The Fissure Swarm of Tungnafellssjökull: Recent Movements

Þórhildur Björnsdóttir

Faculty of Earth Sciences
University of Iceland
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Þórhildur Björnsdóttir

90 ECTS thesis submitted in partial fulfillment of a Magister Scientiarum degree in Geophysics

Supervisors
Páll Einarsson
Haukur Jóhannesson

Examiner
Kristján Sæmundsson

Faculty of Earth Sciences
School of Engineering and Natural Sciences
University of Iceland
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Faculty of Earth Sciences
School of Engineering and Natural Sciences
University of Iceland
Sturlugata 7,
101 Reykjavik
Iceland

Telephone: 525 4000

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I hereby declare that this thesis is written by me and is based on my own research. It has not before been submitted in part or in whole for the purpose of obtaining a higher degree.

______________________________
Þórhildur Björnsdóttir
Abstract

Fissure swarms consist of clusters of normal faults, tensile fractures and volcanic fissures, and often extend from a central volcano. Fissure swarms are often referred to as rift zones, can be found in intraplate, island arc and spreading center volcanoes on Earth, as well as on Venus and Mars. The Tungnafellsjökull fissure swarm is located in Central Iceland Volcanic Zone near the center of the hot spot of Iceland and the triple junction between the Eurasian plate, North-American plate and the Hreppar microplate. The volcanic system of Tungnafellsjökull is a relatively inactive system and only two small Holocene fissure lavas can be associated with the system, the Tunguhraun lava and the Dvergar lava. To gain an overview of the fissure swarm of Tungnafellsjökull and to grasp the interaction between the volcanic system, the fissure swarm and the plate boundary, active fractures and fissures that relate to the volcanic system were mapped. The area, which is approximately 1450 km$^2$, was mapped both from aerial photographs and from the ground. The fissure swarm is, at most, about 40 km in length and 20 km wide. The fissure swarm is wider than the Tungnafellsjökull central volcano and passes it rather than extends from it. A ground check revealed evidence of recent movements in the fissure swarm indicating more activity in the swarm than previously thought. Three types of structures were found that indicated recent movements. Type 1 is a step in a glacial ground moraine that normally doesn’t have any obvious features. The step thus indicates movements in the Holocene. Type 2 and 3 are sinkholes or fractures on the ground. Both these types indicate movements in the Holocene but type 3 has open wounds in the rim of the sinkholes and the edge of the fractures that indicates more recent movements. Earthquake data from the area and InSAR images from the Gjálp eruption revealed two or three tectonic events that may have led to these recent movements. The first event occurred in October 1996 during the Gjálp eruption, the second one in August of 2008 and the third one in November of 2009. These events are expressed by increased seismicity in the Tungnafelljökull area, both in terms of number of earthquakes as well as seismic moment release rates.
Ágrip

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1. Introduction

The main focus of this thesis is on the fissure swarm of the volcanic system of Tungnafellsjökull. The aim of the work was initially to map the fissure swarm of Tungnafellsjökull by mapping active fractures and fissures that relate to the volcanic system. The fractures and fissures where mapped both from aerial photographs and satellite images as well as from the ground. Two trips were made to the study area in the summers of 2009 and 2010. The ground check revealed evidence of recent movements in the fissure swarm that led to a slightly different approach to the study than was initially intended. Indeed, instead of emphasizing the mapping, description of these recent movements became the main goal of the study as well as determining their underlying etiology.

The thesis is comprised of four chapters in total. The main part of the thesis is based on a paper named, Evidence of recent movements in Tungnafellsjökull fissure swarm in Central Volcanic Zone, Iceland, which is presented in Chapter 5. The first three chapters provide an introduction to that paper, with the present chapter supplying an overview of the geology of Iceland. In Chapter 2 the focus is on fissure swarms of the world, including fissure swarms of Iceland, and Chapter 3 provides an overview of the study area.

1.1. Geology of Iceland

Iceland is a 300x500 km platform located in the North Atlantic Ocean. It is the only subaerial section of the Mid-Atlantic Ridge that marks the present day plate boundaries between the Eurasia and North America plate (Einarsson, 1991; Einarsson 2008). Iceland lies on top of a hot spot that is presumably fed by a deep mantle plume. Its excessive volcanism has built up Iceland lava pile and is responsible for Iceland existence. The center of the mantle plume is generally assumed to lie under Central Iceland (e.g. Wolfe et al., 1997).

The structure of the plate boundary that crosses Iceland is strongly influenced by the hot spot that makes it more complicated than the relatively simple tectonic picture of a mid-oceanic plate boundary. The mid-Atlantic plate boundary is clearly defined by the epicenters of earthquakes that show a narrow zone of deformation. As
the plate boundary crosses Iceland the deformation zone becomes wider (Fig. 1) (Einarsson, 2008).


The currently active plate boundary that crosses Iceland consists of a series of volcanic and seismic zones. These zones are constantly developing and moving in a complex manner due to interaction between the Mid-Atlantic Ridge and the mantle plume. The building blocks of the volcanic zones are comprised of about 35-47 volcanic systems, 25-37 on land and 10 on the shelf areas to the north and south depending on definition (Sigmundsson, 2006; Einarsson, 2008; Jóhannesson, 2012). A volcanic system is, according to Walker (1993), the central volcano plus its “plumbing system” that is the magma chambers, conduits, magma source, intrusions, geothermal fields and the associated fissure swarm.

Seven plate boundary segments can be identified, the Reykjanes Peninsula Oblique Rift (RPOR), the South Iceland Seismic Zone (SISZ), the Western Volcanic Zone (WVZ), the Eastern Volcanic Zone (EVZ), the Central Iceland Volcanic Zone...
(CIVZ), the Northern Volcanic Zone (NVZ) and the Tjörnes Fracture Zone (TFZ). In addition three intraplate volcanic areas, or flank zones, can be defined (Einarsson, 2008) (Fig 2).

The Reykjanes Peninsula Oblique Rift is the direct onshore continuation of the Mid-Atlantic Ridge (Fig 2). It is characterized by volcanic systems that are arranged en echelon along the plate boundary. The fissure swarms of the volcanic systems are oblique to the boundary and extend a few tens of km into the plates on either side. Seismicity on RPOR is high and episodic in nature with active episodes occurring every 30 years or so (Einarsson, 2008). The structure of the RPOR differs from the rest of the volcanic zones due to the fact that its overall trend is highly oblique to the plate spreading. This leads to high amount of shearing but relatively little spreading perpendicular to the axis of plate spreading (Sigmundsson, 2006). The Reykjanes Peninsula plate boundary splits up near 21.5°W into the Western Volcanic Zone and the South Iceland Seismic Zone. This triple junction is called the Hengill triple junction as it lies on the Hengill volcanic system, located in the WVZ (Einarsson, 1991).

The South Icelandic Seismic Zone is a seismic zone (or transform zone) that takes up the transform motion between the RPOR and EVZ (Fig 2). SISZ crosses the populated lowland in South Iceland from west to east and extends to the EVZ. The SISZ is characterized by north-south trending arrays of en echelon tension fractures indicating right-lateral faulting. This right-lateral faulting is on many parallel transverse faults and the blocks between them rotate counterclockwise (Einarsson, 1991, 2008, 2010).

The Western Volcanic Zone branches from the Reykjanes Peninsula and SISZ at the Hengill triple junction where it extends NE to the Langjökull area (Fig 2). WVZ seems to have been the main rift in the southern part of Iceland during the last 7 million years but is slowly dying giving way to the Eastern Volcanic Zone where the main rifting is presently taking place in South Iceland (Einarsson, 1991, 2008).
Figure 2: The Volcanic Zones of Iceland. RPOR: The Reykjanes Peninsula Oblique Rift; SVZ: the Snæfellsnes Volcanic Zone; WVZ: the Western Volcanic Zone; SISZ: the South Iceland Seismic Zone; ÖVZ: the Óræfajökull Volcanic Zone; SIVZ: the South Iceland Volcanic Zone; EVZ: the Eastern Volcanic Zone; CIVZ: the Central Iceland Volcanic Zone; NVZ: the Northern Volcanic Zone and TFZ: the Tjörnes Fracture Zone. The fissure swarms are from Einarson and Sæmundsson (1987). The background is from the National Land Survey of Iceland.

The Eastern Volcanic Zone extends from the eastern end of the SISZ and about 100 km to the NE where it joins the NVZ and CIVZ in a triple junction (Fig 2). It is characterized by long, linear structures, eruptive fissures and normal faults. The fissure swarms of the volcanic systems are mostly parallel to the zone itself and define a strong NE trend (Einarsson, 2008).

The Central Iceland Volcanic Zone is highly oblique to the spreading direction. CIVZ consists of two volcanic systems, The Hofsjökull Volcanic System and the Tungnafellsjökull Volcanic System, that do not readily fit to EVZ or NVZ (Fig. 2) (Einarsson, 2008).

The Northern Volcanic Zone extends from Central Iceland to the north coast where it joins with the Tjörnes Fracture Zone (Fig. 2). Volcanic systems are well defined within this zone and their fissure swarms are arranged in a left-stepping, en echelon pattern along the zone (Einarsson, 2008). The NVZ is simpler than other parts.
of the spreading plate boundary in Iceland as here the plate boundary only has one branch that has been active for a long time (Sæmundsson, 1974; Sigmundsson, 2006).

The Tjörnes Fracture Zone is a complex transform zone near the north coast of Iceland. It is a broad zone of transform faulting, crustal extension and seismicity that connects the NVZ with the southern end of the submarine Kolbeinsey Ridge (Fig. 2). The seismicity of the zone is too diffuse to be associated with one fault or a simple plate boundary and is generally divided into 3 seismic zones, the Húsavík-Flatey fault zone, the Dalvík seismic zone and the Grímsey seismic zone. These zones are all NW-trending and lie sub-parallel to each other (Einarsson, 1991; Einarsson, 2008).

Flank zones: Volcanic activity in Iceland is most prevalent in the volcanic systems along the active plate boundaries, although volcanism can also occur in zones outside them. These zones are often called volcanic flank zones. Three flank zones have been identified, the South Iceland Volcanic Zone (SIVZ), the Snæfellnes Volcanic Zone (SVZ) and the Öræfajökull Volcanic Zone (ÖVZ) (Fig. 2) (Einarsson, 2008).

The exposed volcanic material in Iceland is mostly comprised of basalt (or 80-85%), 10% is silicic, whereas intermediate rocks and sediment of volcanic origin comprise the remaining 5-10% (Jakobsson, 1979). The volcanic pile ranges in age back to about 16 million years (m.y.) old. It can be divided into groups based on stratigraphical age: Tertiary (>3.3 m.y.), Plio-Pleistocene (0.8 – 3.3 m.y.), Upper Pleistocene (back to 0.8 m.y.) and Holocene (last 9,000 – 13,000 y) (Jóhannesson and Sæmundsson, 1998).

Rocks older than 3.3 m.y. old make up the Tertiary formation that covers about 50,000 km² or about half of Iceland. The Tertiary formations include the classical plateau basalt series that are typical of the fjord landscapes of eastern, northern and western Iceland. The ages of the rock increases with distance from extinct and active spreading zones. The oldest rocks, 14-15 m.y. old are found in western and eastern Iceland. The tertiary sequence is made up of subaerial tholeiitic lavas and generally associated intermediate and acidic rocks (Sæmundsson, 1979).

The Plio-Pleistocene areas cover about 25,000 km² of Iceland in broad zones located between the Tertiary areas and the active volcanic zones. Rocks formed during the Plio-Pleistocene (0.8 - 3.3 m.y.) include extensive fluvio-glacial and morainic deposits, as well as hyaloclastites formed during subglacial eruptions. The
structure of this rock series is not as uniform as in the Tertiary (Sæmundsson, 1979; Sigmundsson, 2006).

The Upper Pleistocene series comprises rocks formed during the Brunhes magnetic epoch that began 0.8 million years ago, excluding the Postglacial epoch. These rock series covers about 30,000 km² area which lies more or less over the same area as the active volcanic zones today. The series are characterized by more extensive hyaloclastite formation than the Plio-Pleistocene as well as lavas erupted during interglacial times (Sæmundsson, 1979).

Holocene rocks or Postglacial rock series cover about 12,000 km² and comprises fresh lava flows and pyroclastics as well as sediments and soil formed after deglaciation. Lavas erupted during the Holocene are glacially uneroded and cover the most part of the active volcanic zones (Sigmundsson, 2006; Sæmundsson, 1979).

The rock series in Iceland have also been divided into three groups according to petrology, a tholeiitic series, a transitional alkalic series and an alkalic series. Large areas within the Tertiary formation have not been studied petrologically as well as large areas of Plio-Pleistocene and Upper Pleistocene. Rocks that have been studied in the Tertiary formation all belong to the tholeiitic series while rocks in the Plio-Pleistocene and Upper Pleistocene belong to all three rock series. In early Plio-Pleistocene only tholeiitic rocks were developed but later rocks from transitional alkalic series and the alkalic series were developed. In the Postglacial time about 23 volcanic systems have produced rocks belonging to the tholeiitic series, 5 systems have produced rocks from the transitional alcalic series and 4 volcanic systems have produced rocks from the alkalic series (Jakobsson, 1979; Jóhannesson, 2012).

2. Fissure swarms

Fissures in the volcanic zones are found in clusters within each volcanic system. These groups of fissures are called fissure swarms and they consist of normal faults, tensile fractures and volcanic fissures that often extend from a central volcano. They are interpreted as the surface expression of dyke swarms. The fissure swarms are usually about 10 km wide and their length varies from 30 to over 100 km (Sæmundsson, 1978). In Iceland the term rift zone is used for the plate boundary segment as a whole e.g. with many fissure swarms. Elsewhere, however, the term rift


A zone is usually defined as pertaining to narrow zones where ground cracks, normal faults and eruptive fissures are concentrated. Indeed, the term rift zone is used elsewhere in a similar way as the term fissure swarm is used in Iceland. These zones extend from the central volcano in direction perpendicular to the direction of plate spreading. Underlying the rift zones are so-called dyke swarms (Walker, 1993).

It is a common misunderstanding that rift zones/fissure swarms (henceforth referred to as RZ/FS) only occur in connection to plate boundaries. RZ/FS can, however, also be found in intraplate, island arc and spreading center volcanoes. The features that define the zone as a rift zone such as subparallel normal faults, tensile cracks and eruptive fissures may vary with tectonic settings and magma type as well as volcano type (Rubin, 1992). George Walker (1999) describes different kinds of fissure swarms depending on volcano types. The rift zone/fissure swarm may be straight or curved inwardly inclined or annular in form depending on the type of volcano. Active Hawaiian shield volcanoes have the longest and narrowest RZ/FS, while strato- and central volcanoes have the shortest. RZ/FS have not only been found on the Earth but also on the surface of Venus and Mars (Ernst et al., 1995; McKenzie et al., 1992; Ernst et al., 2001) which supports the idea that RZ/FS are not exclusively found at plate boundaries.

### 2.1. Fissure swarms of Iceland

Most of the active volcanic systems in Iceland have a fissure swarm or around 2/3 (Jóhannesson and Sæmundsson, 2009). In these fissure swarms the fracturing of the active volcanic zones is concentrated. The fissure swarms in Iceland are up to 20 km broad and sometimes over 100 km long. Their dominant structures are the volcanic fissures, noneruptive gaping cracks, and normal faults or fault groups with vertical hades. The volcanic fissures are lined up with few tens of meters (m) to a few km spacing, they tend to be curved and branching and they often consist of short en echelon segments. Their trend clusters around a maximum that lies in the direction of the swarm. Cross faults and volcanic fissures that lie perpendicular to the main direction can be seen but are rare. The faults and fissures of the Icelandic fissure swarms are usually assumed to be associated with dyke injections. Normal faults with throw from few meters up to several hundred m also occur in the Icelandic fissure swarms as well as graben structures. Most of the fissure swarms are focused on a
central volcano where the locus of most frequent eruptions and maximum lava production on the swarm occurs. This makes the central volcanoes topographically distinct (Sæmundsson, 1979).

The tectonic and volcanic activity of a volcanic zone occurs episodically rather than continuously with an interval of 100-150 years. During each active period with duration of around 5-20 years only one volcanic system is active and thus normally only one fissure swarm or a part of a fissure swarm (Björnsson et al., 1977). Such active period is often termed rifting episode and during a rifting episode the tensional stress that has accumulate between such episodes is released. The central volcano, that most fissure swarms are associated with, seems to play an important role during a rifting episode by allowing the ascent of magma from a shallow magma chamber under its roots. During a rifting episode magma from the shallow magma chamber is injected into the fissure swarm. This happens when the magma pressure reaches a certain level and triggers a jerk of rifting. If the ascent of magma into the magma chamber continues beyond the widening capacity of the fissure swarm an eruption may eventually result (Sæmundsson, 1978).

According to Buck, Einarsson and Brandsdóttir (2006) not only the magma pressure triggers dyke propagation and thus rifting. Tectonic stress is another key factor. The dyke begins propagation when the driving pressure equals the “breakout” pressure needed to force the magma out of the magma chamber. The driving pressure of dyke propagation is the difference between magma pressure and tectonic stress orthogonal to the dyke. When this driving pressure becomes too small the dyke stops propagating. The first dyke in each rifting episode should be the longest and is then followed by successively shorter dykes. When tectonic stresses close to the magma chamber have been relieved the extrusion of magma may start. Major eruptions can only occur after dyke opening relieves most of the tectonic stress. The larger the magma chamber under the central volcano is the longer the dyke become (Buck et al., 2006).

The 1975-1984 Krafla rifting episode is probably the best-studied dyke intrusion event on a divergent plate boundary. It happened in the Krafla volcanic system that consist of a central volcano and associated fissure swarm and is located in the Northern Volcanic Zone. The fissure swarm extends from Axarfjörður in the north to the mountainous area southeast of Mývatn in the south. It is around 100 km in length and about 5-10 km wide (Fig. 3) (Johnsen et al., 1980).
Figure 3: Most part of Northern Volcanic Zone and its fissure swarms (yellow areas) (Einarsson and Sæmundsson, 1987). In the middle lies the Krafla fissure swarm. The background is from the National Land Survey of Iceland. Mestur hluti Norðurgosbeltisins og sprungusveimar þess (gulu svæðin) (Einarsson and Sæmundsson, 1987). Fyrir miðju liggur sprungusveimur Kröflu. Bakgrunnurinn er fenginn frá Landmælingum Islands.

During the episode magma ascended from depth and accumulated in a magma chamber located at about 3 km depth within the caldera of the Krafla central volcano. The inflation periods were punctuated by sudden deflation events that lasted from several hours to 3 months when the walls of the magma chamber were breeched and
magma was injected laterally into the adjacent fissure swarm where large scale rifting took place. During each event the flanks of a segment of the fissure swarm moved away from each other (Buck et al., 2006).

2.2. Examples of fissure swarms or rift zones in the World

2.2.1. The Main Ethiopian Rift
The Main Ethiopian Rift is a part of the East African Rift. The East African rift is one arm of the Afar Triple Junction where the Arabian plate, Nubian plate and Somalian plate meet, the other arms of the junction are the Gulf of Aden and the Red Sea (Fig. 4) (Hamling et al., 2009; Corti, 2009).
The Main Ethiopian Rift (MER) is an 80 km wide rift valley between the Ethiopian Plateau and the Somalian Plateau. It dies out in the north into the wide Afar depression and in the south by the Turkana depression. It can be subdivided on the basis of structural features into three segments; Northern Main Ethiopian Rift (NMER), Central Main Ethiopian Rift (CMER) and Southern Main Ethiopian Rift (SMER) (Fig. 5) (Corti, 2009). The three segments of MER are somewhat comparable to the Volcanic Zones of Iceland and within each segment is what Kurz et al. (2007) calls tecto-magmatic segments that are similar to the volcanic systems in Iceland.
Figure 5: Digital elevation model of the Ethiopian Rift showing the main rift segments (from north to south): Southern Afar (SAfar), Northern Main Ethiopian Rift (NMER), Central Main Ethiopian Rift (CMER) and Southern Main Ethiopian Rift (SMER). GB stands for Gofa Basin and Range, CB for Chow Bahir Rift and BRZ for Broadly Rifted Zone. Figure from Corti (2009). Hæðarlíkan af Ethiopian Rift sem sýnir helstu hluta þess (frá norðri til suðurs): Southern Afar (SAfar), Northern Main Ethiopian Rift (NMER), Central Main Ethiopian Rift (CMER) and Southern Main Ethiopian Rift (SMER). GB stendur fyrir Gofa Basin and Range, CB fyrir Chow Bahir Rift og BRZ fyrir Broadly Rifted Zone. Mynd fengin frá Corti (2009).

NMER is a NE-oriented rift section in the MER. Within the NMER lie 4 tectomagmatic segments, Gedemsa, Boseti, Kone and Fantale. Each segment is built up by volcanic center with a central volcano and tips characterized by brittle deformation. The area from the central volcano and to the tips is similar to the fissure swarms in Iceland. Nearest to the central volcano the deformation is mostly magmatically induced but moving from the center to the tips the deformation changes to brittle. In the fissure swarm one can find open fissures, aligned basaltic cones and faults (Kurz et al., 2007).
Tectonic settings in Iceland and East Africa are somewhat similar. Iceland is a subaerial portion of the Mid-Atlantic ridge and owes its existence to a hot spot fed by a deep mantle plume located in Central Iceland (Einarsson, 2008). In the Main Ethiopian Rift in East Africa we have continental break-up. In northern MER the crust is in a transitional stage from continental to oceanic as the spreading changes from mid-oceanic spreading in Afar (Wright et al., 2011) to continental break-up in the MER (Kurz et al., 2007). Both in Iceland and East Africa volcanic systems/tecto-magmatic segments and fissure swarms can be found.

### 2.2.2. Rift zones in Hawaii

The Island of Hawaii (Big Island) is a large volcanic island that lies at the southeastern end of the Hawaiian Ridge, a linear chain of mostly submarine volcanic mountains that extends for 3,500 km through the central Pacific Ocean (Fig. 7). The Island of Hawaii is the biggest island of eight main Hawaiian islands that span about 640 km from southeast to northwest. Numerous smaller islands, atolls, reefs and shoals lie farther northwest for about 2,600 km and in continuation lies the exclusive submarine portion of the Hawaiian Ridge for 900 km. The Hawaiian Ridge then bends sharply northward to become the Emperor Seamount chain. The Emperor Seamount chain is a similar linear chain that extends for another 2,500 km as far as the Aleutian Trench (Fig. 7) (Peterson and Moore, 1987).
Figure 7: Tectonics of the Pacific basin. Hawaii, Hawaiian ridge and Emperor Seamount chain. Figure from NOAA (National oceanic and atmospheric administration). Höggunarkort af Kyrrhafinu sem sýnir Hawaii, Hawaii hrygginn og Emperor Seamount keðjuna. Mynd fengin frá Bandarísku Veðurstofunni NOOA.

The combined Hawaiian-Emperor volcanic chain records the persistent movement of the Pacific Plate over a stationary hot spot beneath the crust. The magma generated erupts to build volcanoes at the surface of the plate above the hot spot. As the plate moves these volcanoes cease to grow but new ones are formed (Peterson and Moore, 1987).

Hawaii consist of five individual volcanoes: Kohala, Mauna Kea, Hualalai, Mauna Loa and Kilauea. Kilauea volcano is one if the best studied basaltic volcano in the world as well as one of the most active. The magmatic system of Kilauea consist of a magma source in the mantle, a vertical pathway of magma up to a shallow magma chamber beneath the summit area and horizontal pathways that transport magma along Kilauea rift zones or fissure swarms (Tilling and Dvorak, 1993).

Kilauea has two large RZ/FS, the SRS and the ERS. The ERS forms a ridge extending more than 60 km beyond Cape Kumukahi witch is the easternmost part of Hawaii. The subaerial part of the rift zone is 4-6 km wide (Fig. 8). The southwest rift zone does not form a distinct ridge like the east rift zone and it doesn’t reach far beyond the shoreline. The active part of the rift zone has threads of closely spaced fractures separated by unbroken blocks (Holcomb, 1987).

Moore and Krivoy (1964) suggested that gravitational slumping was the major factor causing the rift to widen and that magma moved into the fractures formed in the head of the slumping block. Later it was proposed that magmatic pressure pushed the rift apart and the slumping was the result rather than the cause of the rifting process.
Both suggestions are in a sense correct as gravitational and magmatic stresses control the evolution of the rift zones (Decker, 1987).

The rift zones of Kilauea volcano have been very active during the past few decades. From 1959 through 1984 there were 19 rapid intrusions into the east rift zone with an eruption and 20 without an eruption. During the same period there were two rapid intrusions into the southwest rift zone with eruptions and eight without. As in other RZ/FS the zone widens to accommodate these multiple intrusions or dykes that are injected into the flanks of the volcano (Decker, 1987).

In comparison to Icelandic fissures swarms the Hawaiian RZ/FS are narrower and with fewer normal faults. Observation on eroded dykes in Iceland and Hawaii show that dykes in Iceland are typically several times thicker than those in Hawaii. Seismic and geodetic data indicate that dykes in active volcanoes in both places are intruded laterally from magma chambers under the central volcano into the adjacent fissure swarm and the height of the dykes seems to be similar. If the elastic properties of the RZ/FS are the same this implies that dykes are intruded with higher driving pressure in Iceland than Hawaii. Due to the fact that in Iceland large normal faults are much more common than in the Hawaii rift zones one can assume that fewer dykes manage to reach the surface in Iceland than in Hawaii. So even though dykes in Iceland are intruded with higher driving pressure they possess lower absolute magma pressure than in Hawaii. These differences are because of different tectonic settings in
the two regions, Iceland at a divergent plate boundary over a hot spot and Hawaii over a hot spot in middle of the Pacific plate (Rubin, 1990).

### 2.2.3. Rift zones on Venus

Radar images of Venus from NASA’s Magellan spacecraft (mission from 1989 – 1994) revealed many bright linear features. These features are likely to be the surface expression of near-surface dyke swarms and thus similar to earth’s rift zones or fissure swarms (Ernst et al., 1995).

Most spectacular features of these features are large, radiating fracture-graben systems. There are at least 163 documented systems whose radial elements are composed primarily of flat-floored graben, V-shaped fissures and fractures. These radial elements are typically less than several km in width. Graben and fissures cluster near the center and then grades into fractures at greater distances. Average length of these features, that is the radii of the radiating systems, is about 325 km. The central area is in more than half of these systems domical or 53%, 15% are flat and 9% depressions. The rest is indistinguishable from the surrounding. The majority of the radiating systems exhibit volcanism (Grosfils and Head, 1994).

These RZ/FS on Venus are believed to be the surface expression of large dykes that propagate in a stress field that is controlled by the elevation at the center. Little is known about surface features associated with the emplacement of such large dykes on Earth. They often underlie plateau basalt provinces and are only exposed at the surface when the overlying basalts are eroded. That is not the case on Venus as no or little erosion occurs (McKenzie et al., 1992).

The dyke intrusions or riftting episodes that have been studied on Earth involve much smaller dykes that don’t always extend to the surface. The extension is instead taken up by the formation of open fissures and normal faults. McKenzie et al. (1992) speculate that the surface expression would be similar to those features observed on Venus if the dykes would be larger and didn’t reach the surface because the magma within them drains at the end of the emplacement event or the pressure within the magma chamber is insufficient.
Figure 9: Giant radiating dyke swarms on Venus. Top: Magellan radar image of a typical giant radially fractured structure on Venus. Arrow 1 points to one of the many surface fractures interpreted to be the surface manifestations of dykes emplaced at shallow depths below the surface and radiating from a central reservoir. Arrow 2 points to a circular feature interpreted as the central reservoir. Middle: Generalized block diagram showing features associated with radially fractured structures. LNB is location of neutral buoyancy zone. Bottom: Portion of the middle figure, the box, showing surface morphology and inferred subsurface configuration of dykes. Bottom: The zoomed box showing surface morphology and inferred subsurface configuration of dykes. Figure taken from Ernst et al. (1995).
3. The research area

The volcanic system of Tungnafellsvatn is located in Central Iceland Volcanic Zone near the center of the hot spot of Iceland and the triple junction between the Eurasian plate, North-American plate and the Hreppar microplate (Figs. 2 and 10). The zone marks the northern boundary of the Hreppar microplate and the relative movement across the zone seems to be slow (Einarsson, 2008).

The volcanic system and the volcanic system of Hofsjökull are the only volcanic systems in the Central Iceland Volcanic Zone. The volcanism of these systems is minimal as few eruptions has been recorded in Holocene. Only two small Holocene lavas can be associated with the Tungnafellsvatn volcanic system, the Tunguhraun lava and the Dvergar lava (Fig. 1 in Chapter 5) (Sæmundsson, 1982). The lavas have not been dated but they have been chemical analyzed (Óskarsson et al., 1982; Óskarsson, Pers. Comm., 2010). Chemical analysis shows that the Tunguhraun lava and Dvergar lava are both of primitive basalts and are almost picrites as they have very high MgO contents.

The Tungnafellsvatn volcanic system consists of two or three central volcanoes, the Tungnafellsvatn central volcano, the Vonarskard central volcano and the Hágöngur central volcano, and a fissure swarm (Fig. 1 in chapter 5) (Friðleifsson and Johannesson, 2005).

Very little literature exists on the volcanic system of Tungnafellsvatn. Sæmundsson mentions Tungnafellsvatn and Vonarskard in an article about calderas in the active volcanic zones of Iceland in the early eighties (Sæmundsson, 1982). Previously, he had also published a schematic map of the fissure swarm (Sæmundsson, 1978). Further research on the Vonarskard and Hágöngur central volcano and their associated high temperature fields can, however, be found in the literature (e.g. Friðleifsson and Johannesson, 2005; Jónsson et al., 2005; Johannesson and Friðleifsson, 2006; Karlsdóttir et al., 2008).
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5. Evidence of recent movements in Tungnafelljökull fissure swarm in Central Volcanic Zone, Iceland

Abstract - The volcanic system of Tungnafelljökull in central Iceland has been considered to be only slightly active. The volcanic system lies in the Central Iceland volcanic zone near the center of the hot spot and the triple junction where the Eurasian plate, the North-American plate and the Hreppar Microplate meet. Activity has been very low in the Holocene, only two small lavas are associated with the system. Earthquakes are not common, with usually fewer than 10 being registered per year. Due to these facts, it came as a surprise when InSAR measurements detected movements on faults in the fissure swarm of Tungnafelljökull during the Gjálp eruption in Vatnajökull in 1996 at a distance of around 37 km. Ground check in 2009 and 2010 revealed evidence of recent movements on faults in the area in the form of fresh sinkholes and fractures. It was obvious from the ground check that some of the sinkholes and fractures had moved as recently as the spring of 2010. By looking at earthquake data from the area and InSAR images from the Gjálp eruption, two or three tectonic events can be identified that may be associated with these movements. The first event occurred in October 1996 during the Gjálp eruption, the second in August of 2008 and the third in November of 2009. These events are expressed by increased seismicity in the Tungnafelljökull area, both in terms of the number of earthquakes as well as rate of seismic moment release.

Introduction

Iceland is located at the mid-Atlantic plate boundary where three plates meet, the North-American plate, the Eurasian plate and the Hreppar microplate. Indeed, the country provides the only place where this plate boundary can be studied on land. The tectonic picture of the plate boundary in Iceland is more complicated than mid-oceanic plate boundaries usually are. The structure of the boundary is influenced by
the Icelandic hot spot with presumed deep root in the mantle. The relative motion of the Mid-Atlantic Ridge with respect to the hot spot leads to ridge jumps, propagating rifts and other complexities (Einarsson, 1991).

The plate boundary in Iceland is defined by complex fracture zones in the north (Tjörnes Fracture Zone) and south of the island (the South Iceland Seismic Zone), as well as rift zones or volcanic zones (Reykjanes Peninsula Rift, Western Volcanic Zone, Eastern Volcanic Zone, Central Iceland Volcanic Zone and Northern Volcanic Zone) (Einarsson, 2008). The structure of the volcanic zones is characterized by structural units called volcanic systems. In Iceland, there are about 30 active volcanic systems of which 2/3 have a fissure swarm and 2/3 have a central volcano (Jóhannesson and Sæmundsson, 1998). The volcanic system of Tungnafellsjökull is an example of a system that has both a fissure swarm and a central volcano. It is located in the Central Iceland Volcanic Zone along with the Hofsjökull volcanic system (Einarsson, 2008).

The Tungnafellsjökull volcanic system lies near the centre of the hot spot and a triple junction were the Central Iceland, Northern and Eastern Volcanic Zones meet. The system consists of two or three central volcanoes, the Tungnafellsjökull central volcano, the Vonarskard central volcano and the Hágöngur central volcano, and a fissure swarm (Friðleifsson and Jóhannesson, 2005). The Tungnafellsjökull central volcano and Vonarskard central volcano are here considered to be one central volcano having two calderas, one is located under Tungnafellsjökull ice cap and the other one is located to the SE of the glacier in Vonarskard. The Hágöngur central volcano is located SW of Tungnafellsjökull (Fig. 1). The central volcanoes are characterized by a significant contribution of silicic products. Volcanic activity in the Tungnafellsjökull volcanic system has been low in the Holocene. There are no known major eruptions and only two small lavas can be associated with the system in the Holocene, the Dvergar lava and the Tunguhraun lava.
Figure 1: Simple geological map of the area around Tungnafellsjökull based on maps from Kjartansson (1965) and Jóhannesson and Friðleifsson (2006a). The background is from the National Land Survey of Iceland.
In 1996, there was a subglacial eruption in Gjálp beneath the Vatnajökull ice cap (Guðmundsson et al., 1997; Einarsson et al., 1997). The eruption was the largest in Iceland in terms of volume since the Surtsey eruption that took place from 1963 until 1967. During the Gjálp eruption, movements of faults in the Tungnafellsgökull volcanic system were detected by InSAR measurements. The movements were of the order of a few cm (Pagli et al., 2007). As the eruption occurred in a different volcanic system, it was therefore surprising that movements at Tungnafellsgökull were measured. Indeed, these movements were the trigger of the present study.

Previous research on the fissure swarm of Tungnafellsgökull is limited. A map of the fissure swarm first appeared in an article by Sæmundsson (1978). That was a structural map of the neovolcanic zones in Iceland, which was later modified by Einarsson and Sæmundsson (1987). Einarsson and Björnsson (1990) made another modification on the map by removing Breiðabunga central volcano from the map, based on new information on subglacial topography. With these modifications on the original structural map by Sæmundsson, the map has since been used (Fig. 2).
Figure 2: Fracture map of the volcanic system of Tungnafellsjökull. The satellite image is from SpotImage© and the delineations of the fissure swarms are from Einarsson and Sæmundsson (1987). - Sprungukort af eldstöðvakerfi Tungnafellsjökuls. Gervihnattamyndin í bakgrunni er frá SpotImage© og útlínur sprungusveimsins eru frá Páli Einarssyni og Kristjáni Sæmundssyni (1987).
The main goal of the present study was originally to gain an overview of the fissure swarm of Tungnafellsjökull by mapping active fractures and fissures that relate to the volcanic system. The area mapped is approximately 1,450 km$^2$ and was chosen in order to grasp the interactions between the volcanic system, the fissure swarm and the plate boundary. The fractures and fissures were mapped from aerial photographs taken at approximately 8,000 m altitude in 1999 by a private company called Loftmyndir ehf. The aerial photographs revealed that the fissure swarm extended further to the west than the map by Sæmundsson indicated and that it was also shorter. The fissure swarm of Tungnafellsjökull is wider than the central volcano, i.e., it passes it, rather than radiating from it, as most of the fissure swarms of Icelandic volcanoes do. During the summer of 2009 and 2010 a ground check was conducted which led to a slightly different approach to the project.

In the ground check, the places where InSAR had detected the measured movements were visited, as well as some of the faults that were mapped by aerial photographs north and west of Tungnafellsjökull. Fractures were found that had obviously moved recently, as well as fresh sinkholes. The sinkholes indicate movements as recent as the spring of 2010. These fresh movements came as a surprise to the researchers and consequently many questions arose. Instead of emphasizing the map of the fissure swarm, descriptions of these fresh sinkholes and fractures, as well as the reasons for them, became the main subject of the study.

Following the discovery of these new movements the data were analyzed, both internally and by comparing them to older data, such as InSAR measurements and earthquake data from the area. The earthquake data were obtained from the Icelandic Meteorological Office (Veðurstofa Íslands) and InSAR data from Amandine Marie-Claude Auriac (2011).

**Definition of terms**

A *volcanic system* in Iceland was first defined by Kristján Sæmundsson in 1974. Sæmundsson defines it as a unit that consist of a fissure swarm with normal faults and eruptive and open fissures passing through a central volcano that marks the locus of the most intense activity (Sæmundsson, 1974). In 1979, Sveinn Jakobsson also defined a *volcanic system*. He described it as a spatial grouping of eruption sites in a
certain period of time with particular characteristics of tectonics, petrography and geochemistry. He also claimed that at a primitive stage the system has the characteristics of an eruptive fissure swarm, with basaltic rocks dominating. Later evolved rocks start to develop in certain centres. In the same area (centers), a caldera and a high-temperature thermal field may develop leading in the end to the formation of a central volcano (Jakobsson, 1979a). The active life of most volcanic systems is between 0.1 and 10 Ma (Walker, 1993).

In both definitions of volcanic systems, the terms central volcano and fissure swarm are used. A central volcano is a centrally situated complex where the discharge of magma is highest. A central volcano may have one or more calderas and a high-temperature area. They have a significant amount of silicic volcanic rocks in addition to basalt (Jakobsson, 1979b; Walker, 1993). Fissure swarms are regarded as the surface expression of dyke swarms. They consist of normal faults, tensile fractures and volcanic fissures that extend from the central volcano. The fissure swarms are usually about 10 km wide and their length varies from 30 to over 100 km. The fissure swarms within each branch of the rift zones are typically arranged en echelon. The arrangement may be dextral or sinistral depending on the direction of maximum principal tensile stress that is parallel to the direction of plate movement (Sæmundsson, 1978).

**Regional Setting**

Tungnafellsjökull is located in the center of Iceland between Vatnajökull glacier and Hofsjökull glacier. The area has very little vegetation, water is sparse, and is characterized by large areas of sand and sandy ridges. The landscape was formed by glacial erosion during the Pleistocene and is covered by ground moraines to a large extent. There are no settlements in this area and the few structures that do exist are simple huts used by travelers during the summertime. The route to this area is only passable by 4wd vehicles and then only during the summer. The obstacles found en route include glacier rivers, which have to be forded.

Past research on the Tungnafellsjökull volcanic system has been limited and its classification within the volcanic zones in Iceland unclear. Friðleifsson and Jóhannesson (2005) classified it within the Northern Volcanic Zone, whereas Jakobsson, Jónasson and Sigurðsson (2008) felt that it is unclear if it lies within the
Northern Volcanic Zone or the Eastern Volcanic Zone. However, Einarsson (2008) puts it within the Central Iceland Volcanic zone along with Hofsjökull and in this study we favor that opinion.

The Tungnafellsgjökull volcanic system consists of two or three central volcanoes: The Tungnafellsgjökull central volcano, the Vonarskarð central volcano and the Hágöngur central volcano (Fig. 1 in chapter 5). Reconnaissance survey by Friðleifsson and Jóhannesson (2005) suggest that the Tungnafellsgjökull central volcano and Vonarskarð central volcano should be considered as a part of the same central volcano complex. Bárdarbunga central volcano, one of the more active volcanoes in Iceland, lies to the SE and is a part of a separate volcanic system (Fig. 1).

The Tungnafellsgjökull central volcano forms a ridge-shaped mountain reaching elevation of 1,500 m and is slightly eroded. It has a radius of about 10 km but doesn’t rise as a perfect cone due to the erosion that has occurred. The Vonarskarð central volcano has an 8 km wide caldera and active high-temperature field in the center. The eastern part of the volcano is covered with subglacial volcanics from the younger Bárdarbunga central volcano. The Vonarskarð volcano is, according to Friðleifsson and Jóhannesson (2005), clearly a slightly younger structure than Tungnafellsgjökull volcano. No eruption is known to have originated from the volcano itself in Postglacial time (i.e., the last 9000 years), although two small lavas beyond the foothills are associated with the system, the Dvergar lava and the Tunguhraun lava (Sæmundsson, 1982; Friðleifsson and Jóhannesson, 2005) (Fig. 1).

Methods
Fractures and fissures within the study area were mapped both from aerial photographs and satellite images. Certain areas were also checked at ground level. These data were combined with data on seismic activity in the area obtained from the Icelandic Meteorological Office (IMO). InSAR images were also used to get a better grip on the activity that has occurred in the area during the previous couple of years.

The ground check was conducted in two trips in the summer of 2009 and in the summer of 2010. In the first trip, the focus was on the area north of Tungnafellsgjökull and in the second the main task was to further observe features in the area that were detected from aerial photographs.
The aerial photographs used were contact images from Landmælingar Íslands (The National Land Survey of Iceland) and digital images from Loftmyndir ehf. These images were taken at approximately 6,700 and 8,000 m altitude in 1996 and 1999, respectively. The satellite images were obtained from SpotImage© and the ASTER archive.

Information regarding earthquakes that have occurred in the area was obtained from the Icelandic Meteorological Office. This was used to compare the locations of earthquakes and tectonic features. The earthquake data covered the period from September 1996 to August 2011. To filter the poorly located earthquakes, earthquakes with larger azimuthal gap than 180° were excluded as well as earthquakes with larger RMS value than 0.25 s and earthquakes that were located using arrival times from fewer than four stations.

**Structural architecture**

**Overview**
The mapped fractures are shown in Fig. 2. The area mapped may be divided into three areas according to its physiographic and tectonic style: The Ógöngur area which is located southwest of Tungnafellsjökull (named after hyaloclastite ridges in the area), the Tómasarhagi area which is northwest of Tungnafellsjökull, and the Langadrag area which is northeast of Tungnafellsjökull (named after a glacier river that runs across the area).

Fractures located within the study area are mostly normal faults, sometimes forming a graben. Features that indicate recent movements like sinkholes and open fissures are common, especially in the Tómasarhagi area. The orientation of fractures and faults is different between the three areas. From north to south the orientation changes from various orientations in the Langadrag area to NE in the Tómasarhagi area to ENE in the Ógöngur area. Hyaloclastite ridges, the product of subglacial fissure eruptions (Kjartansson, 1943), are common in the Ógöngur area.

The fissure swarm extends farther to the west than the fissure swarm drawn in the structural map by Sæmundsson. Many of the faults and fissures of the fissure swarm seem to pass the volcano instead of radiating from it. (Fig. 2).
**Structures indicating recent movements**

Fig. 3 shows three different types of structures that provide evidence of recent movements in the fissure swarm of Tungnafellssjökull. Type 1 (Fig. 3a) shows a step in a glacially eroded area. The step in the glacial ground moraine that normally has no obvious features indicates movements on faults in the Holocene. Type 2 (Fig. 3b and c) shows a sinkhole in glacial moraine. Sinkholes form when there is movement on faults or fractures and loose material is washed into the fracture. This is clear indication of movements in the Holocene since the Pleistocene ice sheet can be assumed to have left fissures packed with debris. Type 3 (Fig. 3d, e and f) show sinkholes and fractures that bear obvious sign of very recent movements. The fresh wounds in the rim of the sinkholes (Fig. 3d and e) and in the edge of the fracture (Fig. 3f) indicate movements as recent as the spring of 2010.
Figure 3a) Fault in the Ógöngur area. An example of type 1. b) Fracture with sinkholes in the Langadrag area. An example of type 2. c) Sinkholes formed above an open fracture in Langadrag area. Another example of type 2. d) Big sinkhole in the Tómasarhagi area. An example of type 3. e) Another big sinkhole in the Tómasarhagi area, also an example of type 3. f) Fracture with evidence of recent movements in the Tómasarhagi area. The third example of type 3.

The Ógöngur area

Hyaloclastite ridges and normal faults that are ENE oriented characterize the area southwest of Tungnafellsjökull. These normal faults are very prominent on satellite images as well on the aerial photographs. Very few fissures or sinkholes can be detected in this area, which indicates that recent movements have been scarce (Figs. 2, 3a and 4).

It has been speculated that Vonarskarð and Tungnafellsjökull are two separate volcanic systems with two fissure swarms (Jóhannesson and Friðleifsson, 2006). Indeed, fissure swarms often have the structure of a shallow graben with boundary faults dipping towards the center of the swarm. If Vonarskarð and Tungnafellsjökull had separate fissures swarms, one would assume that the normal faults in the Ógöngur area would change dip direction along the way from west to east to reflect the two parallel grabens. Normal faults at the east boundary of the graben structure belonging to Tungnafellsjökull fissure swarm would therefore be westward dipping and faults at the western boundary of the graben belonging to the Vonarskarð fissure swarm would be eastward dipping. However, field investigations on a cross section from west to east taken in this area in the summer of 2010 (Fig. 4) revealed only westward dipping faults. This supports the idea of only one fissure swarm. This requires further investigation.

Figure 4 shows mapped faults and fractures in the Ógöngur area as well as cross sections over the faults. The cross section is measured with gps and gives the vertical offset of the faults. The vertical offset over the four cross section measured varied within the range ~5-15 m. Hyaloclastite ridges and pillow lava mountains (or ridges) are prominent in the southeast part of the area. To the west, there are no mountains - only sand ridges and dunes (Fig. 3a). No Holocene lavas are found in this area. All exposed volcanic formations have a normal magnetization and are thus younger than 700,000 years (Piper, 1979).
Figure 4: Fracture map of the Ógöngur area. The satellite image is from SpotImage®. - Sprungukort af Ógöngu svæðinu. Gervihnattamyndin í bakgrunni er frá SpotImage®.
The Tómasarhagi area

Tungnafellsjökull glacier lies in the southeast corner of this area and sand ridges and dunes characterize other parts of it. Three glacier rivers lie from Tungnafellsjökull out into the sands below as well as several smaller streams. In Nýidalur and Tómasarhagi, vegetation in the form of moss, grasses and small bushes can be found.

Numbers of normal faults with open fissures and sinkholes can be found in this area providing evidence of Holocene movements. The area closest to Tungnafellsjökull is characterized by numerous normal faults and graben with open fissures and sinkholes. The fissures and sinkholes are often very deep and indicate movements as recent as spring of 2010 (Fig. 3d, e and f). A cross section over the boundary faults of the graben, measured with gps, gives a subsidence of 2-6 m from the bottom of the graben.

Figure 5 shows mapped faults and fissures in the Tómasarhagi area. Faults and fissures in this area are NE oriented, lying parallel to Tungnafellsjökull central volcano (Fig. 2 and 5). This is not the normal spatial relationship for Icelandic fissure swarms, where the norm is for the fissures to radiate from the central volcano, not to pass it.

The movements detected by InSAR measurements following the Gjálp eruption in 1996 were found in this area (Fig. 4). A ground checks in these places revealed normal faults with fissures and sinkholes.
Figure 5: Fracture map of the Tómasarhagi area. The satellite image is from SpotImage®.

Sprungukort af Tómasarhaga sveðinu. Gervihnattanyndin í bakgrunni er frá SpotImage ®.
The Langadrag area

Figure 6 shows fractures and faults mapped in the Langadrag area. Fractures and faults in the area have variable orientations (Figs. 2 and 6). Indeed, they change from west to east, forming a fan-like structure ending with the Dvergar eruptive fissure in the southeast. The Dvergar lava is formed in a fissure eruption. Figure 7 shows how the craters of the Dvergar eruption are lined up in ENE direction ending the fan-like structure. The connection between the faults and fractures of the Langadrag area and Tungnafellssjökull central volcano is difficult to trace due to steep topography and high degree of erosion.

Compared to the Ógöngur area and the Tómasarhagi area, faults and fractures are scarce in this area. However, along these few faults there is ample evidence of recent movements in the form of sinkholes and fissures. Rows of sinkholes and scarps of 0-2 m height marked the faults as they were mapped on the ground during the field check in the summer of 2009.

Both of the Holocene lavas associated with the Tungnafellsjökull volcanic system are located in the Langadrag area. Tunguhraun from Bokki crater lies in the west and Dvergar lava in the southeast. Both of these lavas are small, volume-wise, indicating small eruptions. Sand ridges and dunes are prominent in the area, although some hyaloclastite ridges can also be seen. A warm pool called Hitalaug is found in the northern part of this area. It is located about 2.5 km to the south of one of the places where movements were detected by InSAR measurements. A ground check on this spot revealed no fresh faults or fractures. The warm pool, on the other hand, is clearly related to old fractures.
Figure 6: Fracture map of the Langadrag area. The satellite image is from SpotImage©.

-Sprungukort af Langadragssvæðinu. Gervihnattamyndin í bakgrunni er frá SpotImage ©.
Figure 7: Map showing the Dvergar volcanic fissures and lavas. The satellite image is from SpotImage®. - Kort sem sýnir gossprungur Dverganna og hraunið sem þeim fylgdi. Gervihnattamýndin í bakgrunni er frá SpotImage®.
Discussion / Conclusions

Fissure swarms in Iceland have been studied to varying degrees. Research on the volcanic systems in the Central Iceland Volcanic zone has been limited, but other volcanic zones have been studied more extensively, e.g. the Northern Volcanic Zone.

The Northern Volcanic Zone lies on the divergent boundary. Characteristics of the fissure swarms in the zone are somewhat similar. They are approximately 5-20 km wide and 40-120 km in length, each extending from a specific central volcano. The fissure swarms consist of volcanic fissures, faults and fractures. Volcanic fissures are usually dominant near the central volcano, but tectonic fractures become more frequent further away from the central volcano. The activity of the fissure swarms seems to be highest in the middle, i.e. their altitude is higher there than elsewhere (Hjartardóttir et al., 2009; Hjartardóttir and Einarsson, 2011). The fissure swarm of Tungnafellsjökull bears some of these characteristics, but nevertheless appears to be a little different.

Indeed, the volcanic system of Tungnafellsjökull lies on the plate boundary, but activity in the system has been scarce for the last ca. 10,000 years. Looking at earthquakes in the area from 1996 to 2011 (Fig. 8), one can see that the earthquake activity is low compared to the earthquake activity in known active volcanic systems (Einarsson, 1991; Jakobsdóttir, 2008). Number of earthquakes per se is not a good measure of the geological importance of the earthquakes, however, so the cumulative seismic moment over time were also examined (Fig. 9a). The cumulative seismic moment shows 2-3 events that may have been associated with movements in faults and fractures in the system. The first one was during the Gjálp eruption in 1996 or in October of that same year (Fig. 9b), the second one was in August of 2008 (Fig. 9c) and the third in November of 2009 (Fig. 9c). The August event in 2008 was the smallest event of the three. The 1996 event is expressed both in the cumulative seismic moment and in the interferograms of Pagli et al. (2007). These events most likely mark the time of the movements observed in the area in the present study. InSAR data from April 2004 to September 2010 do not provide a coherent result (Auriac, 2011).
Figure 8: Earthquake location in the study area from September 1996 to May 2011 obtained from the Icelandic Meteorological Office. The background is from the National Land Survey of Iceland. - Staðsetning jarðskjálfa á rannsóknarsvæðinu frá September 1996 til Maí 20011. Gögn fengin frá Veðurstofu Íslands. Bakgrunnsmyndin er frá Landmælingum Íslands.
a) Cumulative seismic moment around Tungnafelljökull from 1996 to 2011

b) Cumulative seismic moment around Tungnafelljökull in 1996
Three zones or subswarms of faults and fractures may be separated within the Tungnafellsjökull fissure swarm: (1) the ENE oriented Ógöngur subswarm, south or southwest of the volcano; (2) the NE oriented Tómasarhagi subswarm, west of the volcano; and (3) the fan-like structure of the Langadrag subswarm, north of the volcano, with fractures striking from NNE to ENE. Recent movements were detected in the Tómasarhagi area and Langadrag area, but not in the Ógöngur area. In the Tómasarhagi area, at least two graben structures were found, approximately 5-7 m deep and about 500-800 m wide. The length of the fissure swarm mapped is about 40 km and the width is at most around 20 km. The fractures and faults of the swarm don’t only extend from the central volcano, they also pass it; that is, the fissure swarm is wider than the central volcano. Fissure swarms are not often wider than the central volcano, so the question arose whether those fractures could belong to another volcanic system, although this possibility was soon excluded. Indeed, no other central volcano or fissure swarm are found in the vicinity to which these fractures and faults could belong.
Summary of conclusions

1. The fissure swarm of Tungnafellsjökull lies near the active plate boundary in Iceland. It is about 40 km in length and 20 km wide, at most. The fissure swarm is thus relatively short and wide compared to other fissure swarms located on the plate boundary. The fissure swarm is wider than the Tungnafellsjökull central volcano and passes it rather than extends from it. Only two graben structures were found in the fissure swarm, which is fewer than in most fissure swarms in Iceland (Fig. 2).

2. Ground check in the summers of 2009 and 2010 revealed evidence of recent movements on faults in the fissure swarm. Three types of structures were found that indicated recent movements. Type 1 is a step in a glacial ground moraine that normally doesn’t have any obvious features. The step thus indicates movements in the Holocene. Type 2 and 3 are sinkholes or fractures on the ground. Both types indicate movements in the Holocene, but type 3 has open and fresh wounds in the rim of the sinkholes and the edge of the fractures. Such wounds could indicate movements as recent as spring 2010 (Fig. 3 a-f).

3. The cumulative seismic moment obtained from earthquake data from the area in the period from 1996 to 2011 reveals 2-tectonic events that may be associated with the observed movements on faults and fracture in the fissure swarm of Tungnafellsjökull. The first event is in October 1996 at the same time as the Gjálp eruption in Vatnajökull, which was located about 37 km away from the survey area. This event is also detected in interferograms by Pagli et al. (2007) and probably had the biggest influence on a number of active faults in the fissure swarm. The other events are smaller, one in August 2008 and the other in November 2009 (Fig. 9).
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