



***The fissure swarm of the Askja
central volcano***

by

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Hér með lýsi ég því yfir að ritgerð þessi er samin af mér og að hún hefur hvorki að hluta né í heild verið lögð fram áður til hærri prófgráðu.

Ásta Rut Hjartardóttir

Abstract

The Askja volcanic system forms one of the 5-6 volcanic systems of the Northern Volcanic Zone, that divides the North-American and the Eurasian plates. Historical eruptions have occurred both within the central volcano and in its fissure swarm. As an example, repeated fissure eruptions occurred in the fissure swarm, and a Plinian eruption occurred within the volcano itself in 1875. This led to the formation of the youngest caldera in Iceland, which now houses the Lake Öskjuvatn. Six eruptions occurred in the 1920's and one in 1961 in Askja. No historical accounts have, however, been found of eruptive activity of Askja before 1875, likely due to its remote location. To improve the knowledge of historic and prehistoric activity of Askja, we mapped volcanic fissures and tectonic fractures within and north of the Askja central volcano. The 1800 km² area included as an example Mt. Herðubreið, Mt. Upptyppingar and the Kollóttadyngja lava shield, as well as Askja. The results indicate that the activity of different subswarms of the Askja central volcano alternates with time, as the NE subswarm ends suddenly at a 3500-4500 BP lava flow. This may possibly occur due to different locations of inflation centers in Askja. If, as an example, the inflation center is easterly in Askja, a dike might propagate from this inflation center into the eastern part of the fissure swarm. Volcanic fissures are most common close to Askja, but the number of tectonic fractures increases with distance from the volcano. This may indicate a higher magma pressure in dikes close to Askja, than farther away. The number of fractures decreases with altitude in Kollóttadyngja, which may indicate more depth to the top of the dikes under the center of Kollóttadyngja, than beneath its slopes, due to altitude. Shallow earthquakes are mostly originated at non-fractured areas, like the ones that occur near Mt. Herðubreið, where fault-plane solutions have indicated the formation of strike-slip faults. In only about 4 km distance from Herðubreið, dilatational fractures, aged 4500-10.000 BP can be found. This may indicate that the maximum stress axis may have rotated since the formation of the dilatational fractures took place. The latest dike intrusions into either the Askja or the Kverkfjöll fissure swarms may have caused this rotation. Volcanic fissures are either oriented away from, or circle around the calderas in Askja. The volcanic fissures that are oriented away from the calderas may have formed after an inflation in a caldera, and the ones that circle around the calderas may have formed shortly after an inflation started in a previously deflating caldera. The first four eruptions that took place in the 1920's, and occurred around the newly formed caldera, may therefore indicate that an inflation had started in the caldera. The irregular orientation of fissures and fractures close to Askja suggests that it has a local stress field. The 1.7 km long pit crater chain in the Kollóttadyngja lava shield lies in and parallel with the Askja fissure swarm. We suggest that the topography of Kollóttadyngja caused a horizontal component of magma flow in an underlying dike. Increased magma flow in the upper part of the dike caused lower magma pressure, causing even more magma to flow into this part of the dike. A pipe was eventually formed which later collapsed, and formed the pit crater chain.

Ágrip

Askja í Dyngjufjöllum myndar eitt af 5-6 eldstöðvakerfum Norðurgosbeltisins, sem skilur að Norður Ameríku og Evrasíuflekann. Umbrot hafa orðið í eldstöðinni og sprungusveim hennar á sögulegum tíma, t.a.m. urðu endurtekin sprungugos í sprungusveim eldstöðvarinnar og sprengigos í eldstöðinni sjálfri árið 1875. Þessi umbrot leiddu til myndunar yngstu öskju Íslands sem nú hýsir Öskjuvatn. Sex eldgos urðu á þriðja áratug síðustu aldar í Öskju ásamt gosi þar árið 1961. Engar sögulegar heimildir finnast hins vegar um virkni í eldstöðinni og sprungusveim hennar fyrir árið 1875, líklega vegna þess hve afskekkt eldstöðin er. Til að fá betri mynd af sögulegri og forsögulegri virkni í sprungusveim Öskju voru sprungur í Öskju sjálfri og svæðinu norður af henni kortlagðar. Alls var rannsóknarsvæðið um 1800 km², og þakti m.a. Herðubreið, Upptyppinga og Kollóttudyngju ásamt Öskju sjálfri. Niðurstöðurnar benda til þess að virkni mismunandi hluta sprungusveimsins sé breytileg í tíma, þar sem NA hluti sprungusveimsins endar snögglega við 3500-4500 ára hraunlag. Þetta gæti hugsanlega stafað af mismunandi staðsetningu rismiðja í Öskju, ef rismiðja er t.d. austarlega í Öskju gæti gangur þaðan skotist austarlega í sprungusveiminn. Gossprungur eru flestar næst Öskju, en tektónískum sprungum fjölgar með fjarlægð frá henni. Þetta gæti bent til hærri kvikuþrýstings í göngum nærri Öskju heldur en fjær. Sprungum fækkar með hæð í Kollóttudyngju, sem gæti stafað af því að meira dýpi sé niður á gang þar heldur en í hlíðum dyngjunnar, vegna hæðar hennar. Grunnir jarðskjálftar verða aðallega á nánast ósprungnum svæðum milli sprungusveimanna, t.a.m. við Herðubreið, þar sem brotlausnir jarðskjálfta benda til sniðgengishreyfinga á NA-lægum sprungum. Í einungis 4 km fjarlægð frá Herðubreið liggja gliðnunarprungur. Þetta bendir til þess að ás mestu höfuðspennu hafi snúist frá myndun þessara sprungna, en þær mynduðust fyrir u.þ.b. 4500-10.000 árum. Hugsanlega hafa endurtekin kvikuinnskot í sprungusveim Öskju eða Kverkfjalla valdið þessum snúningi. Sprungur nærri öskjunum í Öskju hringa sig um þær eða stefna þvert út frá þeim. Gossprungur sem myndast þvert út frá öskjunum gætu hafa myndast eftir ris í öskjunum, en þær sem hringa sig um öskjurnar gætu hafa myndast stuttu eftir að ris byrjaði í öskju sem seig áður. Fyrstu 4 gosin sem urðu á þriðja áratug síðustu aldar, og lágu meðfram hinni nýmynduðu öskju, gætu þannig bent til þess að þá hafi ris verið hafið í hinni ungu öskju. Hin óreglulega stefna sprungna nærri Öskju bendir til þess að hún hafi staðbundið spennusvið. Hin 1.7 km langa fallgígaröð í Kollóttudyngju liggur í og samsíða sprungusveim Öskju. Samkvæmt okkar hugmynd olli hæð Kollóttudyngju láréttum þætti í kvikuflæði í gangi undir henni. Hið aukna kvikuflæði í þessum hluta gangsins leiddi til lægri þrýstings. Enn meiri kvika flæddi inn í þennan hluta gangsins. Pípa myndaðist, sem síðan hrundi, og myndaði fallgíganna.

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1 Introduction

This M.Sc. thesis consists of the following papers:

1. Structure of the northern fissure swarm of the Askja volcanic system in the volcanic zone of Northern Iceland
2. A pit crater chain in Kollóttadyngja, Iceland and its association with altitude and the Askja fissure swarm

The main goal of this work was to get a detailed map and observe the structure of volcanic fissures and tectonic fractures at a part of the Mid-Atlantic plate boundary, in the Northern Volcanic Zone of Iceland. The approximately 1800 km² area includes the Askja central volcano, a part of its fissure swarms as well as small parts of the fissure swarms of the Kverkfjöll central volcano, the Fremrinámar central volcano and the Krafla central volcano. The area chosen shows well the interaction between the fissure swarms, the Askja central volcano and the plate boundary. The purpose was also to see whether the style of the eruptive fissures and tectonic fractures changes with distance from Askja central volcano, to look at the relationship between earthquakes and fissure swarms in the research area and to study the characteristics and behavior of the Askja fissure swarm. We also studied the relationship between fissure swarms and pit craters located in the southeastern part of the Kollóttadyngja lava shield.

The volcanic fissures, tectonic fractures as well as the pit craters in Kollóttadyngja were mapped from aerial photographs, taken at approximately 6000 meters altitude in August 1987 by the National Land Survey of Iceland (Landmælingar Íslands). When necessary, a study in the field was also conducted. We rectified the aerial photographs with the ArcInfo software to get improved accuracy in locations of the mapped features, and made a digital fissure and fracture map. The accuracy is in most cases better than 100 m. The data were then analyzed, both internally and by comparing them to other data, such as the earthquake data obtained from the

Icelandic Meteorological Office (Veðurstofa Íslands) and data on the known age of lava flows in the area from Sigvaldason et al., (1992).

The following two chapters give a review on the background of this thesis. In the former chapter we will focus on fissure swarms, how they form and what their relationship with dikes is. In the latter chapter, a review will be given on the general geology of the research area, and on the history of volcanic activity in Askja central volcano.

2 Fissure swarms

2.1 The fissure swarms of Iceland

Iceland is located at the plate boundary between the North American plate, the Eurasian plate and the Hreppar microplate. This plate boundary is defined both by rift zones (the Western, Eastern, Northern and the Reykjanes Peninsula Volcanic Zones), and transform zones (the South Iceland Seismic Zone and the Tjörnes Fracture Zone) (Einarsson, 1991). The rift zones consist of several volcanic systems and fissure swarms that extend from each of these volcanic systems. The fissure swarms typically form dextral or sinistral en echelon arrays (Saemundsson, 1978). They are about 5-20 km wide and 40-100 km long at the surface (Figure 1), including tension fractures, volcanic fissures and normal faults. The tension fractures are generally shorter than the normal faults, as their length is characteristically about 100 m compared with the characteristic length of 1000 m for the normal faults (Guðmundsson, 1995).

There are five or six volcanic systems in the Northern Volcanic Zone (NVZ) (Figure 1). They are arranged en echelon along the volcanic zone. These volcanic systems are from south to north the Kverkfjöll, Askja, Fremrinámar, Krafla and Peistareykir volcanic systems. Saemundsson et al. (2005) argue that the sixth central volcano in the NVZ is located in Hróthálsar, NNW of Kollóttadyngja. The fissure swarms of these volcanic systems bear similar characteristics. They are approximately 20 km wide and tens of kilometers (up to 100 km) in length. In the middle of the fissure swarm the activity seems to be highest, with a higher altitude than elsewhere. In this central area, places with geothermal activity can be found and calderas may develop, as well as silicic magmas. The density of the fractures is highest in a 5-10 km wide zone in the central area (Sigvaldason, 1981).

2.1.1 The Askja fissure swarm

The Askja fissure swarm extends almost 30 km south from Askja central volcano, until it disappears under the Vatnajökull glacier (Figure 1). The length of the fissure swarm toward north is, however, either about 120 km or about 170 km, as there is a gap in the fissure swarm that may either be interpreted as being the end of the fissure swarm or a gap in it. If the length of the fissure swarm toward north is 170 km, it

extends northward from Askja until it disappears under the sea. Here, a brief overview will be given on previous studies of the Askja fissure swarm.

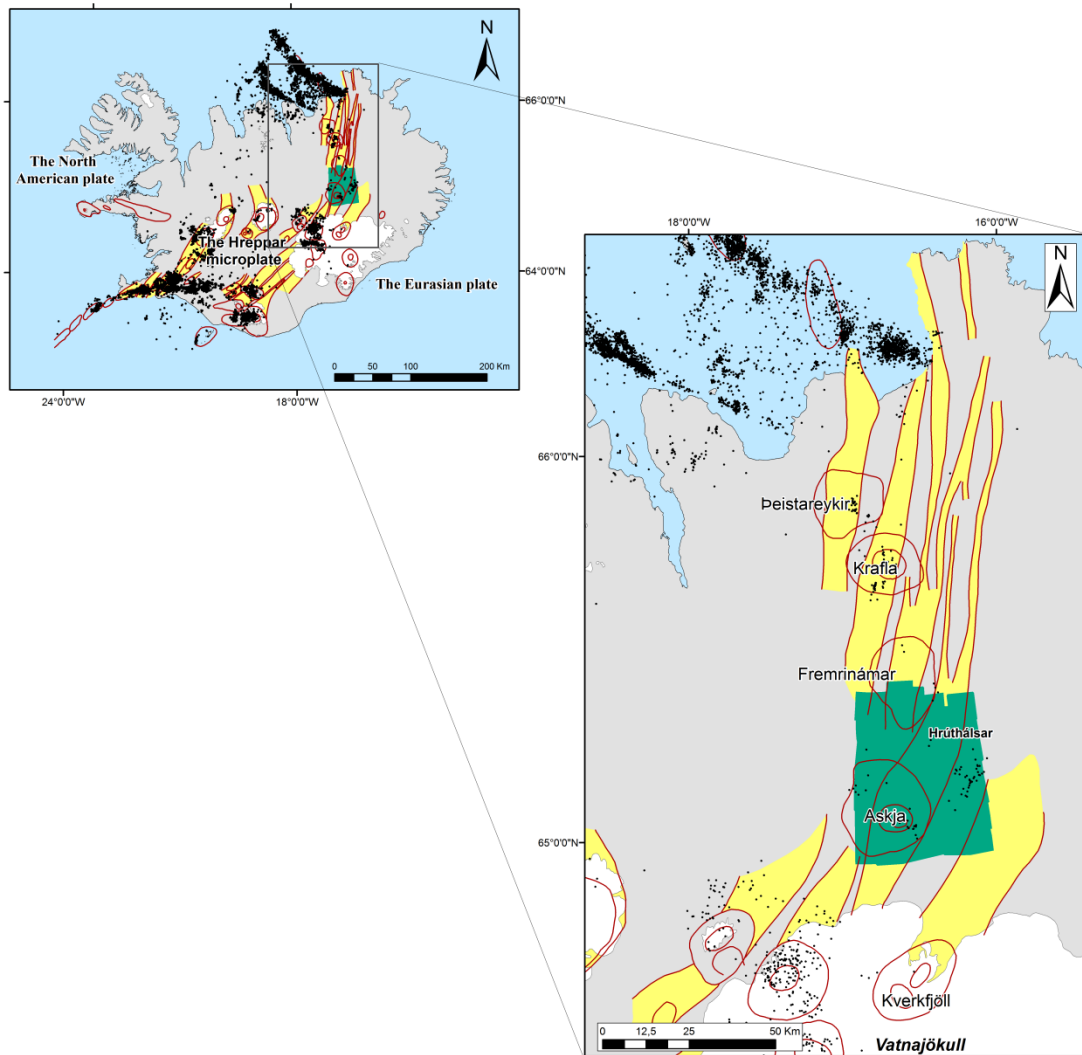


Figure 1 The fissure swarms of Iceland (yellow areas) (Einarsson and Sæmundsson, 1987), central volcanoes (red circles) and earthquakes from 1994-2000 (black dots) (data from the Icelandic Meteorological Office). The research area is indicated as a green area. The volcanic systems located at the Northern Volcanic Zone (NVZ) of Iceland are shown in the right frame. *Sprungusveimar Íslands (gul svæði)* (Páll Einarsson og Kristján Sæmundsson, 1987), *megineldstöðvar (rauðir hringir)* og *jarðskjálftar frá 1994-2000 (svartir punktar)* (gögn frá Veðurstofu Íslands). *Rannsóknarsvæðið er merkt í grænum lit.* *Í rammanum til hægri má sjá eldstöðvakerfi í Norðurgosbeltinu.*

It was already in 1938 that a German expedition studied fissures and fractures in various areas in Iceland. In the Askja fissure swarm, they focused mainly on the Sveinagjá graben and its surrounding area, where they mapped fractures and faults.

They did however also study the area close to Mt. Herðubreið and the Askja central volcano (Niemczyk, 1943).

Bemmelen and Rutten (1955) mapped a part of the fractures and fissures north of Askja with aerial photographs. They declared that the Dyngjufjöll mountains are a part of series of faults and fissures, where several fissure eruptions and lava shields were formed, extending from Rauðhólar in Jökulsárgljúfur canyon and all the way under Vatnajökull glacier (Bemmelen and Rutten, 1955).

The fissure swarm of Askja is mapped all the way from the Nýjahraun lava and the Rauðuborgir craters in the south and to Mt. Sauðafellsmúli in the north in a report from Sigurðsson et al. (1975). This geological report was made because of plans of damming the river Jökulsá á Fjöllum.



Figure 2: A cross-section of a part of the Askja fissure swarm, as seen in the Jökulsárgljúfur canyon. The arrow points to a cross section of a dike feeding an eruptive cone above. *Þversnið af hluta sprungusveims Öskju í Dyngjufjöllum, myndin er tekin í Jökulsárgljúfrum. Örin bendir á þversnið gangs sem kvika hefur ferðast uppúr og myndað gjallgíginn ofan á ganginum.*

Sigurðsson and Sparks (1978a) reviewed historical data on the 1870's period of unrest in Askja. Then, several eruptions took place in the Askja region, amongst

them being the large Plinian eruption 29th March 1875 and fissure eruptions in the Sveinagjá area, both before and after the Plinian eruption. The Öskjuvatn caldera started to form during the same time. They concluded that the Öskjuvatn caldera was formed when basaltic magma was drained from a magma chamber in Askja to flow horizontally along the fissure swarm to feed the Sveinagjá eruptions.

Pétursson (1979) wrote a report on the geology of Núpasveit, located in Melrakkaslétta, North Iceland. There he mapped an area which may be the northernmost part of the Askja fissure swarm, characterized by the Blikalónsdalur graben.

In the eastern wall of the canyon of the river Jökulsá á Fjöllum, a rare example of a cross section of a young dike can be seen, along with a crater on top of it (Figure 2). Þórarinnsson (1981) described this dike which is a part of the Askja fissure swarm. He also showed a drawing of this cross section.

Sigbjarnarson (1988) published a geological map and a report with it, which covers a small part of the area which is mapped in this study, as well as an area farther to the east of it. Included in Sigurbjarnarson's map is the area where the Vikrafell, Herðubreiðartögl and Herðubreið mountains are located. In his report he points out that in Herðubreiðartögl, faults are quite frequent, especially in the south part, where remains of a lava shield are located. He also points out that late in the last glaciation, an eruptive fissure was opened, which can be traced all the way from the south part of Herðubreiðartögl, where the lava shield is, and to the north end of Herðubreiðartögl.

Werner (1990) studied the petrology and sedimentology of the Mt. Herðubreiðartögl. He also mapped dikes in Herðubreiðartögl and found at least 20 large basaltic dikes, where approximately three of them strike E-W, four NW-SE and thirteen N-S or NNE-SSW.

Gudmundsson and Bäckström (1991) and Bäckström and Gudmundsson (1989), studied the Sveinagjá graben. They measured the boundary faults of the main graben. They suggested that the boundary faults were generated from large-scale tension fractures which developed from joints or from sets of inclined joints, when the lava pile had become tilted. They also concluded that Sveinagjá is a young formation, formed mostly or completely during the Holocene.

Sigvaldason (2002) showed an overview of the main tectonic lineaments in the area north and south of Askja. He concluded that the Dyngjufjöll centre is formed on

two slightly differently striking fissure swarms along with a transverse fault system, which cuts both of the fissure swarms at nearly right angles. This transverse fault swarm was in fact first described by Reck (1910).

A part of the study of Tentler and Mazzoli (2005) focused on the propagation and architecture of normal faults in the Sveinar, Sveinagjá and Veggir grabens in the Askja fissure swarm. They found that there is a gradual systematic change in the orientation of fractures in their research area, as they strike 10° - 20° in the south part (~40 km north from Askja central volcano), but in the north part (~70 km north of Askja) the strike changes to 350° - 360° .

Tentler (2005) studied faults in the active and extinct volcanic systems of Iceland, amongst them being the Sveinagjá and Veggir grabens. The results indicated that planar ruptures in fissure swarms are probably initiated as magma-filled vertical fractures at depth, lengthening laterally and upward with time, and probably changing into inclined normal faults at shallower levels in the crust.

2.2 Dike swarms

The central volcanoes and fissure swarms found in the neovolcanic zones of Iceland are considered to be equivalent to the extinct Tertiary central volcanoes and dike swarms found in eastern Iceland (Walker, 1963; Sæmundsson, 1974; Sæmundsson, 1978). Accordingly, Bodvarsson and Walker (1964) suggested that the eruptive fissures found in a part of the Northern Volcanic Zone (NVZ) are fed by dikes, and that the non-eruptive rifts may represent dikes that did not reach the surface.

The chemistry of the rocks in the extinct central volcanoes is different from the chemistry of the surrounding rocks in Eastern Iceland. The regional flood basalts in Eastern Iceland are made of tholeiites, olivine basalts and feldspar-porphyrific basalts with abundant bytownite phenocrysts. Silicic rocks are, however, only found in the central volcanoes. The central volcanoes contain a volume of about 100 - 500 km³. They consist of icelandites, rhyolites, acid pitchstones and tholeiites. Olivine basalts and porphyritic basalts are, however, seldom observed in the central volcanoes (Walker, 1974).

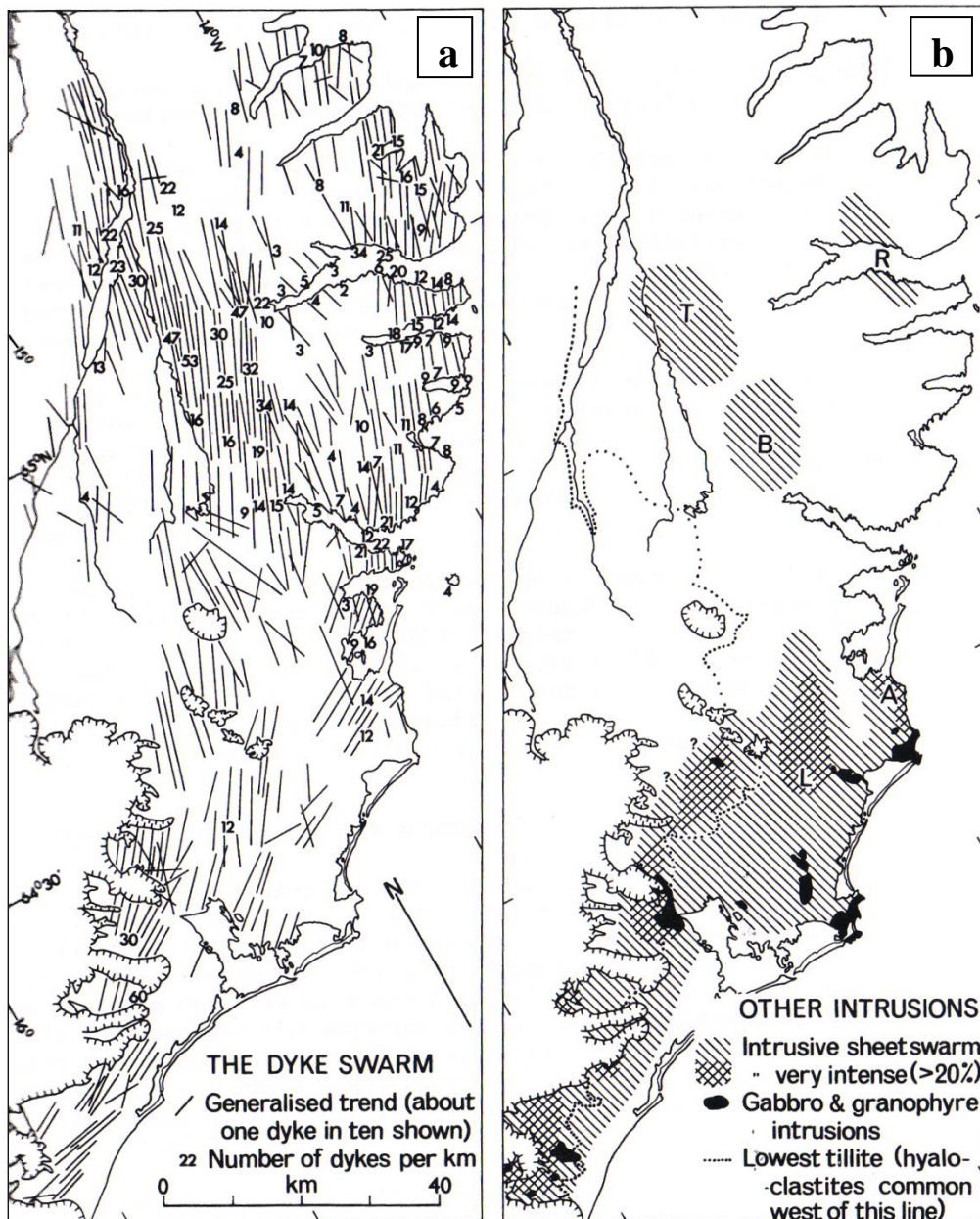


Figure 3 The dike swarms (a) and sheet swarms (b) in Eastern Iceland. Letters mark extinct central volcanoes; A=Álftafjörður, B=Breiðdalur, L=Lón, R=Reyðarfjörður and T=Þingmúli. Figure from Walker (1974). *Gangasveimar (a) og laggangar (b) á Austurlandi. Bókstafir tákna útkulnaðar megineldstöðvar; A=Álftafjörður, B= Breiðdalur, L=Lón, R=Reyðarfjörður og T= Þingmúli. Mynd frá Walker (1974).*

One dike swarm extends in opposite directions from each extinct central volcano, but the intensity of dikes in the dike swarms decreases with altitude. Basic dikes are located both close to the center of the volcanoes, as well as at greater distances, but acid and composite dikes are found close to the extinct central volcanoes (Walker, 1960, 1963, 1974). The individual dikes in the Tertiary dike swarms are on the

average 4-6 m wide, while the average dike thickness in the Pleistocene swarms is less than 2 m (Gudmundsson, 1995). The dike swarms are often about 5-10 km wide and up to 40 km long. Generally, the dike trend is N-S in the northern part of Iceland, while it is NE-SW in the southern part (Figure 3a). The trend of volcanic fissures and tectonic fractures in south and north Iceland show the same pattern (Saemundsson, 1978).

Each of the extinct central volcanoes also has a swarm of sheets (Figure 3b). Intrusive sheets in those sheet swarms are however usually basic and with an average width of less than 1 m (Walker, 1974).

2.3 The formation of dikes in fissure swarms

2.3.1 The deformation cycle

Although the Eurasian and North American plates diverge continuously for about 1.96 cm/yr in Iceland, the rifting along the fissure swarms of Iceland is not a continuous process. The deformation pattern along each of the fissure swarms of Iceland may be described as a deformation cycle. During rifting episodes, several rifting events occur, where magma intrudes a fissure swarm of a given volcano, widening and forming tectonic fractures and faults. Sometimes these dike intrusions lead to fissure eruptions (Sigmundsson, 2006). After rifting episodes, a post-rifting deformation with higher extension rates than the average spreading rate may be observed in the rifted area for years or decades (Foulger et al., 1992; Sigmundsson, 2006). During inter-rifting periods, the extension rates are reduced, and are consistent with the average spreading rate. Stresses are gradually built up during these periods, later to be released in rifting episodes (Sigmundsson, 2006).

2.3.2 Rifting episodes

Several rifting episodes have occurred during historical time in Iceland. In the Northern Volcanic Zone, at least three rifting episodes have been reported, the Mývatn Fires in Krafla from 1724-1729, a rifting episode thought to have originated from Askja 1874-1875 and finally the Krafla Fires in Krafla, 1975-1984. The Krafla Fires are, however, the only rifting episode that has been instrumentally recorded in Iceland (Einarsson, 1991b; Sigmundsson, 2006).

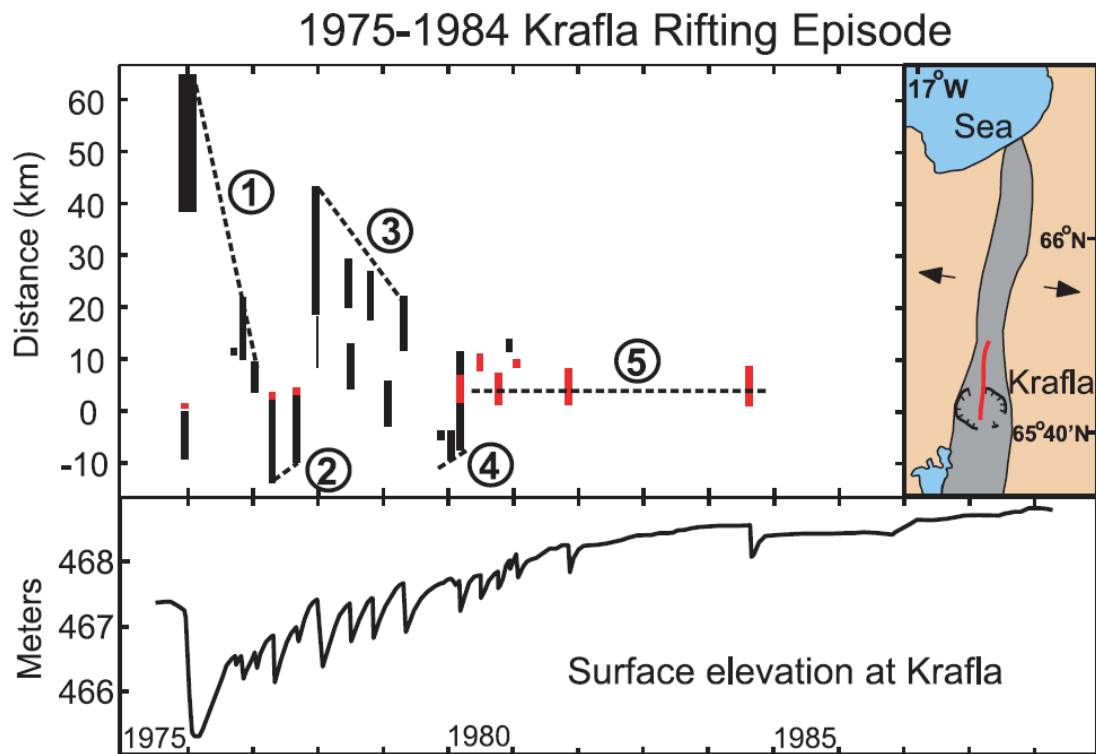


Figure 4 The propagation direction and distance of dikes from the Krafla central volcano during the Krafla rifting episode, and the surface elevation of Krafla central volcano (from Buck et al., 2006, originally from Einarsson, 1991b). *Fjarlægð og stefna ganga sem ferðuðust frá Kröflu í Kröflueldum, ásamt hæðarbreytingum í Kröflu sjálfri* (mynd frá Buck o.fl., 2006, upphaflega frá Páli Einarssyni, 1991b).

When the Krafla Fires began in 1975, seismic activity had already increased in the Krafla caldera area. In December, the first volcanic activity in this episode of events took place. It soon became clear that these events had certain characteristics. Leveling measurements indicated slow uplift in the Krafla caldera between the events, but sudden subsidence was measured during the events. In the subsidence events, volcanic tremor was detected in the caldera and shortly after the deflation started earthquakes also increased and then migrated away from the caldera, either to the north or to the south, into Krafla's fissure swarm (Björnsson et al., 1977; Einarsson and Brandsdóttir, 1980). This occurred about 20 times, and 9 of these events ended in an eruption. The first dikes were the longest, the latter dikes becoming shorter and shorter as time passed. Different dikes propagated into opposite directions, either towards north or south (Figure 4). Similar pattern has been observed in various volcanoes, where the locations of fissure eruptions migrate linearly, spirally or radially toward the volcano center (Takada, 1997). This is

thought to occur when a dike changes the stress distribution, making the subsequent dikes propagate in other directions and distances than the former dike. Late in the Krafla rifting episode, eruptions very close to Krafla itself became more frequent compared with dike intrusions with no eruptions. This was taken as an indicator that the tectonic stresses close to the magma chamber had been largely relieved (Buck et al., 2006).

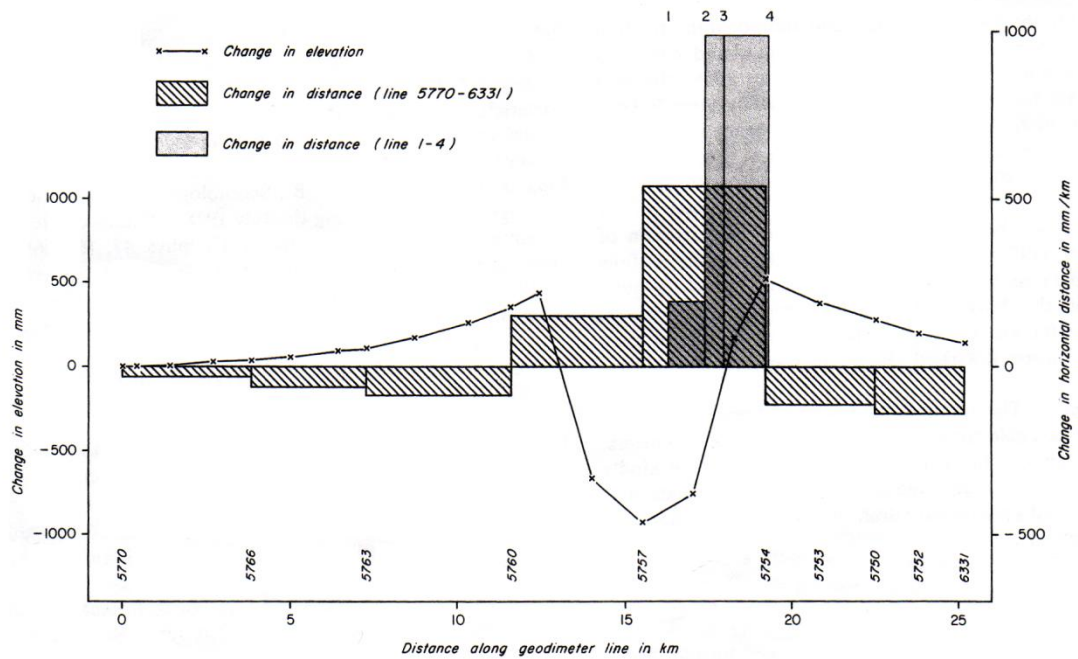


Figure 5 Vertical and horizontal deformation across a profile of the Krafla fissure swarm during the 8th dike intrusion in the Krafla fires, image from Sigurdsson (1980). Line 1-4 is not perpendicular to the fissure swarm. *Lóðrétt og lárétt aflögun eftir þversniði í sprungusveim Kröflu í áttunda gliðnunaraburði Kröfluelda. Mynd frá Oddi Sigurðssyni (1980). Mælilína 1-4 er ekki hornrétt á sprungusveiminn.*

During the Krafla Fires, magma is thought to have propagated as far as 80 km from the Krafla central volcano, along the fissure swarm. The rifting then took place in confined areas in the fissure swarm (Sigurdsson, 1980). It was usually in these areas where the maximum earthquake activity was detected. Einarsson and Brandsdóttir (1980) suggested that these areas were the ones where the dike width is the largest or where the dike top is closest to the surface. In those areas, a subsidence was measured in the central zone but a small uplift on either side (Figure 5). It is supposed that this subsidence is caused by slumping into the void above the dike

(Tryggvason, 1980), causing old fissures to be widened and new ones to be formed (Sigurdsson, 1980). It was however noted in the 8th event that the extension along the subsidence zone was inelastic as there was extensive surface faulting there, but in the uplifted zone no recent surface faulting was detected, which indicated an elastic contraction (Sigurdsson, 1980).

Rifting episodes, strikingly similar to the Krafla Fires, have been observed in the Kilauea volcano, Hawaii. A slow rise has been observed in the summit area of Kilauea and then rapid subsidence when magma moves laterally from the summit reservoir to Kilauea's fissure swarm. Dikes propagate into opposite directions during different events (Klein et al., 1987; Tilling and Dvorak, 1993), as it did in Krafla (Einarsson and Brandsdóttir, 1980; Einarsson, 1991b; Buck et al., 2006). Yet another common behavior is the migration of earthquakes away from a magma reservoir as time passes (Einarsson and Brandsdóttir, 1980; Heliker and Wright, 1991). The origin of the fissure swarms in Hawaii are however different from the origin of the fissure swarms in Iceland. The fissure swarms (or rift zones) of Kilauea are created by large-scale gravitational slumping of the slopes of the volcanic edifice (Tilling and Dvorak, 1993). Therefore, there is no deep dilatation source as at the plate boundary in Iceland.

2.3.3 The deformation of fissure swarms

A fissure swarm is developed during many eruptive and intrusive events. A great number of intrusive events relative to eruptive events may lead to a well-developed topography (Pollard et al., 1983). Deformation above propagating dike was measured during the Krafla Fires. There, a ridge-trough-ridge profile was observed; a subsidence was measured above the new dike, while uplift was detected beside the dike (Figure 5) (Sigurdsson, 1980). Same pattern has also been observed in Hawaii (Pollard et al., 1983). In general, a shallow dike of a constant height $a=1$ produces more vertical displacement than its deeper counterpart. The horizontal distance from the surface above the dike to the maximum surface displacement also gets less with decreasing depth of the dike (Figure 6a). This pattern characterizes a steeply-dipping dike. If the dike is vertical, the height difference of the two ridges is the same, but even a small dip of the dike results in asymmetry of the graph (Figure 6b). The ratio of ridge height differences is therefore a good indicator of the dip of the dike (Pollard

et al., 1983). According to Pollard et al. (1983), the subsidence above a dike changes, however, to uplift if the dike cuts the surface, causing an eruption.

The surface fractures can also indicate the dept to the underlying dike, as open cracks and normal faults tend to display a bimodal distribution. The distance between the most intensive ground cracking is approximately equal to twice the depth to the top of the pressurized crack, occupied by the dike (Pollard et al., 1983).

Although most of the deformation in fissure swarms occurs during rifting episodes, deformation is also measured during quieter times. In inter-rifting periods, geodetic measurements in Iceland have shown not only the regular horizontal plate spreading deformation, but also a subsidence in individual fissure swarms, likely due to the stretching caused by the plate spreading (Sigmundsson, 2006).

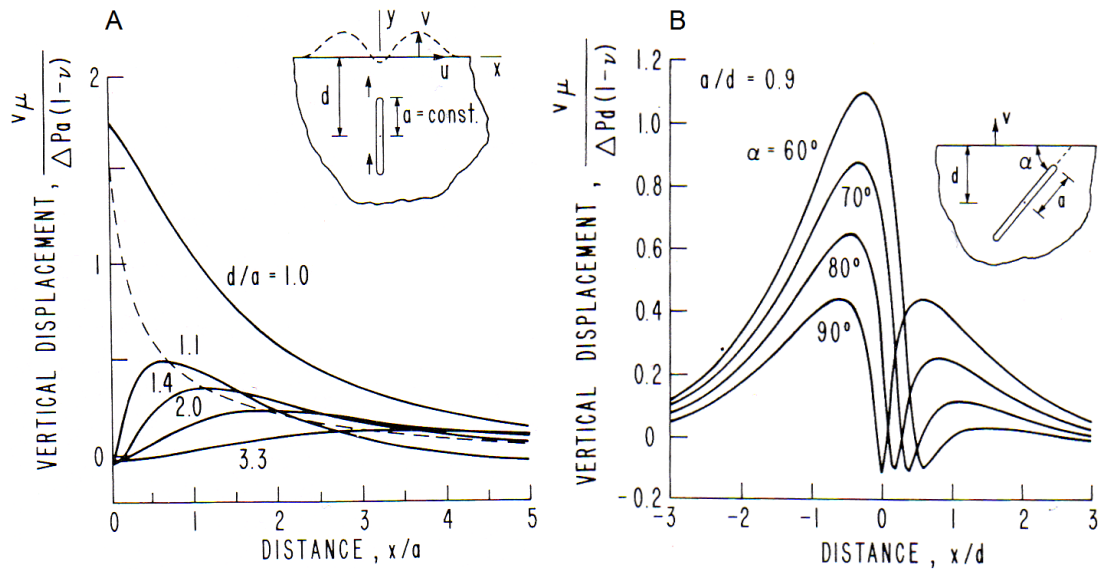


Figure 6. The effect of dike parameters on surface displacement. V is a displacement component, μ is the elastic shear modulus, ΔP is the driving pressure, d is the depth and ν is the Poisson's ratio. (A) The effect of the dike depth to the surface displacement. (B) The effect of the dip of the dike on the vertical displacement observed on the surface above the dike (from Pollard et al., 1983). *Áhrif eiginleika gangsins á yfirborðsaflögun. V er aflögunarþáttur, μ er skúfstuðullinn, ΔP er mismunurinn milli kvikuþrýstingsins og hinnar svæðisbundnu minnstu þrýstispennu, d er dýpið og ν er Poisson's hlutfallið. (A) áhrif dýpis gangs á yfirborðsaflögun. (B) Áhrif halla gangs á lóðréttu aflögun melda á yfirborði (mynd frá Pollard o.fl. 1983).*

2.4 Physics of dikes

2.4.1 The start of a magma intrusion

A dike intrusion is sometimes the corollary of inflation in a magma chamber (e.g. Björnsson et al., 1977). It has been assumed that fracturing, leading to a dike intrusion, occurs in the chamber walls when the tensile stresses exposed to them are greater than the tensile strength of the chamber wall rock (McLeod and Tait, 1999 and references therein). According to this assumption, there is no previously existing crack in the magma chamber. It must be considered likely, however, that such cracks exist in the magma chamber, due to the intense fracturing of the crust, as well as due to thermal fracturing caused by the magma (Furlong and Myers, 1985; McLeod and Tait, 1999). With previously existing cracks, dikes will start to propagate at much lower magma pressures than those necessary for tensional fracturing (McLeod and Tait, 1999). The propagation time of a dike from a magma chamber depends, however, also on viscosity. The viscosity of magma in a magma chamber controls the timing of dike propagation, as it is important in determining at which rate a crack in a chamber wall pressurizes. Silicic magma chamber does therefore require higher chamber overpressure before the pressure in the crack(s) is high enough for failure to occur. In stratified magma chambers, this promotes dikes to originate from the lower, more mafic part of the magma chamber (McLeod and Tait, 1999).

2.4.2 The length of dikes

The length of dikes is determined by various factors. Amongst them are the magma pressure and regional tectonic stress, the viscosity of the magma and possibly the width of dikes.

Silicic dikes are usually thicker and shorter than basaltic dikes (Rubin, 1995a). For equivalent driving pressures, it has been shown that basaltic dikes can travel much farther than their rhyolitic, higher viscosity counterparts. If the pressure contrast driving the rhyolitic dike is larger, then the length difference between the basaltic and rhyolitic dike will be less (Rubin 1993; 1995b). This might indeed be the case, as silicic magma chambers may require larger chamber overpressures before the dike starts to form, than the basaltic magma chambers (McLeod and Tait, 1999). Generally, it has however been observed that basaltic dikes are much more common on a regional scale than silicic dikes (Rubin 1995a).

Whether there is a relationship between the thickness and length of dikes is debated. In order to investigate the role of magma freezing in limiting the propagation distance of lateral dike intrusions, Fialko and Rubin, (1998) calculated the “thermal arrest” lengths, how far a dike can propagate before freezing. Their results indicated high dependence on the dike thickness, suggesting that thicker dikes tend to propagate farther distances than thinner dikes. This has in fact been observed both in the British Tertiary Province as well as in eroded rift zones in Iceland (Fialko and Rubin, 1998). Geodetic data from the Krafla rifting episode did, however, not support this prediction, as it indicated similar widening of the fissure swarm in each event, regardless of the propagation distance of the dike (Buck et al., 2006).

The magma pressure and tectonic stresses influence the dike lengths. This effect was investigated by Buck et al., (2006), who made a model of a multiple diking event, inspired by the regularity of the crustal behavior during the Krafla rifting episode, 1975-1984 (Figure 4). For each dike intrusion event, they consider the magma chamber and the dike involved to be a closed system. As the magma leaves the magma chamber during an event to form a dike, the magma pressure is reduced linearly. The relative tectonic tension in the lithosphere is also reduced linearly as the width of the dike increases. This model explains the pattern seen in Figure 4, with dike sequences propagating either towards north or south in the Krafla rifting episode, along with the observation that the first dike in each sequence propagates farthest away from the magma chamber, compared to the latter dikes, which propagate shorter and shorter distances (Buck et al., 2006).

2.4.3 The orientation and emplacement depth of dikes

If the magma pressure is slightly higher than the least compressive stress, dikes will form perpendicularly to the least principal stress (σ_3). If the magma pressure does, however, exceed the highest compressive stress, then magma can intrude fractures of any orientation (Rubin 1995a). It is, however, unlikely that magma will follow such a fracture for a long distance. A fracture which is not oriented parallel with the principal stresses is imposed with ambient resolved shear stress, that is reduced to almost zero due to the dike intrusion. This leads to a concentration of shear stress on the dike tip, and at the closed fracture in front of the dike, which may lead to the formation of oblique fractures, if the frictional resistance to the slip is adequate. The

dike may then exit the fracture and travel in a direction controlled by the ambient stresses (Rubin, 1995a).

The topographic load can affect both the orientation and emplacement depth of magmas, as the load creates a gravitational stress that can be a principal component of the external stress of the uppermost few kilometers in the crust (Watanabe et al., 2002). According to Watanabe et al. (2002) experiments, the topographic load reduce the driving forces of magma ascend through the stress gradient. This leads to increased depth of magma emplacement for higher mountain loads, than for lower mountain loads. Evidences also suggest that topographic load may affect the orientation of dikes. According to Muller's et al. (2001) laboratory experiments and numerical models, a surface load can attract an ascending dike. The effect of gravitational stress has also been shown to influence the orientation of Hawaiian rifts (Fiske and Jackson, 1972), as well as in Etna, Italy. There, McGuire and Pullen (1989) suggested that the gravitational stress regime, caused by the gross morphology of the Etna volcano, and the regional stress regime contribute both to the distribution and orientation of feeder dikes on the volcano.

2.4.4 Freezing of magma in a dike

Freezing of the magma in a dike is determined by various factors, such as the depth, the width of the dike, the loss of heat into the wall rock and the initial and acquired magma temperature. Here, a brief overview will be given on these factors.

As magma traverses through the colder crust in dikes, a heat loss will occur. There are several mechanisms in which the heat is transferred from the magma into the wall rock. Amongst them are the downstream and cross-stream advection in the magma, conduction from the magma out through the dike walls and possibly radiation in non-crystallized iron-poor magmas. Hydrothermal effects in the host rock might also play some role (Rubin, 1995a).

The initial and acquired magma temperature also controls the freezing time of magma. The release of latent heat during crystallization, excess magma temperature above depth-dependent effective solidus and viscous dissipation can retard the magma freezing (Rubin, 1995a).

The heat flux is sensitive to the dike thickness. The fact that fissure eruptions tend to shrink from the long, continuous curtains of fire into few localized vents

within the first hours or days of an eruption may be explained by this effect. The dikes may have small variations in their width, which can probably amplify with time. The narrower parts of the dike may solidify, while the wider parts might freeze more slowly and/or melt the host rock, leading to the localized vents observed on the surface (Delaney and Pollard, 1982; Rubin, 1995a).

Magma freezing depends also on depth. A dike that propagates laterally farther than the thickness of the lithosphere is likely to breach the entire lithosphere and possibly also into the asthenosphere. As the temperature at the base of the lithosphere is much higher than in the upper part (more than 1000°C compared with less than 600°C) (Fialko and Rubin, 1998; Hirth et al, 1998; Buck et al, 2006), a propagating dike reaching down to the lower part of the lithosphere might propagate farther than the upper part of the dike (Buck et al., 2006).

2.4.5 The lateral or vertical flow of magma in dikes

In general, density of rocks in the lithosphere increases with depth. When magma travels through crust with higher density, it moves upward, and vice versa. However, at the level of neutral buoyancy (LNB), the magma may move laterally. This is thought to explain lateral movement of magma in dikes. Dikes can in fact be driven to propagate laterally by the buoyant forces due to the difference in density between the over- and underlying rocks and the magma (Lister and Kerr, 1991).

Whether magma flows vertically or horizontally along dikes has, however, been a matter of debate. Probably both instances can happen. Knight and Walker (1988) determined the direction of magma flow by magnetic fabric studies in the Kooalu complex in Oahu, Hawaii. They found that pure lateral or vertical flow was rare. They found lateral flow in four dikes ($<5^\circ$ dip from the horizontal), in three dikes the magma flowed steeply upward ($50-75^\circ$) and in one the flow was steeply downward. In most of the dikes, the flow was however not far away from being lateral. In twelve of the dikes magma flowed at $5-30^\circ$ from the lateral and in five dikes, it flowed down dipping $5-20^\circ$.

Although it can be seen that pure lateral or vertical flow is probably rarely the case, usually those cases are taken as representatives of two different mechanisms which could account for the formation of dikes. If the magma flows laterally, the magma is extruded horizontally from a magma chamber into a fissure swarm. If the

magma flows vertically, it flows directly from the mantle up to the fissure swarm to form a dike. During an eruption, however, the magma flow toward the surface is most likely vertical, whether the feeding dike has propagated vertically or horizontally.

In the Krafla fires, earthquakes migrated away from the caldera as time passed, when dikes were injected into the Krafla fissure swarm (Einarsson and Brandsdóttir, 1980). This has been taken as a manifestation of a lateral traveling of magma from the Krafla magma chamber (Sigurdsson and Sparks, 1978b; Einarsson and Brandsdóttir, 1980). Guðmundsson (1990) argues that even though the failure spreading could be lateral, the magma could still travel vertically from the reservoir.

Guðmundsson (1990) also concludes that magma traveled vertically from the reservoir up to the surface in the Sveinagjá eruption 1874-1875. On the other hand, Sigurdsson and Sparks (1978b) found good chemical match of the basaltic magmas of Sveinagjá and Askja and concluded that the Sveinagjá eruption was the result of lateral injection of magma from a magma chamber in Askja. They point out that this could explain the caldera formation in Askja approximately one century ago, as this explains the large volume of magma which left the magma chamber. They argued that the Lakagígar fissure eruption which started in June 1783 resulted from lateral injection of magma from the Grímsvötn central volcano, since the chemistry of basalts from the eruption and the Grímsvötn central volcano is similar. Also, the trend of the fissure along with reports of eruptions in the direction of Grímsvötn in May and September 1783 led to their conclusion. Sigurdsson and Sparks (1978b) likewise observed the trend of the Eldgjá fissure along with the similarity of the chemistry of the prehistoric Eldgjá lava and that of the products of Katla central volcano and concluded that large volume of basaltic magma traveled from Katla central volcano to feed the Eldgjá fissure eruption.

2.4.6 The local stress fields of volcanoes

The orientation of fissures and fractures close to and in central volcanoes is sometimes different from the orientation of fissures and fractures in the associated fissure swarm, as the fissures and fractures near volcanoes sometimes radiate or are concentric around a central area.

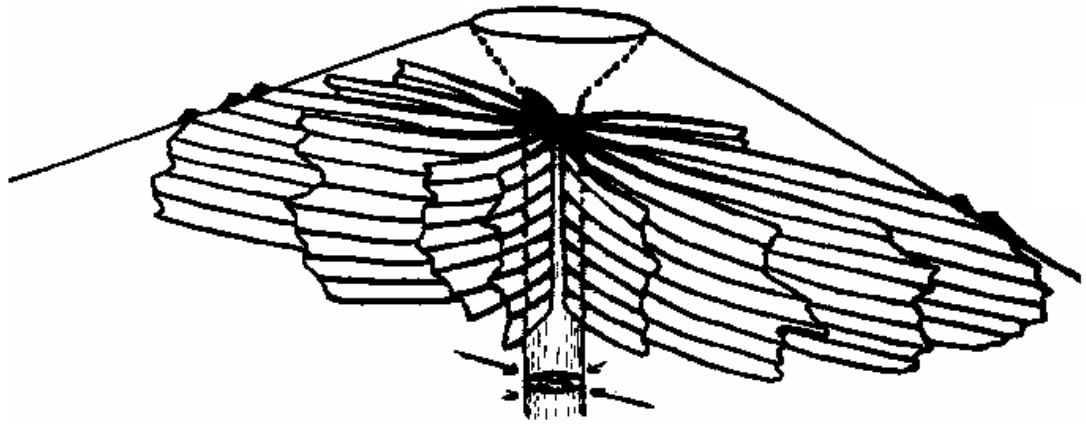


Figure 7 The radial dikes and flank volcanoes of a polygenetic volcano under a differential horizontal stress. The zone of flank volcanoes corresponds to the trend of radial dike concentration (image from Nakamura, 1977). *Geislagangar og gosstöðvar í hlíðum eldfjalls, sem verður fyrir láréttri mismunaspennu. Gosstöðvar í hlíðum eldfjallsins raða sér upp yfir gangi sem fóðrar þær. Myndin er frá Nakamura (1977).*

The normal consequence of magma excursion in a volcano, located in an area where there is no regional deviatoric stress and is not buttressed by a neighboring volcano, is to generate radial fissures. Ideally, the traces of these radial swarms would radiate from a common point and the fissures would be straight. The dike intensity would also be uniform in all directions. This is however rarely the case for basaltic volcanoes. Often, fissures tend to be more concentrated in some sections than in others. When some fissures are traced outward, they curve to become approximately parallel. When fissures are concentrated in two sectors 180° apart and tend towards parallelism when followed outward, they are called “fascicular” (Walker, 1993). In Figure 7, a simplified image of the structure of such a volcano is shown. This indicates that the stress field close to the volcano is dominated by the volcano’s local stress field and that the regional stress field becomes gradually more dominant with distance from the volcano (Nakamura, 1977).

Similar phenomena are observed on Venus. Many long linear troughs have been observed in synthetic aperture radar images from Venus. These troughs are thought to be the surface representation of dike swarms. They are characterized both by radial patterns which are centered on closed depressions and by almost circular lines which are centered on the same holes (McKenzie et al., 1992).

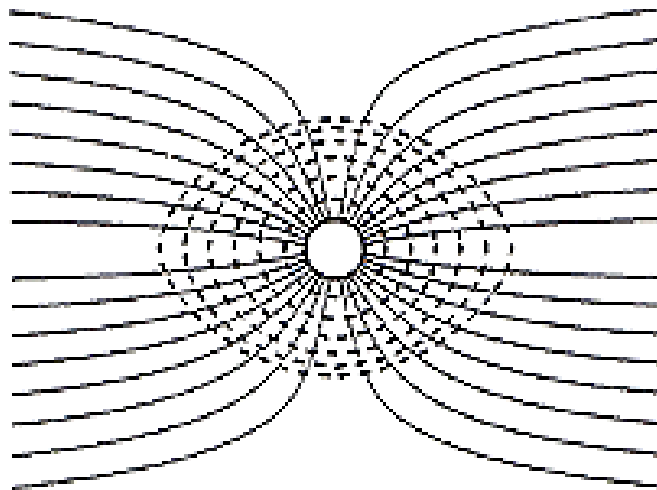


Figure 8 Stress trajectories normal to the lesser principal stress, with negative pressure in the hole (circular lines) or positive pressure in the hole (radial lines). The figure is from McKenzie et al. (1992). *Spennusvið hornrétt á minnstu höfuðspennu (σ_3), með annars vegar neikvæðan þrýsting í hólfinu (línur sem hringa sig um hólfið) og hins vegar jákvæðan þrýsting í hólfinu (línur sem geisla frá hólfinu). Mynd frá McKenzie et al. (1992).*

Mainly two families of lines are seen near the depressions. Those two types can be seen in the model in Figure 8 (McKenzie et al., 1992). The figure shows stress trajectories normal to the lesser principal stress. The radial lines form when the pressure in the hole is positive, and the circular lines form when the pressure in the hole is negative (corresponds to depression). This model suggests that radial dikes will form when magma is injected into a magma chamber, leading to inflation of the volcano. If magma is drained from a magma chamber, causing deflation, circular dikes will form early during the inflation of the depression. The radial dikes could facilitate the production of circular dikes, if they propagate to a sufficient distance where they reach a region of lower elevation that leads to drainage and deflation of the magma chamber (McKenzie et al., 1992).

According to the theory of Anderson (1951), pressure change in a magma chamber can explain all three types of dikes found around volcanoes, i.e. radial dikes, cone sheets and ring dikes. Radial dikes radiate away from the center of a magma chamber (Figure 9). They are formed when σ_3 follows the circular pattern and are thought to represent an inflating magma chamber. Cone sheets are also likely formed close to an inflating magma chamber. When they are formed, σ_3

follows the radial pattern (Figure 9). Cone sheets dip inward towards the magma chamber. Ring dikes are, however, formed when a magma chamber has deflated. Because of the deflation, σ_3 is perpendicular to the surface of Earth. Contrary to cone sheets, ring dikes dip outward (Figure 10). They are also usually thicker than cone sheets (Macdonald, 1972; Park, 1989).

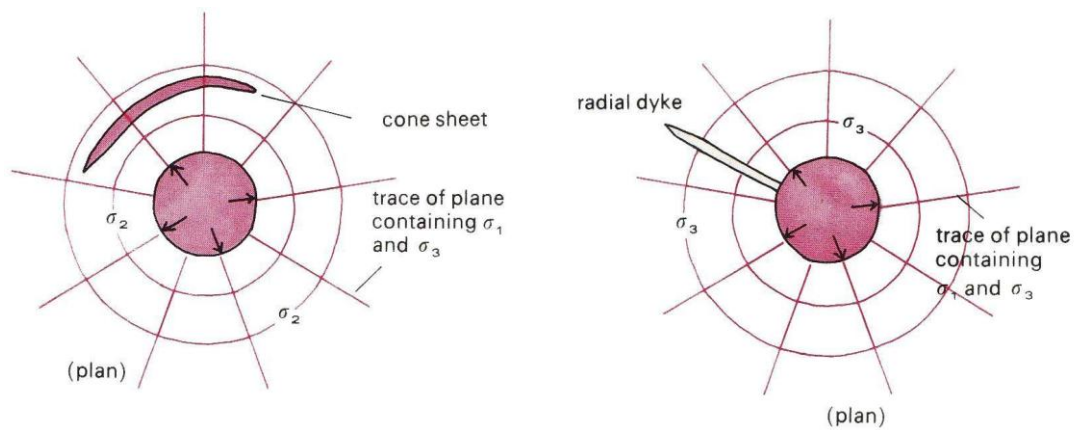


Figure 9: Overview of a cone sheet (left) and a radial dike (right). The figures are from Park (1989).
Horft ofan á keilugang (til vinstri) og geislagang (til hægri). Myndir frá Park (1989).

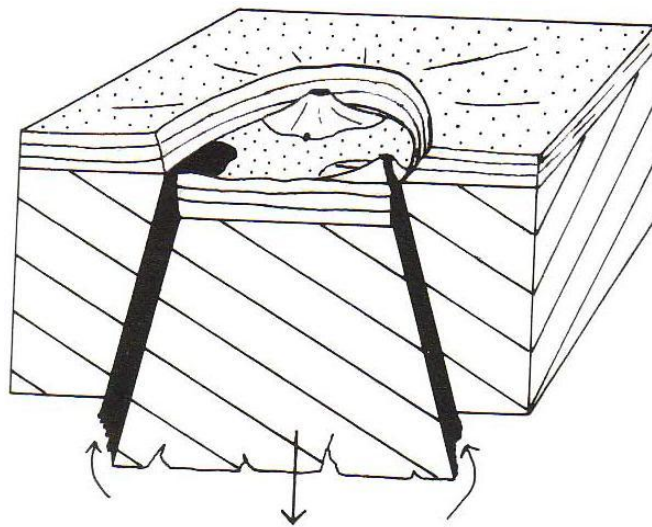


Figure 10: The formation of a ring dike. The figure is from Park (1989). *Myndun hringgangs. Mynd frá Park (1989).*

3 The research area

The study area is situated in the Northern Volcanic Zone (NVZ) of Iceland, an offshore part of the Mid-Atlantic ridge, which is the plate boundary between the Eurasian and the North American plate. The Hreppar microplate is located southwest of the research area and might also influence the tectonics in the area (Figure 1).

Measurements have indicated that the center of a hotspot is located in the proximity of the research area, under northwest Vatnajökull glacier. This hotspot has been interpreted to be caused by a mantle plume. The mantle plume theory is used to explain various anomalies, like excess crustal thickness, geochemical anomalies, low P - and S - wave velocity anomalies, topographic anomalies and the offset of the neovolcanic zones relative to the ridges (e.g. Sæmundsson, 1974, Wolfe et al., 1997). The hotspot does in fact possibly influence our research area. Maclennan et al. (2001) analyzed 70 basalt samples from an area about 25 km northeast of Askja and found that the average light rare earth element concentration of these samples is more than a factor of 2 higher than of the Þeistareykir volcanic system basalts. Þeistareykir is located in the northern part of the NVZ, ~90 km NNW of Askja. Maclennan et al. (2001) explain this anomaly with a plume-driven mantle upwelling, the upwelling rates near the base of the melting region (>100 km) being ~10 times higher than those expected from plate-driven upwelling alone. Alternate view, favouring the absence of the mantle plume has been given by G. R. Foulger and her coworkers (e.g. Foulger and Natland, 2003; Foulger et al., 2003; Foulger and Anderson, 2005).

The area which this study covers consists of lava shields, fissure lava flows, hyaloclastite ridges, as well as the Askja central volcano. The total lack of vegetation cover makes this area ideal to study tectonism. The area is remote, as an example it is not known of any people traveling to Askja until 1838, when the surveyors Björn Gunnlaugsson and Jón Austmann arrived there (Jónsson, 1962). In the latter years, studies have been focused on Askja, while the surrounding area has been less studied, most likely due to the limited accessibility. Because of this, the focus will mainly be on Askja central volcano in this chapter.

3.1 The Askja central volcano - introduction

Askja central volcano consists of calderas as well as the Dyngjufjöll massif (Figure 11), which was likely formed in late Pleistocene (Þórarinnsson, and Sigvaldason, 1962; Sæmundsson, 1982; Sigvaldason, 2002). The massif extends over a 400 km² area and is mainly formed of pillow lava and hyaloclastite (Sæmundsson, 1982; Sigvaldason, 2002). The Askja caldera in Dyngjufjöll is the clearest example of a caldera in Iceland. In fact, Sigurður Þórarinnsson used its name as the Icelandic word for caldera (*askja*) (Sæmundsson, 1982).

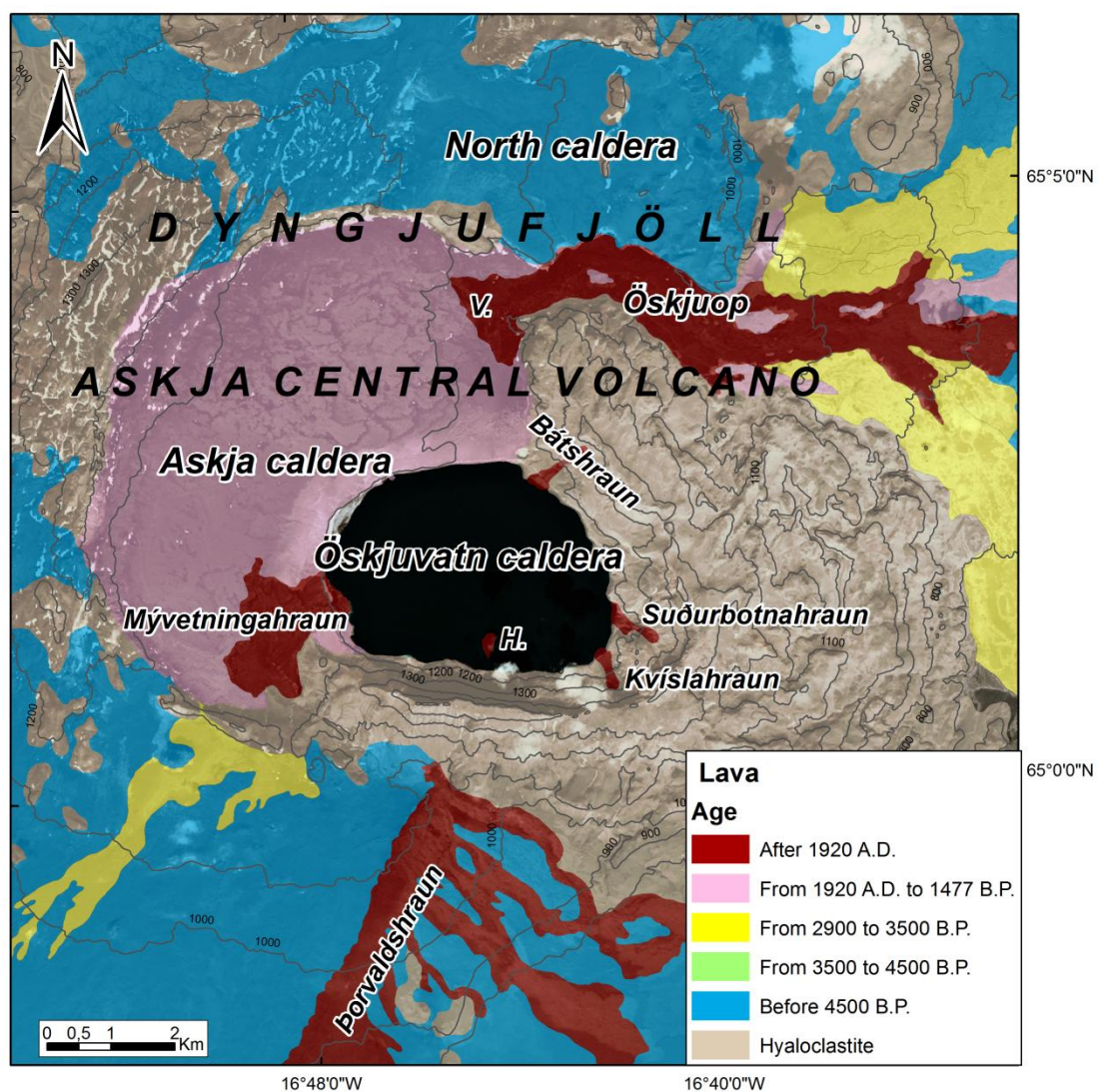


Figure 11: Askja in Dyngjufjöll, the age of the lava flows is from Sigvaldason et al., (1992) The background is from SpotImage©. H. marks the Hornfirðingahólmi island, V. marks Vikraborgir, the eruption site of 1961. *Askja í Dyngjufjöllum, upplýsingar um aldur hraunlaga eru frá Guðmundi E. Sigvaldasyni o.fl. (1992). Bakgrunnurinn er frá SpotImage©. H. táknar staðsetningu Hornfirðingahólma, V. táknar staðsetningu Vikraborga.*

Three calderas have been identified in Askja central volcano. They are of different sizes and are not concentric (Figure 11). The youngest is the Öskjuvatn caldera, which was formed between 1875 and 1907, and is therefore just over 100 years old. This caldera is approximately 3.0-3.5 km in diameter from north to south and 4.0-4.5 km from east to west. Another caldera, the largest of the three calderas is simply called the Askja caldera. The Öskjuvatn caldera overlaps the southeast part of this caldera, which is approximately 7-8 km in diameter from north to south, but the east-west diameter is unknown because of the overlapping. The third one, the North caldera, is not as obvious as the other two calderas. It is located northeast of the large Askja caldera (Figure 11). Its diameter is 3.5-4.0 km from north to south, but as the western rim is unclear, no estimate will be made on the east-west diameter. It seems that the calderas were not only formed by subsidence but also by eruptions on ring fractures on the rims of the calderas (Sigurdsson and Sparks, 1978a; Brown et al., 1991).

Increased rate of volcanic productivity occurred in the neovolcanic zones of Iceland at the Pleistocene/Holocene boundary and extended into the first millennia of the Holocene (Sigvaldason et al., 1992). To explain the relationship between the high volcanic production rate and the deglaciation that occurred at the same time, several suggestions have been made. Sigvaldason et al., (1992) proposed that magma either accumulated due to the ice load instead of erupting, or that differential tectonic movements during the deglaciation opened crustal pathways. Gudmundsson (1986) argued that the increased volcanic productivity rate during the deglaciation occurred due to induced stresses in the roofs of shallow magma reservoirs. Jull and McKenzie (1996) suggested that decompression in the mantle due to ice thinning increased the melting of magma in the mantle, therefore increasing the volcanic productivity rate. This pulse of high volcanic activity has been documented in the area in and close to Askja central volcano. Sigvaldason et al., (1992) reported at least 20 to 30 times higher lava production during 10,000-4500 BP than after 2900 BP. This can be observed by the amount of lava shields and fissure lavas formed early after the deglaciation, compared with later volcanic productivity in the area (Figure 12).

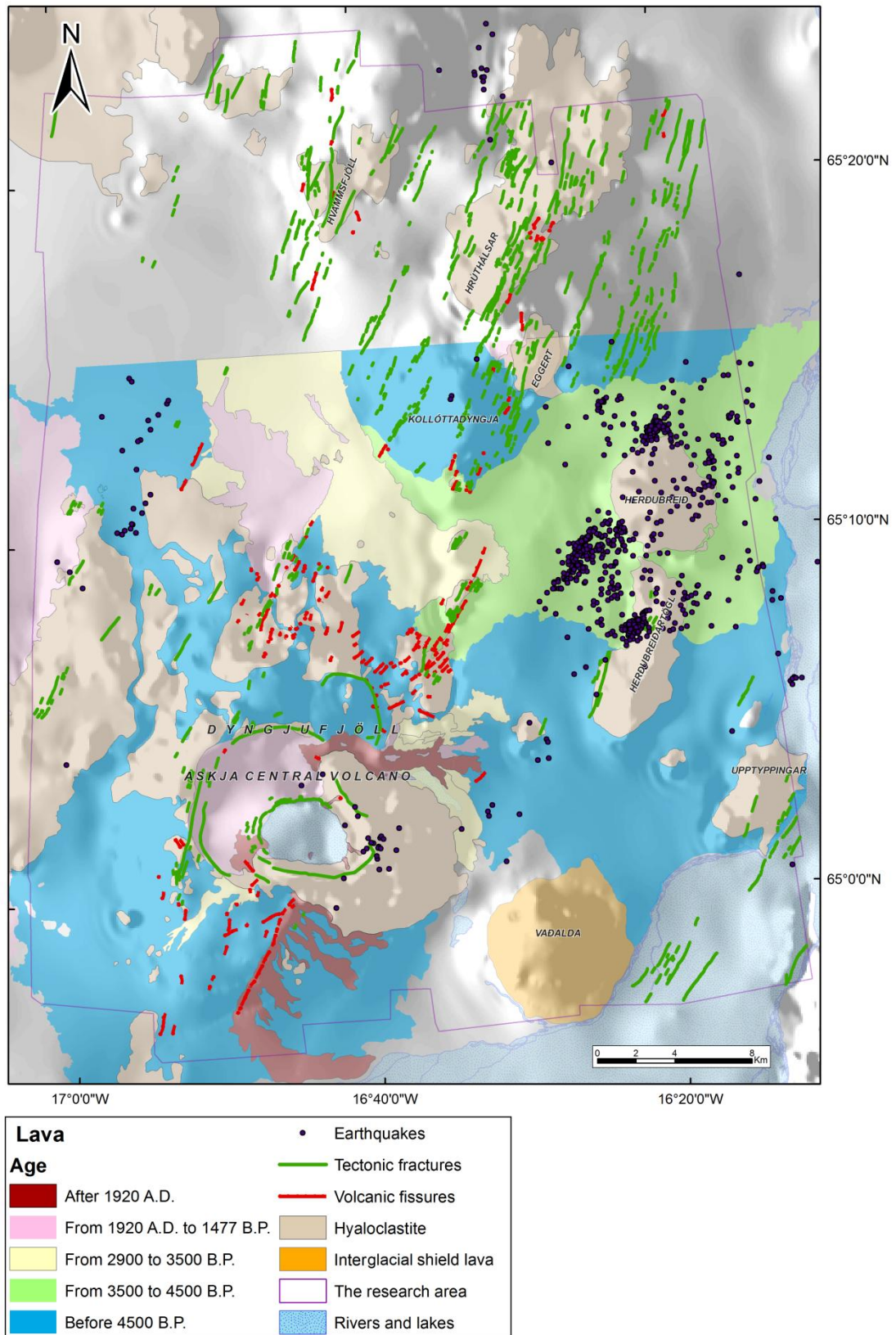


Figure 12 Earthquakes (from October 1998 to March 2007), lava flows, tectonic fractures and volcanic fissures in the research area. The information on the lava flows and most of the hyaloclastite is from Sigvaldason et al., (1992), except for the hyaloclastite in the northern part, which we mapped. The earthquake data is from the Icelandic Meteorological Office. Volcanic fissures and tectonic

fractures are also indicated, along with the area covered by the aerial photographs. *Jarðskjálftar (frá október 1998 til mars 2007), hraunlög, gossprungur og tektónískar sprungur á rannsóknarsvæðinu. Rannsóknarsvæðið er innan fjólubláa rammans. Upplýsingar um hraunlögin og móbergið eru fengnar frá Guðmundi E. Sigvaldasyni o.fl. (1992), nema hvað varðar móbergið á nyrsta hluta kortsins, sem við kortlögðum. Jarðskjálftagögnin eru frá Veðurstofu Íslands.*

A Plinian eruption occurred in Dyngjufjöll during the deglaciation, approximately ten thousand years ago. The pressure release is thought to have caused the eruption, which produced 1-2 km³ (dense rock equivalent). At this time, glaciers were still on the highlands of Iceland, but when the Askja caldera was formed, the glacier had retreated (Sigvaldason, 2002).

3.2 Historical eruptions in Askja

3.2.1 The Askja eruptions 1875

In 1874, Askja began to show signs of unrest. Steams were seen rising from Dyngjufjöll, and earthquakes were felt over a large area of North Iceland (Sigvaldason, 1982). An eruption was seen somewhere close to Askja on the 3rd of January 1875. In the Sveinagjá graben, located in the Askja fissure swarm approximately 40 km north of Askja central volcano, an eruption took place lasting from 18-25th February (Jónsson, 1945; Sigurdsson and Sparks, 1978; Sigvaldason, 1982). At 10th March an eruption started north of the lava flow of 18th February. This eruption lasted until at least 28th March. At the 29th of March 1875 a powerful Plinian eruption took place in Askja itself (Jónsson, 1942; Sigurdsson and Sparks, 1978; Sigvaldason, 1982) and the 4th April a period of eruptions occurred in the Sveinagjá area that lasted until 24th April. Eruption occurred in the Sveinagjá area again on 15th of August, and on 17th of October. Witnesses also reported evidences of other eruptions than mentioned here. Still, those were unclear evidences and due to the remote location, no manifestations were made whether these were eruptions or some other phenomena (Jónsson, 1945; Sigurdsson and Sparks, 1978).

The Askja eruption of 1875 was the largest eruption in Iceland since the great Lakagígar eruption in 1783. An ash fall from the Askja eruption was even observed in Scandinavia (Þórarinnsson, 1963; Sigvaldason, 1982). During this eruption, the explosive crater Víti (e. Hell) was formed. Earlier it was assumed that the

widespread pumice from the Plinian eruption of 29th March was erupted from Víti. Later it was discovered that the volcanic vents of the Plinian eruption are now located at the bottom of Lake Öskjuvatn. Víti was, however, formed when magma met groundwater (Sigvaldason, 1982).

But why did the large Plinian eruption occur? Chemical analyzes have revealed that the eruptive material of the Plinian eruption on 29th of March 1875 is a mixture of two types of eruptive material. The main material is dacite, but it is mixed with basalt. This has been taken as an indication that basaltic magma was injected into rhyolitic magma in the Askja magma chamber which in turn led to the Plinian eruption (Sigvaldason, 1982). Sparks and Sigurdsson (1977) and Sigvaldason (1982) do not share the same opinion on how this happened. Sparks and Sigurdsson (1977) assume that an acidic magma in the magma chamber was superheated when a hotter, basaltic magma was injected into it. The convection and increased magma pressure, induced by the superheating of the magma, in turn led to vesiculation that fractured the volcanic edifice and triggered the Plinian eruption. Gottsmann and Rymer (2002) suggest that this mixing or mingling of magma might have occurred as the roof above the magma chamber collapsed into the magma chamber. On the other hand, Sigvaldason (1982) assumes that the basaltic magma did not break *into* the magma chamber where the acidic magma was located, but was instead injected into the layers *above* the magma chamber. This led to heating of the magma which triggered the eruption, when the acidic magma broke its way through the basaltic magma and up to the surface.

Soon after the end of the Askja eruption in 1875, people began observing the formation of a new lake, as the Öskjuvatn caldera had started to form (Figure 13). Even though few people traveled to Askja, reports exist on the formation of the caldera. In fact it was as early as 16th of February 1875, *before the Plinian eruption*, that four men from Mývatn, Árni Jónsson, Helgi Jónsson, Sigurður Hinriksson and Sigurður Kráksson, observed that a subsidence had occurred west of the geothermal area in the southeast corner of Askja. The subsided area was about 15-20 meters in maximum depth and about 200 meters in diameter (Jónsson, 1962; Þórarinsson, 1963). Watts and his partners arrived in Askja the 16th or 17th of July 1875 and were the first to visit Askja after the large Plinian eruption. They observed a triangular shaped depression approximately 8 km in circumference (Jónsson, 1942).

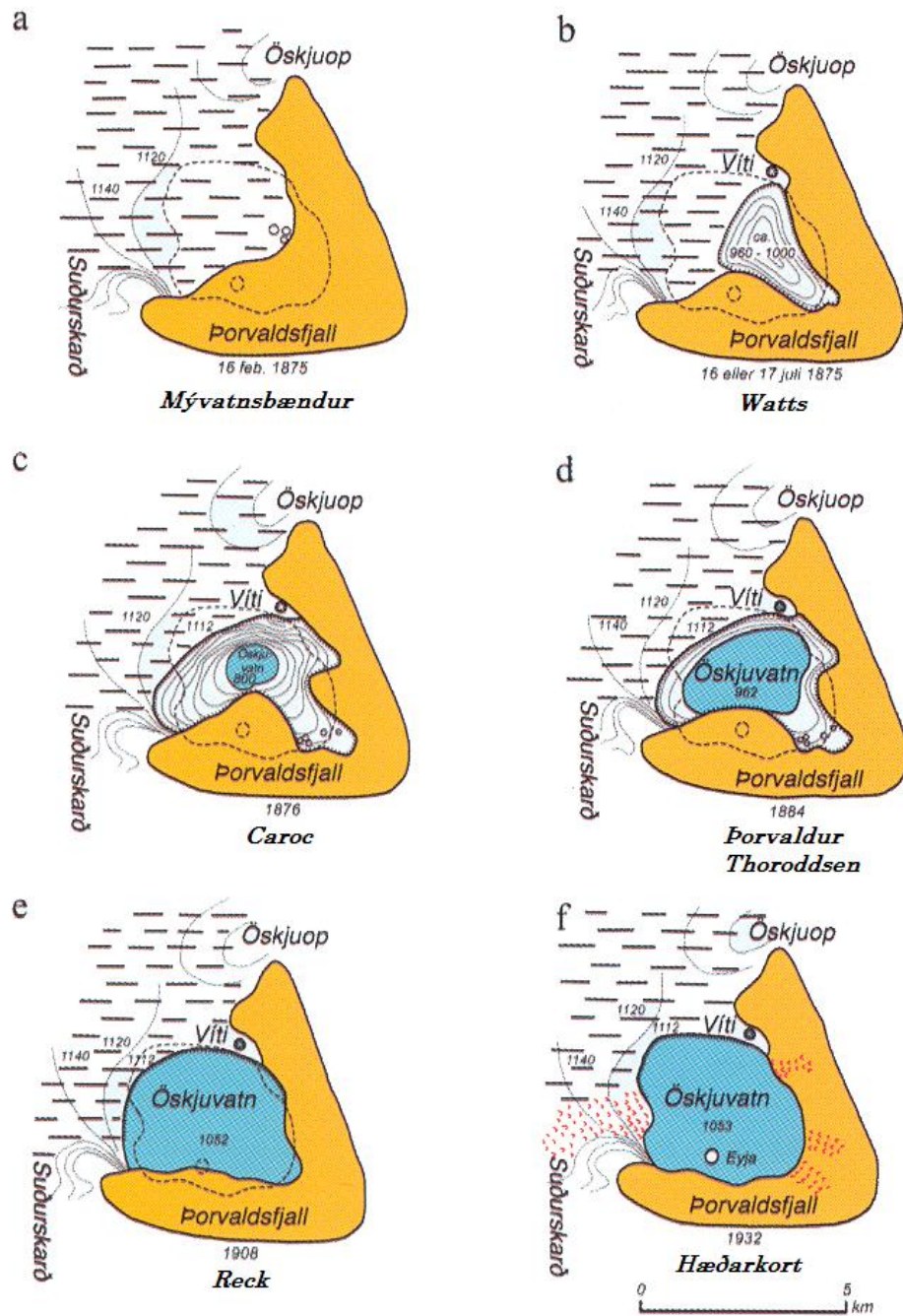


Figure 13: The formation of the Öskjuvatn caldera, inferred from descriptions of people that traveled to Askja. The figure is from the article of Sturkell (2002) but is originally from Jónsson (1942). *Myndun Öskjuvatns, myndin er teiknuð eftir lýsingum fólks sem ferðaðist til Öskju á þeim tíma sem askjan var að myndast. Myndin er frá Sturkell (2002) en er upphaflega frá Ólafi Jónssyni (1942).*

When Johnstrup and Caroc came to Askja in 1876, a pond had been formed in the depression, with the approximate size of 7.2 km^2 (Jónsson, 1942). Lock visited Askja in 1878 and 1880 and observed that the surface of the lake had risen about 12 meters per year (Jónsson, 1942). Þorvaldur Thoroddsen and Ögmundur Sigurðsson

visited Askja in 1884, then the depression was triangular shaped and the surface of the lake had risen of 82 meters since 1876 (Jónsson, 1942). In 1910, it became clear that the rate of the subsidence was slowing down, when Spethmann (along with Erkes and Sigurður Sumarliðason) arrived again in Askja, and saw no obvious changes except an area in the northwest corner of Askja, which had subsided few meters (Spethmann, 1913; Jónsson, 1942). Today, the young Lake Öskjuvatn, located within the Öskjuvatn caldera, is the deepest lake in Iceland, 220 meters deep.

The origin of the Sveinagjá eruptions has puzzled people. Can an eruption, in 40 km distance from Askja, be in some connection with the eruptions in Askja? It became clear in the Krafla rifting episode that this could indeed be the case. There it was observed that magma can travel long distances underground before it arrives to the surface. The experience gained from these events led to the general assumption that magma traveled laterally from a magma chamber in Askja central volcano and was erupted in Sveinagjá (Sigurdsson and Sparks, 1978a; Sigurdsson and Sparks, 1978b; Sigvaldason, 1982). Sigvaldason (1982) thinks that the same applies to the Holuhraun lava, near Dyngjujökull in Vatnajökull glacier. Guðmundsson (1990) does however not agree and argues that the magma traveled vertically from the mantle.

3.2.2 The Askja eruptions 1921-1930

Although Askja produced the powerful Plinian eruption in 1875 along with the other eruptions at that time, a long time did not pass until it showed unrest again. From 1921 to 1930, six basaltic eruptions took place in Askja central volcano. In March 1921 the Båtshraun lava near Víti was formed, and Mývetningahraun lava was formed in November 1922. In 1923, Guðmundur G. Bárðarsson and Pálmi Hannesson found Kvíslahraun and Suðurbotnahraun lavas (Jónsson, 1962). Jónsson (1942) assumes that these two lavas were formed in 1922, but Þórarinnsson and Sigvaldason (1962) argue that they were formed in 1923. All these lavas were formed from fractures located around the Öskjuvatn caldera. On the other hand, in 1926 a phreatomagmatic eruption took place in the lake, forming the Hornfirðingahólmi Island (also called Askur). Because of the isolated location of Askja, few people traveled to this area. Therefore, it is hard to find out exactly when

the Þorvaldshraun lava located south of Askja was erupted. This lava has an area of 16 km² and a volume of 0.11 km³. It is estimated that this happened sometimes between 1924 and 1930 (Þórarinnsson and Sigvaldason, 1962). This lava was discovered by three men from Hornafjörður. They had traveled from Hornafjörður, across Vatnajökull glacier and to Askja on their way to North Iceland. They also observed the new island, Hornfirðingahólmi, in the lake, as well as Bárður Sigurgeirsson and his partners from Mývatn. In 1932 Steinþór Sigurðsson and I. Jensen came to Askja. They made measurements and Steinþór Sigurðsson found the fissure south of Þorvaldsfjall Mountain, where the lava with the unknown date had been erupted from (Jónsson, 1962).

3.2.3 The Askja eruption 1961

Unrest in Askja was observed again approximately thirty years after the last episode. This time seismometers in Iceland detected earthquakes on 6th and 9th of October 1961 with origins in the Dyngjufjöll area, and three new hot springs were discovered on the 10th of October just south of Öskjuop, in the eastern wall of Askja caldera (Þórarinnsson and Sigvaldason, 1962). Earthquakes were detected again the 26th of October 1961. That day an eruptive column was observed from an airplane on its way from Akureyri to Reykjavík (Þórarinnsson and Sigvaldason, 1962). From 26th of October to 5th of November an aa type of lava was erupted, but after that and until the end of the eruption (sometime between 28th November and 17th December 1961), pahoehoe lava was erupted. This eruption left a row of scoria cones, named Vikraborgir (Figure 11) (Þórarinnsson and Sigvaldason, 1962).

3.3 Present deformation in Askja

Crustal deformation measurements show that a magma chamber is situated at approximately 3 km depth in Askja. It is currently contributing to a 4.2 cm subsidence each year on the surface at the center of the caldera, while a magma chamber located at approximately 16 km depth contributes to about 1.0 cm subsidence on the surface (Sturkell et al., 2006). Measurements of vertical deformation in Askja have been done since 1966, when Eysteinn Tryggvason installed twelve benchmarks for the Askja levelling profile. In 1968 this profile was

extended to include 30 benchmarks. These early measurements in Askja make its time series of deformation the longest of an Icelandic volcano (Sturkell et al., 2006). Both deflation and inflation has been observed in Askja during this time. In fact, Askja is the volcano in Iceland that has shown the most deformation without erupting at the time measurements have been made (Tryggvason, 1989). Measurements have also been made on the height of the surface of Lake Öskjuvatn with 12 optical leveling tilt stations used to calculate a tilt vector and an EDM (Electronic Distance Measurement) technique used (Sturkell and Sigmundsson, 2000). In 1993, a network of 24 GPS stations was measured for the first time (Camitz, et al., 1995; Sturkell et al., 2006). These measurements were repeated in 1998, but since then only a few key stations have been measured yearly (Sturkell et al., 2006).

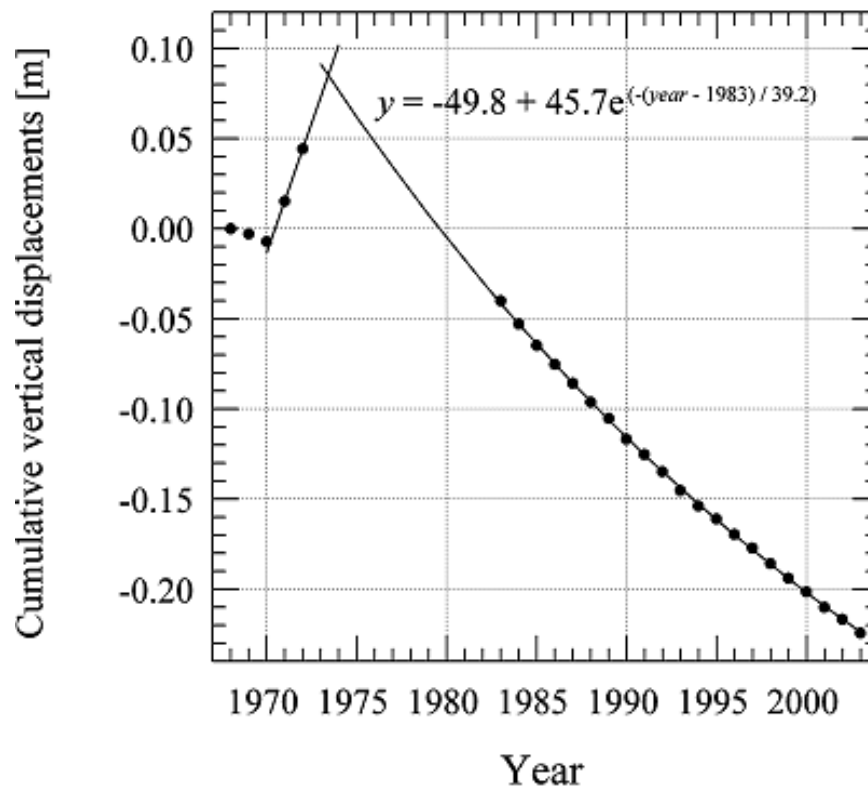


Figure 14 Cumulative vertical displacement between benchmarks at each end of a leveling profile in Askja central volcano. From Sturkell et al., (2006). *Uppsöfnuð lóðrétt aflögun milli endapunkta hallamælilínu í Öskju. Mynd frá Sturkell o.fl. (2006).*

For over 20 years, measurements have shown continuous deflation in Askja (Figure 14). Today, this subsidence seems to be slowing down. According to Sturkell et al. (2006) the equation $e^{-t/\tau}$ where τ is 39.2 years can be used to describe

the decaying rate of subsidence. In the years of 1970-1972, a rapid inflation, possibly up to 20 cm/yr, was observed in Askja. After the Krafla rifting episode started, leveling measurements were not done for 10 years (1973-1983). Deflation occurred at this time, but it is not known whether that was a continuous deflation, but it is clear that the subsidence at this time was less than in the years of 1983-1987 (Tryggvason, 1989).

Pagli et al. (2003) used InSAR images (Interferometric Analyses of Synthetic Aperture Radar) for measuring vertical deformation in Askja for the years 1999-2000. The deflation bowl observed was about 20 km in diameter and its center was in Askja, elongated in the north-south direction.

Gravity measurements have also been made in Askja. In the years of 1988-2003, the subsidence in Askja was in accordance with a decreasing volume of 0.018 km^3 and a decreasing mass of $1.6 \cdot 10^{11} \text{ kg}$ (de Zeeuw-van Dalssen et al. 2005).

3.3.1 The causes of deformation in Askja

Tryggvason (1989) proposed that the deformation in Askja can be traced to variations of the activity of the supposed mantle plume. De Zeeuw-van Dalssen et al. (2005) think that there are at least three possible reasons for the deflation in Askja. The first one is cooling and contraction of magma in a shallow magma chamber (Rymer and Tryggvason, 1993), the second one contraction of the crustal material under Askja, and the third that magma is flowing out of the shallow magma chamber. De Zeeuw-van Dalssen et al. (2005) measured a net microgravity decrease of 115 μGal in the middle of the Askja caldera from 1988-2003, due to a subsurface mass decrease. They concluded that the subsidence was due to a combination of two factors, contraction because of cooling and escaping of magma out of the magma chamber. Sturkell et al. (2006) reached similar conclusion, that the reason was pressure decrease and/or magma crystallization.

Camitz et al. (1995) point out that for longer time, a deflation in a magma chamber located at a divergent plate boundary is a normal process as the volume of the magma chamber is increasing due to the extension of the plate boundary. Yet another possible reason of deformation of a volcano has to do with the interaction of different neighbor volcanoes, which will be dealt with in the next chapter.

The young Öskjuvatn caldera was however probably formed when magma was drained from the magma chamber under it, to travel north along the fissure swarm to feed the Sveinagjá eruption (Sigurdsson, and Sparks, 1978a; Sigurdsson and Sparks, 1978b; Sigvaldason, 1979; Sigvaldason, 1982; Brandsdóttir, 1992). This magma then fed the Sveinagjá eruption.

3.4 Relationship between volcanoes in the Northern Volcanic Zone (NVZ)

Tryggvason (1989) suggested that the subsidence in Askja started in 1976 or before. Likewise, Sturkell et al., (2006) estimated that the subsidence in Askja started in 1973 by extrapolating the inflation trend of 1970-1972 and deflation trend of 1983-2003 (Figure 14). A relationship between the deformation of Askja and the Krafla rifting event (70 km away from Askja) has been suggested, as magma of unknown source was injected into Krafla's magma chamber from 1975 to 1985 (Björnsson, et al. 1979; Tryggvason, 1986 and 1989; Sturkell et al. 2006). The idea is that magma was moved upward to the magma chamber in Krafla that led to a decreased pressure in the mantle, causing a deflation in the nearby volcanoes (Einarsson 1987a, 1987b and 1991a; Sturkell et al. 2006). In 1996, an eruption occurred in Gjálp in Vatnajökull glacier which did not cause any changes of the deformation in Askja (Sturkell and Sigmundsson, 2000).

In general there is a significant, but weak, relationship between the timing of earthquakes and eruptions in Iceland (Gudmundsson and Saemundsson, 1980). In the timeline shown in Figure 15, it can be seen that large earthquakes and eruptions sometimes coincide in time in North Iceland. Included in this comparison are the earthquakes and eruptions that have occurred on the transform fault boundary north of Iceland since 1800 (Thoroddsen, 1905; Tryggvason, 1978a, 1978b, 1979; Ottósson, 1980; Sólnes, 1985; Einarsson, 1991b). Known examples are as an example the Krafla rifting episode (1975-1984) and the magnitude 6.4 (Ms) Kópasker earthquake that shook northern Iceland in 1976. Another such episode happened in the years of 1872-1885. In 1872, large earthquakes occurred near Húsavík, the large Plinian eruption of Askja and the Sveinagjá fissure eruptions took place in 1875, and in 1885 a large earthquake shook Kelduhverfi, apparently originating in the Þeistareykir fissure swarm (Thoroddsen, 1905). The timeline

shows events since the year 1800. It has to be pointed out, however, that sources of information are scarce in the beginning but get better as time passes, although it could be inferred viewing the timeline that events get more frequent as time passes, it is unlikely.

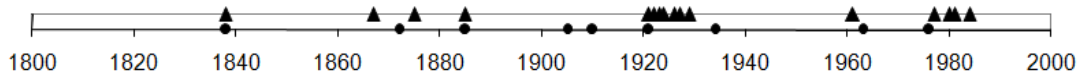


Figure 15: Eruptions (triangles) and earthquakes (dots) in North Iceland since the year 1800. Earthquakes taken into account are of magnitude 5.5 or larger, when data is available on the size of the earthquake. Older earthquakes are also taken into account when they have been destructive. Here it can be observed that large earthquakes sometimes coincide in time with eruptions in North Iceland. *Eldgos (bráhyrningar) og jarðskjálftar (hringir) á Norðurlandi frá árinu 1800. Jarðskjálftar sem teknir eru með eru þeir sem eru jafnt og eða stærri en 5.5 að stærð, þegar upplýsingar um stærð skjálfta eru tiltækar. Eldri skjálftar sem hafa haft mikil áhrif eru einnig teknir með. Á línuritinu sést að stórir jarðskjálftar verða stundum á svipuðum tíma og eldgos.*

3.5 Earthquakes in and near Askja

Brandsdóttir (1992) investigated historical data on earthquakes in and near Askja. This information reached back to 1874-1876, when the Plinian eruption took place, but no information is available on earthquakes in this area before that time. Brandsdóttir (1992) proposed that the earthquakes that occurred in the autumn of 1874 and preceded the eruptions in Askja in 1875 had a similar explanation as when earthquakes happened in the Krafla rifting episode. Then, magma was likely propagating through the Askja fissure swarm from the magma chamber, causing high seismic activity. During the period of multiple eruptions in the 1920's, no earthquakes were reported. When Askja showed unrest again, in 1961, the network of seismic stations had been improved. Unrest was detected in Askja in October 1961, followed by an eruption on the 26th October. Earthquake swarms were also detected on the 30th January and the 12th June 1962. These swarms have been suggested to occur due to a shallow magma intrusion within the Askja caldera (Brandsdóttir, 1992).

Nowadays, shallow earthquakes occur mainly in three regions in and near Askja (Figure 12). The earthquakes in Askja itself are mainly located in the southeast corner of the Öskjuvatn caldera. These earthquakes are supposedly caused by

geothermal heat. Northwest of Askja, another earthquake zone can be found and the third one east and northeast of Askja. This area was first observed in earthquake sequences in the summers of 1982 and 1983 (Einarsson, 1991a; Sturkell and Sigmundsson, 2000). The seismic activity of the latter two areas is most likely not associated with the volcanic activity in Askja but only the plate boundary (Sturkell and Sigmundsson, 2000).

Deep earthquakes have recently been identified both north and east of Askja, as well as in Upptyppingar, in the eastern part of the research area. Knox (2007), found several 10-34 km deep earthquakes that are located 10-20 km east and north of Askja and suggested that those earthquakes occur due to magmatic activity in the lower crust. Clusters of deep earthquake activity have also recently been detected in and close to Mt. Upptyppingar (Roberts et al., 2007). This activity has gradually been migrating upward to shallower levels.

The earthquakes near Askja happen in swarms. The largest measured swarms occurred in 1998, in late 2003 and early in 2004 (Sturkell et al., 2006). It has however been a problem for a long time when interpreting earthquakes located in or around Askja, that seismometers are not located in the vicinity of the volcano.

3.6 Fissures and fractures

Although rifting episodes are episodic events, the stretching of the rift zones is a continuous process. From 1987 to 1990, the fissure swarm of Askja was extended in the east-west direction by 2.4 ± 0.5 cm/yr in the direction of $N99^\circ \pm 12^\circ$. The deformation zone was approximately 30-45 km wide and extensional strain was accumulated at a rate of ~ 0.8 μ strain/yr (~ 0.8 mm/km each year) (Camitz et al. 1995).

Tectonic lineaments are good indicators of prehistoric deformation in and close to Askja central volcano. Sigvaldason (2002) studied fissures and fractures in and close to Askja central volcano. He concluded that in the Askja fissure swarm, two 5 - 20° striking fissure swarms lie side by side, one on either side of the large Askja caldera along with a transform fault swarm with the direction of 300° (Figure 16).

In the mountain south of the Öskjuvatn caldera, Sigvaldason (2002) observed sub parallel fissures striking 20° . The fact that the mountain is very steep at the side that lies to the Öskjuvatn caldera gives the impression that vertical displacement has

occurred. The Öskjuvatn caldera, formed after the unrest period of 1875, is like a parabola in shape, and this parabola cuts into the mountain. The axis of the parabola is almost perpendicular to the direction of the eruptive fissures (Sigvaldason, 2002).

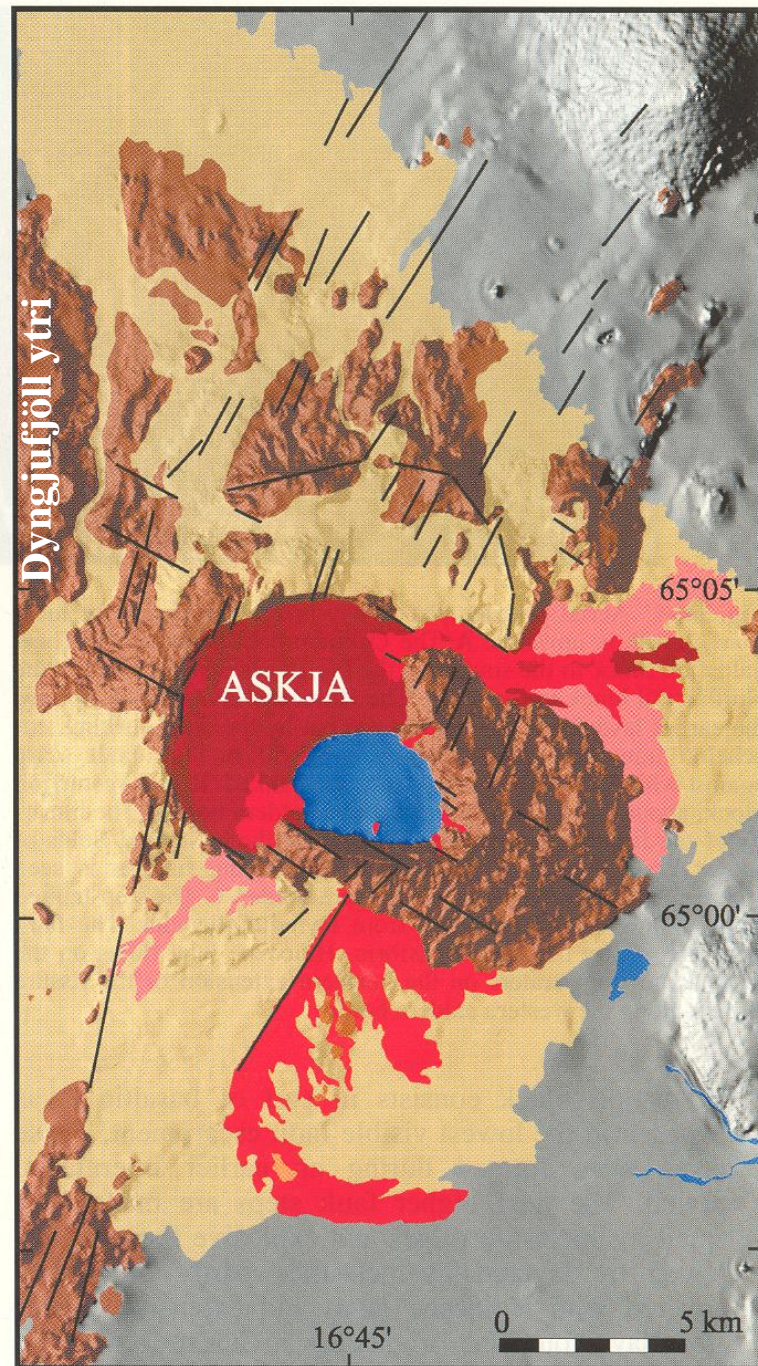


Figure 16: Faults and fractures close to Askja as observed by Sigvaldason (2002). *Sprungur og misgengi nálægt Öskju í Dyngjufjöllum, eftir Guðmund E. Sigvaldason (2002).*

In the mountains north of the Askja caldera, Sigvaldason (2002) found evidences of vertical uplift. There, the least obvious North caldera is located. It is most likely that it was formed during the last interglacial (Sigvaldason, 2002).

The mountains west of the Askja caldera were formed on eruptive fissures striking 5-10°. There, uplift seems also to have occurred (Sigvaldason, 2002). The general impression is that the Dyngjufjöll Mountains have been uplifted several times (Reck, 1910; Bemmelen and Rutten, 1955; Sigvaldason, 2002). Sigvaldason (2002) points out several evidences for his suggestion that some of the uplift occurred in connection with the crustal rebound at the end of the last glaciation and that this uplift was amplified by the high magmatic pressure that was provoked by the same reason.

Hundreds of recent hydrothermal explosion craters are located in Mt. Dyngjufjöll ytri, an elongated mountain situated west of the Askja central volcano. Sigvaldason (1992) noticed a fissure with the same strike as Dyngjufjöll ytri, just south of Dyngjufjöll ytri. He suggested that this fissure continued as an intrusion under Dyngjufjöll ytri, causing the formation of the craters, by converting water in the gas pipes in the hyaloclastite into high-pressure steam which led to explosions, and created the hydrothermal explosion craters.

3.7 Is there a central volcano in Hrúthálsar?

In and near Hrúthálsar (Figure 12), Sæmundsson et al. (2005) found evidence for a central volcano. A rhyolite has been found in the eastern part of Mt. Eggert and in the northern part of Eggert, as well as in Hrúthálsar, a high-temperature alteration has been observed. They also point out the existence of a lava shield, east of Hrúthálsar and Eggert. A fissure swarm, where the largest vertical movement of faults (in hyaloclastite) observed is approximately 50 meters, also crosses this area (Sæmundsson et al., 2005).

3.8 Concluding remarks

The current deformation of the Askja central volcano and the earthquakes in and close to the volcano show how active our research area is today (e.g. Sturkell and Sigmundsson, 2000; Sturkell et al., 2006; Knox, 2007; Roberts et al., 2007).

Evidences of previous unrest can also be found in the area. The fissure swarm of the Askja central volcano is likely formed during repeated occurrences of rifting episodes, where magma from the Askja central volcano intruded Askja's fissure swarm. Evidences from the instrumentally recorded Krafla rifting episode in 1975-1984, as well as from the historical rifting episode in Askja in 1875, support this conclusion (e.g. Jónsson, 1942; Björnsson et al., 1977; Sigurdsson and Sparks, 1978). Mapping of fractures and fissures migrating from Askja central volcano can therefore give valuable information on prehistoric rifting episodes in the area.

We mapped tectonic fractures and volcanic fissures in the Askja central volcano and a part of Askja's fissure swarm to get a better understanding of the previous and present deformation in our research area. The principal results of this study are presented in two papers. Paper 1 focuses on the general tectonics in the area and on the interaction between Askja's local stress field and the regional stress field. The amount of volcanic fissures and tectonic fractures with respect to distance from Askja central volcano is studied, as well as the relationship between tectonic features and topography and the relationship between earthquakes and tectonic features. In paper 2, the main focus is on a pit crater chain located in Askja's fissure swarm, in the Kollóttadyngja lava shield. The pit craters are examined and a conceptual model of their formation presented.

Many revealing studies have been conducted in the research area, especially in the Askja central volcano, although much is still to be done. Only rudimentary geological maps are available for the plate boundary area between Askja and Krafla volcanoes. As for future studies, mapping and age determinations of lava flows north of the Kollóttadyngja lava shield would give valuable information on the activity of the fissure swarm with respect to distance from the Askja central volcano. A detailed comprehensive mapping of tectonic fractures and volcanic fissures in all the Northern Volcanic Zone would also be beneficial, as it is the longest visible segment of the Mid-Atlantic plate boundary on land. It may as such improve the general understanding of the plate boundary, as well as on the interaction between volcanoes and their associated fissure swarm.

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5 Paper I: Structure of the northern fissure swarm of the Askja volcanic system in the volcanic zone of Northern Iceland: Uneven distribution of fractures in space and time

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5.1 Abstract

Divergent plate boundaries, such as the one crossing Iceland, are characterized by high density of subparallel volcanic fissures and tectonic fractures, collectively termed rift zones, or fissure swarms when extending from a specific volcano. Volcanic fissures and tectonic fractures in the fissure swarms are formed during rifting events, when magma intrudes fractures to form dikes and even feeds fissure eruptions. We mapped volcanic fissures and tectonic fractures in a part of the divergent plate boundary in N-Iceland. The study area is $\sim 1800 \text{ km}^2$, located within and north from the Askja central volcano. The style of fractures changes with distance from Askja. Close to Askja the swarm is dominated by eruptive fissures. The proportion of tectonic fractures gets larger with distance from Askja. This may indicate that magma pressure is generally higher in dikes close to Askja than farther away from it. Volcanic fissures and tectonic fractures are either oriented away from or concentric with the 3-4 identified calderas in Askja. The average azimuth of fissures and fractures in the area deviates significantly from the azimuth perpendicular to the direction of plate velocity. As this deviation decreases gradually toward north, we suggest that the effect of the triple junction of the North American, Eurasian and the Hreppar microplate is a likely cause for this deviation. Shallow, tectonic earthquakes in the vicinity of Askja are often located in a relatively unfractured area between the fissure swarms of Askja and Kverkfjöll. These earthquakes are associated with strike-slip faulting according to fault plane solutions. We suggest that the latest magma intrusions into either the Askja or the Kverkfjöll fissure swarms rotated the maximum stress axis from being vertical to horizontal, causing the formation of strike-slip faults instead of the dilatational fractures related to the fissure swarms. The activity in different parts of the Askja fissure swarm is uneven in time and switches between subswarms, as shown by a fissure swarm that is exposed in an early Holocene lava NW of Herðubreið but disappears under a younger (3500-4500 BP) lava flow. We suggest that the location of inflation centers in Askja central volcano controls into which part of the Askja fissure swarm a dike propagates. The size and amount of fractures in the Kollóttadyngja lava shield decreases with increasing elevation. We suggest that this occurred as the depth to the propagating dike(s) was greater under central Kollóttadyngja than under its flanks, due to topography.

Keywords: Askja volcano, fissure swarm, Mid-Atlantic plate boundary, Iceland, rift zone, Northern Volcanic Zone, rifting

5.2 Introduction

Iceland is the only area where the mid-Atlantic plate boundary can be studied on land. There, the boundary is marked by volcanic systems including central volcanoes and fissure swarms (Saemundsson 1978), where crustal accretion takes place by magmatism. On the surface this process is manifested by eruptions and fracturing. The plate boundary can be divided into segments, each with its own tectonic and volcanological characteristics (e.g., Einarsson 1991). One of them is the Northern Volcanic Zone, located in the northern part of Iceland. It consists of at least five volcanic systems, including the Askja volcanic system. In this paper we will focus on fissures and fractures in and close to Askja central volcano. The fissure swarm of Askja can be traced at least 120 km from Askja toward the northern coast and nearly 30 km distance from Askja southward to Vatnajökull glacier (Saemundsson 1974) (Figure 1).

Crustal accretion at the plate boundary is not a steady-state process. Episodes of rifting have occurred in the Northern Volcanic Zone about every 100-150 years (Bjornsson et al. 1977). A rare opportunity to observe such a rifting episode was offered by the Krafla activity of 1975-1984. Slow inflation of the Krafla caldera was followed by a rapid deflation and earthquakes migrating north or south from the caldera, indicating the propagation of a dike. During these events, surface fissuring and faulting was observed in Krafla's fissure swarm, in up to 45 km distance from Krafla central volcano, and in 9 out of 20 such events, eruption took place in Krafla's fissure swarm. After such an event, inflation started again in the Krafla caldera, and the cycle repeated itself (e.g., Bjornsson et al. 1977; Buck et al. 2006; Einarsson 1991; Einarsson and Brandsdottir 1980; Tryggvason 1980). The latest major rifting episode at Askja occurred in 1874-1875 (Sigurdsson and Sparks 1978a; 1978b). Minor episodes probably took place in the 1920s and in 1961-1962.

In this study, we have several goals:

1. Map a part of the fissure swarm of the Askja volcanic system.

2. Find if the style of eruptive fissures and tectonic fractures in the fissure swarm depends on their distance from the Askja central volcano.
3. Define the characteristics of the Askja fissure swarm.
4. Look at the relationship between fissure swarms and earthquakes located in this area.

To do this, we mapped fissures and fractures using aerial photographs. The area which we mapped is an almost rectangular $\sim 1800 \text{ km}^2$ area located north of the Vatnajökull glacier. The Askja central volcano is situated in the south part of this area (Figure 2). From this we made a digital fissure and fracture map. We also made a few trips to areas that needed ground check. Then these data were combined with earthquake locations to see the relationship between the earthquakes and the fissures and fractures. This information was also combined with the age of the lava flows (where it is known) from Sigvaldason et al. (1992), to get a better overview on the relationship between the age of the lava flows and the fissures and fractures in them.

We find that both the strike and the ratio of volcanic fissures to tectonic fractures changes with distance from Askja central volcano. Fissures and fractures close to Askja's calderas are either oriented away from the calderas or are concentric around them. We also find evidences that there might be periods of high or low activity at different subswarms of the Askja fissure swarm.

5.2.1 Definition of terms

A volcano is defined as a *central volcano* when it fulfills several criteria's (Johnson 1989; Walker 1993). Central volcanoes are shield volcanoes or stratovolcanoes. They have a significant amount of silicic volcanic rocks in addition to basalts, while rocks intermediate in composition are scarce or absent. Central volcanoes often have one or more calderas that have resulted from subsidence after large silicic eruptions (Walker 1993). The concept of *volcanic systems* is used to acknowledge that the visible edifice of a volcano is only a part of a bigger entity. This concept includes the magma chambers, conduits, magma source, intrusions, geothermal fields as well as the volcano itself (Walker 1993). It also includes the associated rift zone.

The term "rift zone" is conventionally used in a different sense in Iceland, than elsewhere. The usual definition of this term is that rift zones are narrow extensional

zones where eruptive fissures, faults and ground cracks are concentrated. These zones extend from central volcanoes, nearly perpendicularly to the direction of plate velocity. Underlying these rift zones are dike swarms, where magma has intruded into fissures (Walker 1993). In Iceland, the term “rift zone” applies to whole volcanic zones, consisting of several central volcanoes along with their volcanic systems. The term “fissure swarm” is used for areas where eruptive fissures, faults and fractures are concentrated and extend from a specific central volcano, that is, in a similar way as the term “rift zone” is often used elsewhere. As an example, the zones of fissures and fractures extending from Kilauea, Hawaii are usually called rift zones, but equivalent structures would be called fissure swarms in Iceland. The Askja fissure swarm is thus a part of the Northern Volcanic Zone, which is a branch of the plate boundary.

5.2.2 Regional settings

The volcanism in the area is characterized by the formation of hyaloclastite ridges, fissure lavas and lava shields (Figure 2) (Sigvaldason et al. 1992). Earthquakes are common and occur mainly NW and NE of Askja central volcano, as well as in its SE corner (Figure 2) (Brandisdóttir 1992; Einarsson 1991). Several 10-34 km deep earthquakes have recently been detected 10-20 km east and north of Askja (Knox 2007; Soosalu et al., submitted 2008) and since February 2007 a persistent earthquake swarm has been in progress at 15-20 km depth 20 km east of Askja. The fissures and fractures in the research area have been assumed to belong to four volcanic systems; the Askja, Kverkfjöll, Fremrinámar and the Krafla volcanic systems (Figure 1) (Einarsson and Sæmundsson 1987). Most of the volcanic products in the area are basaltic but small volumes of silicic rocks are found at the central volcanoes.

Askja central volcano is located at the southern part of the research area. It is characterized by at least three calderas, hyaloclastite mountains and fissure lavas (Figure 2). The oldest North caldera is from Pleistocene, while the Askja caldera was formed in early Holocene (Sigvaldason 1979). The Öskjuvatn caldera formed during and after a major volcano-tectonic episode in 1875 (Jónsson 1942; Sigurdsson and Sparks 1978a). Askja showed unrest again in the 1920s, with six basaltic eruptions close to and around the newly formed Öskjuvatn caldera (Jónsson 1942;

1962; Sigvaldason 1982; Þórarinnsson and Sigvaldason 1962). In 1961, the latest eruption to date in Askja occurred in the NE corner of the Askja caldera (Þórarinnsson and Sigvaldason 1962). It was followed by an earthquake swarm in 1962, possibly a dike intrusion (Brandsdóttir 1992).

Levelling measurements have been conducted in Askja since 1966, with a break from 1973 to 1983 (Sturkell et al. 2006a; Sturkell et al. 2006b; Tryggvason 1989). Since 1983, various measurements indicate continuous deflation in Askja, but at a decreasing rate (Camitz et al. 1995; de Zeeuw-Van Dalftsen et al. 2005; Pagli et al. 2006; Sturkell et al. 2006a; Sturkell and Sigmundsson 2000; Sturkell et al. 2006b; Tryggvason 1989).

5.3 Methods

Fractures and fissures in the research area were mapped from aerial photographs, and in certain areas, a ground check was also conducted. These data were then combined with data on seismic activity from the Icelandic Meteorological Office (IMO), and the age of the lava flows in the area, where it is known (Sigvaldason et al. 1992).

Four trips were made to the research area, in the summers of 2004 and 2005. In 2004, the focus was on fractures in the Askja caldera, while in 2005, the main task was to observe selected features north of Askja, found on the aerial photographs.

The aerial photographs used to map the fractures are from the National Land Survey of Iceland, taken in August 1987 at approximately 6000 meters altitude. From these photographs, fractures and fissures were mapped. The aerial photographs were scanned and then rectified with the aid of the ArcInfo software and satellite images to get accurate positions. For most of the area, a Landsat image from the summer of 2001 was used, but for a small area at the western part of the map, a higher resolution SPOT 5 image from 3 October 2002 was used. A small part of the southeastern part of the map is also covered with SPOT 5 image from the summer of 2002. Also, contour lines, a road layer and a river and lake layer were used to get better locations. Overall, the uncertainty of the location of the fractures and fissures is in most cases less than 100 meters.

Seismic data from October 1998 to March 2007 were obtained from the Icelandic Meteorological Office. Poorly located earthquakes were filtered out by only admitting epicenters determined by a network with maximum azimuthal gap of 130°.

Ash layers from different volcanoes in Iceland have been dated and used for determining the relative age of lava flows. Sigvaldason et al. (1992) used this method to determine the relative age of the post-glacial lava flows in and close to Askja central volcano (Figure 2). They used the marker ash layers H1, H3 and H4 from Hekla, dated at 1158 AD, 2900 BP and 4500 BP respectively (Kjartansson et al. 1964; Thorarinnsson 1971). They also used a previously unknown silicic ash layer called 'x', possibly corresponding to the Selsund pumice from Hekla, which has an age of approximately 3500 years BP, as well as the Örafajökull 1362 AD ash layer and the 1477 AD 'a' layer from Veiðivötn. They studied the ash layers on top of the lava flows in and close to Askja central volcano and found the relative age of the lava flows. By combining these data with data on the location of the lava flows, they made a map of the different lava flows and their ages. We got the vector data of the outlines of the lava flows (Sigvaldason et al. 1992 and unpublished), transferred them to raster data using the ArcInfo software and added the information on the age of different lava flows in the layer. Unfortunately, lava flows covering a large part of the research area are of unknown age.

5.4 Results

5.4.1 Overview

The results of our mapping efforts are shown in Figs. 3-9. Along this part of the plate boundary, fractures and faults are not distributed evenly. Part of this is because of age difference of formations. Generally, older formations are more fractured than the younger ones. Even though the rate of erosion is higher in basaltic glasses like hyaloclastite than in crystallized basalts (e.g., Wolff-Boenisch et al. 2006), the hyaloclastite in the research area is generally more fractured than the lava flows. As an example, the hyaloclastite mountain ridge Herðubreiðarfjöll in the northern part of the map is densely fractured, while the 2900-3500 BP lava flow south of Kollóttadyngja is almost not fractured at all. The uneven distribution of faults and fractures has also been explained by fissure swarms, as fissure swarms from four different central volcanoes intersect the study area (Figure 1) (Einarsson and Sæmundsson 1987). There are however exceptions in the pattern of fissures and fractures in the research area that can neither be explained by the age of the lava

flows or the fissure swarms. As an example, some of the lava flows north of Askja central volcano, which are older than 4500 BP according to Sigvaldason's et al. (1992) dating, are not fractured at all despite their age and the fact that they are located in an area between Askja central volcano and the highly fractured area farther north.

In general, most of the fissures and fractures found in the study area strike 0-40°, and the longest ones usually strike 10-30° (Figure 3). There is however a gradual and systematic change in the orientation of tectonic features in this area. In the northern part, the tectonic features trend more toward north than in the southern part, where they trend more toward NNE (Figure 2). In fact, fractures north of our research area also continue to trend more and more toward north (Tentler and Mazzoli 2005). The direction of plate spreading in this area is 106° as calculated from the rotation pole from the NUVEL-1A model of plate motions (Demets et al. 1994), but 104° if it is calculated from the rotation pole from the REVEL-2000 global model for recent plate velocities (Sella et al. 2002). We will use 106° as the direction of plate velocity. The fissures and fractures are on average not oriented perpendicular to that direction (Figure 4). The highest deviation is in the southern part but it decreases toward north.

Volcanic fissures are dominant in the fissure swarm close to Askja, but tectonic fractures become more frequent as the distance to Askja increases. Most of the tectonic fractures are located in the northern part of the map, both in hyaloclastite ridges and post-glacial lava flows (Figure 2 and 6). Volcanic fissures are mainly located in two areas in the northern part of the map, in and close to Hvammsfjöll and in and close to Hróthálsar, defined as a central volcano by Sæmundsson et al. (2005). Volcanic fissures become dominant closer to Askja, especially just north and south of Askja (Figure 5). In the center of the volcano, tectonic fractures related to caldera subsidence are quite frequent.

The distribution of earthquakes in the area is uneven as the earthquakes usually cluster in certain areas (Figure 2). Surprisingly, the shallow earthquakes are mostly located between fissure swarms, while deep earthquakes are commonly located under fissure swarms. There are about 4-5 areas of high earthquake activity in the research area, NW of Askja, in the SE part of Askja, in and close to the Herðubreið table mountain and in Upptyppingar in the SE most part of the research area as well as in the NE part of Askja. The area of high seismicity NW of Askja shows a very low

fracture density, although a volcanic fissure was identified there. The only visible fractures close to the area of high seismic activity in the SE corner of Öskjuvatn caldera circle around a part of the Öskjuvatn caldera. There, it has been suggested that the seismic activity is due to hydrothermal activity (Einarsson 1991). The intense seismicity in and close to Herðubreið is due to northeasterly striking left lateral strike-slip faults, which are nearly vertical (Þorbjarnardóttir et al. 2007). Still, very few tectonic lineaments were found in this area, and none with the strike of the faults. Deep earthquakes have also recently been detected in and close to Upptyppingar in the SE part of the research area. This deep seismicity is located under a part of the fissure swarm of the Kverkfjöll central volcano. There are therefore several clusters of earthquakes in the research area, but they do not always cluster under the fissure swarms.

5.4.2 Tectonic features in and close to Askja central volcano.

The Askja central volcano has at least three calderas. The 100-132 years old Öskjuvatn caldera is the youngest of these three. The fractures delineating the west side of this caldera are located in fissure lava flows dating from 1920 AD to 1477 BP (Figure 6) (Sigvaldason et al. 1992). These fractures are usually shorter than 300 m, the main exception being the long and sharp caldera rim itself. On the south, east and northeast side however, the caldera rim is located in a hyaloclastite and is not as sharp as on the west side. The fractures observed in the hyaloclastite are longer and fewer than the fractures in the lava flow at the western side of the caldera. A large area of this caldera is under the Öskjuvatn Lake. Most of the fractures associated with this caldera are non-eruptive. Still, eruptive fissures are found along the caldera rim. All the eruptive fissures that were mapped were formed during the episode of eruptions from 1921 to 1930. Fractures in the Mývetningahraun lava (Figure 2 and 7) are located in small gaps in the lava flow that have not been mapped by Sigvaldason et al. (1992) and are therefore not located in the lava flow itself. Most of the volcanic fissures and tectonic fractures close to the newly formed caldera do therefore circle around the caldera, the tectonic fractures in the lava flow being sharper and shorter than the ones in the hyaloclastite.

The Askja caldera is located northwest of the new Öskjuvatn caldera. In fact, the Öskjuvatn caldera is formed in the southeastern side of this caldera. The

southeastern boundary of the Askja caldera is not very clear, due to the overlapping of the new Öskjuvatn caldera. To the west however, the boundary is clear, but there it is influenced by a regional fissure swarm. Instead of the oval or circular shape which characterizes a typical caldera rim, the western part of this caldera is cut by an almost straight fracture striking 13° which delineates the western rim of the caldera (Figure 6). There are also more fractures located west of the northern part of this fracture, striking $11-18^\circ$. The eruptive fissure of the 1961 eruption, trending approximately 116° , is located at the northern boundary of the Askja caldera. Volcanic fissures were also found on its western boundary. Most of the fractures associated with this caldera are tectonic fractures and most of them are located on the western rim of the caldera. The fractures are usually rather large, although few smaller ones can be found on the western rim. The fractures are found in a hyaloclastite that circles the caldera. The only tectonic fractures found in the caldera floor are the ones that are clearly linked to the formation of the Öskjuvatn caldera. A large part of the caldera floor is not fractured at all on the surface. The surface of the caldera is, however, relatively young, having the age of 1920 AD to 1477 BP, according to Sigvaldason et al. (1992). Most of the fissures and fractures in and close to the Askja caldera are therefore formed either by the subsidence of the Askja caldera, some of which influenced by a regional fissure swarm or by the formation of the Öskjuvatn caldera.

The North caldera is located north of the Askja caldera. The North caldera is the least obvious of the three calderas. There is, however, a rather clear oval lineament on the north and northeast side of this caldera, clearly of tectonic nature (Figure 6). This lineament is in fact the only circular or oval lineament that can be found which circles this caldera. Still, several eruptive fissures located NE of this caldera are oriented away from the caldera, forming a fan-like structure. The North caldera is therefore different than the Askja and Öskjuvatn calderas in the sense that volcanic fissures are oriented away from the caldera instead of circling around the caldera, as they do at the other two calderas.

A sharp and long rim cutting the southern part of the North caldera possibly delineates the fourth caldera in Askja central volcano (Figure 6). Oval lineations are also found in the hyaloclastite south of Öskjuop, one of them fits well with the delineation in the southern part of the North caldera.

Eruptive fissures of various lengths and orientations are by far the most common structural feature south of Askja. The closer they are to Askja, the more irregular the orientation of these fissures is. To the south of the straight fractures that mark the western caldera rim of the Askja caldera, the fracture type changes from dominantly tectonic fractures, to dominantly eruptive fissures. The long eruptive fissure in the eastern part of this area of volcanic fissures erupted some time during the years of 1924-1930 (Pórarinnsson and Sigvaldason 1962). The only tectonic fractures identified in this area are found east of this fissure. These are fractures located in older lava flows that have been mostly covered by the younger lava flow. Apart from this lava flow, most of the area is covered by fissure lavas older than 4500 BP. There is however a fissure lava flow to the west of this lava flow that is relatively young, from 2900 to 3500 BP (Sigvaldason et al. 1992). The tectonic features south of Askja are therefore characterized by irregular strike and high number of volcanic fissures compared with tectonic fractures.

5.4.3 Kollóttadyngja

Kollóttadyngja is a lava shield, and is older than 4500 BP (Sigvaldason et al. 1992). The volcanic fissures and tectonic fractures in Kollóttadyngja form a part of the Askja fissure swarm (Einarsson and Sæmundsson 1987). Most of the tectonic features in Kollóttadyngja are located on the eastern side of it. In the northern part, fractures and faults are the dominant features, but at the southern side, eruptive fissures and pit craters are common. The pit craters are located within, or near, a pit crater chain, which is within and parallel with the Askja fissure swarm. The fractures and faults seem to be most common and largest in the lower slopes of Kollóttadyngja, but as the elevation increases, the fractures and faults become smaller and fewer. The volcanic fissures that lie in the northern part of Kollóttadyngja seem to lie on a straight line from the volcanic fissures and pit craters in the southern part of it (Figure 7).

On the western part of Kollóttadyngja, the fractures are smaller than on the east side. They are arranged in several lines and some of them even group together, forming pairs of lines lying side by side (Figure 7). Most of these features are rather short fractures, ranging between ~27 to 476 m in length. However, the easternmost line has a volcanic fissure at the southern end of it. The fractures in the western part

of Kollóttadyngja have the dominant azimuth of 20-40° while at the eastern side the dominant direction is 10-30°.

Some very small and fine fractures are found at the top of Kollóttadyngja. Their length ranges from ~24 to 249 m, but the mean length is 83 m. This line of fractures is in line with a volcanic fissure that is located south of it.

The tectonic features on the northern and eastern part of Kollóttadyngja are fractures and faults, but two areas of volcanic activity can also be found. The tectonic fractures and faults are of different sizes, ranging from ~24 to 3088 m with an average of 208 m. The longest fault, located in the lower slopes of Kollóttadyngja lava shield, extends all the way from the middle of the lava shield and into the hyaloclastite mountain to the north of it, Eggert. In general, the slopes of the lava shield are densely fractured between the elevations of 700-900 m.a.s., while the 900-1200 m.a.s. slopes are much less fractured (Figure 7). There seems therefore to be a tendency that longer and wider faults and fractures are located lower in Kollóttadyngja while the few fractures found higher in Kollóttadyngja are very short and narrow (Figure 7).

5.4.4 The northeastern subswarm

A considerable amount of small fractures can be found in the subswarm of the Askja fissure swarm in the northeastern part of the research area (Figure 8). This subswarm is located in lava flows; the southernmost part of it is in a lava flow older than 4500 years BP (Sigvaldason et al. 1992), while the northern part of it is located in lava flows of unknown age. Viewing SPOT5 images, it can, however, be observed that in our research area, the northeastern subswarm is mostly located within the 4500 BP or older lava flow (Figure 8). In the northernmost part, it seems to cut an even older lava flow. The fissure swarm does, however, not cross the narrow lava flow that seemingly originated from fissures south of Mt. Herðubreiðarfjöll and northwest of Mt. Eggert (Figure 8). In the southern part, lines of fractures can be found, where the fractures are parallel, en echelon or in a line. No evidence of volcanic activity can be found in the southern part, but two eruptive fissures are located in the northern part. One is in line with the subswarm; the other one is smaller and oblique to it. In the northern part, the tectonic fractures are longer than in the south part. A few kilometers north of the research area, this subswarm turns into a series of grabens.

At the southern end of the subswarm, a 3500-4500 BP shield lava flow covers the lava flow where this subswarm is located. No tectonic features could be traced into this younger lava flow. The fractures in the northeastern subswarm are therefore rather small, but increase in size toward north and become more graben-like.

The crustal extension across fissure swarms may possibly be taken to indicate the width of the underlying dike(s). After a rifting event in April 1977 in the Krafla fissure swarm, measurements of openings of cracks in the frozen ground there gave an east-west widening of 2 meters on a given profile, which occurred during the rifting event. The same widening of 2.0 meters was also observed when a geodimeter line was remeasured across the same profile (Bjornsson et al. 1979). This may indicate that the width of the underlying dike is comparable to the cumulative width of fractures on the surface. We therefore measured the width of the fractures we encountered as we crossed the northeastern subswarm, toward Mt. Eggert. As we did not manage to go all the way, some estimation had to be made. The total width of the fractures was 11 m over an approximately 1360 m long profile, the percentage of dilatation being 0.80% (see Table S1 in Electronic supplementary material). We estimated from the aerial photographs that the width of the fissures, which we did not cross, is 1-4 meters. From that we conclude that the overall widening of this fissure swarm, and therefore the total width of the dike(s) contributing to this dilatation is approximately 12-15 meters. As the length of the profile including the rest of the fissure swarm is approximately 2050 m, the percentage of dilatation across this profile is 0.59-0.73%. This dilatation occurred between 3500 and 10 000 BP, as the fissure swarm did not cut the 3500-4500 BP lava flow south of it, and glacier does not seem to have covered the >4500 BP lava flow which the fissure swarm lies in (Figure 8). If we assume that this dilatation occurred in 6500 years, and that the deformation zone was 40 km wide across the plate boundary, the yearly spreading rate between 3500 and 10 000 years ago was about 3.6 cm/yr. This is a crude estimate, however, as this fissure swarm is only one of several parallel fissure swarms that cross this part of the plate boundary and it is unclear whether the long-time dilatation of different fissure swarms is the same. We do not know the exact width of the deformation zone during that time, and the dilatation might also have occurred in less than 6500 years. This spreading rate is, however, not inconsistent with the current spreading rate of 2 cm/yr.

5.5 Discussion

We mapped fissures and fractures to see how their structure relates to the mid-Atlantic plate boundary, where it crosses Iceland, as well as to see how they interact with the Askja central volcano. This part of the plate boundary is unusual in the sense that the alleged center of the Iceland hotspot is located south of the area, in Vatnajökull glacier, less than 30 km from Askja. A triple junction is also located at or south of the research area, where the Eurasian plate, the North American plate and the Hreppar microplate meet (Figure 1).

Askja is in some ways similar to Kilauea volcano, Hawaii. At both volcanoes, shifts in the location of inflation/deflation centers have been observed, shown by different locations of calderas in Askja, and the apparent shifts in the locations of pressure centers within the caldera in Kilauea (Tilling and Dvorak 1993). Both the volcanoes have distinct fissure swarms, extending in opposite directions from the volcanoes and pit crater chains can be found in the fissure swarms of both of the volcanoes (e.g., Okubo and Martel 1998). This occurs despite the different dilatational sources and tectonic settings of the volcanoes. While Askja is located at a divergent plate boundary, the subsiding southern flank of Kilauea causes the dilatation there (Tilling and Dvorak 1993).

5.5.1 The ratio of tectonic fractures and volcanic fissures.

The ratio of volcanic fissures vs. tectonic fractures is highly dependent on the distance from Askja central volcano (Figure 9). The lower ratio in the northern part of the map suggests a lack of magma, compared to the area closer to and in Askja. The cumulative amount of fissures and fractures increases with distance northward from Askja. There are several possible mechanisms that can explain this pattern:

a) The lava cover might be generally younger close to Askja than farther away from it. The lack of tectonic fractures close to Askja might therefore imply that lava has covered the fractures. The lava close to Askja is, however, not all that young. A large part of it is older than 4500 BP, according to Sigvaldason et al. (1992), but still with a very low fracture density. Although lava covers most of the research area, hyaloclastites also cover a part of it. As the hyaloclastites are formed when glacier covered the research area, they are older than most of the lava flows mapped by

Sigvaldason et al. (1992). Hyaloclastites do, however, not display the fractures well, due to weathering, erosion and the low cohesion and low strength of the hyaloclastite rocks. The hyaloclastites in the northern part of the research area are, despite this, densely fractured.

b) The ratio of volcanic fissures vs. tectonic fractures might depend on the distance towards the center of the hotspot. As the ratio lowers with increasing distance toward north from Askja, the distance toward the center of the hotspot, south of Askja, also increases. If the ratio was to depend on the distance from the hotspot, the ratio should increase toward south from Askja to the Vatnajökull glacier, towards the center of the hotspot, but it does not. Instead, we observed with overview mapping by SPOT5 images south of the research area that the ratio also lowers with increasing distance toward south from Askja.

c) The magma pressure in propagating dikes might be higher close to Askja central volcano than farther away from it. The high ratio of volcanic fissures vs. tectonic fractures close to Askja might suggest that magma pressure is generally high in the dikes there during dike propagation, and that magma pressure gets lower with distance from the volcano, leading to lower ratio of volcanic fissures vs. tectonic fractures.

As the older lava flows close to Askja display a low fracture density, we conclude that although the first suggestion might have some effect, it is not the dominant factor controlling the ratio of volcanic fissures vs. tectonic fractures. The hotspot theory is also unlikely, since the ratio does not increase all the way toward Vatnajökull glacier, where the center of the hotspot is located. We conclude that the third explanation explains best the pattern observed. Then, magma pressure in dikes is highest close to Askja but decreases with distance from it. This is consistent with horizontal propagation of dikes, but it does not exclude other explanations, e.g. that the magma productivity is higher in the mantle beneath Askja than farther away from it.

5.5.2 Orientation of fissures and fractures.

As the orientation of the volcanic fissures and tectonic fractures close to Askja central volcano is quite different to the orientation of volcanic fissures and tectonic fractures in the fissure swarm farther away from the volcano, it can be inferred that Askja produces a strong local stress field, compared to other central volcanoes in the Northern Volcanic Zone. As an example, Krafla central volcano has little effect on its fissure swarm, as faults and fissures of the swarm extend through the caldera (see e.g. maps in: Bjornsson et al. 1977; Opheim and Gudmundsson 1989). The high local stress field of Askja as well as its youthful appearance indicates high activity of the Askja central volcano.

The average azimuth of fissures and fractures seems to diverge less and less from the azimuth perpendicular to the direction of plate velocity as the distance from Askja increases toward north (Figure 4). The azimuth of fissures and fractures is quite oblique to the azimuth perpendicular to the direction of plate velocity in a large part of the research area, even in the northern part of the map. The reasons for this might be:

- a) The proximity of the Askja central volcano can possibly have an effect on the strike of the nearby fissures and fractures in the fissure swarms. The fractures related to the calderas of Askja and the local stress field of Askja clearly have an effect on the deviation seen in Figure 4. The deviation does however decrease continuously all the way north in the research area, approximately 40 km north of Askja, that is, to distances where it is unlikely that the volcano's stress field has an effect.
- b) The southern part of the research area is located at the triple junction of the Eurasian plate, the North American plate and the Hreppar microplate. This might cause abnormalities in the strike of fissures and fractures in this area, which should decrease toward north as the distance toward the triple junction increases.

As the deviation continues to decrease for large distances from Askja we doubt that the local stress field of Askja central volcano is the controlling factor in this case. The fissure swarms in the Eastern Volcanic Zone are located east of the Hreppar microplate. These fissure swarms, which delineate the boundary between the

Hreppar microplate and the Eurasian plate, are also oblique to the spreading direction, and even more so than the fissure swarms in our research area (Figure 1) (Einarsson and Sæmundsson 1987). This pattern suggests that the obliqueness increases with decreasing distance toward the Hreppar microplate, possibly implying that the Hreppar microplate has an effect on the strike of fissures and fractures in the area. The mechanism of this effect is not clear, but the counterclockwise rotation of the Hreppar microplate (Einarsson et al. 2006) could have some influence on the orientation of fissures and fractures in this area. We therefore conclude that the effect of the triple junction and the Hreppar microplate is the most likely cause for the deviation in the orientation of fissures and fractures in this area from perpendicular to the spreading direction.

5.5.3 Variable activity in the subswarms

The activity of each of the subswarms of the Askja fissure swarm may vary in time, as periods of high or low activity may be observed in individual subswarms, on the timescale of thousands of years. The subswarm in the NE part of the map that disappears under a lava flow of the age of 3500-4500 BP may be an example of this (Figure 8). The southernmost part of the NE subswarm is in a post-glacial lava flow older than 4500 BP (Sigvaldason et al. 1992), but younger than 10 000 BP, since glacier has not covered this lava flow. This implies that the subswarm was active during and/or after the emplacement of the lava, but almost or completely inactive after the 3500-4500 BP lava formation, which indicates an episodic activity in this subswarm. Sæmundsson (1991) described similar pattern in the Krafla central volcano, where the activity in the Krafla fissure swarm seems to switch between the western and eastern part of it. This might imply:

a) Different amounts of deviatoric stress may be induced at the same latitude within the Askja fissure swarm. As stress accumulates over a broad area, the magma might intrude the subswarm where the deviatoric stress field is highest, relieving the stress in that subswarm. Then, there could be other subswarms at the same latitude where the stress is relieved due to the dike intrusion(s), but not as much as in the subswarm where the dike(s) were intruded. The next dike intrusion(s) would propagate to the

subswarm with the highest deviatoric stress, i.e. to another subswarm than it did last time.

b) Different inflation/deflation locations within the Askja central volcano could be associated with activity in different parts of the fissure swarm. The three calderas of Askja are not concentric and reveal different locations of inflation/deflation centers. Unrest in the easternmost caldera might be connected with a rifting episode in the easternmost part of a fissure swarm, and unrest in a magma chamber in the western part might influence the western part of Askja's fissure swarm.

We assume that a dike may propagate obliquely to the regional fissure swarm close to Askja due to the local stress field of the volcano, but as it is rather unlikely that a dike will propagate oblique to the regional fissure swarm once out of the volcano's stress field, we conclude that different inflation locations is the most likely cause for the suggested episodic activity in each of the subswarms.

5.5.4 Lava shields and fracture density

Fractures in the upper part of the Kollóttadyngja lava shield are fewer and smaller than in its lower slopes. The fractures in Kollóttadyngja are a part of the Askja fissure swarm and have nothing to do with the formation of the lava shield. We suggest three possible explanations for how this pattern was formed.

a) Magma from the eruption which formed the Kollóttadyngja lava shield could have been intruded into fractures under Kollóttadyngja, therefore relieving the accumulated tectonic stress at this part of the plate boundary at the time the lava shield was formed. It is unlikely that fractures would form for a long time after such a stress relief. According to this idea, the fractures should start to form in the lower slopes of Kollóttadyngja, progressing upward as time passes.

b) The depth to the propagating dike might have been greater under the center of Kollóttadyngja than under its lower flanks due to topography, as the Kollóttadyngja lava shield rises 400-500 m above its surroundings. This might have lead to less surface fracturing in the upper part of Kollóttadyngja than on its lower slopes.

Our calculations indicate that since the Kollóttadyngja lava shield was formed, it has been dilated 2 - 14 m/km, taking into account the yearly spreading rate at the plate boundary (2 cm/yr), the age of the Kollóttadyngja lava shield (4500 - 10 000 BP) (Sigvaldason et al. 1992), and the distance across the plate boundary the spreading should affect (14-50 km). Although the former suggestion might have some effect, we consider it unlikely that such a high amount of dilatation should not contribute to larger fractures in the upper slopes of Kollóttadyngja. We suggest that the topography of Kollóttadyngja affects the depth to the top of the dike. Less surface fracturing should occur above deep dikes than the ones that are shallower in the crust, which could explain the lack of fractures in the upper slopes of Kollóttadyngja. The small and narrow fractures on top of Kollóttadyngja, however, remain enigmatic.

5.5.5 The features related to the calderas.

The volcanic fissures near the North caldera are oriented away from it, forming a fan-like structure, while the fissures and fractures near the Askja caldera and the Öskjuvatn caldera circle around them (Figure 6). We suggest that the dikes beneath the volcanic fissures which are oriented away from the North caldera are formed during an inflation in the North caldera, while most of the dikes close to the Askja caldera and the young Öskjuvatn caldera are formed after a period of deflation, shortly after a inflation had started, as McKenzie et al., (1992) suggested for similar cases seen on Venus and Earth. This would indeed explain the multiple eruptions in the 1920s in Askja. As the eruptions occurred around the newly formed Öskjuvatn caldera or close to it, the sudden burst of six eruptions in nine years might imply inflation in the newly formed caldera. The first four eruptions (from 1921 to 1923) were located around the newly formed caldera, but for the latter two, one originated in the south part of the caldera itself (Hornfirðingahólmi, formed in 1926) and another one occurred south of Öskjuvatn caldera, sometime between 1924 and 1930 (Pórarinsson and Sigvaldason 1962). That fissure strikes parallel with the fissures in the regional fissure swarm and nearly perpendicular to the Öskjuvatn caldera. This may indicate that the stress field in this area rotated after the fourth eruption, favoring eruptions of fissures parallel (and within) the fissure swarm instead of

eruptions around the caldera. The volcanic fissures near the calderas of Askja central volcano are therefore both oriented away from the calderas and circled around them, indicating a change in the stress field close to the calderas at the times the volcanic fissures and their subsurface dikes were formed.

5.5.6 Earthquakes in and close to Mt. Herðubreið

A remarkable outcome of our study is the apparent inverse relationship between shallow earthquakes and fractures. Earthquakes included in our comparison are dated from October 1998 to March 2007. The highest seismicity is found in the relatively unfractured area in the Herðubreið and Herðubreiðartögl area, between the fissure swarms of Askja and Kverkfjöll. The distribution of hypocenters and fault plane solutions there indicate left-lateral strike slip on faults striking NE, oblique to the fissure swarms (Þorbjarnardóttir et al. 2007). As post-glacial dilatational fractures are located in only about 4 km distance from Mt. Herðubreið (Figure 2), the maximum stress axis in this area must have rotated. A similar pattern has been observed in the Reykjanes peninsula, where the maximum stress axis seems to switch between being vertical, indicating the formation of normal faults, and horizontal in the NE direction, indicating the formation of strike-slip faults. The minimum stress axis there is, however, consistently NW oriented (Klein et al. 1973; 1977). We speculate that the stress release after a dike intrusion in either the Askja fissure swarm west of Herðubreið or the Kverkfjöll fissure swarm east of Herðubreið might lead to a rotation of the maximum stress axis near Herðubreið. This might imply that the magnitude of the maximum stress axis is close to the lithostatic pressure, even when horizontal, as it is likely that the magnitude of the maximum stress axis does not change much when rotated. The minimum stress axis, however, does not rotate and is consistently approximately parallel with the plate velocity.

5.6 Main conclusions

- 1.** Askja volcano has a pronounced effect on the regional stress field around the plate boundary, as can be seen from the azimuth of the volcanic fissures and tectonic fractures in the fissure swarms close to Askja.

2. Volcanic fissures are most common in the fissure swarms close to Askja, but as the distance from the volcano increases, the proportion of tectonic fractures increases, and the proportion of eruptive fissures decreases. This implies that magma pressure is highest close to the volcano and decreases with distance from the volcano into the fissure swarm of Askja central volcano.
3. Volcanic fissures around the borders of the calderas in Askja are either oriented away from the calderas, like in the North caldera where they form a fan-like structure, or circle around them, like around the Öskjuvatn caldera. The ones that are oriented away from the calderas are interpreted as having formed during inflation of the calderas, whilst the ones that circle around the calderas are considered to have formed during inflation, shortly after a deflation of the caldera, as McKenzie et al. (1992) suggested for similar cases observed in Venus and on Earth.
4. The density and width of fissures and fractures in a lava flow increases with the age of the lava flow, showing time progression. Some of the older lava flows situated north of Askja central volcano do, however, show immediately unexplained low fracture density.
5. Different subswarms of the Askja fissure swarm might show periods of high or low activity, on the timescale of thousands of years. The NE subswarm is as an example located in a lava flow that is older than 4500 BP but disappears under a 3500-4500 BP lava flow, indicating inactivity in the subswarm after that time. We suggest that different inflation/deflation locations in the Askja central volcano might cause variable activity of the subswarms of the volcano. Unrest in the easternmost caldera might therefore relate to a rifting event in the easternmost subswarm of the Askja fissure swarm.
6. The measured dilatation of 12-15 m in a 2050 m wide profile in the NE subswarm seems to have occurred between 3500 and 10 000 BP. This dilatation is not inconsistent with the total spreading rate of 2 cm/yr across the plate boundary.

7. The central volcano which Sæmundsson et al. (2005) proposed to be in Hnúthálsar does not affect the strike of fissures and fractures there, as the strike is similar to that of the tectonic features in the surrounding area.

8. An area of intense seismicity and low fracture density is located between the fissure swarms of Askja and Kverkfjöll central volcanoes. The NE-striking left lateral strike-slip faults revealed by the seismicity and InSAR images (Soosalu et al. 2006; Þorbjarnardóttir et al. 2007) cannot be identified on the aerial photographs from 1987. The seismicity indicates a stress accumulation between the fissure swarms of Askja and Kverkfjöll central volcanoes. We suggest that magma intrusions into either the Askja or Kverkfjöll fissure swarm might rotate the maximum stress axis from being vertical to horizontal. This would lead to the formation of strike-slip faults as the ones observed in and close to Mt. Herðubreið instead of the normal faults formed when the maximum stress axis is vertical. The minimum stress axis, however, does not seem to change its orientation.

9. Lava shields apparently affect fissure swarms that cross them. The size and amount of fractures in Kollóttadyngja lava shield depends on topography, as the fractures get fewer and smaller with increasing elevation. We suggest that this might have occurred as the depth to the top of the dike(s) might depend on the topography of Kollóttadyngja. The top of the dikes might therefore generally be located deeper under the center of Kollóttadyngja than under its flanks.

Acknowledgements. We thank Guðmundur E. Sigvaldason, who sadly passed away at early stages of this project, as well as Erik Sturkell and Halldór Ólafsson from the Institute of Earth Sciences, University of Iceland, for their help with the fieldwork and their constructive comments. We would also like to express our gratitude to Kristján Sæmundsson for fruitful discussions. Thanks are due to Rósa Ólafsdóttir from the Institute of Earth Sciences who provided contour lines as well as the outlines of many lava flows in the research area, and Gunnar B. Guðmundsson from the Icelandic Meteorological Office, who provided data on the seismic activity in the area. We are grateful for the help with the ArcInfo software received from Hulda Axelsdóttir, then a student at the University of Iceland, and Bjarki Þór Kjartansson

from the Agricultural University of Iceland, who also provided satellite images. Thanks are also due to Bryndís Brandsdóttir, who provided SPOT5 images.

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5.8 Figure captions

Figure 1:

The fissure swarms of Iceland (yellow areas) (Einarsson and Sæmundsson 1987), central volcanoes (red circles) and earthquakes from 1994-2000 (black dots) (data from the Icelandic Meteorological Office). The research area is indicated as a green area. The volcanic systems located in the Northern Volcanic Zone are shown in the right frame. H marks the Hreppar microplate.

Figure 2:

Earthquakes, lava flows and tectonic features in the research area. The information on the lava flows and most of the hyaloclastite is from Sigvaldason et al., (1992), except for the hyaloclastite in the northern part, which we mapped. The earthquake data (from October 1998 to March 2007), is from the Icelandic Meteorological Office. Volcanic fissures and tectonic fractures are also indicated, along with the area covered by the aerial photographs. A high-resolution figure on the fractures is included (see Figure S1 in the Electronic Supplementary Material).

Figure 3:

a. The length (m) and strike ($^{\circ}$) of all tectonic features in the area. b. The length and strike of fractures in the area with strike of $0-60^{\circ}$ and length of up to 2000 m.

Figure 4:

The average deviation from perpendicular to the spreading direction (106°) at given profiles across the research area. The deviation is highest close to Askja, partly due to tectonic features related to caldera subsidence. The profiles are 2 km wide, oriented parallel with the spreading direction in the area (106°). The numbers at the x-axis indicate distance from the center of Öskjuvatn caldera in km, either toward north (N) or toward south (S).

Figure 5:

The amount of volcanic fissures, tectonic fractures and scoria cones (with no apparent volcanic fissures) at a given profile across the research area. The profiles are 2 km wide, oriented parallel with the spreading direction in the area (106°). The numbers at the x-axis indicate distance from the center of Öskjuvatn caldera in km, either toward north (N) or toward south (S). Profiles from 4 km south of the center of Öskjuvatn caldera to 10 km north of the center cover one or more calderas of Askja central volcano. The Kollóttadyngja lava shield is located 20-28 km north of the center of the Öskjuvatn caldera.

Figure 6:

Volcanic fissures (red), tectonic fractures (green) and unclear lineaments (black) in Askja central volcano. The age of the lava flows is from Sigvaldason et al., (1992). “Cinder cones” mark the cinder cones that are not a part of any visible volcanic fissures in the aerial photographs. H = the Hornfirðingahólmi Island, V = the Vikraborgir crater row. The background is a SPOT image of Askja (Spot Image©).

Figure 7:

Tectonic fractures (green), volcanic fissures (red) and tectonic fractures with vertical offset (yellow) in Kollóttadyngja lava shield. The background is a SPOT image of Kollóttadyngja (Spot Image©).

Figure 8:

The northeastern subswarm of the Askja fissure swarm. Most of the lava flows that are cut by this subswarm are of unknown age. The swarm is truncated by a 3500-4500 years old lava flow at the south margin of the map. The information on the lava flows and the hyaloclastite in the southernmost part is from Sigvaldason et al., (1992). The background is from Spot Image©. A high resolution image of the fractures in the NE subswarm is provided in the Electronic Supplementary Material (Figure S2).

Figure 9:

The ratio of volcanic fissures to tectonic fractures at given profiles across the research area. The profiles are 2 km wide, oriented parallel with the spreading direction in the area (106°). The numbers at the x-axis indicate distance from the center of Öskjuvatn caldera in km, either toward north (N) or toward south (S). Profiles from 4 km south of the center of Öskjuvatn caldera to 10 km north of the center cover one or more calderas of Askja central volcano. The Kollóttadyngja lava shield is located 20-28 km north of the center of the Öskjuvatn caldera.

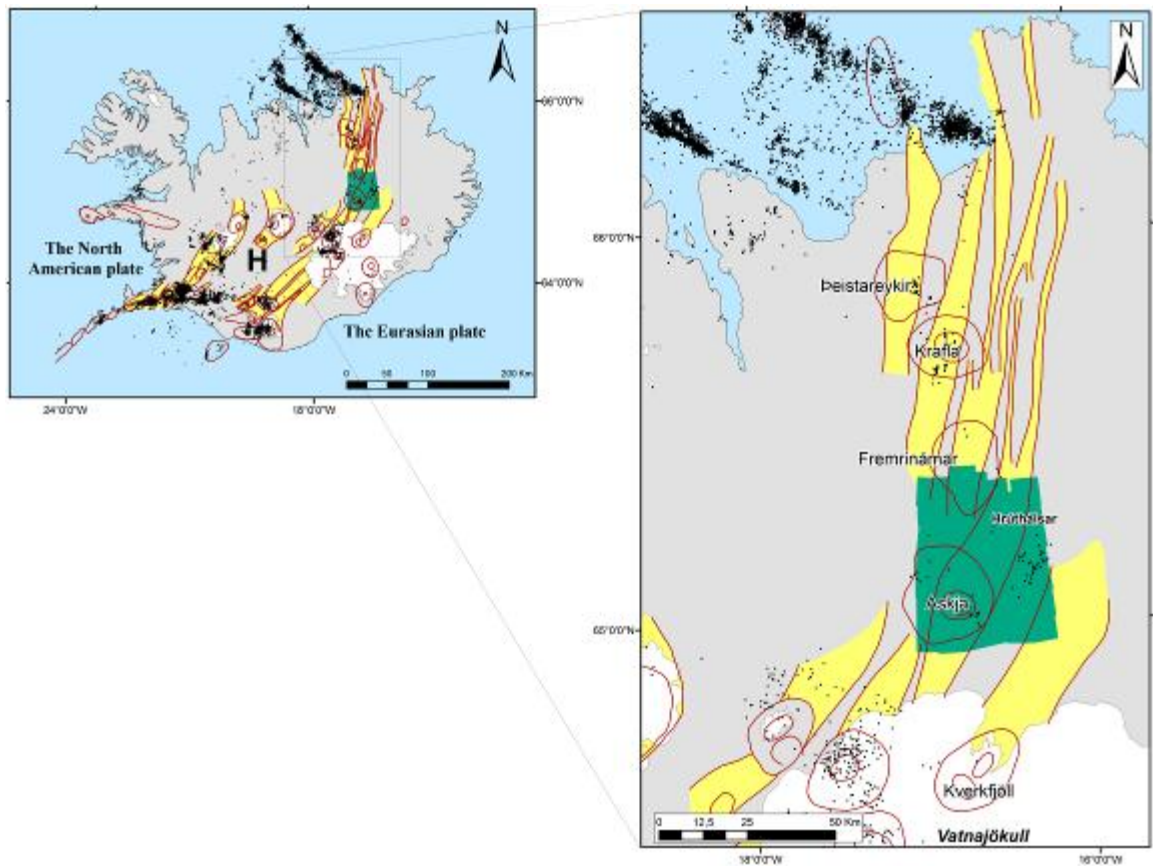


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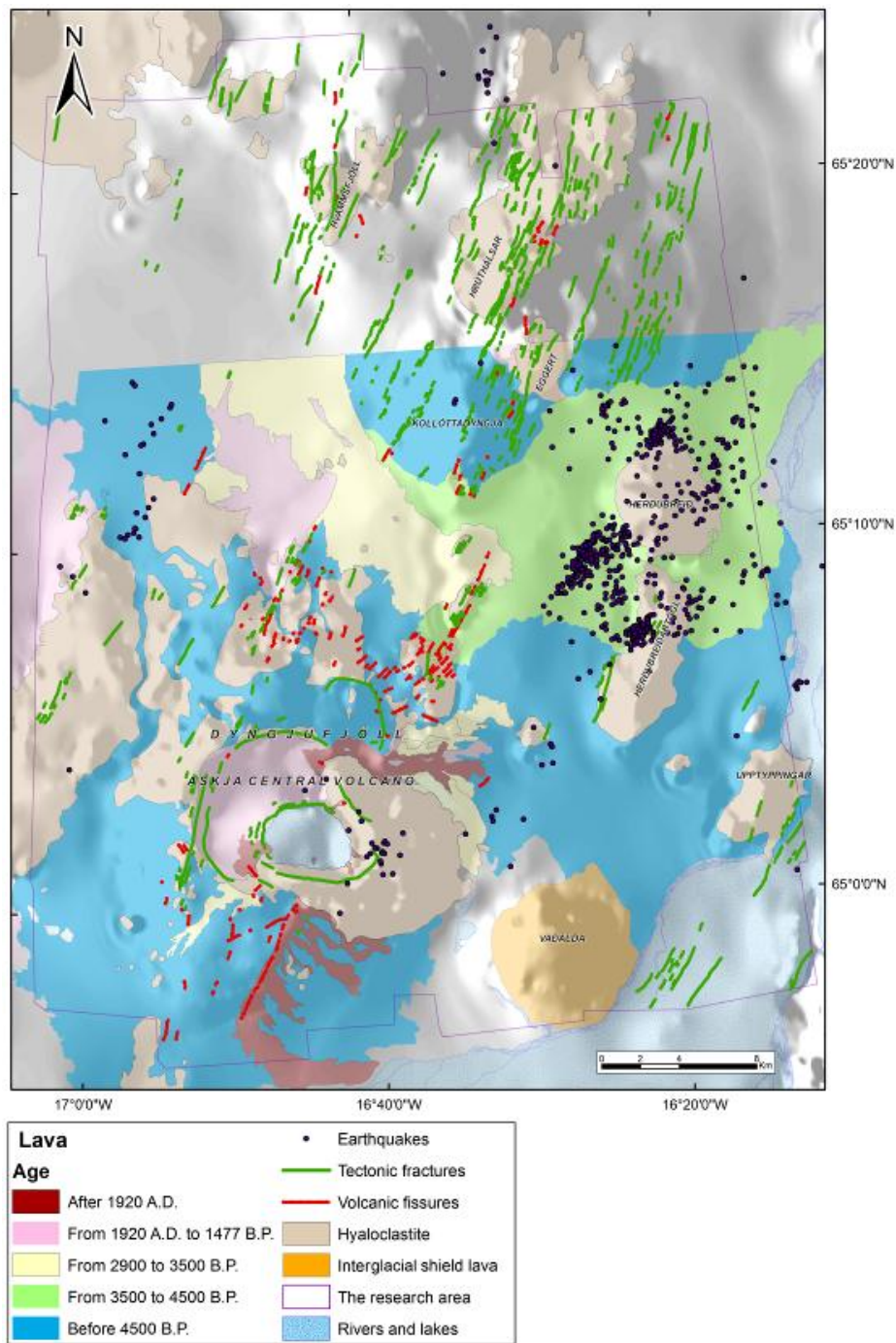


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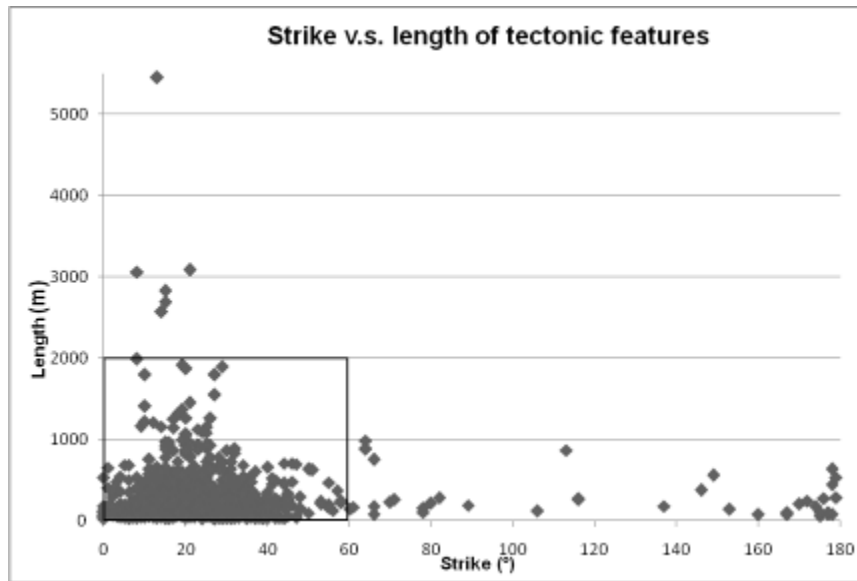


Figure 3 a

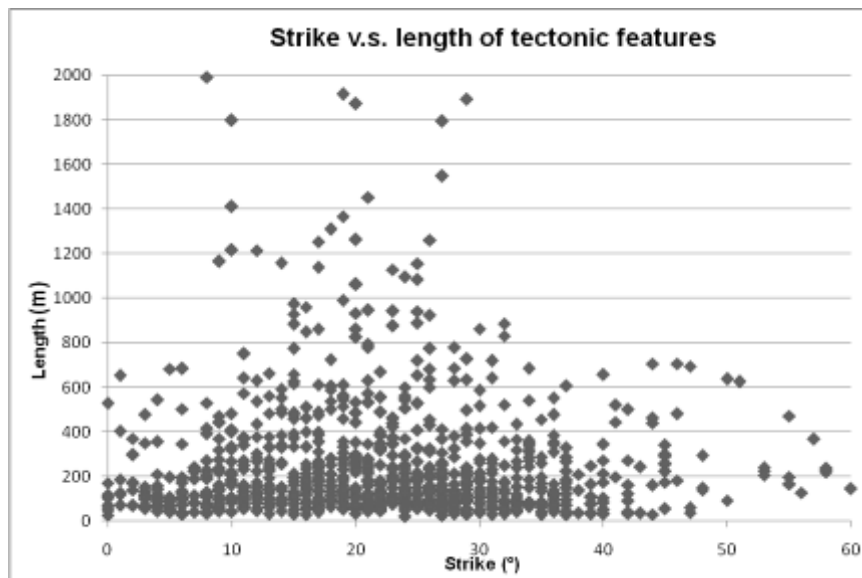


Figure 3 b

Figure 3:

a. The length (m) and strike (°) of all tectonic features in the area. b. The length and strike of fractures in the area with strike of 0-60° and length of up to 2000 m.

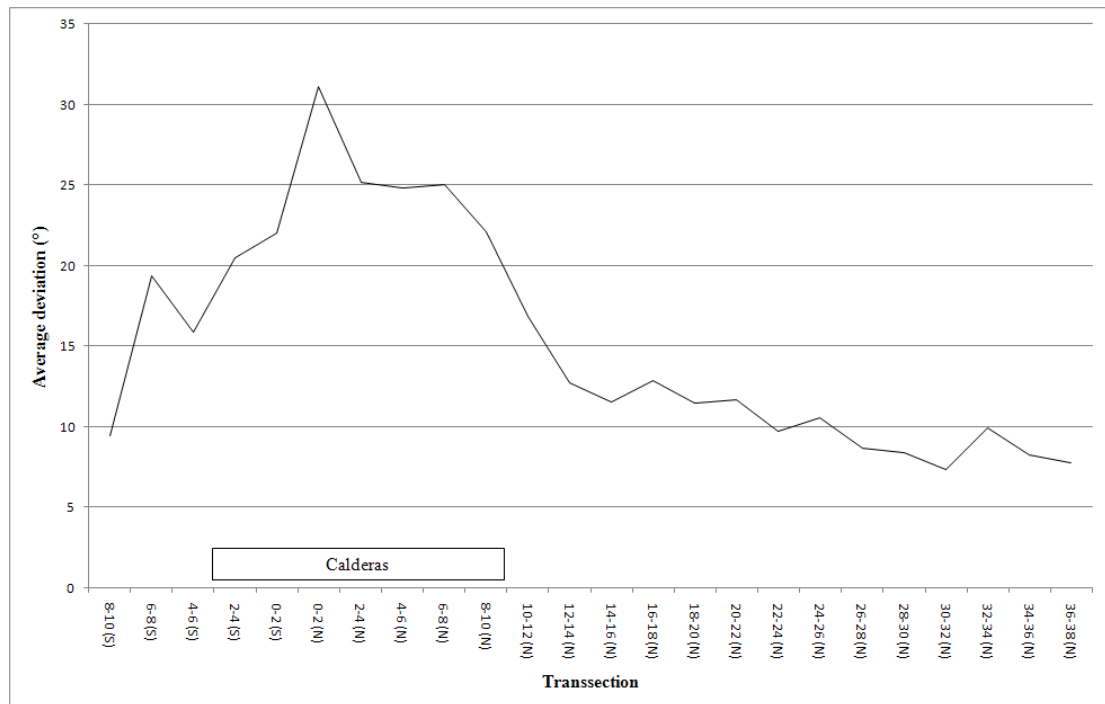


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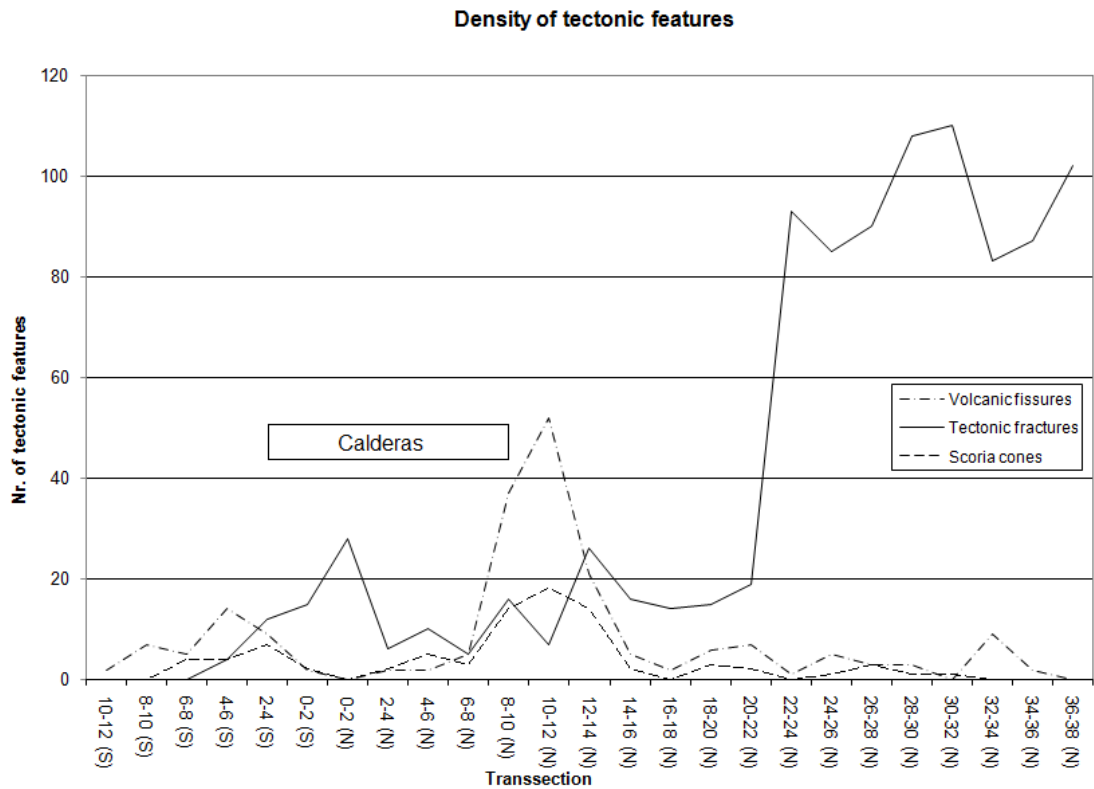


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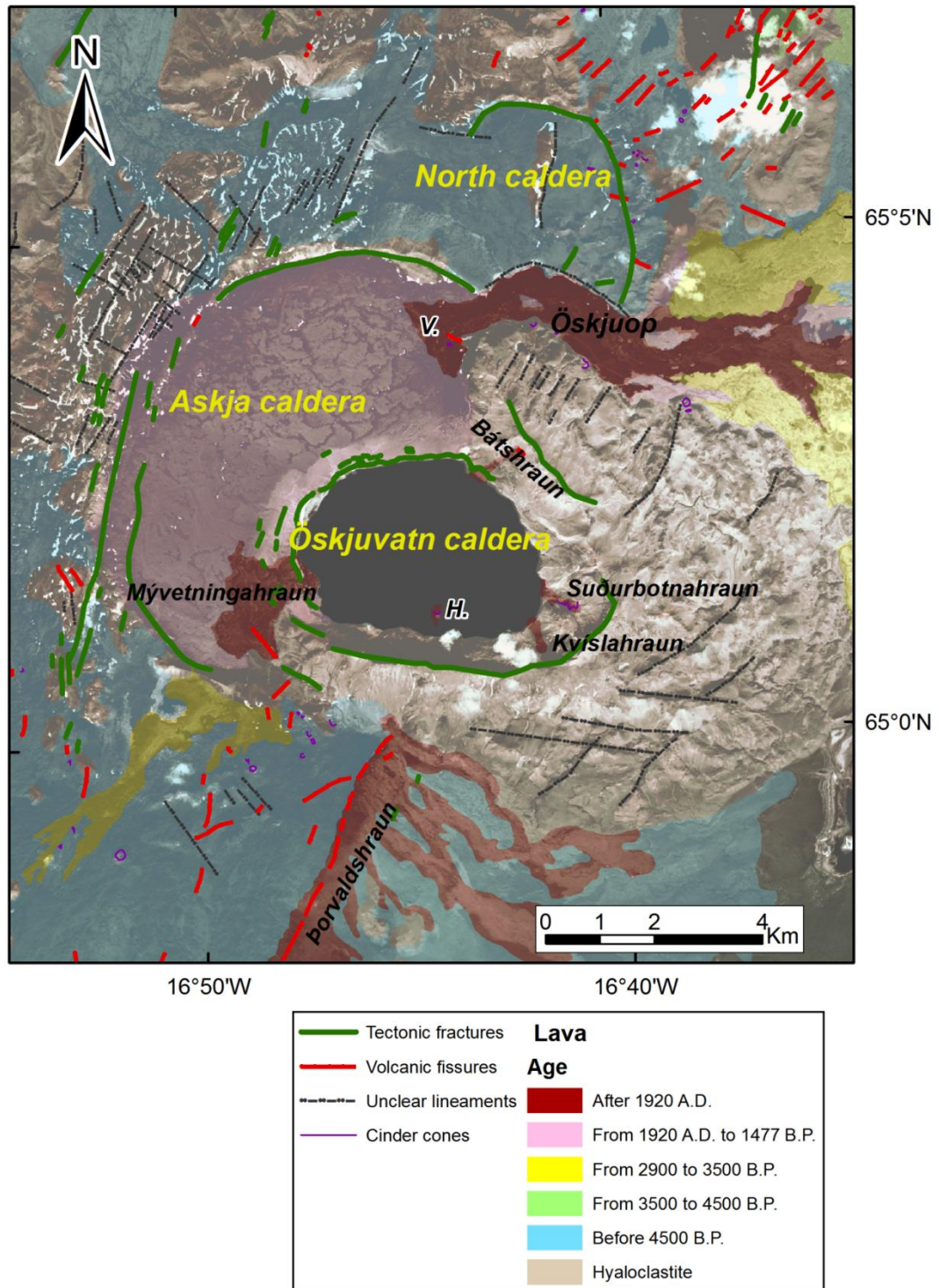


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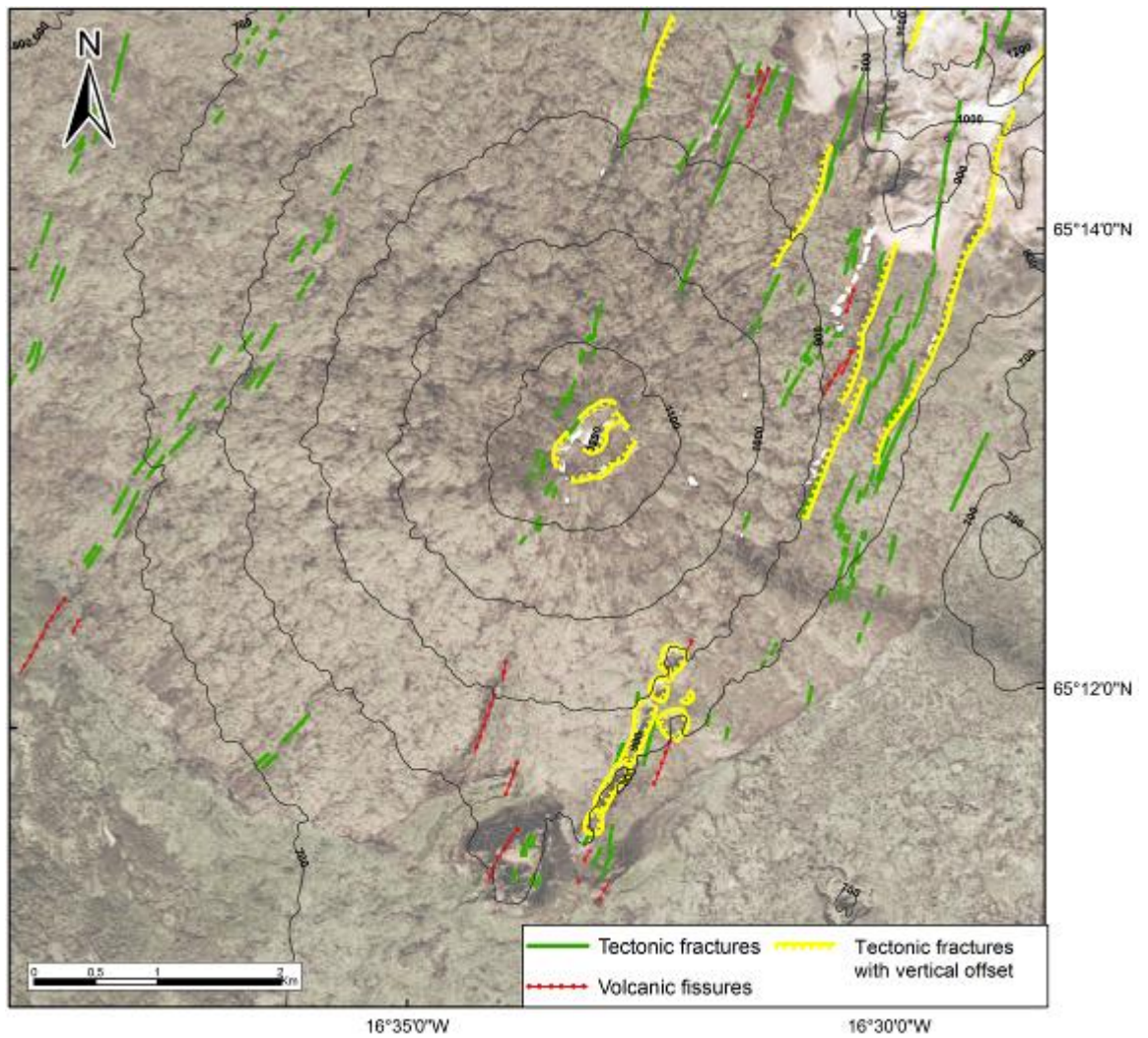


Figure 7:

Tectonic fractures (green), volcanic fissures (red) and tectonic fractures with vertical offset (yellow) in Kollóttadyngja lava shield. The background is a SPOT image of Kollóttadyngja (Spot Image©).

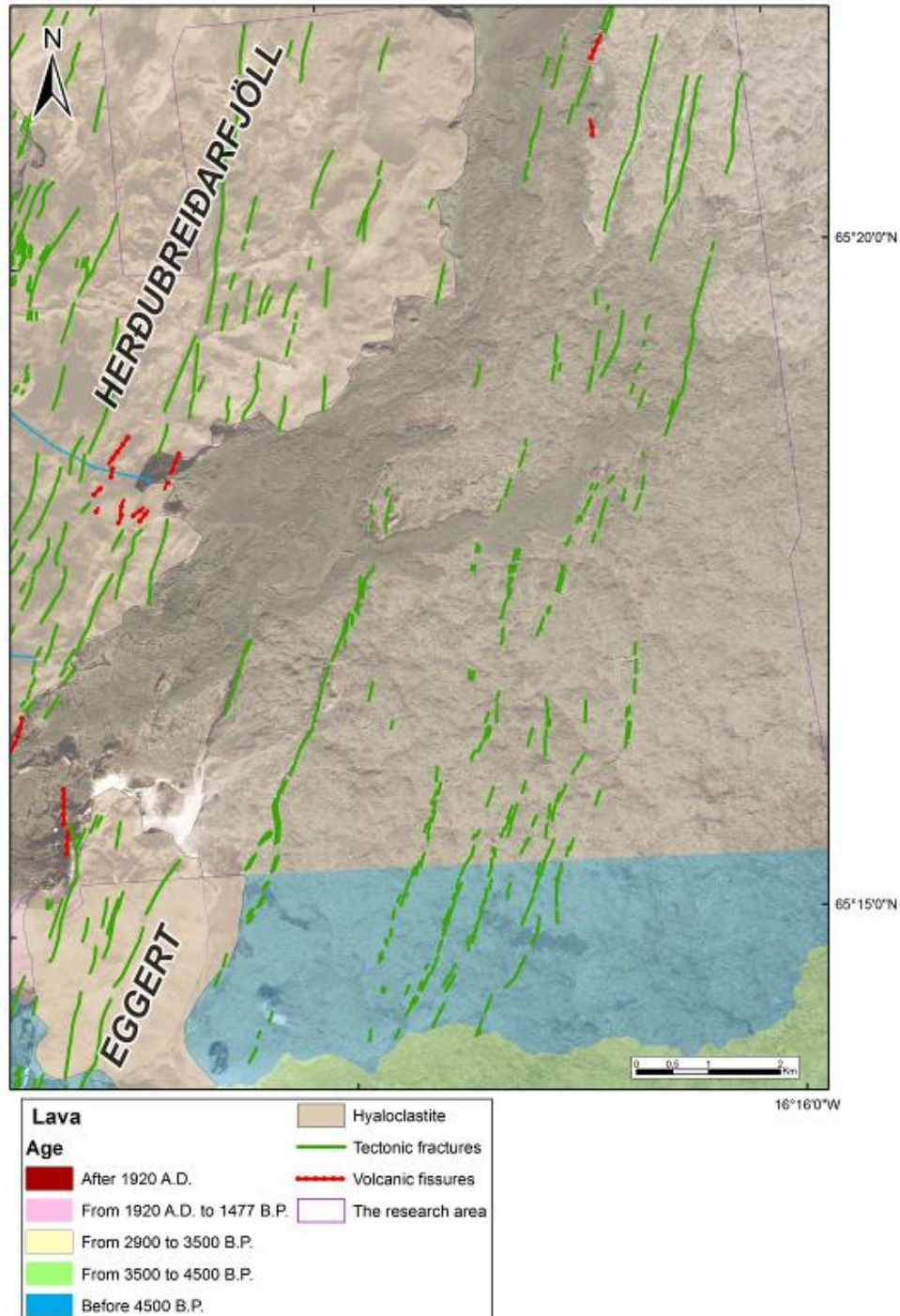


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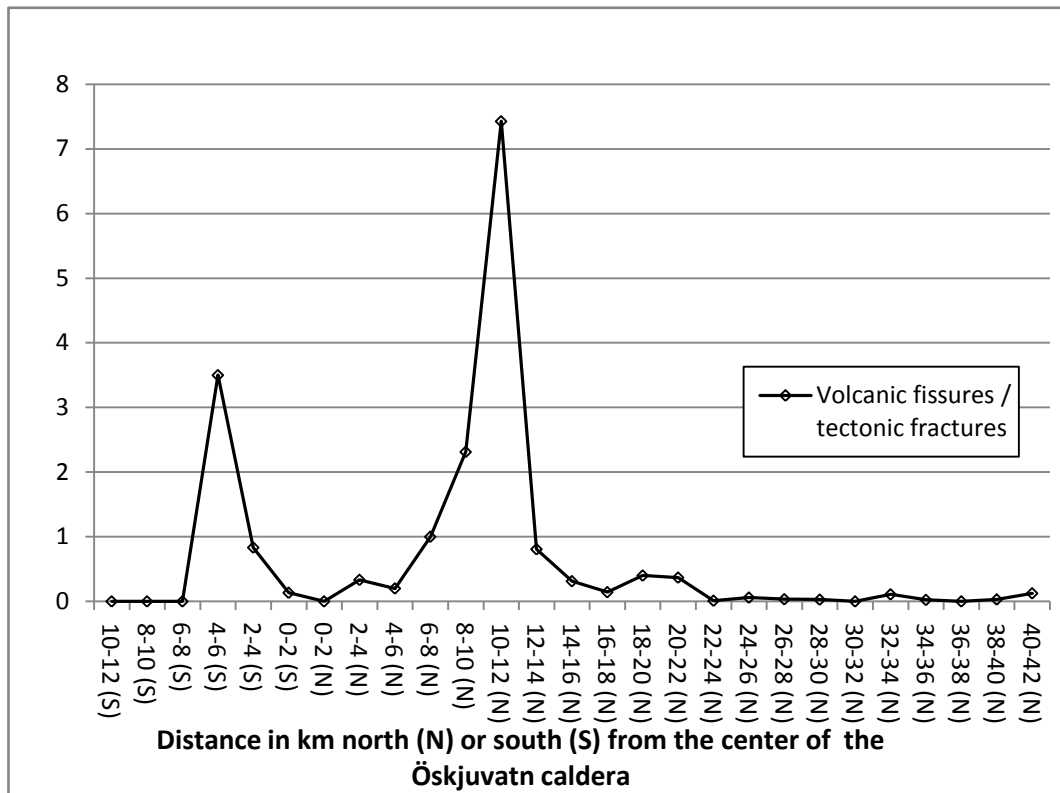


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Electronic supplementary material

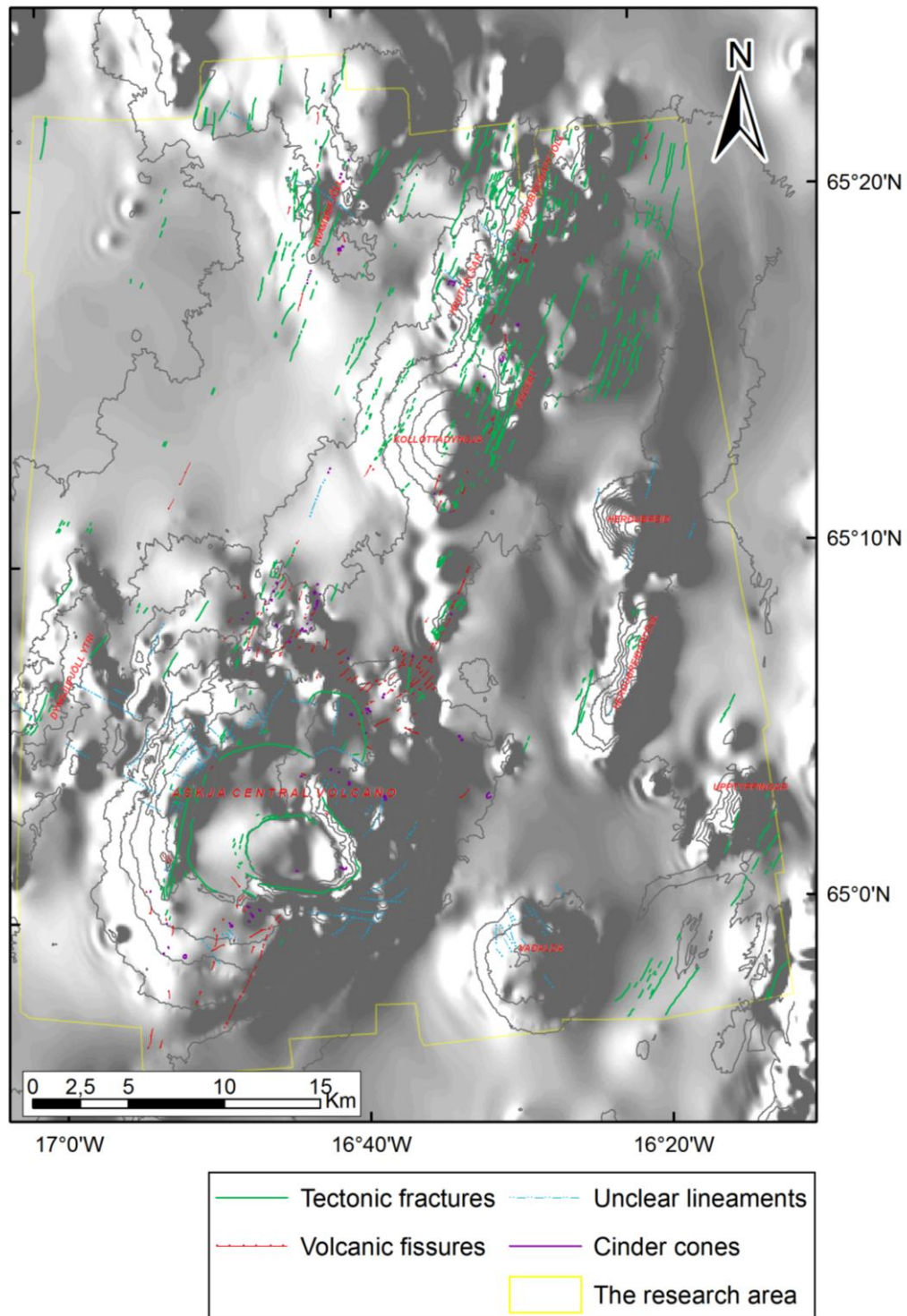


Figure S1

Volcanic fissures (red), tectonic fractures (green) and unclear lineaments (blue) mapped from aerial photographs.

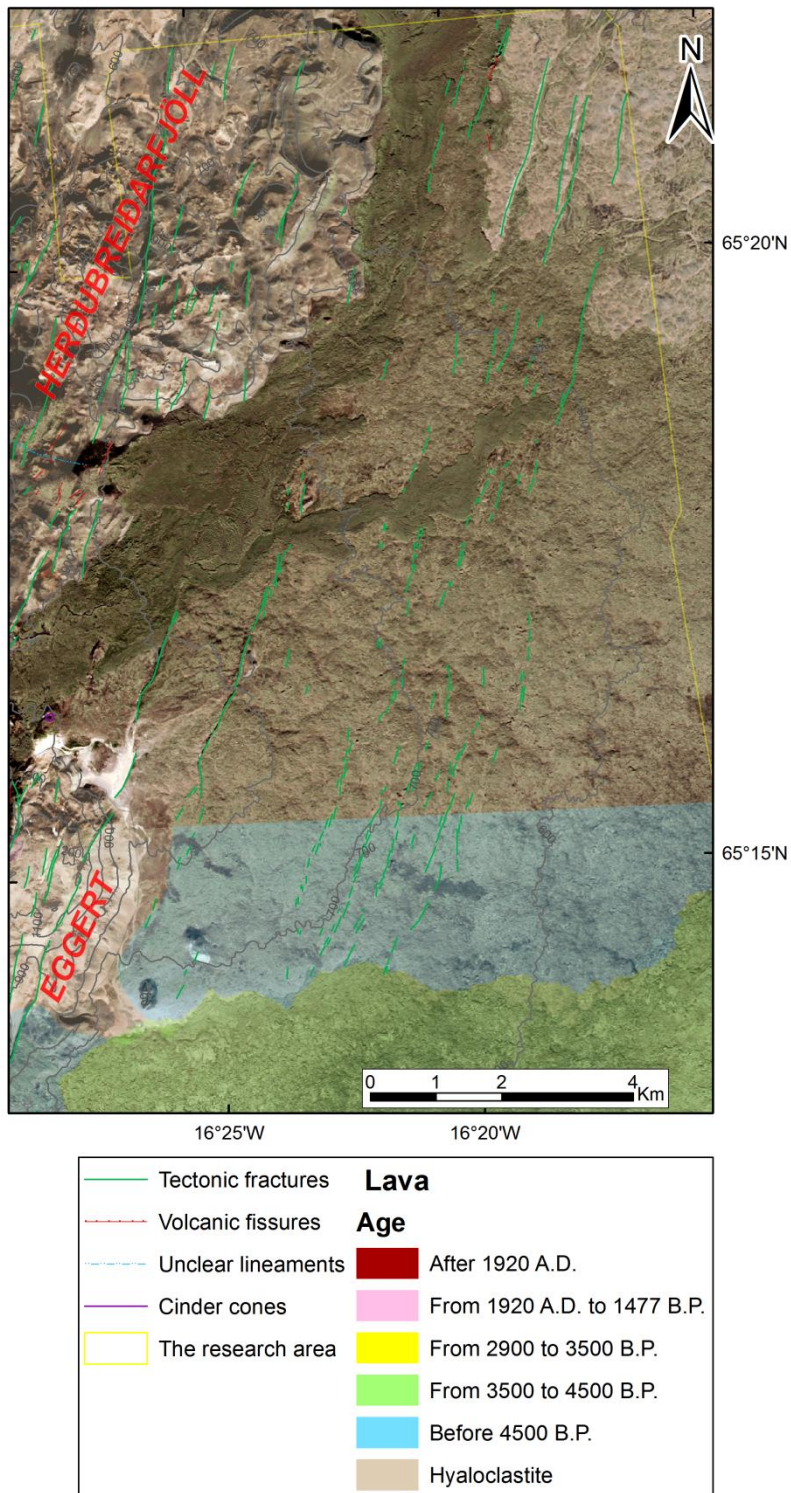


Figure S2

Tectonic fractures and volcanic fissures in the NE subswarm of the Askja fissure swarm.

Fracture	Width (m)	Northing	Easting	Altitude (m.a.s.)	Comments
1	0.5	N 529696	A 624092	626	
2	0.85	N 530018	A 623850	636	No vertical displacement.
3	0.45	N 530508	A 623499	642	No vertical displacement.
4	1.2				Fractures 4 - 7 are located in the same area
5	1				
6	0.8				
7	0.5				
8	0.5	N 530552	A 623078	681	
9	0.8	N 530541	A 622762	697	
10	0.8	N 530555	A 622730	695	Strike-slip movement 0.35 m (probably local movement)
11	1.1				Just west of fracture 10
12	0.55	N 530418	A 623784	634	
13	1.8	N 530357	A 623998	633	
Total:	10.85				

Table S1

The width of fractures (in meters) found by inspection on ground in the northeastern subswarm of the Askja fissure swarm, across a given profile. The profile is located east of Mt. Eggert and is perpendicular to the fissure swarm.

6 Paper II: The origin of the pit crater chain in Kollóttadyngja, Iceland

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6.1 Abstract

A 1.7 km long pit crater chain in the Kollóttadyngja lava shield is located in and parallel with the Askja fissure swarm. The fissure swarm forms a part of the Northern Volcanic Rift Zone, which delineates the plate boundary between the Eurasian and the North American plate in central and north Iceland. The pit crater chain consists of about five pit craters, along with another two that are located 70-200 m east of the chain. The pit craters in the southern (and lower) part of the pit crater chain are generally longer and narrower than the pit craters in the northern part of the chain, even though the amount of wall-slumping is higher in the southern pit craters. An eruptive fissure is located in direct continuation of the eastern wall of the northernmost pit crater, and another eruptive fissure is located south of the southernmost pit crater. Two faults, dipping 60-70°, can also be found in the southern wall of the southernmost pit crater. We suggest that the pit crater chain was formed during or after a rifting event, when magma intruded fractures to form a dike, and caused eruption near the later formed pit crater chain. We suggest that during most of the time the eruption lasted, the driving pressure of the magma was only sufficient to drive the magma towards the lower slopes of Kollóttadyngja, where the southern eruptive fissure had opened. The topography of Kollóttadyngja, reinforced by the low pressure regime close to the eruption, caused a horizontal magma flow in the dike towards the eruptive site, probably only tens of meters beneath the later formed pit crater chain. As the eruption was prolonged, this horizontal magma flow widened this part of the dike and eventually led to the formation of a magma conduit. When the magma pressure dropped at the end of the eruption, the roof above the conduit collapsed, forming the pit crater chain.

6.2 Introduction

The ~1.7 km long pit crater chain in southeastern Kollóttadyngja lava shield consists of approximately five pit craters, up to 150 m in width and approximately 50 m in depth. Two pit craters are also located few tens of meters east of the chain (Figures 1, 2 and 3).

The pit crater chain is aligned 20 km north of the Askja central volcano, and forms a part of the Askja fissure swarm, as it is situated in and parallel with the

fissure swarm. The northern part of this fissure swarm extends northward from Askja, crosses the Kollóttadyngja lava shield and the nearby area, and continues to at least a 100 km distance north of the lava shield. The existence of the pit crater chain can therefore give important information on the subsurface magmatic plumbing system along the fissure swarm.

Although pit crater chains are uncommon in the fissure swarms of Icelandic central volcanoes, examples can be found in other areas than Kollóttadyngja. Pit crater chains have as an example been found in the fissure swarms of Kilauea, Hawaii, but there the individual pit craters are often circular, as opposed to the sharp-edged pit craters commonly seen in the pit crater chain in the Kollóttadyngja lava shield. In Kilauea, the formation of the pit craters has been attributed either to the supposed existence of a subsurface magma conduit, or to stoping above a magma-filled fracture. Walker (1988) suggested that a wide and well-established horizontal magma conduit that can possibly be a wide dike or a widened portion of a dike exists under the Chain of Craters in Kilauea's East Rift Zone. According to Walker's (1988) theory, there is occasionally a local collapse of the conduit roof. The debris is then carried away by magma flowing in this magma conduit, creating an underground vault. As this process occurs repeatedly, the conduit roof gets thinner. Finally, the roof is so thin that the vault breaks through the surface, forming a pit crater which is then widened by collapses of its walls (Walker, 1988). Several authors have proposed that pit craters form due to stoping above a magma-filled fracture (e.g. Stearns and Clark, 1930; Okubo and Martel, 1998). To explain how such a large quantity of material can collapse through narrow dikes, like most dikes in Hawaii which are 1 m or less in width (Walker, 1987), Okubo and Martel (1998) suggested that a magma flow in the dike evacuates the debris, and widens the walls of the dike by thermal and mechanical erosion.

Two conceptual models have been proposed to explain the formation of the pit crater chain in Kollóttadyngja. Geirsson (1989) imagined the pit crater chain formation in Kollóttadyngja as follows: the eruption in Kollóttadyngja had recently finished when a rifting event took place in the area. As only the outer crust of Kollóttadyngja had fully solidified, it rifted more easily than it else would have. Therefore, large fissures, the pit craters in SE Kollóttadyngja, were formed that opened a gateway for the magma. Jónsson (1945) suggested that the pit crater chain in SE Kollóttadyngja lava shield was formed during eruption which led to the

formation of the lava shield itself. According to Jónsson's (1945) suggestion, this might have occurred as magma from a vertical magma conduit under the center of Kollóttadyngja flowed into fractures in SE Kollóttadyngja, eventually leading to the formation of the pit crater chain as the roof above the propagating dike collapsed.

The pit craters were mapped from an aerial photograph from Landmælingar Íslands (National Land Survey of Iceland). The aerial photograph is taken at approximately 6000 m altitude in August 1987. The aerial photograph was rectified with the aid of the ArcInfo software for locating the pit craters. A field trip was made to the pit craters to estimate the depth of the pit craters and to have a closer look at their characteristics. Their width and length was measured from the rectified aerial photographs.

We conclude that the pit craters are formed during or after a rifting event in the fissure swarm, possibly originated from the Askja central volcano. The different overburden pressures under the Kollóttadyngja lava shield due to the mass of the lava shield, along with a low pressure regime due to an eruption south of the later formed pit crater chain, caused a horizontal component in the magma flow and led to concentration of the magma flow along the top of the dike. This led to an increased velocity in the magma at the top of the dike, which lowered the pressure there, due to the Bernoulli Effect, which in turn led to an even more concentration of magma at the top of the dike. Eventually a magma conduit was formed at the top of the dike, due to melt erosion.

6.3 Definition of terms

Collapse structures formed by magmatic activities can have various forms and sizes. Calderas and pit craters at the top of basaltic shield volcanoes and basaltic to intermediate stratovolcanoes are common (Geshi et al. 2002), but pit craters do also form in volcanic rift zones (Walker, 1988). Pit craters often bear similar characteristics as calderas, but are considerably smaller (Walker, 1993). They are circular to elliptical depressions, without elevated crater rim that have overhanging or steeply dipping walls. The floors of the pit craters are partially or totally covered by talus due to the instability of the walls (Roche et al. 2001; Wyrick et al. 2004).

6.4 The research area

The monogenetic Kollóttadyngja lava shield has an altitude of 1180 m.a.s. and rises 400-500 m above its surroundings. It is older than 4500 B.P. (Sigvaldason et al., 1992), but since its surface has not been eroded by glacier, it can be inferred that it is younger than 10,000 B.P, when the last glaciation ended. Sigvaldason et al., (1992) also mapped fissure lavas, originated from volcanic fissures close to the pit crater chain.

Kollóttadyngja is located within the Northern Volcanic Zone (NVZ) in the northern part of Iceland, which is the plate boundary between the North American Plate and the Eurasian Plate. The NVZ consists of several central volcanoes and their associated fissure swarms. Kollóttadyngja is situated within the fissure swarm of the Askja central volcano, although it is not necessarily related to Askja. The characteristics of this fissure swarm depend in various aspects on the distance from the Askja central volcano itself (Hjartardóttir et al., submitted 2008). As an example, the amount of volcanic fissures is highest close to the volcano, but has decreased significantly at the northerly latitude where Kollóttadyngja is located. However, there is a 4-5 fold increase in the amount of tectonic fractures in Kollóttadyngja compared with areas in and close to Askja central volcano itself. Partly this can be explained by the age of the fractured lava flows, as older lava flows are generally more fractured than their younger counterparts. However, this increase in fracture density in Kollóttadyngja cannot be solely attributed to the age of the lava flows. As an example, a 3500-4500 BP lava flow, located directly south of Kollóttadyngja is unfractured, despite its age. The strike of the fissures and fractures also depends on distance from the Askja central volcano. Close to the central volcano, the strike varies greatly, and the deviation from the strike perpendicular to the plate velocity vector is high. This deviation decreases as distance from Askja increases, but is still observable 40 km north of Askja. Due to this deviation, Hjartardóttir et al., (submitted 2008) concluded that the Hreppar microplate might affect the strike of the fissures and fractures in the area. It is therefore clear that the fissures and fractures in and close to Kollóttadyngja are not perpendicular to the strike of the plate spreading vector, as they should be if the plate spreading of the North American Plate and the Eurasian Plate were the only parameters that control the strike of the fissures and fractures in this area. According to Hjartardóttir et al., (submitted 2008), the width and length of tectonic fractures in Kollóttadyngja depend strongly on altitude. Large

faults are located at the lower slopes of Kollóttadyngja, which have the elevation of 700-900 m.a.s. The few fractures that are located in the upper slopes, 900-1200 m.a.s., are, at the other hand, very small and narrow. They suggest that this might occur as the depth to the top of the dike is likely to depend on topography. The top of the dikes should then be stored deeper under the center of Kollóttadyngja than below the slopes of it. As surface fracturing is likely to depend on the depth to the top of the dike, fracturing should be less in the upper slopes of Kollóttadyngja than in the lower slopes of it.

6.5 Results

Five out of the seven pit craters in southeastern Kollóttadyngja form an approximately ~1.7 km long pit crater chain. The other two are located only about 70 –200 m east of the pit crater chain. Approximately 400 and 550 m SSE of the pit crater chain there are also two circular holes in the ground that can possibly be a part of the pit crater chain formation. The pit craters are of different lengths, widths and depths, even the pit craters that are located within the pit crater chain.

The pit craters in the southern part of the pit crater chain are approximately three times longer than the ones in the northern part. The southernmost pit crater is however split into two parts, but the section between them has collapsed, so it is considered to be one pit crater. In the northern part of the pit crater chain are two 140 and 200 m long pit craters, with one small pit crater between them. The section in which the small pit crater is located, the one which separates the two square pit craters, has had a vertical displacement (Figure 4), but contrary to the section in the southernmost pit crater, it has not collapsed. To the east, the triangular-shaped pit crater is much larger, approximately 230 m long, than the little 70 m long pit crater north of it. Generally, the pit craters in the southern part of the pit crater chain are therefore longer than the ones in the northern part.

The pit craters in the northern part of the pit crater chain are however not only shorter than the pit craters in the southern part, they are also generally wider, even though the amount of wall slumping is much higher in the pit craters in the southern part. The lithology is, however, not the same in the pit craters. In the southernmost pit crater, a hyaloclastite is located at shallow levels under the shield lava (Figure 3), while the shield lava in the northernmost pit crater is a much thicker formation, with

no visible hyaloclastite (Figure 4). This indicates that the depth to the hyaloclastite increases from south to north in the pit crater chain, possibly leading to higher amounts of wall slumping in the southernmost pit craters, compared with the pit craters farther north. As an example of how the widths of the pit craters changes from north to south, the northernmost pit crater is about 150 m wide, while the southernmost pit crater is about 80-110 m wide. The widest pit crater is however the triangular shaped pit crater east of the pit crater chain. It has a maximum width of about 220 m, measured perpendicularly to the fissure swarm. The little pit crater north of it is, however, not wide, probably only about 50 m, although it is so shallow that it is hard to see it clearly on the aerial photograph. There seems therefore to be a tendency towards narrower pit craters in the southern part of the pit crater chain, where the elevation is lower, compared with the wider pit craters in the higher northern part.

It is clear that the pit craters in the pit crater chain are generally deeper than the two pit craters to the east of it. Most of the pit craters in the pit crater chain are about 20-50 m deep, the exception being the little pit crater between the two square pit craters in the northern part, which is shallow. The two pit craters in the eastern part are also shallow although the triangular-shaped one is considerably deeper than the little pit crater north of it. There is therefore a clear difference in depth between most of the pit craters in the pit crater chain and the pit craters east of it, as the pit craters in the pit crater chain are deeper than the pit craters east of the pit crater chain.

The amount of wall slumping is variable in different pit craters. The two southernmost pit craters exhibit the highest amount of wall slumping of all the pit craters in southeastern Kollóttadyngja. There, the pit craters are U-shaped due to the slumping, whereas the two square pit craters in the northernmost part of the pit crater chain have vertical walls and a low amount of wall slumping. In the wall of the southernmost pit crater, the shield lava is thin and the underlying hyaloclastite can be seen (Figure 3). The hyaloclastite might possibly cause the high amount of wall slumping in the southernmost pit craters, compared with the wall slumping in the pit craters located farther towards north, as discussed previously in this chapter.

Most of the pit craters in southeastern Kollóttadyngja are nearly or completely sharp-edged. Note in particular the two almost square pit craters, at the northern part of the pit crater chain. The corners of the two long pit craters in the southern part of the chain are more rounded although they have an elongated box-shape. This

rounded shape may be due to wall slumping in the southernmost pit craters. Not all the pit craters are box-shaped, however. The large pit crater east of the chain is triangular-shaped, and the pit crater north of it is oval, similarly as the little pit crater between the two square pit craters in the northern part of the chain. Overall, all the four large pit craters in the chain are box-shaped, which differs from the pit crater chains in Kilauea, Hawaii, where the pit craters are usually circular.

Fractures and faults in and close to the pit craters testify to the movements that have occurred during the formation of them. There are in fact few tectonic fractures or faults in the southeastern Kollóttadyngja, where the pit craters are located, compared with the high density of fractures and faults in the northeastern part of Kollóttadyngja (Figure 1). Most of the fractures and faults found in southeastern Kollóttadyngja are located close to the walls of the two southernmost pit craters. The southern wall of the southernmost pit crater has in fact a cross-section of normal faults dipping 60-70°, where the vertical movement has been about 3 m down to the east (Figure 5). A cross-section of a fault is also found in the southern wall of the northernmost pit crater (Figure 4). In addition to these fractures and faults, unclear pair of lines extends north from the northernmost pit crater, parallel with the strike of the western and eastern wall of it. The eastern line is in fact a volcanic fissure. A similar pattern is also observed SSW from the triangular-shaped pit crater east of the pit crater chain (Figure 2), where the eastern line is also a volcanic fissure. Unfortunately, chemical analyses have not been made on the materials from these volcanic fissures. The pit craters seem therefore to be associated with most of the tectonic fractures and faults located in southeastern Kollóttadyngja.

In southern Kollóttadyngja, about eight volcanic fissures can be found in a ~1.5 km wide area (Figure 1). Four of them are located close to the pit craters. Volcanic fissures are located both directly north of the northernmost pit crater in the pit crater chain, and south of the pit crater chain. The volcanic fissure at the northern part lays NNE from the northernmost pit crater, in direct continuation from its eastern wall. The volcanic fissure south of the pit crater chain is aligned with the chain but at a distance of 140 m from the southernmost pit. It is also notable that a small amount of scoria can be found along the sides of the pit craters in the chain. The triangular-shaped pit crater east of the pit crater chain is also intersected by a volcanic fissure. The volcanic fissure is rather long, about 350 m, and has formed a lava pond in the pit crater itself. It is unclear whether the lava flowed into the pit crater or if it

originated in the pit crater itself. A cluster of volcanic fissures is located at the northeastern side of Kollóttadyngja, in direct continuation of the pit crater chain (Figure 1). The distance between the pit crater chain and this cluster is about 2.5 km. In that area several large westward dipping faults are found, indicating subsidence in the area where the volcanic fissures are located. There seems therefore to have been high volcanic activity close to and in the pit craters, as well as in the direct continuation of the pit craters, in the northeastern part of Kollóttadyngja.

6.6 Discussion

The fact that the pit crater chain is located in and parallel with the Askja fissure swarm, and that there is a volcanic fissure extending north from the northernmost pit crater, indicates a relationship between the fissure swarm and the pit crater chain. This relationship is further reinforced by the fact that there is a 4 km wide graben in the northern part of Kollóttadyngja, just NNE of the pit crater chain. This indicates that the pit crater chain was formed in or after a rifting event, probably originated from Askja central volcano, when one or more dikes were intruded under Kollóttadyngja.

Viewing maps in Hjartardóttir et al. (submitted 2008), it can be observed that volcanic fissures are often located in the lower slopes of mountains and lava shields, but usually not located in the upper slopes of these features. This might indicate that the magma driving pressure has not been sufficient to drive the magma to the surface of the upper slopes in these areas, while it has been sufficient to drive it to the surface of the lower slopes of the topographic highs. Sigvaldason (1992) noted a similar phenomenon, located just SW of the research area of Hjartardóttir et al. (submitted 2008), in the Dyngjufjöll ytri ridge. A volcanic fissure, located south of the ridge, has the same strike as the ridge, and ends at its southern slope. Cylindrical gas pipes, up to 9 m in diameter, are, however, found on top of the southern part of the ridge. Sigvaldason (1992), points out evidences for his suggestion that the cylindrical gas pipes were formed as the volcanic fissure continued as an intrusion under the ridge, converting water in gas pipes into a high-pressure steam that exploded through the overlying unconsolidated formations (Sigvaldason, 1992).

If the magma continues as an intrusion under a mountain, but has not enough driving pressure to continue to the surface, as in the lower slopes or beside the

mountain, we consider it unlikely that the magma in the dike is stationary under the mountain. Instead, we suggest that the magma flow in this part of the dike might have a horizontal component, both due to the topography of the mountain, and also as it should be drawn towards the low pressure regime where the eruption is located. This might lead to an increased flow of magma in the uppermost part of the dike under the mountain, leading to a higher magma velocity, which would in turn lead to a lower magma pressure there (due to the Bernoulli effect). This would cause even more magma to be drawn to the upper part of the dike, under the mountain, which, if the eruption is prolonged, might lead to the formation of a subsurface horizontal pipe beneath the mountain (Figure 6). If the roof above the pipe is not strong enough, it might collapse, when the pressure drops at the end of the eruption, forming a chain of pit craters.

In SE Kollóttadyngja, where the pit craters are located, most of the eruptive activity seems to have taken place at the lower or middle slopes of the lava shield. As a small amount of scoria has been erupted from the northernmost pit crater, it can be inferred that a dike was situated beneath it, and we consider that the same dike extended southwards, beneath the later formed pit crater chain, and to the volcanic fissure located south of the pit crater chain. We suggest that the topography of Kollóttadyngja and an eruption in the lower slopes of Kollóttadyngja caused a horizontal component in the magma flow in the uppermost part of a dike under the later formed pit crater chain. In a similar manner as described previously, this led to the formation of the pit crater chain.

This explains why the pit craters are located in the slopes of Kollóttadyngja, their orientation along the fissure swarm, as well as the excessive width of the underlying cavity that made the formation of the pit crater chain possible, compared with normal widths of dikes in Iceland. A less magma flow in the northeastern part of the dike might explain why there are no pit craters in NE Kollóttadyngja.

For a process like this to occur, there need to be special circumstances. The dike intrusion needs to be long-lasting, as it takes time for a magma conduit to form, and a fissure swarm has to cross a slope, like those of lava shields, to cause the horizontal component in the magma flow.

Compared with other conceptual models on the formation of pit crater chains, ours contrasts with the other ones mainly by the fact that we take the influence of surface elevation into account. We agree with Geirsson (1989) that the pit craters in

Kollóttadyngja were formed in a rifting episode, but contrary to Geirsson's (1989) model, our model does not assume that the pit craters were large fissures, as the vertical walls of the pit craters indicate a collapse, and there is only a small amount of scoria beside the pit craters. Considering Jónsson's (1945) model, that the pit craters were probably formed when magma flowed horizontally from a vertical magma conduit into fractures in SSE Kollóttadyngja, we consider it possible that magma flowing horizontally underground in the lava shield might have flowed into a pre-existing fracture in the ground, widened it and formed a subsurface lava tube. However, Jónsson's (1945) model suggests that this occurred at the same time as the Kollóttadyngja lava shield was formed, but a thick part of the crust of Kollóttadyngja must have been solidified when the pit craters were formed, as the walls of the northernmost pit craters are nearly vertical. If the pit craters were formed by the eruption that formed Kollóttadyngja itself, the pit craters should also have been solely formed in the newly formed Kollóttadyngja lava flow. It can, however, be observed from Figure 3, that the southernmost pit crater is also formed in a hyaloclastite. This does not indicate a pit crater formation in an ongoing shield lava flow eruption.

The pit crater chains found in Hawaii might possibly be of similar origin as the one found in Kollóttadyngja, although their origins might also differ. In Hawaii, the pit crater chains are sometimes not parallel with the orientation of fissures and fractures in the same area, like in the Upper East Rift Zone in Kilauea (see map in Okubo and Martel, 1998), as the pit crater chain in Kollóttadyngja is. This might possibly explain why the pit craters in Kollóttadyngja are often sharp-edged, contrary to the commonly ring-shaped pit craters in the pit crater chains of Hawaii. We agree with Walker (1988), that a collapse of a magma conduit might form a pit crater chain. Walker (1988) does however not take the effect of topography into account, as we do. Models that consider pit craters to be formed due to stoping above magma-filled fractures (e.g. Stearns and Clark, 1930; Okubo and Martel, 1998), can explain the shape of the pit craters in Kollóttadyngja, and the fact that there is little vertical movement just north of the pit crater chain. However, we consider it unlikely that the subsurface magma flow in a regular 1-10 m wide dike was capable of transferring the high amount of material necessary to form the pit crater chain of Kollóttadyngja. A wider magma conduit, formed at the uppermost part of the dike

due to the topography of Kollóttadyngja like we suggest, might, however, be capable of transferring this amount of material.

6.7 Conclusions

The ~1.7 km long pit crater chain in Kollóttadyngja is located in and parallel with the fissure swarm of the Askja central volcano. There are several volcanic fissures belonging to this fissure swarm close to the pit crater chain in Kollóttadyngja. Volcanic fissures are located both directly north from the northernmost pit crater as well as south of the southernmost pit crater. Approximately 2.5 km north of the pit crater chain, in direct continuation of the chain, is also an area with several volcanic fissures. The individual pit craters in the pit crater chain show different characteristics. The pit craters located in the upper northern part are shorter and wider than the pit craters in the lower southern part, despite the fact that the amount of wall slumping is higher in the southern part. Even though the pit crater chain in Kollóttadyngja shows similar characteristics as the pit crater chains in Kilauea, Hawaii, there is a difference in the shape of the pit craters. The pit craters in Kollóttadyngja are generally box-shaped, as opposed to the circular pit craters in Kilauea, Hawaii.

We suggest that the topography and mass of Kollóttadyngja caused a horizontal component in the magma flow of a dike under Kollóttadyngja. As the pressure is higher under the center of Kollóttadyngja than under the flanks of it, due to the overburden mass, the magma flow can bend away from the area of maximum pressure. This leads to a horizontal component in the magma flow, which would increase the magma flow in the uppermost part of the dike, below the lower slopes of Kollóttadyngja. A low-pressure regime due to an eruption south of the pit crater chain might also have reinforced this process. The increase in magma flow also increases the velocity of the magma in this part of the dike, which leads to lower pressure there, due to the Bernoulli Effect. This in turn draws even more magma from other parts of the dike into this part, and eventually a pipe is formed by thermal erosion. When the magma supply ceases, this pipe empties, leaving a large void. Eventually, the roof above the void collapses, forming the pit crater chain in Kollóttadyngja.

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6.9 Figure captions

Figure 1

Iceland and the Kollóttadyngja lava shield (in the extended frame). The data on the location of the fissure swarms (yellow areas) and central volcanoes (red circles) is from Einarsson and Sæmundsson (1987). Askja central volcano is the central volcano south of Kollóttadyngja. The data on the tectonic fractures, volcanic fissures and tectonic fractures with vertical offset is from Hjartardóttir et al., (submitted 2008). The SPOT image of Kollóttadyngja is from Spot Image©. The frame in the southern part of Kollóttadyngja indicates the location of Figure 2.

Figure 2

The pit crater chain in SE Kollóttadyngja, along with the volcanic fissures in the area (see Figure 1 for location). The Mt. Bræðrafell is located in the SW part of the figure. The aerial photograph is from Landmælingar Íslands (The National Land Survey of Iceland).

Figure 3

The pit crater chain in SE Kollóttadyngja. The picture is taken toward north from the southernmost end of the pit crater chain. The contact between the shield lava and the underlying hyaloclastite can be seen in the right wall. One of the authors of this article, Páll Einarsson (with a red rucksack) can be seen to the left of the pit craters.

Figure 4

A vertical fault located in the northernmost pit crater. This fault indicates a subsidence in the section that divides this pit crater and the box-shaped pit crater south of it. In this middle section is also a small pit crater.

Figure 5

The two faults located in the southern wall of the southernmost pit crater.

Figure 6

Our suggestion on how the pit crater chain in Kollóttadyngja was formed. This image is a cross-section through Kollóttadyngja, from south (S) to north (N). The arrows indicate the flow of magma in a dike into a channel (under southern Kollóttadyngja), that later collapsed and formed the pit crater chain.

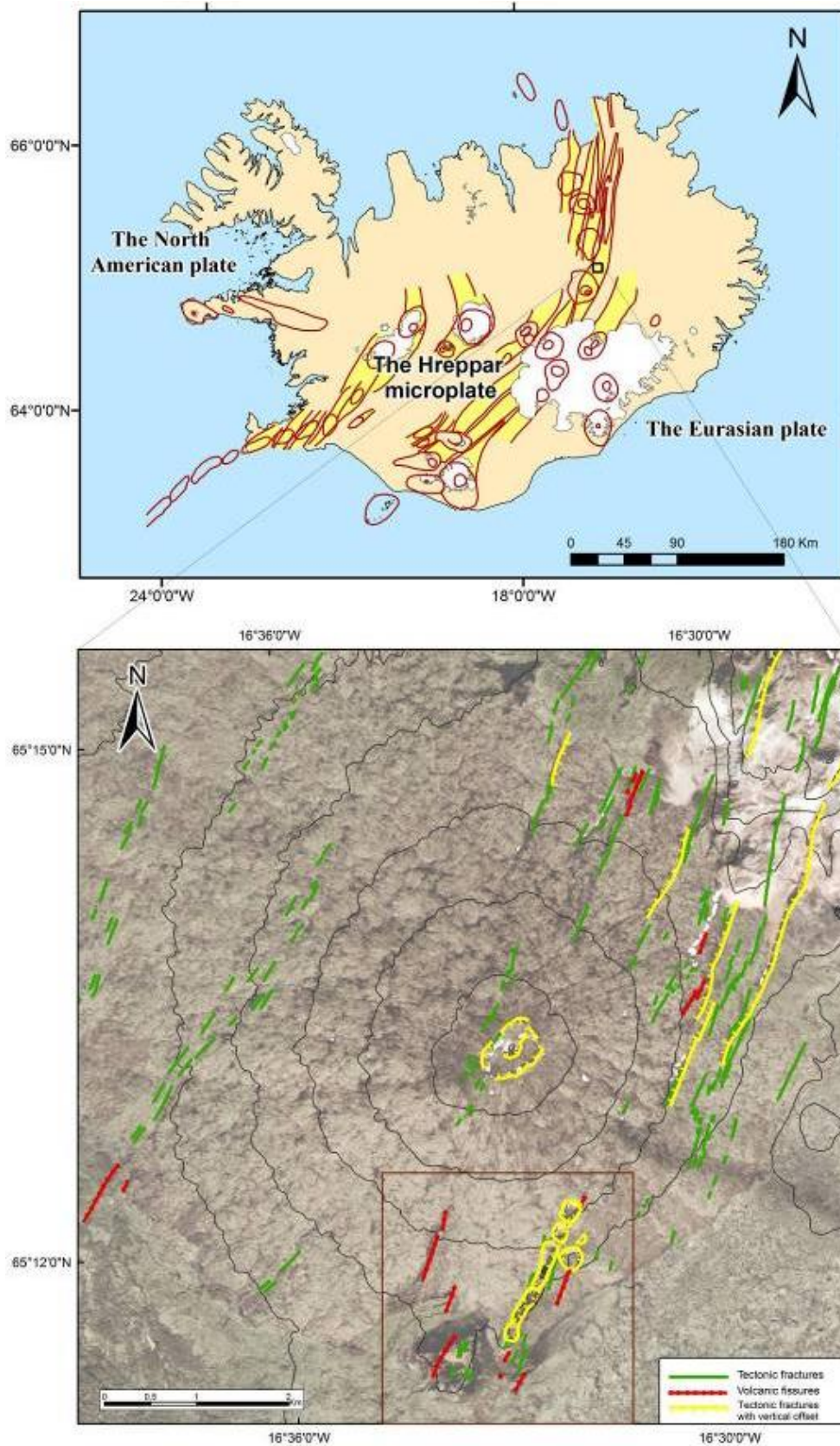


Figure 1

Iceland and the Kollóttadyngja lava shield (in the extended frame). The data on the location of the fissure swarms (yellow areas) and central volcanoes (red circles) is

from Einarsson and Sæmundsson (1987). Askja central volcano is the central volcano south of Kollóttadyngja. The data on the tectonic fractures, volcanic fissures and tectonic fractures with vertical offset is from Hjartardóttir et al., (submitted 2008). The SPOT image of Kollóttadyngja is from Spot Image©. The frame in the southern part of Kollóttadyngja indicates the location of Figure 2.

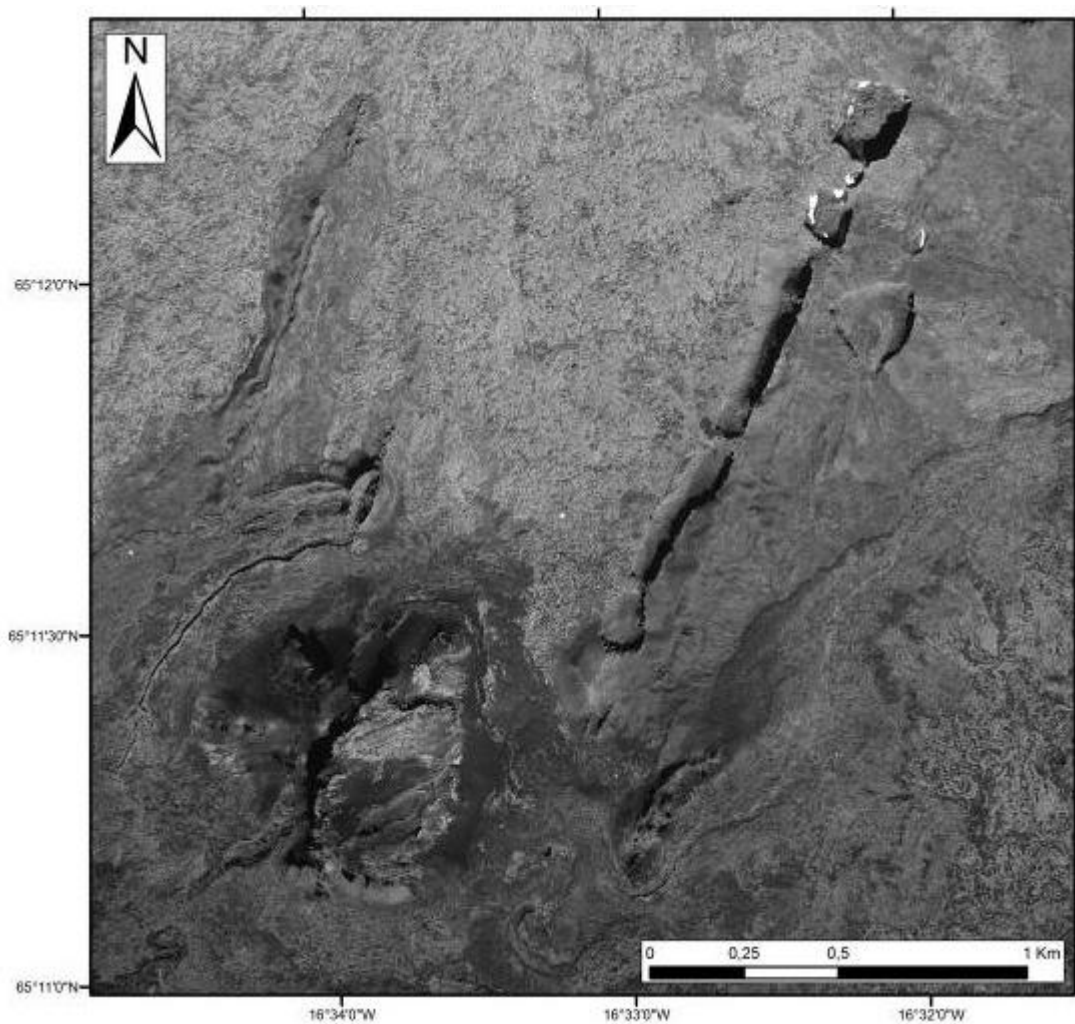


Figure 2

The pit crater chain in SE Kollóttadyngja, along with the volcanic fissures in the area (see Figure 1 for location). The Mt. Bræðrafell is located in the SW part of the figure. The aerial photograph is from Landmælingar Íslands (The National Land Survey of Iceland).

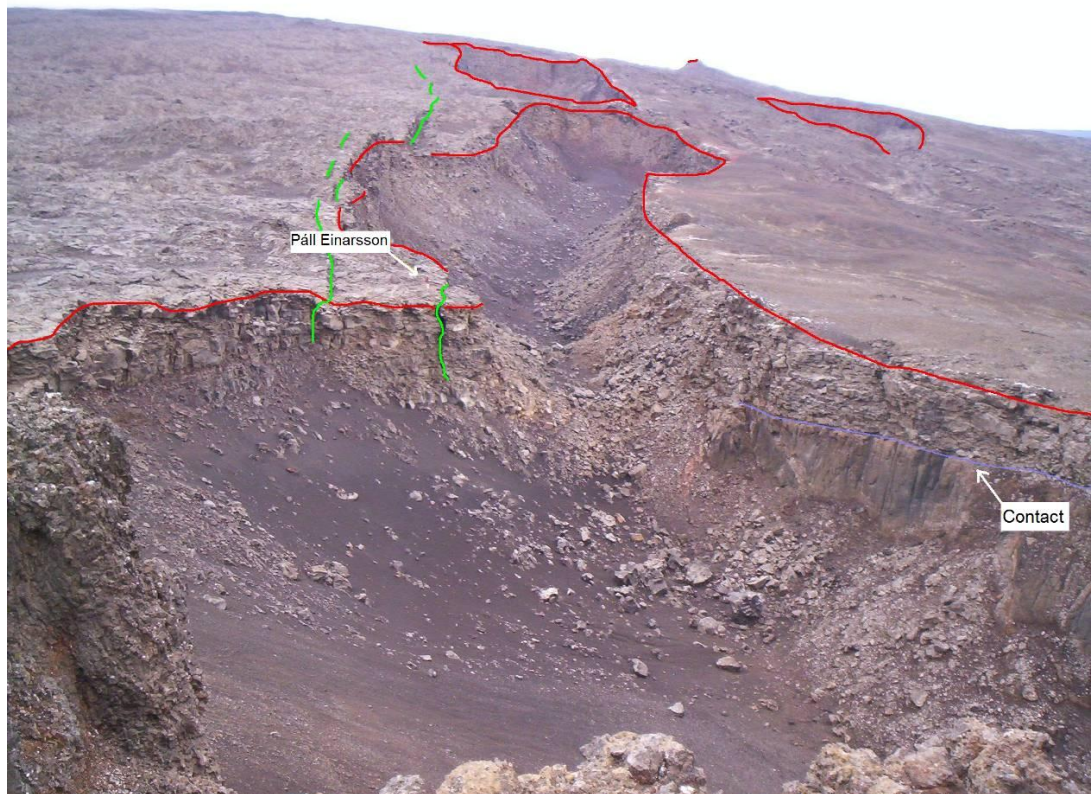


Figure 3

The pit crater chain in SE Kollóttadyngja. The picture is taken toward north from the southernmost end of the pit crater chain. The contact between the shield lava and the underlying hyaloclastite can be seen in the right wall. One of the authors of this article, Páll Einarsson (with a red rucksack) can be seen to the left of the pit craters.



Figure 4

A vertical fault located in the northernmost pit crater. This fault indicates a subsidence in the section that divides this pit crater and the box-shaped pit crater south of it. In this middle section is also a small pit crater.



Figure 5

The two faults located in the southern wall of the southernmost pit crater.

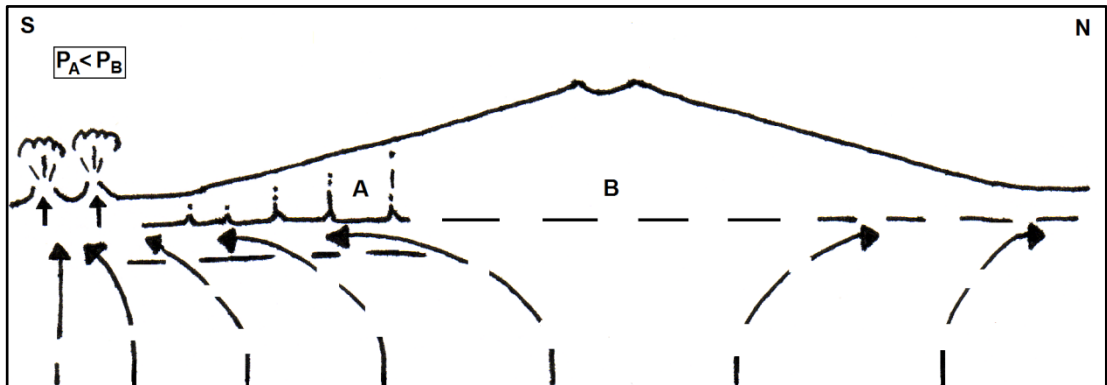


Figure 6

Our suggestion on how the pit crater chain in Kollóttadyngja was formed. This image is a cross-section through Kollóttadyngja, from south (S) to north (N). The arrows indicate the flow of magma in a dike into a channel (under southern Kollóttadyngja), that later collapsed and formed the pit crater chain.