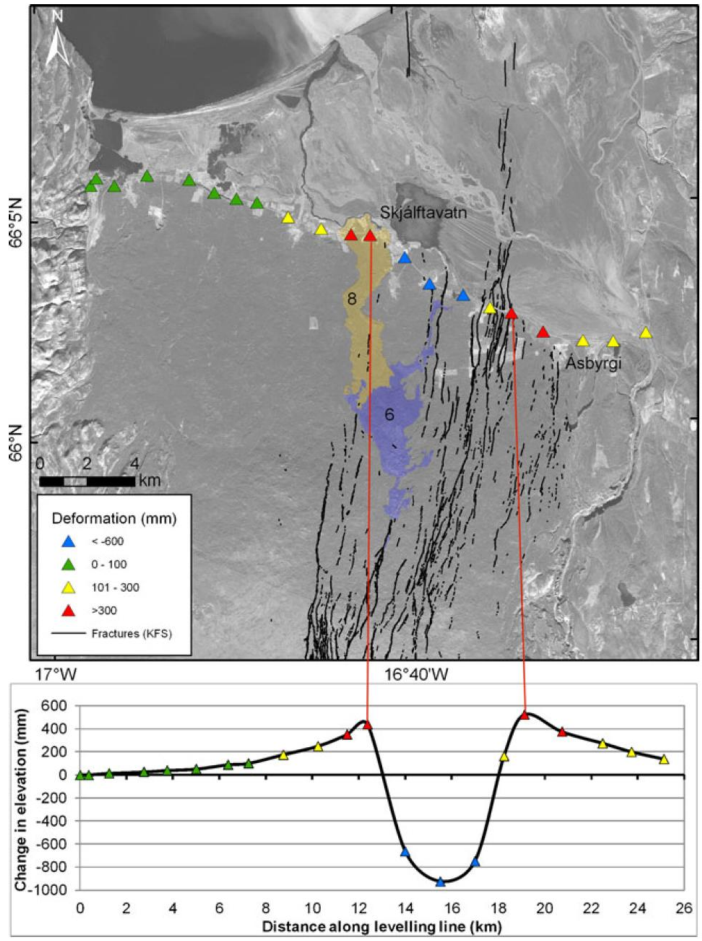

Fig. 10 The deformation that took place during a rifting event in the northernmost part of the KFS in January 1978. *Numbers* denote lava flows (Table 1). The graph is from Sigurðsson (1980)

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

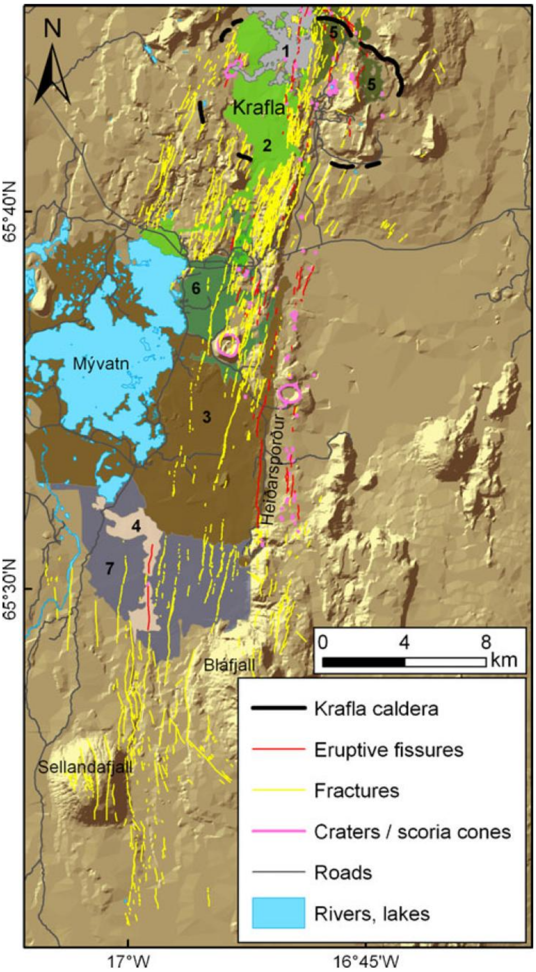

Fig. 11 The southern KFS. *Numbers* denote lava flows (Table 1). The cartographic data is from the National Land Survey of Iceland. Information on the extend of the lava flows is from Sæmundsson (1991), Þórarinsson (1951) and Höskuldsson et al. (2010)

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

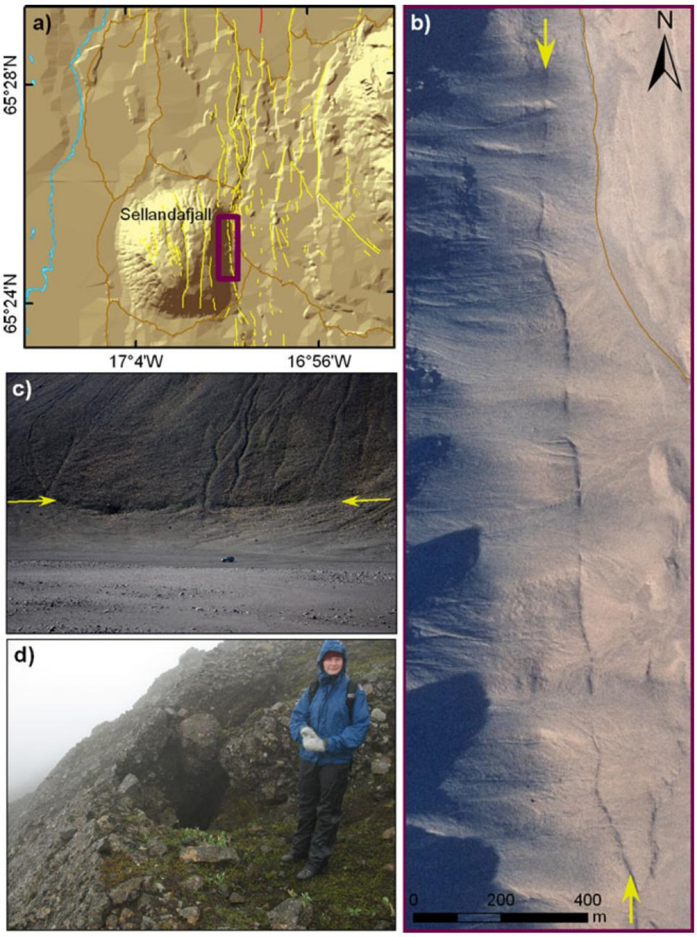

Fig. 12 A fault in the scree slopes of Mt. Sellandafjall (see location in Fig. 11). **a** The location of the fault (*purple* frame outlines frame **b**). **b** Aerial photograph showing the fault in the scree slopes, the photograph is from Loftmyndir©. **c** *Yellow arrows* pointing at the fault, see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

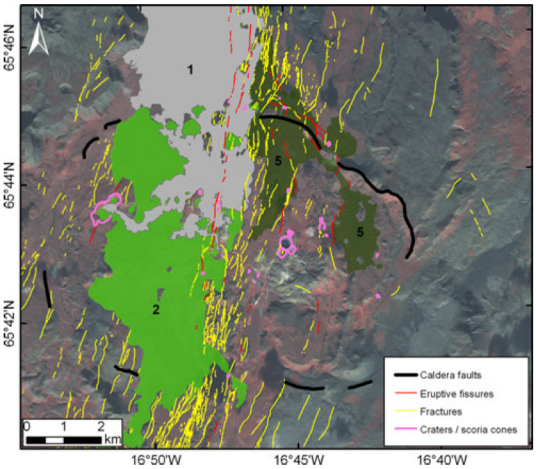

Fig. 13 Eruptive fissures and fractures in the Krafla caldera. *Numbers* denote lava flows (Table 1). Satellite image from SpotImage©

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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Paper 4

Hjartardóttir, Á.R., Einarsson, P., Magnúsdóttir, S., Björnsdóttir, Þ. and Brandsdóttir, B. Fracture systems of the Northern Volcanic Rift Zone, Iceland – An onshore part of the Mid-Atlantic plate boundary. Will be submitted to the Geological Society of London Special Publication issue on "Magmatic Rifting and Active Volcanism".

Fracture systems of the Northern Volcanic Rift Zone, Iceland – an onshore part of the Mid-Atlantic plate boundary

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Abstract

Iceland is the only subaerial part of the Mid-Atlantic plate boundary. It is raised above sea level by the interaction between a hotspot and the divergent plate boundary. The Northern Volcanic Rift Zone is the expression of the plate boundary in north Iceland. It is 200 km long and 50 km wide and is composed of 5-6 volcanic systems which are arranged in left stepping, en-echelon manner along the rift zone. Each volcanic system consists of a central volcano with a transecting fissure swarm. Eruptive fissures within the fissure swarms are most common at distances less than 20-30 km from the centre of the respective central volcano, while non-eruptive fractures characterize the distal parts of the fissure swarms. Fractures within the fissure swarms are generally subparallel to each other, with a N to NNE strike. More irregular orientations are present near the calderas in the rift zone; Askja and Krafla, and at the junction of the Northern Volcanic Rift Zone and the Tjörnes Fracture Zone. High fracture densities were also observed in the parts of the fissure swarms that were located at these junctions. East-west oriented fractures and eruptive fissures in the southernmost part of the Northern Volcanic Rift Zone are possibly related to stresses caused by load variations of the nearby Vatnajökull glacier. WNW-oriented fractures at the southern end of the Krafla Fissure Swarm, and in the northern end of the Kverkfjöll Fissure Swarm may be remnants of an almost extinct transform zone. The fissure swarms within the rift zone are for the most part seismically and geodetically inactive between rifting episodes, becoming highly active during rifting events that occur at time intervals of few hundred years.

Keywords:

Iceland, Northern Volcanic Rift Zone, rifting events, fissure swarm, divergent plate boundary

Introduction

Few parts of the World‘s divergent plate boundaries are subaerial. These parts include active rifts in eastern Africa (e.g. Corti 2009) and in Iceland (e.g. Einarsson 1991a; 2008) that therefore provide valuable information on divergent spreading processes, rifting and faulting.

In this study, fractures and Postglacial eruptive fissures in the Northern Volcanic Rift Zone (NVZ) were mapped and analysed to study the characteristics and behaviour of fissure swarms and rift zones (Fig. 1). These features were mostly mapped from aerial photographs, and in a few instances, satellite images. This is the first paper presenting a detailed fracture map of this entire plate boundary segment. However, several studies have been made of individual fissure swarms (e.g. Opheim and Guðmundsson 1989; Guðmundsson and Bäckström 1991; Tentler and Mazzoli 2005; Hjartardóttir et al. 2009; Magnúsdóttir and Brandsdóttir 2011; Hjartardóttir et al. 2012; Hjartardóttir and Einarsson 2012; Björnsdóttir and Einarsson (submitted 2012)). Similar studies have been published on other segments, the Reykjanes Peninsula Oblique Rift, the Western Volcanic Zone and the South Iceland Seismic Zone (Fig. 1) (e.g. Guðmundsson 1987; Clifton and Schlische 2003; Clifton and Kattenhorn 2006; Einarsson 2010).

The NVZ is a 200 km long boundary segment extending from the central area of the Iceland hotspot to the Tjörnes Fracture Zone. The zone consists of several volcanic systems with central volcanoes and transecting fissure swarms (Fig. 1) (Sæmundsson 1974). The fissure swarms contain a high density of fractures and eruptive fissures, the latter becoming more common closer to the central volcanoes. The Icelandic volcanic systems with their fissure swarms and underlying dyke swarms are identical to the structural elements termed “magmatic segments” in the Main Ethiopian Rift (e.g. Ebinger and Casey 2001).

Here we show that deformation and eruptive activity in the fissure swarms of the NVZ, as indicated by density of eruptive fissures and fractures in similarly-aged lava flows, is generally highest in the parts of the fissure swarms that are closer to the central volcanoes. Similarly, deformation peaks are observed at the junctions between fissure swarms and transform zones, even in the Krafla Fissure Swarm, where surface traces of the Húsavík Transform Zone do not extend to the fissure swarm. The orientation of fractures in the fissure swarms of the NVZ is generally subparallel to the plate spreading vector. Deviations from this pattern occur mainly close to calderas, near the Vatnajökull glacier and at the junctions with transform zones.

Regional settings

The part of the mid-Atlantic plate boundary which crosses Iceland is characterized by transform fault zones and volcanic zones (Einarsson 2008). In southern Iceland, the spreading is taken up by three volcanic zones, the Eastern and Western Volcanic Zones and the Reykjanes Peninsula Oblique Rift, along with the South Iceland Seismic Zone, a transform zone which connects these volcanic zones (Fig. 1). The plate boundary in Northern Iceland is simpler, as the plate spreading there is only taken up by the Northern Volcanic Rift Zone (NVZ), and the transform Tjörnes Fracture Zone north of the NVZ including the Grímsey Oblique Rift and the Húsavík Transform Zone (Fig. 1). The centre of the Iceland hotspot is located at the southern part the NVZ, in central Iceland (Wolfe et al. 1997).

Even though the far-field spreading rate of ~2 cm/yr is constant (DeMets et al. 1994), the spreading in individual fissure swarms is episodic (Sæmundsson 1978; Heki et al. 1993). This occurs as fractures within the fissure swarms are mainly activated during rifting events, when magma intrudes the fissure swarms to form dykes, or even fissure eruptions (e.g. Sæmundsson 1978; Sigmundsson 2006). Historically documented rifting events within the NVZ have occurred within the Krafla Volcanic System (1975-1984 and 1724-1729), within the Askja Volcanic System (1875-1876), and within the Þeistareykir Volcanic System (1618 and possibly also in 1885) (Sæmundsson 1907; Elíasson 1976; Björnsson et al. 1977; Sigurðsson and Sparks 1978; Sæmundsson 1991; Einarsson 1991a; 1991b; Magnúsdóttir and Brandsdóttir 2011). The last Krafla rifting episode was instrumentally monitored and observed (e.g. Brandsdóttir and Einarsson 1979; Einarsson and Brandsdóttir 1980; Sigurðsson 1980; Hauksson 1983; Tryggvason 1994).

Seismic activity in the NVZ is restricted to several well-defined zones, often within the central volcanoes, or at the transform zones (Fig. 1). Some have been persistently active since the start of seismic measurements in the 1960s and 1970s, e.g. clusters within the Tjörnes Fracture Zone (Einarsson 1976) and near the Askja and Bárðarbunga Central Volcanoes (Einarsson 1991a). Other seismic clusters, such as near Upptyppingar in 2007 and 2008, are isolated events most likely associated with magmatic intrusions (Fig. 1) (e.g. Jakobsdóttir 2008; Jakobsdóttir et al. 2008; Hooper et al. 2011). Currently, geodetic measurements indicate local subsidence both within the Krafla and Askja calderas (e.g. Sturkell et al. 2006; Pedersen et al. 2009; Rymer et al. 2010). On the other hand, uplift has been detected just north of the Krafla Central Volcano and in the vicinity of the Þeistareykir Central Volcano (Zeeuw-van Dalfsen et al. 2004; Metzger et al. 2011).

Methods

Fractures and eruptive fissures in the NVZ were mapped from aerial photographs. Satellite images were used for a more comprehensive view, and ground truthing was conducted during numerous field studies. In total, we mapped 46,611 eruptive fissures, fractures and fracture segments.

The ArcGIS software was used to map the fractures and the eruptive fissures from aerial photographs, acquired from the National Land Survey of Iceland (Landmælingar), and from Aerial Photographs Inc. (Loftmyndir ehf.). Contact images from Landmælingar were used to map a part of the northern fissure swarm of Askja, the Fremrinámar Central Volcano as well as to map the Kverkfjöll Fissure Swarm (Fig. 2). These images were taken at an altitude of about 6000 m. Since the images acquired were not stereo-pairs, a 3D viewing was not done. Digital aerial photographs from Loftmyndir were used to map other parts of the NVZ. These images have a resolution of 0.5 m/pixel, except images of villages, which have a resolution of 0.15 m/pixel. Differences in light and contrast which affect the quality and clarity of individual images, also decrease image resolution. We used ASTER and SPOT 5 satellite images to investigate larger features within the study area.

Field trips were made to parts of all the fissure swarms within the NVZ. Some areas were studied specifically, such as the junction of the NVZ and the Grímsey Oblique Rift, the Krafla Fissure Swarm and the southernmost part of the Bárðarbunga Fissure Swarm, where anomalous E-W oriented fractures and eruptive fissures are located. During the field trips, lineaments which had been found on aerial photographs, but had an uncertain origin were studied specifically. Features on aerial photographs that were clearly fractures or eruptive fissures were also visited for comparison with aerial photographs. Papers on the Krafla, Askja and Kverkfjöll Fissure Swarms and on the Kerlingar Fault have already been published as a part of this project (Hjartardóttir et al. 2009; Hjartardóttir et al. 2010; Hjartardóttir et al. 2012; Hjartardóttir and Einarsson 2012).

Earthquake data from the Icelandic Meteorological Office, extending between the years of 1991 and 2012, were used to identify active fractures in the NVZ. Only earthquakes with the rms of the arrival time residuals less than 0.2 s were used. Earthquake data from the Krafla Fissure Swarm during the Krafla rifting episode in 1975-1984 were also used, to illuminate where deformation occurred in the fissure swarm. The uncertainty in horizontal location of the Krafla earthquakes is about 1-3 km.

In order to map the variation in fracture orientation and distribution along each volcanic system, each fissure swarm was divided into 2 km wide transects, oriented parallel to the plate spreading vector (106°) as calculated from DeMets et al. (1994). To calculate fracture density in similarly-aged lava flows in the Askja Fissure Swarm, the "Line Density" tool in ArcToolbox was used. The tool finds the cumulative measured fracture lengths within a given search circle (0.5 km in radius) and divides the cumulative fracture lengths by the area of the circle. A raster file is created from these calculations, with 0.5 km pixels. Such calculations were made for fractures within differently-aged lava flows in the Askja Fissure Swarm, where the maximum fracture density in each of the 2 km wide grids were found.

Structural architecture

Overview

The NVZ is characterized by fissure swarms, strike-slip faults and boundary faults or tindars (also termed hyaloclastite ridges). The fissure swarms constitute the main part of the NVZ. They are situated in the centre of the NVZ, arranged in an en echelon pattern and are often striking nearly perpendicular to the spreading vector (106°) (Figs. 2 and 3). The eastern edge of the NVZ is characterized by an arc-shaped elongated area of tindars. However, the western edge of the NVZ has no such feature. The northern part of the western edge is characterized by large-offset normal faults, while the southern part shows no evidence of large-scale faulting. In the northern part of the NVZ, the zone meets with two strike-slip zones; the Húsavík Transform Zone and the Grímsey Oblique Rift. Below, we will address these different types of fracture systems in the NVZ.

A fissure swarm extends from each of the ~5-6 central volcanoes in the NVZ (Fig. 1). Two additional central volcanoes have been suggested to exist within the NVZ, Heiðarsporður and Hrúthálsar, located within the Krafla and Askja Fissure Swarms, respectively (Sæmundsson 1974; Jóhannesson and Sæmundsson 1998; Sæmundsson et al. 2005). The Tungnafellsjökull Fissure Swarm, at the southern boundary of the NVZ, is also included in this study.

Fissure swarms

The fissure swarms in the NVZ extend tens of kilometres away from the central volcanoes (Fig. 1). In most cases, it is difficult to estimate their exact length, as they disappear beneath glaciers or below sea level. However, they may extend from the central volcanoes as short distances as 30 km (Tungnafellsjökull) or as long distances as 125 km (Fremrinámar). The other fissure swarms, Þeistareykir, Krafla, Kverkfjöll, Askja and Bárðarbunga are at least 40, 50, 60, 120 and 90 km long, respectively (Fig. 1).

The fissure swarms are narrow features, 0.5-15 km in width. They are generally wider adjacent to the central volcanoes (except at Fremrinámar) (Fig. 1). The narrowest part of a fissure swarm within the NVZ is in the Melrakkaslétta Peninsula (Fig. 1). There, narrow grabens (often less than 1 km in width), extending from the Askja and/or Fremrinámar Central Volcanoes (Einarsson and Sæmundsson 1987), cut the peninsula.

The density of eruptive fissures within the fissure swarms is greatest close (<20-30 km) to the central volcanoes (Fig. 4). This applies to the Krafla, Fremrinámar, Askja, Kverkfjöll and Bárðarbunga Fissure Swarms. The Krafla and Askja Central Volcanoes, both located in the central part of the NVZ, have the highest density of eruptive fissures. Those two volcanoes are also the only volcanoes within the NVZ where numerous eruptions have taken place during the ~1200 years of historical time in Iceland (Thordarson and Larsen 2007). However, the fissure swarms at the western boundary of the NVZ have either no

Postglacial eruptive fissures (Þeistareykir) or just one (Tungnafellsjökull). Eruptive activity in the Þeistareykir Volcanic System is primarily in the form of lava shields. The lack of eruptive fissures in the Þeistareykir Fissure Swarm is notable given the high density of fractures there (Fig. 4).

The density of non-eruptive fractures is often greater closer to the central volcanoes, although the fracture density is lower where the density of eruptive fissures is high, i.e. where younger lava flows have covered fractures (Fig. 4). Nevertheless, fracture density in some of the fissure swarms does not show this pattern, such as in the Bárðarbunga, Fremrinámar and (to some extent) the Kverkfjöll Fissure Swarms (Fig. 4).

Fractures of the fissure swarms within the NVZ often strike close to perpendicular to the spreading vector (Fig. 2). Exceptions from this occur mainly within the central and northern Þeistareykir Fissure Swarm, in the area where the Húsavík Transform Zone intersects the fissure swarm, and in the southernmost Tungnafellsjökull Fissure Swarm, which is generally north-easterly trending (Fig. 2). The anomalous orientation in the southern Tungnafellsjökull Fissure Swarm is probably an expression of its tectonic position at the triple junction in Central Iceland. In general, fewer of the fractures are close to being perpendicular to the spreading vector north of the transform faulted areas (Grímsey Oblique Rift and the Húsavík Transform Zone) than south of these areas (Fig. 3). Fracture populations with orientations that deviate from the general strike of fractures in the NVZ can be found, as an example near the Askja Central Volcano (Fig. 5). There, the fractures or eruptive fissures form a fan-like structure from the outer border of the calderas, or are arcuate around them (Hjartardóttir et al. 2009). Other examples involve WNW oriented fractures which are found in various areas within the NVZ; in the southernmost Krafla Fissure Swarm, in the northernmost Kverkfjöll Fissure Swarm, and in southern Melrakkaslétta, close to the Fremrinámar and Askja Fissure Swarms (Fig. 5). Those features are considerably more eroded than the general N to NNE-oriented fractures within the fissure swarms. WNW-oriented fractures are also found in the continuation of both the Húsavík Transform Zone, and in the continuation of the Grímsey Oblique Rift. The third example involves east-west oriented fractures and eruptive fissures in the Bárðarbunga Fissure Swarm, located in the southernmost part of the NVZ; at Hrímalda and Urðarháls (Figs. 2 and 6).

Faults at the east and west boundaries of the NVZ

Several parallel tindars, indicating subglacial fissure eruptions, mark the eastern NVZ boundary (Fig. 1). The ~30 km long Kerlingar Fault, situated at the northern part of the boundary, has been suggested to have been activated early in Postglacial times, due to deglaciation (Hjartardóttir et al. 2010).

There is no clear evidence of similar faults or tindars at the western NVZ boundary except possibly in the northern part, where large offset normal faults are located. Those faults are likely a part of the Þeistareykir Fissure Swarm.

Rift-transform intersections

The Húsavík Transform Zone and the Grímsey Oblique Rift are located in or close to northern NVZ (Fig. 1). The Húsavík Transform Zone is both located onshore and offshore (Figs. 1 and 7). The subaerial part of it consists of large–offset faults, extending between the town of Húsavík, and the Þeistareykir Fissure Swarm (Fig. 7). However, the eastward extension of it is less known. It has been suggested by Sæmundsson (1974), that traces of the fault extend farther eastwards than can be seen from the surface strike-slip fractures. High variations in fracture orientations, which occur due to widening of a graben, and high densities of fractures at the junction of the Krafla Fissure Swarm and the continuation of the Húsavík Transform Zone support this suggestion (Figs. 2, 4 and 7) (Hjartardóttir et al. 2012).

Anomalies in fracture orientations are also seen at the junction of the Þeistareykir Fissure Swarm and the Húsavík Transform Zone. Several fractures in the Þeistareykir Fissure Swarm bend from the N-S orientation to the NW-SE orientation, until they merge with the Húsavík Transform Zone (Fig. 7). In general, the fracture orientations within the Þeistareykir Fissure Swarm are more variable in the central and north part of the fissure swarm, which is where it joins with the Húsavík Transform Zone, than in the south part of the fissure swarm (Fig. 2). The highest density of fractures within the Fremrinámar Fissure Swarm also occurs at its junction with the Grímsey Oblique Rift (Fig. 4).

The Grímsey Oblique Rift is mostly offshore. Its existence is mainly evident from intense seismic activity extending offshore from the SE corner of the Öxarfjörður bay towards the northwest (Figs. 1 and 8) (Einarsson 1976; Einarsson 1991a). However, there are WNW oriented fractures situated in the southern part of the Melrakkaslétta Peninsula, which may be related to this fault zone (Fig. 8). Such a link has previously been suggested by Mamula and Voight (1985). In one of the WNW-oriented lineaments, an en-echelon fracture pattern was found (Fig. 8), which is typically found in strike-slip faults (e.g. Einarsson 2010).

Discussion

General

We have mapped the fracture systems that constitute the NVZ, along with the onshore part of two strike-slip zones that link the NVZ with the Kolbeinsey ridge to the north. The southern end of the NVZ is situated at the northern border of the Vatnajökull glacier. However, the volcanic zone continues below the glacier, to the triple junction where it joins with the Eastern Volcanic Zone (EVZ) and the Central Iceland Volcanic Zone (Fig. 1).

The NVZ shows similarities to other rift zones that have a long-axis oriented close to perpendicular to the spreading vector, such as the northern part of the continental Main Ethiopian Rift. In both rift zones, fissure swarms are arranged in en-echelon manner, enveloped by border faults or, as in the case of the NVZ, by tindars. The highest lava productivity in each fissure swarm is found in the central part of the fissure swarms (Sæmundsson 1978; Kurz et al. 2007). Although the fissure swarms are close to being perpendicular to the spreading direction, the border faults are often oblique to it (Ebinger and Casey 2001; Kurz et al. 2007). Similar pattern of en-echelon volcanic systems, with normal faults at the boundaries of the rift zone, can also be found at the Reykjanes Ridge (e.g. Searle and Laughton 1981).

Eruptions and dyking within the fissure swarms

Eruptive fissures within the fissure swarms of the NVZ are most common within 20-30 km distance from the central volcanoes, while the distal parts of the fissure swarms are mostly defined from non-eruptive fractures (Fig. 4). Such pattern has been observed in other areas, as an example in Reykjanes (Jakobsson et al. 1978), and in the Main Ethiopian Rift (Kurz et al. 2007).

Fractures within fissure swarms mainly form and are activated during rifting events, when dykes intrude the fissure swarms, and sometimes cause fissure eruptions (Wright et al. 2012). The decrease of the number of eruptive fissures with distance from the central volcanoes, along with the finding that fracture density in similarly-aged lava flows in the Krafla Fissure Swarm generally decreases with distance from the Krafla Central Volcano (Hjartardóttir et al. 2012), suggests that the density of dykes beneath many of the fissure swarms gradually decreases with distance from the central volcanoes. This is in agreement with findings from extinct, eroded central volcanoes and dyke swarms in Eastern Iceland, where the highest densities and dyke ratio in dyke swarms also tend to be close to extinct central volcanoes (Walker 1963).

Fissure swarms intersecting strike-slip zones

The Þeistareykir Fissure Swarm is the only fissure swarm which is clearly intersected and partly terminated by a strike-slip zone, as it visibly connects with the Húsavík Transform Zone on land (Fig. 7). There are also indications that the Krafla Fissure Swarm is influenced by the Húsavík Transform Zone (Hjartardóttir et al. 2012). Additionally, WNW oriented fractures on land and fractures with en-echelon pattern, suggesting strike-slip faulting are found in the continuation of the Grímsey Oblique Rift (Fig. 8).

The parts of the fissure swarms that are influenced and/or intersected by strike-slip zones show certain characteristics:

- They have higher variability in fracture orientations (especially Þeistareykir) (Fig. 2).

- The maximum fracture densities in each of the fissure swarms occur at their junction (seen at Þeistareykir, Krafla and Fremrinámar) (Fig. 4).

Such a link between the Grímsey Oblique Rift and the fissure swarms has previously been suggested, both by Mamula and Voight (1985), who observed WNW oriented structures on-land, and by Guðmundsson et al. (1993), who pointed out the stark change in orientation of the fissure swarms that occurs at the junction of the Grímsey Oblique Rift and the rift zone. Irregular fracture orientations are also found in the fissure swarms of the Reykjanes Peninsula Oblique Rift, where fissure swarms are cross-cut by strike-slip faults (Clifton and Schlische 2003; Clifton and Kattenhorn 2006).

Anomalous fracture orientations within the NVZ

Fissure swarms within the NVZ, along with their fractures, are generally N to NE oriented. In the southern part, NE oriented fractures are common, while northerly oriented fractures are more common in the northern part of the NVZ, giving the volcanic zone as a whole an arcuate form. Although the majority of fractures and eruptive fissures are N to NE oriented, there are several exceptions to that, which can be categorized as follows:

a) Fractures and eruptive fissures in the vicinity of calderas

In the vicinity of the calderas of Askja and Krafla (the only calderas of the NVZ not covered by a glacier), a few of the fractures and eruptive fissures tend to be either concentric around the caldera rim or radiate away from it (Fig. 5), although the main trend of the fractures near the central volcanoes is similar to the trend of the northern and southern fissure swarms (Fig. 2) (Hjartardóttir et al. 2009; Hjartardóttir et al. 2012).

Radial fractures have generally been associated with pressure increase in a magma reservoir, while concentric fractures have either be linked with uplift (forming cone sheets) or subsidence and ring dike formation when caldera collapse occurs (e.g. Anderson 1938; Walker 1984; Marti et al. 1994; Walter and Troll 2001). We suggest that the concentric fractures around the Öskjuvatn caldera are formed by gravitational slumping, since they are situated less than 500 m away from the main caldera faults.

b) E-W eruptive fissures close to the Vatnajökull glacier

E-W oriented fractures and eruptive fissures can be found in the southernmost part of the NVZ, both near Mt. Hrímalda (Sigbjarnarson 1995) and in the Urðarháls lava shield (Fig. 6). In the Urðarháls lava shield, the E-W eruptive fissure is situated within an E-W oriented graben. Although the eruptive fissures are eroded due to frequent sand storms in the area, they have not been eroded by glacier, which indicates that they are Postglacial features.

To explain the anomalous orientation of these fractures, Hooper et al (2011) suggested that during periods when the tensile plate-spreading stresses had been relieved by rifting episodes (forming the regular N to NE oriented dykes), a remnant stress-field caused by the retreating Vatnajökull glacier facilitated the formation of the E-W oriented eruptive fissures in Hrímalda and Urðarháls. According to their suggestion, stress field induced by deglaciation can, in special circumstances, control the orientation of dykes although the plate spreading stresses are generally the governing factor. Their suggestion was inspired by the 2007-2008 Upptyppingar events, when a dyke with an orientation highly oblique to the regional fracture orientations was formed beneath the Kverkfjöll Fissure Swarm. It can also be pointed out that the E-W oriented fractures and eruptive fissures are located close to the Central Iceland Volcanic Zone (CIVZ). The volcanic zone has an E-W orientation, even though the majority of fractures within it have northerly trends (Fig. 1).

c) WNW-oriented fractures

Several WNW-oriented fractures are located in the southern part of the Krafla Fissure Swarm (Fig. 5). Similarly oriented fractures are situated in direct continuation of these fractures; in the northern part of the Kverkfjöll Fissure Swarm, and intermittently between these fissure swarms. It is tempting to assume that these WNW-oriented fractures are a part of the same structure, forming a WNW-oriented belt across the NVZ (Fig. 5).

The WNW-oriented belt is situated where the northern part of the Kverkfjöll Fissure Swarm ends, and the southern part of the Krafla Fissure Swarm begins (Fig. 5). The spreading of the NVZ is therefore shifted westwards north of the WNW-oriented belt, suggesting that the WNW-oriented belt acts as a transform zone.

While the western part of the WNW-oriented belt has little seismic activity, the eastern part is active. The WNW-oriented belt extends to Mt. Herðubreið, where persistent seismicity has been recorded for decades (Figs. 1 and 5) (Einarsson 1991a; Jakobsdóttir 2008). Fault plane solutions indicate that these earthquakes occur due to left-lateral strike slip faulting on several parallel NE-oriented fractures (Þorbjarnardóttir et al. 2007; Hjartardóttir et al. 2009; Martens and White, submitted 2013). Assuming that the strike-slip faults are a part of the WNW-oriented belt, their NE orientation indicates that they are bookshelf faults, similar to the bookshelf faults in the South Iceland Seismic Zone (Einarsson 2010).

The east and west borders of the NVZ

Rift zones affect broad areas around them during the initial rifting stages. As time passes, the extensional strain is concentrated on the axial rift zone. This generally causes the margins of the rift zone to become inactive (Favre and Stampfli 1992). This is the case of the border faults in the northern Main Ethiopian Rift, while the border faults of the less evolved central and south Main Ethiopian Rifts are still active (Agostini et al. 2011). We have found a ~30 km long fault at the northern part of the eastern boundary, which is parallel to the boundary, but oblique to the rift zones within the NVZ. Interestingly, the fault dips towards the east, indicating that it is not a typical boundary fault of a rift zone. This fault appears to have been activated during Postglacial times (Hjartardóttir et al. 2010). The existence of this fault, the total lack of interglacial lavas and the subglacially-formed tindars, indicate that the eastern boundary of the NVZ becomes temporarily active, especially during glaciations or deglaciations (Hjartardóttir et al. 2010).

During deglaciations, when a glacier is retreating, the decrease of mass causes the crust to uplift. The magnitude of this uplift is dependent on various factors, such as the density of the crust, its effective viscosity and Young's modulus (Hjartardóttir et al. 2010). Therefore, the magnitude of uplift is dependent on the type and thickness of crust being uplifted. The eastern margin of the NVZ sits next to the Tertiary Eastern Fjords Block (EFB) in Iceland. As the magnitude of uplift of the EFB should be different than of the NVZ during deglaciations, this causes differential movements which may lead to activation of older border faults. The ~30 km long Kerlingar fault may be an example of such a fault. Some of the reactivated faults may have been intruded by magma, forming the row of tindars which delineate the eastern boundary of the NVZ (Hjartardóttir et al. 2010).

This relationship between glaciations and volcanism would explain why hyaloclastite/pillow lava ridges are dominant up to about 150-160 km distances from the Kverkfjöll Central Volcano, while Postglacial activity has mostly taken place within only 60 km distance from the central volcano. Such a recession of volcanic activity towards the Kverkfjöll Central Volcano after glaciations has also been suggested by Carrivick et al. (2009) based on variations in morphology of the ridges with distance from the volcano.

Notably, no such rim of tindars is found on the west site of the NVZ. The southern part of it does not have any fractures or tindars except those that are associated with the active fissure swarms within the NVZ. However, there are large-offset normal faults in the northern part, although it is unclear whether they are related to the Þeistareykir Fissure Swarm, or whether they are to be considered as non-magmatic, NVZ boundary faults.

Earthquakes within the NVZ

Fractures within the fissure swarms appear to be mostly inactive between rifting episodes. This can be seen by comparing earthquake activity and InSAR images with the fracture data of the NVZ (Einarsson 1991a; Jakobsdóttir 2008; Pedersen et al. 2009). Earthquakes during non-rifting periods are concentrated within the central volcanoes, or at distinct places which are often not within the main fissure swarms (Fig. 1). During rifting events, this pattern is remarkably different. Then, intense earthquake activity occurs in the fissure swarm that is being rifted (Fig. 1). Very little deformation occurs in general within fissure swarms between rifting episodes, when there is either no subsidence, or less than few millimetres per year (Tryggvason 1974; Pedersen et al. 2009).

Fractures vs. the ages of the lava flows

A high proportion of fractures within the NVZ are located within Postglacial lava flows, i.e. lava flows that were formed after glacier left the area, or in hyaloclastite formations which stick out of the Postglacial lava flows (Figs. 5 and 9). However, the fracture density within the Postglacial lava flows varies significantly, often depending on the age of the lava flows. An example of this can be seen within the Askja Fissure Swarm (Fig. 10). There, some of the oldest Postglacial lava flows (> 4500 years BP) situated north of the Askja Central Volcano are intensively fractured, while younger (<4500 BP) lava flows located in the continuation of these fractures are not fractured at all (Figs. 10 and 11) (Sigvaldason et al. 1992). The same general pattern emerges within the Krafla Fissure Swarm, where the fracture density within the lava flows also increases with age of the lava flows (Hjartardóttir et al. 2012). Interestingly, there is an exception from this south of Askja, where an 4500-10.000 years BP lava flow is almost not fractured at all (Fig. 10).

Conclusions

1. The NVZ is characterized by 5-6 central volcanoes with fissure swarms that extend approximately perpendicular to the spreading vector. The eastern boundary of the NVZ is an arcuate shaped area of tindars, while no such feature is found at the western boundary.

2. The NVZ is intersected by two active transform zones, the Húsavík Transform Zone and the Grímsey Oblique Rift in the northern part of the NVZ. In addition, traces of a possible third transform zone may be found in the middle of the NVZ, extending between the southern end of the Krafla Fissure Swarm in the western NVZ and the northern end of the Kverkfjöll Fissure Swarm in the eastern part of it. This zone may be almost extinct, but the eastern part of it produces persistent seismicity by strike-slip faulting on several transverse faults.

3. The parts of the fissure swarms that are situated at the junction with extrapolated transform zones show certain characteristics. There, a high density of fractures is found, and the variability in fracture orientations is greater than elsewhere in the fissure swarms.

4. Eruptive fissures within fissure swarms are most common close to central volcanoes, and are mainly situated within 20-30 km distance from the central volcano. On the other hand, the distal parts of the fissure swarms have almost only non-eruptive fractures. This, along with the decreasing density of fractures in similarly-aged lava flows with distance from the Askja and Krafla Central Volcanoes implies that the density of dykes beneath the fissure swarms decreases with distance from the central volcano.

5. Fractures within fissure swarms are mainly oriented ~perpendicular to the spreading vector. However, there are deviations from this. A few of the fractures and eruptive fissures near the calderas of Krafla and Askja have more variable orientations. East-west oriented eruptive fissures and fractures are also found in the southernmost part of the NVZ. Hooper et al. (2011) pointed out a possible analogy with the Upptyppingar intrusion of 2007 and 2008 and suggested that their orientation is caused by a local stress field perturbation during times of rapid deglaciation. WNW-oriented faults are found in a distinct belt across the rift zone, possibly a transform zone.

6. Fractures within the fissure swarms of the NVZ are mostly inactive between rifting events. However, intense earthquake activity occurs along part of or even along an entire fissure swarm during a rifting event, marking the active area where fractures are activated and new ones formed. This, along with intense deformation during rifting events, indicates that fissure swarms are mostly formed during such events, when dykes propagate into the fissure swarms.

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Figure captions

Fig. 1 Iceland and the Northern Volcanic Rift Zone (NVZ). a) Fissure swarms and central volcanoes in Iceland. Outlines of the fissure swarms are from Einarsson and Sæmundsson (1987), except for the revised NVZ outlines. RPOR= Reykjanes Peninsula Oblique Rift, WVZ= Western Volcanic Zone, EVZ= Eastern Volcanic Zone, SISZ= South Iceland Seismic Zone, CIVZ= Central Iceland Volcanic Zone, TFZ= Tjörnes Fracture Zone (including the Húsavík Transform Zone and the Grímsey Oblique Rift). b) Fractures and eruptive fissures in the NVZ. c) Outlines of the fissure swarms in the NVZ, drawn with respect to the fracture clustering in b). Earthquake data from the years of 1991-2011 were obtained from the Icelandic Meteorological Office, while information on the earthquakes that occurred during the Krafla rifting events is from Buck et al. (2006). The background image is from the National Land Survey of Iceland.

Fig. 2 Orientation of fractures and fracture segments within the studied fissure swarms. "Central" area is denoted as the part of the fissure swarms that extend 10 km in opposite directions from the inferred centre of the central volcano. North and south areas are situated in 10-30 km distance from the central volcanoes. Distal parts of the fissure swarms were omitted as gradual changes of orientations with distance in some fissure swarms could increase variability in fracture orientations in the graphs. 0° lines denote north. Each bin has an orientation range of 5°, black bins denote the cumulative length (km) of fractures with orientations of 0-5°.

Fig. 3 Percentage of fractures or fracture segments within each fissure swarm that are oriented within 5° from the plate spreading vector (106°) calculated from DeMets et al. (1994).

Fig. 4 The number of fractures (lines) and eruptive fissures (columns) with distance from the central volcanoes in the NVZ. Dashed boxes indicate where the extrapolated intersections with the Grímsey Oblique Rift and the Húsavík Transform Zone are.

Fig. 5 The ages of lava flows and surface formations in northeast Iceland. Fractures are coloured according to their orientations. Central volcanoes: Þ = Þeistareykir, K = Krafla, F = Fremrinámar, A = Askja, B = Bárðarbunga, Kv = Kverkfjöll, T = Tungnafellsjökull. Frame indicates a belt of WNW oriented fractures. Information on lava flows from the Icelandic Institute of Natural History.

Fig. 6 East-west oriented fractures and eruptive fissures in the southernmost part of the NVZ. The background image is from the US/Japan ASTER project.

Fig. 7 Fracture patterns where the Húsavík Transform Zone meets the Þeistareykir and Krafla Fissure Swarms. The town of Húsavík is coloured in red. The background image is from the US/Japan ASTER project.

Fig. 8 a) Fracture patterns where the Grímsey Oblique Rift meets the NVZ. Earthquake data from the Icelandic Meteorological Office, background satellite image from the US/Japan ASTER project. Black frame in the smaller image represents the location of the larger image. b) Fractures with en-echelon pattern, suggesting strike-slip faulting (for location, see red frame in a).

Fig. 9 Cumulative length of fractures within the NVZ that are located in Postglacial or Pleistocene lava flows, or in hyaloclastite formations.

Fig. 10 Lava flows and fractures near the Askja Central Volcano. Note the correlation between the ages of the lava flows and the fracture density. Information on the lava flows from Sigvaldason et al. (1992). The background is from the National Land Survey of Iceland.

Fig. 11 Fracture densities of differently-aged lava flows in the Askja Fissure Swarm. Older lava flows generally have higher fracture densities, although exceptions occur.

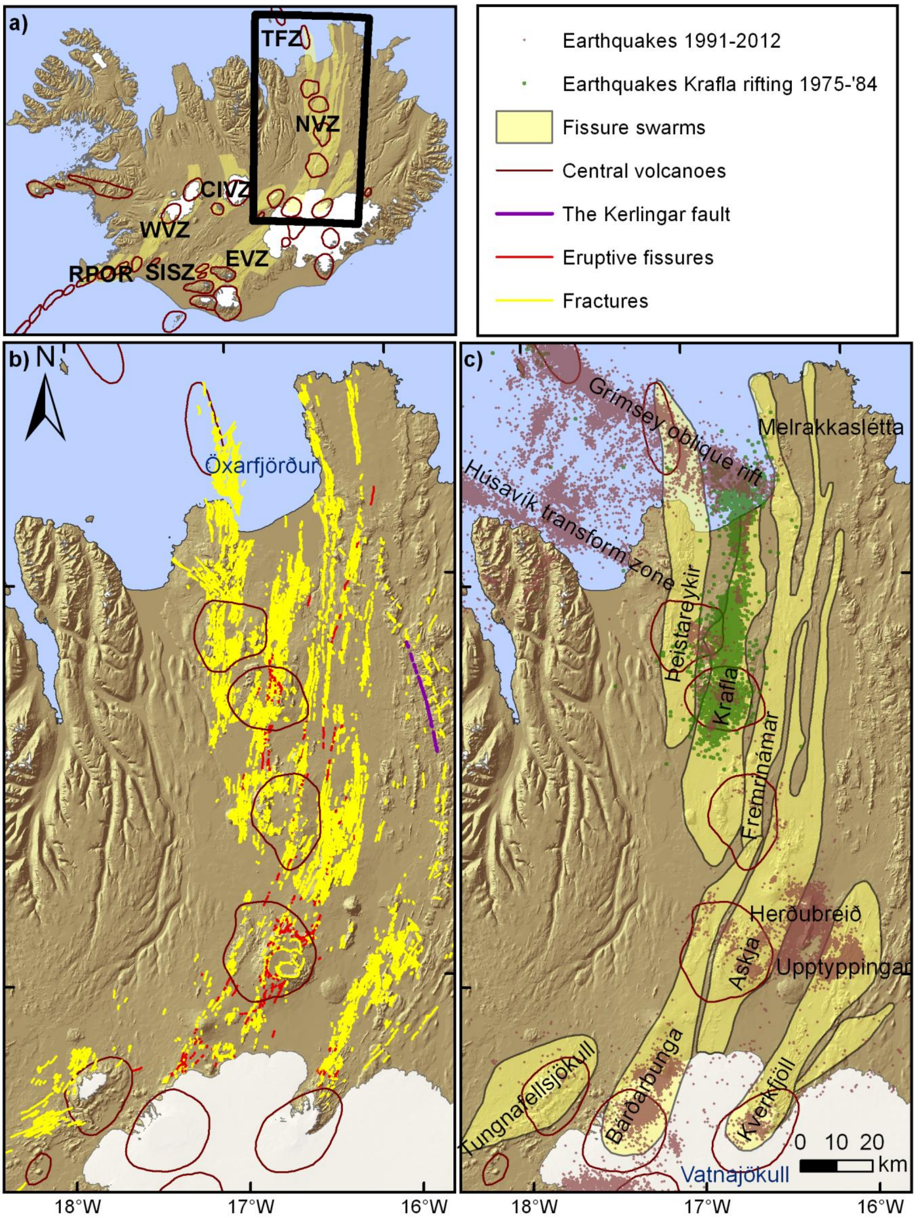
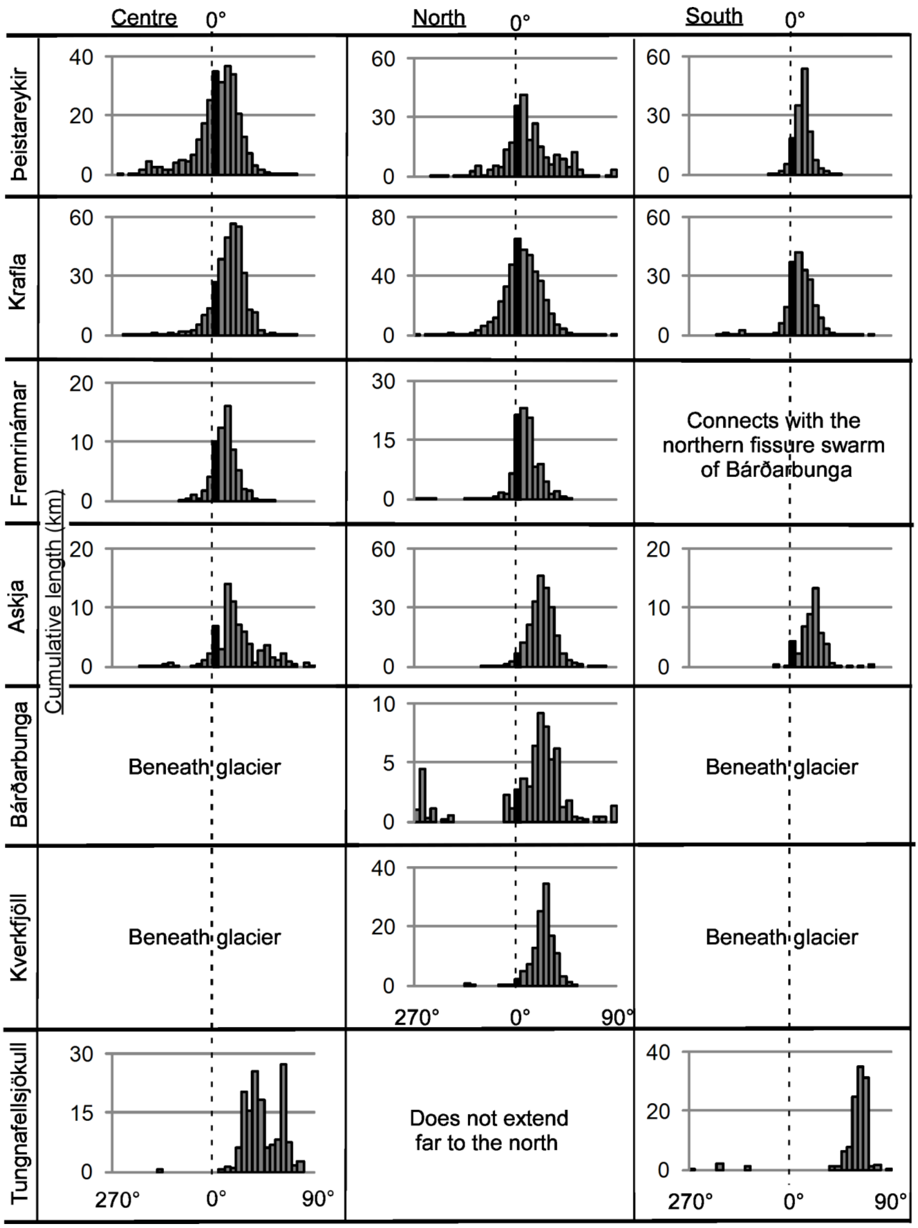

a)
TFZ
NVZ
CIVZ
WVZ
EVZ
RPOR
SISZ
Earthquakes 1991-2012
Earthquakes Krafla rifting 1975-'84
Fissure swarms
Central volcanoes
The Kerlingar fault
Eruptive fissures
Fractures
b)
N
Öxarfjörður
66°N
65°N
18°W
17°W
16°W
c)
Grímsey oblique rift
Melrakkaslétta
Húsavík transform zone
Þeistareykir
Krafla
Fremrinámar
Herðubreið
Askja
Upptyppingar
Tungnafellsjökull
Bárðarbunga
Kverkfjöll
0 10 20
km
Vatnajökull
18°W
17°W
16°W

Figure 1



Centre
North
South
0°
Þeistareykir
Krafla
Fremrinámar
Askja
Bárðarbunga
Kverkfjöll
Tungnafellsjökull
Cumulative length (km)
Connects with the northern fissure swarm of Bárðarbunga
Beneath glacier
Does not extend far to the north
270°
90°

Figure 2

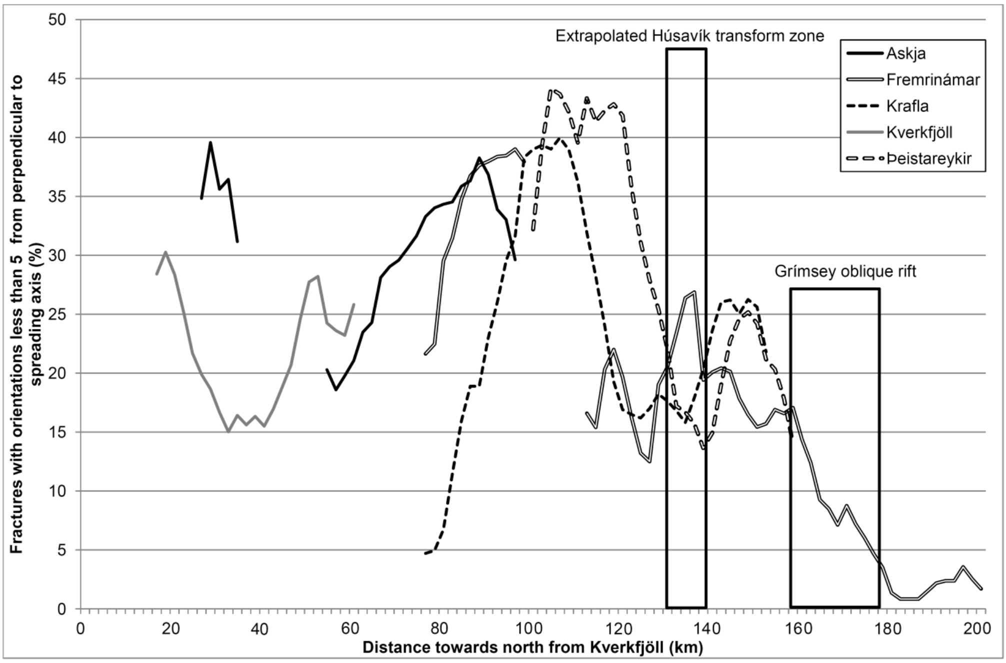
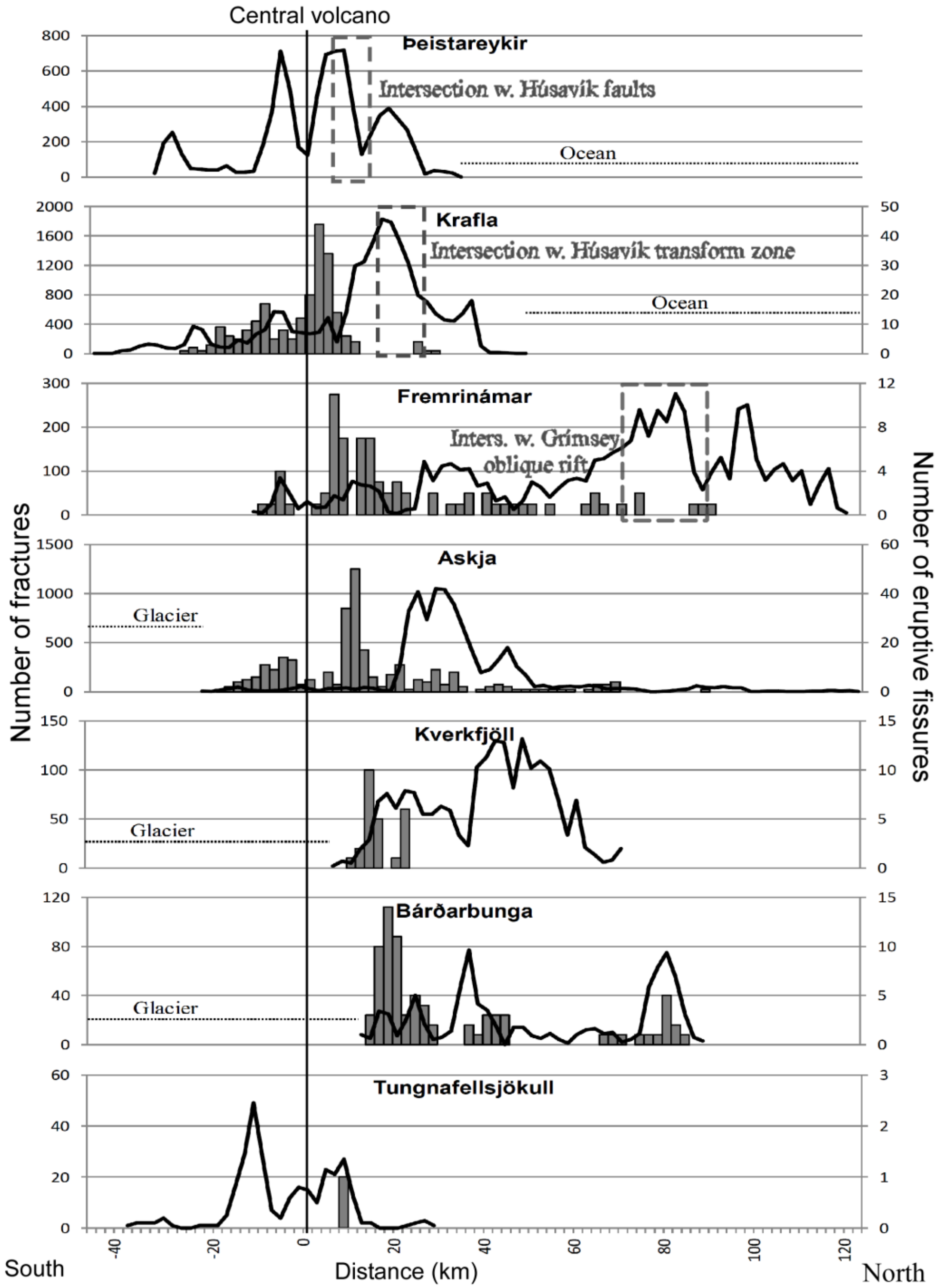

Extrapolated Húsavík transform zone
Grímsey oblique rift
Askja
Fremrinámar
Krafla
Kverkfjöll
Þeistareykir
Fractures with orientations less than 5 from perpendicular to spreading axis (%)
Distance towards north from Kverkfjöll (km)
0
5
10
15
20
25
30
35
40
45
50
0
20
40
60
80
100
120
140
160
180
200

Figure 3



Central volcano
Þeistareykir
Intersection w. Húsavík faults
Ocean
Krafla
Intersection w. Húsavík transform zone
Ocean
Fremrinámar
Inters. w. Grímsey oblique rift
Askja
Glacier
Kverkfjöll
Glacier
Bárðarbunga
Glacier
Tungnafellsjökull
Number of fractures
Number of eruptive fissures
South
Distance (km)
North

Figure 4

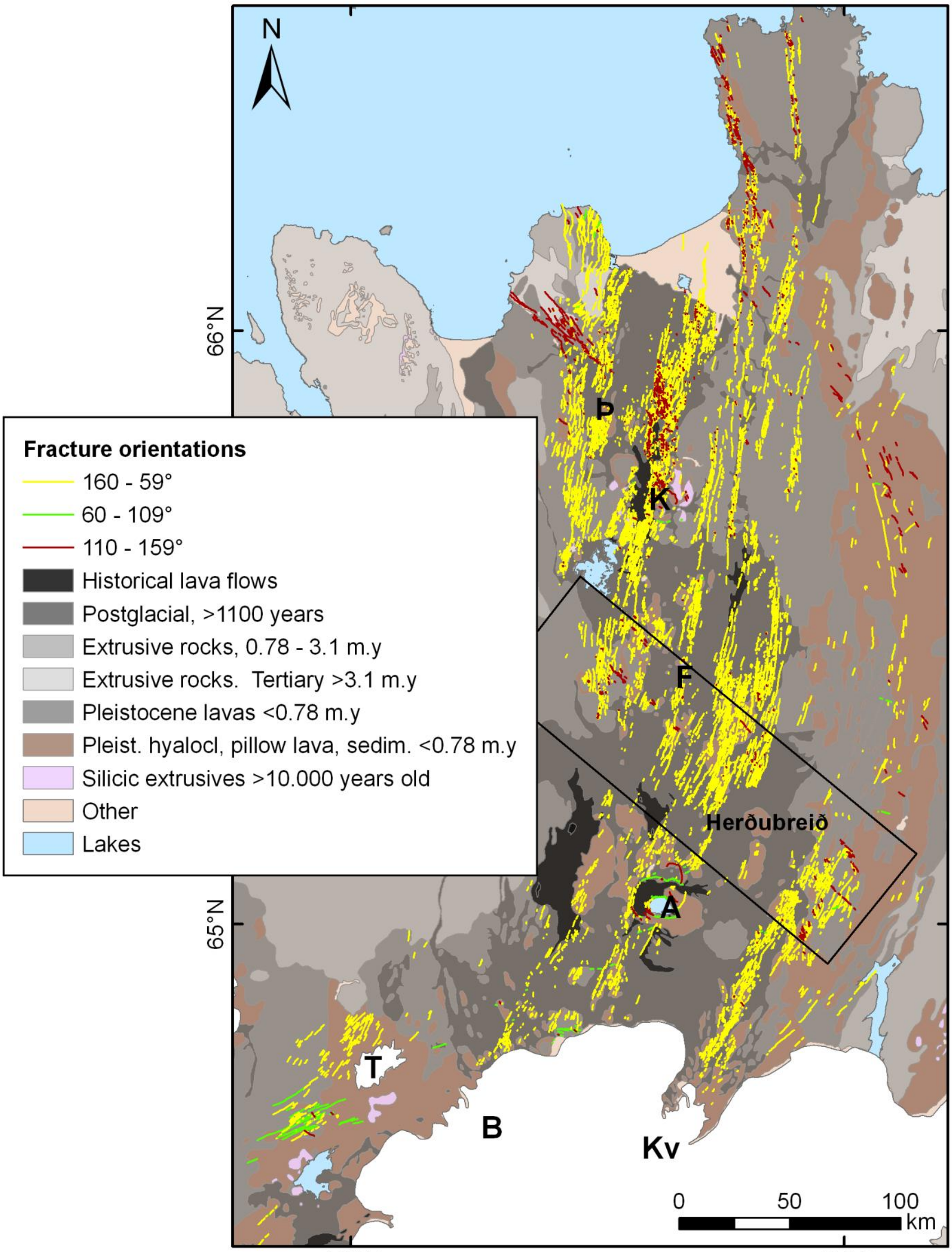

N
66°N
65°N
18°W
16°W
Fracture orientations
160 - 59°
60 - 109°
110 - 159°
Historical lava flows
Postglacial, >1100 years
Extrusive rocks, 0.78 - 3.1 m.y
Extrusive rocks. Tertiary >3.1 m.y
Pleistocene lavas <0.78 m.y
Pleist. hyalocl, pillow lava, sedim. <0.78 m.y
Silicic extrusives >10.000 years old
Other
Lakes
P
K
F
Herðubreið
A
T
B
Kv
0
50
100
km

Figure 5

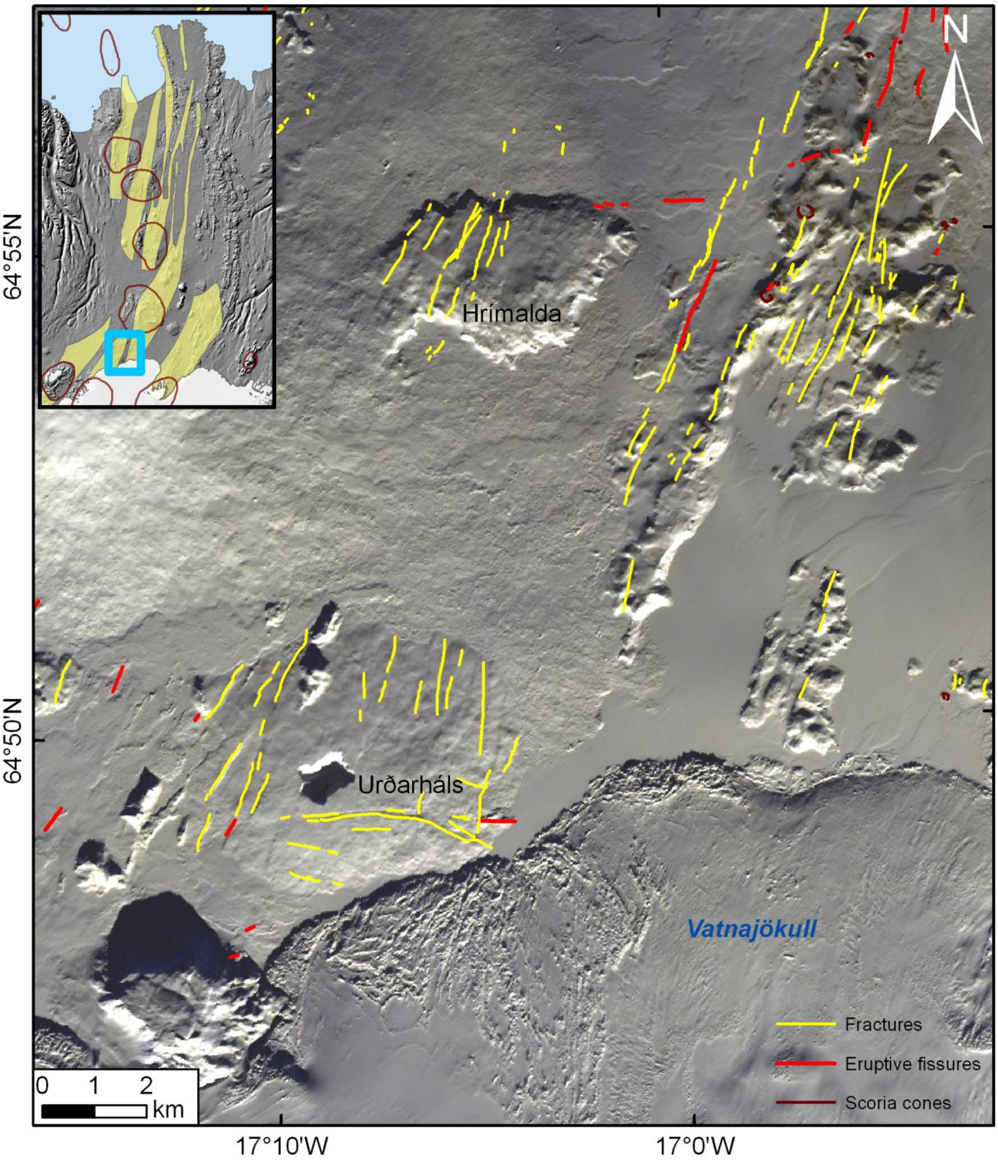

N
64°55'N
64°50'N
Hrímalda
Urðarháls
Vatnajökull
Fractures
Eruptive fissures
Scoria cones
0 1 2
km
17°10'W
17°0'W

Figure 6

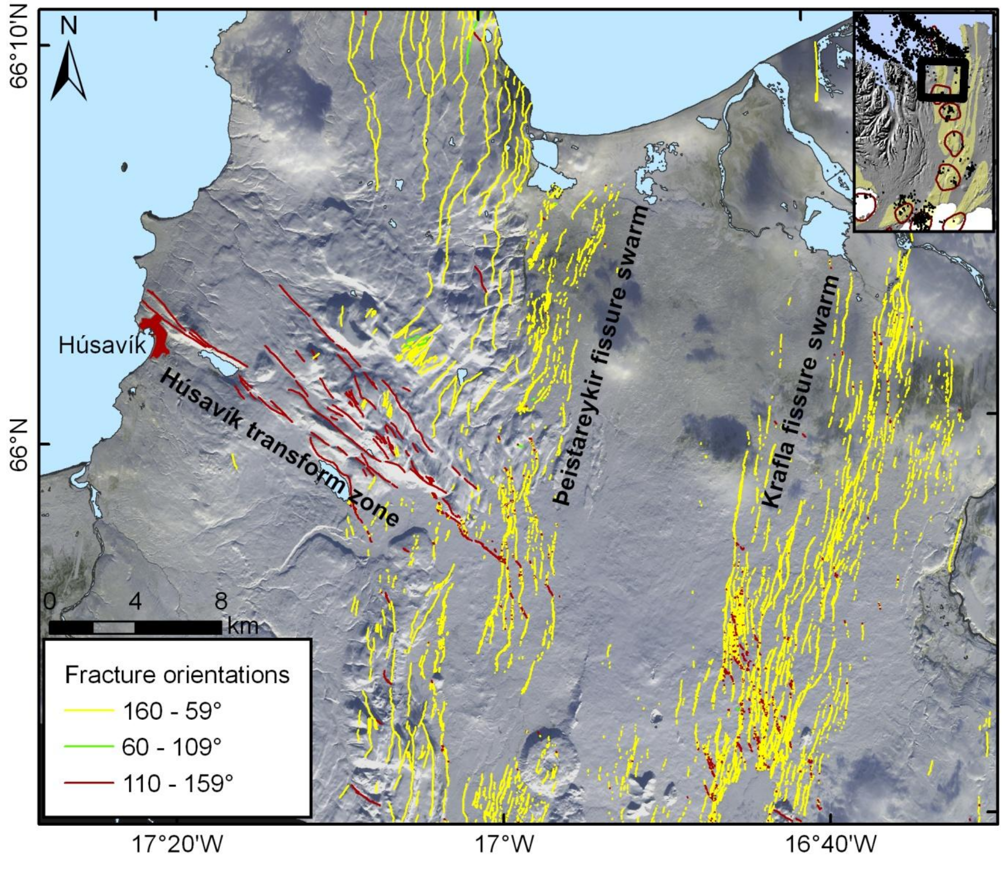
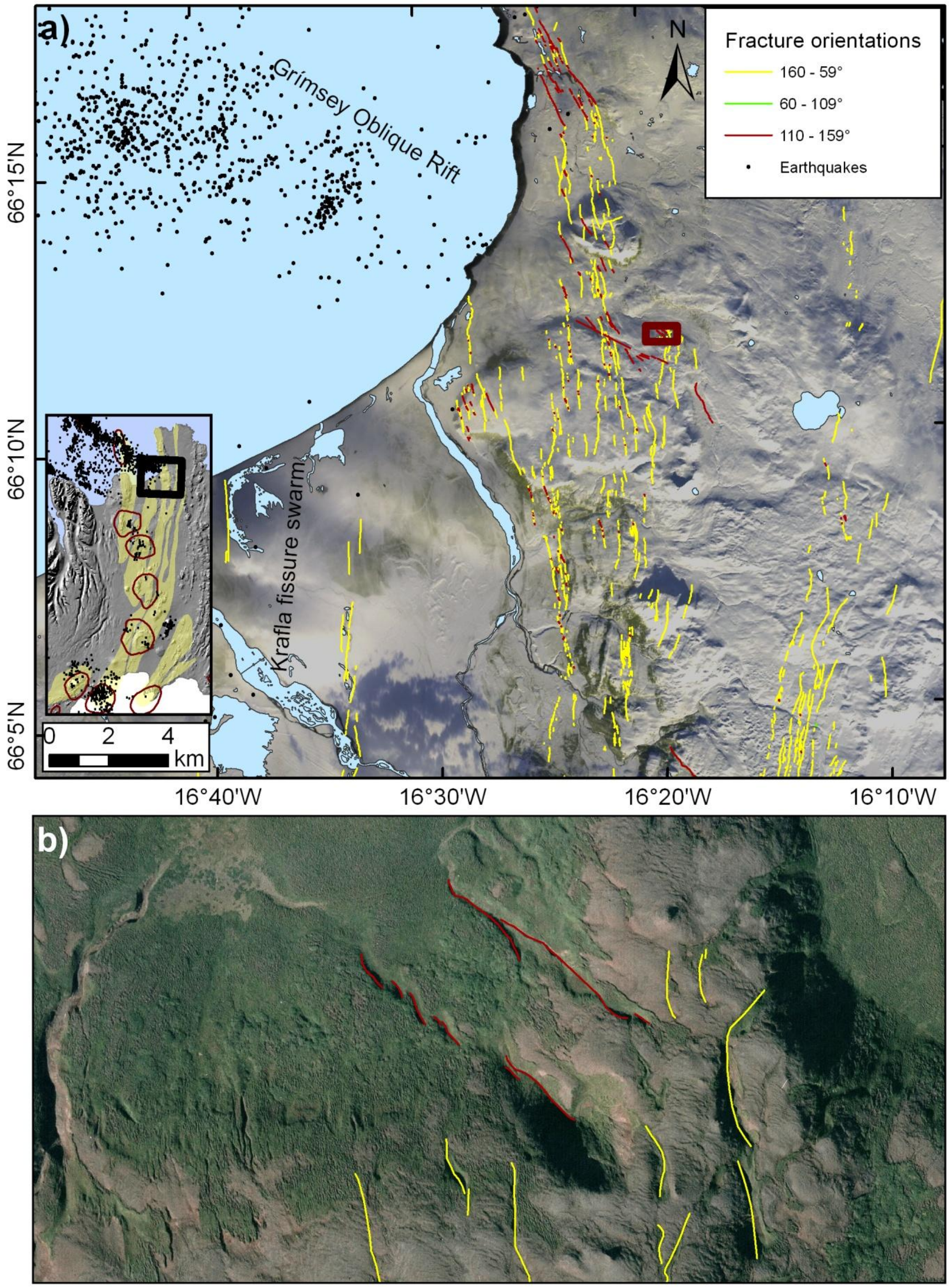

66°10'N
66°N
N
Húsavík
Húsavík transform zone
Þeistareykir fissure swarm
Krafla fissure swarm
0
4
8
km
Fracture orientations
160 - 59°
60 - 109°
110 - 159°
17°20'W
17°W
16°40'W

Figure 7



a)
Grímsey Oblique Rift
Krafla fissure swarm
N
Fracture orientations
160 - 59°
60 - 109°
110 - 159°
Earthquakes
66°15'N
66°10'N
66°5'N
0 2 4 km
16°40'W
16°30'W
16°20'W
16°10'W
b)

Figure 8

Cumulative length of fractures (km)
2500
2000
1500
1000
500
0
Holocene lava flows
Pleistocene lava flows (<0.78 m.y)
Hyaloclastites

Figure 9

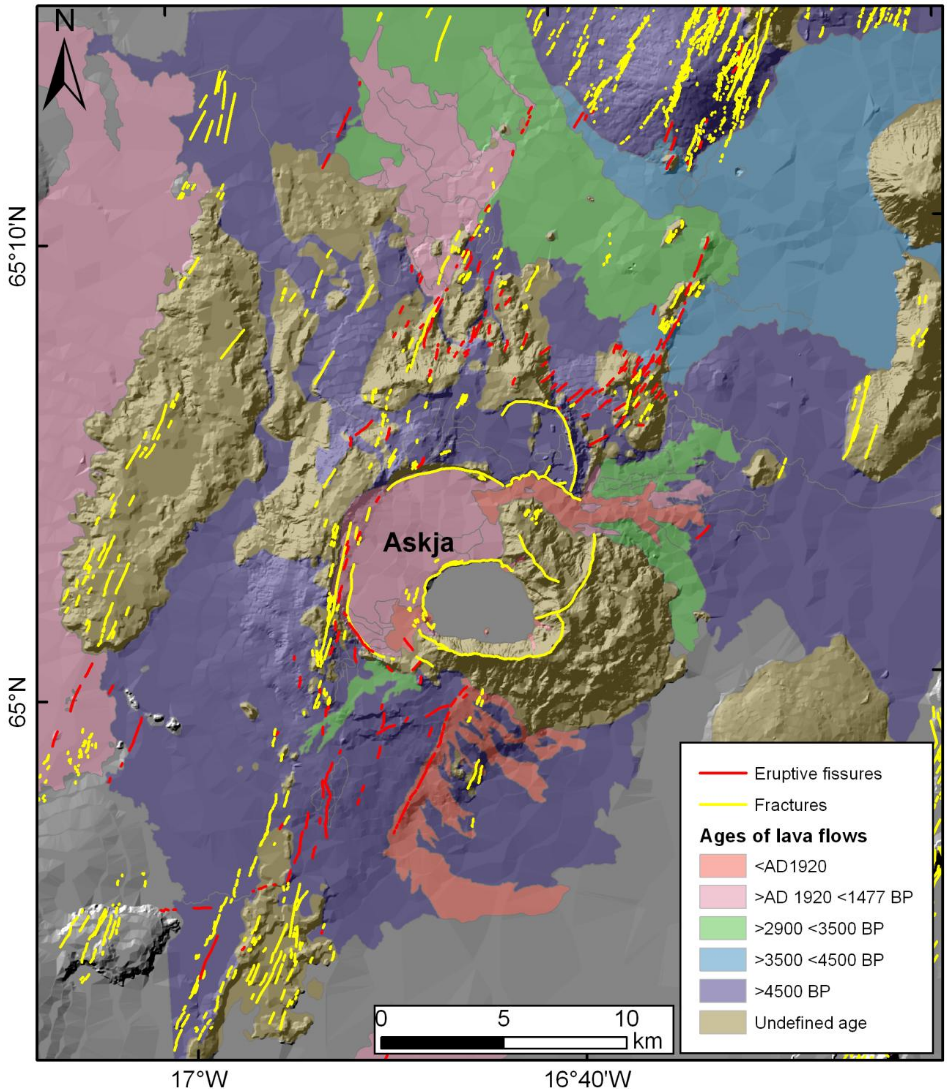
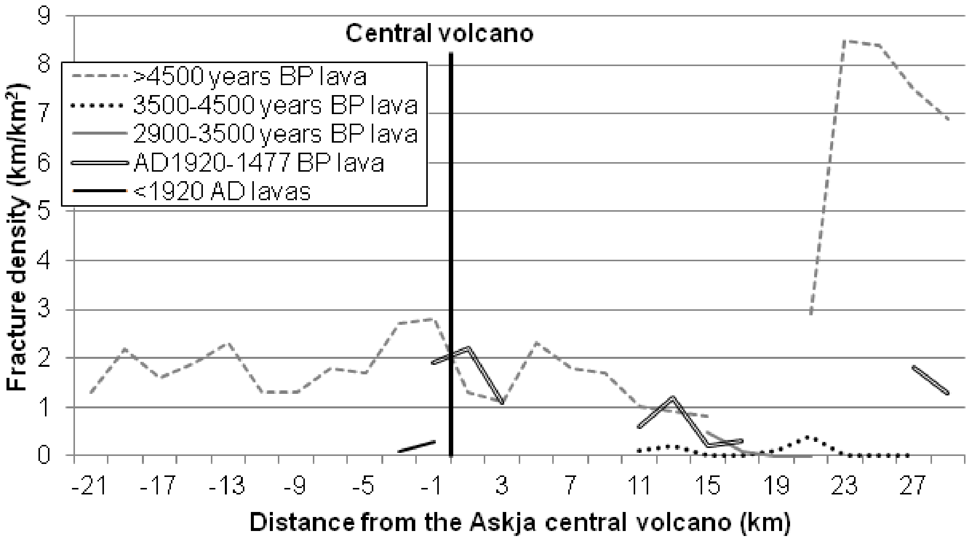

N
65°10'N
65°N
17°W
16°40'W
Askja
Eruptive fissures
Fractures
Ages of lava flows
<AD1920
>AD 1920 <1477 BP
>2900 <3500 BP
>3500 <4500 BP
>4500 BP
Undefined age
0
5
10
km

Figure 10



Central volcano
>4500 years BP lava
3500-4500 years BP lava
2900-3500 years BP lava
AD1920-1477 BP lava
<1920 AD lavas
Fracture density (km/km²)
Distance from the Askja central volcano (km)
9
8
7
6
5
4
3
2
1
0
-21
-17
-13
-9
-5
-1
3
7
11
15
19
23
27

Figure 11