Evidence of recent fault movements in the Tungnafellsjökull fissure swarm in the Central Volcanic Zone, Iceland

Þórhildur Björnsdóttir1,2 and Páll Einarsson1

1 Institute of Earth Sciences, University of Iceland, Sturlugata 7, 101 Reykjavík, Iceland
2 now at Akureyri Junior College, Eyrarlandsvegur 28, 600 Akureyri, Iceland
thorhildur@ma.is, palli@hi.is

Abstract — The volcanic system of Tungnafellsjökull lies in the Central Iceland volcanic zone near the center of the hot spot and the triple junction where the Eurasian Plate, the North-American Plate and the Hreppar Microplate meet. Holocene activity in the Tungnafellsjökull system has been very low, only two small lavas are associated with the system. The Tungnafellsjökull fissure swarm is rather short and wide compared with fissure swarms of other volcanic systems at the divergent plate boundary, 40 km long and 20 km wide. Earthquakes are not common, with usually fewer than 10 being registered per year. Due to these facts, it came as a surprise when InSAR measurements detected movements on faults in the fissure swarm of Tungnafellsjökull during the Gjálp eruption in Vatnajökull in 1996 at a distance of around 37 km from the eruption site. Ground check in 2009 and 2010 revealed evidence of recent movements on faults in the area in the form of fresh sinkholes and fractures, some of which had moved as recently as the spring of 2010. Fresh sinkholes are known to form mostly during faulting events. They are formed when surface soil is washed into underlying, widening cracks in the bedrock. Based on earthquake data and InSAR images these fault movements occurred during three tectonic events, in October 1996 during the Gjálp eruption, in August 2008 and in November 2009. The events are expressed by increased seismicity in the Tungnafellsjökull area, both in terms of number of recorded earthquakes as well as rate of seismic moment release. The earthquakes were all small. The total released seismic moment is equivalent to that of a single earthquake of magnitude 3.4. The widespread evidence of recent fault movements and the small magnitude of the earthquakes suggests that the fault activity is related to magma movements rather than tectonic faulting.

INTRODUCTION

Iceland is located at the mid-Atlantic plate boundary where two major plates meet, the North-American plate and the Eurasian plate. In addition, a microplate has been defined between two branches of the boundary, called the Hreppar microplate (Einarsson, 1991, 2008). The country provides the only place where a divergent part of this plate boundary can be studied on land. Being hot-spot influenced the tectonic picture of the plate boundary in Iceland is more complicated than most other mid-oceanic plate boundaries. The relative motion of the Mid-Atlantic Ridge with respect to the hot spot leads to ridge jumps, propagating rifts and microplate complexities. Complex fracture zones are found in the north (Tjörnes Fracture Zone) and south of the island (the South Iceland Seismic Zone), as well as volcanic zones (Reykjanes Peninsula Rift, Western Volcanic Zone, Eastern Volcanic Zone, Central Iceland Volcanic Zone and Northern Volcanic Zone) (Einarsson, 2008). The volcanic zones are made up of structural units called volcanic systems, which consist of a central volcano and transecting rift zones or fissure swarms (Sæmundsson, 1974; Jakobsson, 1979a). A central volcano is a centrally situated
complex where the discharge of magma is highest. A central volcano may have one or more calderas and a high-temperature geothermal area. They produce a significant amount of silicic volcanic rocks in addition to basalt (Jakobsson, 1979b; Walker, 1993). Fissure swarms are regarded as the surface expression of dyke swarms. They consist of normal faults, tensile fractures and volcanic fissures that extend from the central volcano. The fissure swarms are usually about 10 km wide and their length varies from 30 to over 100 km. The fissure swarms within each branch of the rift zones are typically arranged en echelon. The arrangement may be dextral or sinistral depending on the direction of maximum principal tensile stress that is parallel to the direction of plate movement (Sæmundsson, 1978). Of about 30 active volcanic systems in Iceland, 2/3 have a fissure swarm and 2/3 have a central volcano (Jóhannesson and Sæmundsson, 1998). The active life of most volcanic systems is between 0.1 and 10 Ma (Walker, 1993).

The volcanic system of Tungnafellsjökull is located in the Central Iceland Volcanic Zone (Einarsson, 2008), Figure 1. The Tungnafellsjökull system consists of two or three central volcanoes, the Tungnafellsjökull central volcano, the Vonarskarð central volcano and the Háögungur central volcano, and a fissure swarm (Friðleifsson and Jóhannesson, 2005). The Tungnafellsjökull and Vonarskarð central volcanoes are here considered to be one central volcano having two calderas, one under Tungnafellsjökull glacier and the other SE of the glacier, in Vonarskarð. The Háögungur central volcano is located about 15 km SW of Tungnafellsjökull. These central volcanoes are characterized by a significant contribution of silicic products signifying their maturity.

Volcanic activity in the Tungnafellsjökull volcanic system has been low in the Holocene. Only two small lavas can be associated with the system in this time, the Dvergar lava and the Tunguhraun lava. Previous research on the fissure swarm of Tungnafellsjökull has been limited. A map of the fissure swarm first appeared on a structural map of the neovolcanic zones in Iceland, in an article by Sæmundsson (1978) which was later modified by Einarsson, and Sæmundsson (1987).

In light of the modest activity of the Tungnafellsjökull system it came as a surprise that an InSAR study of the Gjálp eruption of 1996 by Pagli et al. (2007) revealed fault movements of the order of a few cm in two places within the Tungnafellsjökull fissure swarm. The 1996 Gjálp subglacial eruption beneath the Vatnajökull ice cap was the largest in Iceland in terms of volume since the Surtsey eruption in 1963–1967 (Guðmundsson et al., 1997; Einarsson et al., 1997). But it occurred at a distance of more than 35 km from Tungnafellsjökull and within a different volcanic system. This discovery spurred a field study of the area to see if surface ruptures could be found that corresponded to the displacements measured by InSAR. A map of the fissure swarm was prepared from aerial photographs and satellite images. Critical places were then visited during two field campaigns in 2009 and 2010. In this paper we report the findings of these studies, the most remarkable of which was the evidence that fractures had opened in several places in recent years, as recently as the spring of 2010. This study was a part of an MS-project at the University of Iceland (Björnsdóttir, 2012).

REGIONAL SETTING

The Tungnafellsjökull area is located at elevation of 800–1500 m and has very little vegetation, water is sparse. The area is characterized by large areas of sand and sandy ridges. The landscape was formed by glacial erosion during the Pleistocene and is covered by ground moraines to a large extent. There are no settlements in this area and the few man-made structures that do exist are simple huts used by travelers during the summertime. The route to this area is only passable by 4wd vehicles and then only during the summer. The obstacles found en route include glacier rivers, which have to be forded.

Past research on the Tungnafellsjökull volcanic system has been limited and its classification within the volcanic zones in Iceland is ambiguous. Friðleifsson and Jóhannesson (2005) classified the Tungnafellsjökull volcanic system within the Northern Volcanic Zone, whereas Jakobsson, Jónasson and Sigurðsson (2008) considered it unclear whether it lies within the Northern Volcanic Zone or the Eastern Vol-
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Figure 1. Simple geological map of the area around Tungnafellsjökull based on maps from Kjartansson (1965) and Jóhannesson and Friðleifsson (2006a). The background is from the National Land Survey of Iceland.

Figure 1. Einfaldað jarðfræðikort af svæðinu kringum Tungnafellsjökul byggt á kortum frá Guðmundi Kjartanosyni (1965) og Hauki Jóhannessyni og Guðmundi Ómari Friðleifsson (2006a). Bakgrunnur frá Landmælingum Íslands.
canic Zone. However, Einarsson (2008) places the Tungnafellsjökull volcanic system within the Central Iceland Volcanic zone along with the Hofsjökull volcanic system and we favor that opinion. The younger Bárðarbunga central volcano, one of the more active volcanoes in Iceland, is SE of Tungnafellsjökull. It is in a separate volcanic system (Figure 1) and clearly belongs in the Eastern Volcanic Zone. Its northern fissure swarm extends beyond the triple junction well into the Northern Volcanic Zone.

The Tungnafellsjökull central volcano forms a ridge-shaped mountain reaching elevation of 1500 m and is slightly eroded. It has a radius of about 10 km but doesn’t rise as a perfect cone due to the erosion that has occurred. The volcano has an elongated summit caldera (Figure 1), covered to a large degree by a glacier that caps the edifice. A separate, 8 km wide caldera is found at the SE foot of the mountain, called the Vonarskarð caldera, with an active high-temperature field in the center. This caldera with its eruptive units is sometimes considered as a separate central volcano (Friðleifsson and Jóhannesson, 2005). The eastern part of the volcano is covered with subglacial volcanics from the neighbouring Bárðarbunga central volcano. Based on geological mapping the Vonarskarð caldera is slightly younger than the Tungnafellsjökull volcano. No eruption is known to have originated from the volcano itself in Post-glacial time (i.e., the last 9000 years), although two small lavas beyond the northeastern flank are associated with the system, the Dvergar lava and the Tunguhraun lava (Sæmundsson, 1982; Friðleifsson and Jóhannesson, 2005) (Figure 1).

METHODS
Fractures and fissures within the study area were mapped both from aerial photographs and satellite images. Field observations were conducted in the summer of 2009 and 2010. In 2009, the focus was on the area north of Tungnafellsjökull and in 2010 the main task was to further observe rifting features detected from aerial photographs. Our observations were combined with data on seismic activity obtained from the Icelandic Meteorological Office (IMO). InSAR images were also used to evaluate fault movements during the previous couple of years. The aerial photographs used were contact images from Landmælingar Íslands (The National Land Survey of Iceland) and digital images from Loftmyndir ehf. These images were taken at approximately 6,700 and 8,000 m altitude in 1996 and 1999, respectively. The satellite images were obtained from SpotImage© and the ASTER archive. Care was taken not to confuse tectonic lineaments with glacial striae, which are abundant in the area (Kaldal and Vikingsson, 1990).

Earthquake data from September 1996 to August 2011 were used to evaluate recent faulting activity. Earthquake locations with larger azimuthal gap than 180° were excluded as well as earthquakes with larger RMS value than 0.25 s and events recorded at fewer than four stations.

STRUCTURAL ARCHITECTURE
Overview
The mapped fractures are shown in Figure 2. The area mapped may be divided into three areas according to its physiographic and tectonic style: The Ógöngur area (Figure 3) southwest of Tungnafellsjökull (named after hyaloclastite ridges, tindars, in the area), the Tómasarhagi area (Figure 4) northwest of Tungnafellsjökull, and the Langadrag area (Figure 5) northeast of Tungnafellsjökull.

Fractures located within the study area are mostly normal faults, sometimes forming a graben. The orientation of fractures and faults is different between the three areas. From north to south the orientation changes from various orientations in the Langadrag area to NE in the Tómasarhagi area, to NE in the Ógöngur area. Hyaloclastite ridges, tindar in recent terminology, the product of subglacial fissure eruptions (Kjartansson, 1943), are common in the Ógöngur area. Features that indicate recent movements like sinkholes and open fissures are common, especially in the Tómasarhagi area. The fissure swarm is wider towards the west than the fissure swarm drawn in previous structural maps by Sæmundsson. Many of the faults and fissures of the fissure swarm lie west of the volcano, thus bypassing it rather than transecting it (Figure 2).
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Figure 2. Fracture map of the volcanic system of Tungnafellsjökull. The satellite image is from SpotImage© and the delineations of the fissure swarms are from Einarsson and Sæmundsson (1987). Roads and tracks are shown in grey. – Sprungukort af eldstödvakerfi Tungnafellsjökuls. Gervihnattamyndin í bakgrunni er frá SpotImage© og útlínur sprungusveimsins samkvæmt Páli Einarssyni og Kristjáni Sæmundssyni (1987). Vegir og slóðar eru sýnd með gráum línum.

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Figure 3. Mapped faults and fractures in the Ógöngur area. The locations of measured cross sections to estimate throw are shown in blue. The satellite image is from SpotImage©. – Sprungukort af Ógöngusvæðinu. Staðir þar sem hæðarfærsla var metin med þversniðsmælingu eru sýndir með bláu. Gervihnattamýndin í bakgrunni er frá SpotImage©.
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Figure 4. Fracture map of the Tómasarhagi area. The satellite image is from SpotImage©. – Sprungukort af Tómasarhágasvæðinu. Gervihnattamyndin í bakgrunni er frá SpotImage©.
Figure 5. Fracture map of the Langadrag area. The satellite image is from SpotImage©. - Sprungukort af Langadragssvæðinu. Gervihnattamýndin í bakgrunni er frá SpotImage©.
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The Ögöngur area

The Ögöngur area is characterized by tindars and pillow lava mountains (or ridges) in the southeastern part grading into sand ridges and dunes toward the west (Figures 3 and 6a). All exposed volcanic formations have a normal magnetization and are thus younger than 700,000 years (Piper, 1979) with no Holocene lavas. Both tindars and normal faults are ENE oriented. The normal faults are prominent on satellite images and aerial photographs. However, few fissures or sinkholes were found indicating that recent movements have been minimal.

It has been suggested that Vonarskarð and Tungnafellsjökull are two separate volcanic systems with separate fissure swarms (Jóhannesson and Friðleifsson, 2006). Fissure swarms often have the structure of a shallow graben with boundary faults dipping towards the center of the swarm. If Vonarskarð and Tungnafellsjökull had separate fissures swarms, one would assume that the normal faults in the Ögöngur area would change dip direction from west to east forming two parallel grabens with westward and eastward dipping normal faults between them. A surface cross section, surveyed from west to east, southwest of Ögöngur (Figure 3) revealed only westward dipping faults. The fissure swarm thus has the form of a half graben at this latitude which is rather exceptional for Icelandic fissure swarms. The question of the existence of two separate fissure swarms remains open.

Figure 3 shows mapped faults and fractures in the Ögöngur area. Fault throw was estimated in four places by measuring cross sections over the faults by GPS. Their offsets were within the range 5–15 m.

The Tómasarhagi area

The Tungafellsjökull volcano with its glacier lies in the southeast corner of Tómasarhagi area (Figure 4) encompassed by alluvial and glacially formed sand ridges and with sparse vegetation. Three glacial rivers drain the Tungafellsjökull glacier as well as several smaller streams. Faults and fissures in this area are NE oriented, lying parallel to, but offset from the major axis of the Tungafellsjökull central volcano (Figures 2 and 4). This is not the normal spatial relationship for Icelandic fissure swarms, where the norm is for the fissures to transect their central volcano. The area closest to Tungafellsjökull is characterized by numerous normal faults and a graben with open fissures and sinkholes providing evidence of Holocene fault movements. Some of the fissures and sinkholes are very deep and indicate movements as recent as spring of 2010 (Figures 6d, e and f). A cross section over the boundary faults of the graben, measured with GPS, gives a subsidence of 2–6 m of the graben floor. Movements detected by InSAR measurements following the Gjálp eruption in 1996 were also located in this area (red stars in Figures 2 and 4). Field observations in these places revealed normal faults with fissures and fresh-looking sinkholes (yellow stars in Figures 2 and 4).

The Langadrag area

Sand ridges and dunes characterize the Langadrag area, although some hyaloclastite ridges and pillow mounts can also be seen. Faults and fractures are scarce, compared to the Ögöngur and Tómasarhagi areas. However, there is ample evidence of recent movements in the form of sinkholes and fissures along the Langadrag faults. Rows of sinkholes and scarps of 0–2 m height marked the faults that were discovered and mapped on foot during fieldwork in the summer of 2009 (yellow lines in Figure 5). Both Holocene lavas associated with the Tungafellsjökull volcanic system are located in the Langadrag area. Tunguhraun from the Bokki crater lies in the west and the Dvergar lava in the southeast. Both lavas are small in volume, indicating small eruptions. A warm pool called Hitalaug is located about 2.5 km south of one of the sites where movements were detected by InSAR measurements. A ground check at this site revealed no fresh faults or fractures. The warm pool is located on an old fractures. Fractures and faults in the Langadrag area have somewhat variable orientations (Figures 2 and 5). With one NE aligned fissure mapped in the south and several NNE aligned fractures and fissures further north. The Dvergar eruptive fissure in the southeast strikes in an ENE direction (Figure 6). The connection between the faults and fractures of the Langadrag area and the main edifice of the Tungafellsjökull central volcano is difficult to establish due to steep topography and high degree of erosion.
Figure 6. Map showing the Dvergar volcanic fissures and lavas. The satellite image is from SpotImage©.

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Structures indicating recent movements
Figure 7 shows three different types of structures that provide evidence of recent movements in the fissure swarm of Tungnafellsjökull. Type 1 (Figure 7a) shows a step in a glacially eroded area. The step in the glacial ground moraine that normally has no obvious features indicates movements on faults in the Holocene. Type 2 (Figure 7b and c) shows sinkholes in glacial moraine. Sinkholes form when there is movement on faults or fractures and loose surface material is washed into the underlying fracture. This is clear indication of movements in the Holocene since the Pleistocene ice sheet can be assumed to have left fissures packed with debris. Type 3 (Figures 7d, e and f) show sinkholes and fractures that bear obvious sign of very recent movements. The fresh wounds in the rim of the sinkholes (Figures 7d and e) and in the edge of the fracture (Figure 7f) indicate movements as recent as the spring of 2010 since they cannot be expected to survive the spring thaw. These features are not commonly observed in the rift zones except in the areas were very recent movements have taken place. A reconnaissance in 2010 of fractures and sinkholes produced during the Krafla rifting episode in 1975–1984, e.g. did not reveal structures as fresh-looking as these.

Earthquake activity
Seismic activity at Tungnafellsjökull is relatively low (Figure 8) compared to many other volcanic systems (Einarsson, 1991; Jakobsdóttir, 2008). The earthquake epicenters form a diffuse pattern, which is not explained by uncertainty of epicentral determination. A plot of cumulative seismic moment for the years 1995–2011 (Figure 9) shows 3 earthquake swarms that may have been associated with surface movements in faults and fractures. The first swarm occurred during the Gjálp eruption in October 1996, the second in August 2008 and the third in November 2009. The August 2008 swarm was the smallest event of the three. InSAR detected surface movements, which coincided with the 1996 earthquake locations (Pagli et al., 2007) most likely mark the time of the movements observed in the area as InSAR data from April 2004 to September 2010 do not provide coherent results (Amandine Auriac, pers. comm. 2011).

None of the earthquakes is large. If the total seismic moment was released in one earthquake its magnitude would be only 3.4. The length of the three fractures identified by the InSAR study of Pagli et al. (2007) was in the range 3–4 km and the displacements of the order of one fringe, i.e. about 3 cm. If converted to seismic moment this corresponds to one earthquake of magnitude 5.0. Additional displacements since the study of Pagli et al. (2007) would add to the size of that event. There is clearly a discrepancy between the observed seismic moment release and the surface faulting. This discrepancy suggests that the fault movements are of magmatic origin rather than purely tectonic (see e.g. Pedersen et al., 2007).

DISCUSSION
Research on the fissure swarms of the volcanic systems in the Central Iceland Volcanic zone has been more limited than in other volcanic zones. Some of the rift zone branches have been studied more extensively, e.g. the Northern Volcanic Zone (Hjartardóttir et al., 2009; Hjartardóttir and Einarsson, 2012, Hjartardóttir et al., 2012), and the Reykjanes oblique rift (e.g. Clifton and Kattenhorn, 2006). The Northern Volcanic Zone, on the divergent boundary, is characterized by fissure swarms, approximately 5–20 km wide and 40–120 km in length, each extending through a specific central volcano. The fissure swarms consist of volcanic fissures, faults and fractures. Volcanic fissures are usually dominant near the central volcano, but non-eruptive fractures become more frequent further away from the central volcano. The activity of the fissure swarms seems to be highest in the middle and their altitude is higher there than elsewhere (Hjartardóttir et al., 2009; Hjartardóttir and Einarsson, 2012). These characteristics can also be found elsewhere in the world for example in the Northern Main Ethiopian Rift (NMER) in East Africa. The NMER contains 4 tectono-magmatic segments. Each segment consists of a volcanic center and rift tips characterized by brittle deformation. The area between the central volcano and the tips is similar to the fissure swarms in the Northern Volcanic Zone in Iceland. Nearest to the central volcano the deformation is mostly magmatically induced but moving
Figure 7. a) A fault scarp in the Ógöngur area. b) Fracture with sinkholes and c) sinkholes formed above an open fracture in the Langadrag area. d) and e) Large sinkholes in the Tómasarhagi area. f) Fracture with evidence of recent movements in the Tómasarhagi area. – Misgengi, niðurföll og sprungur á rannsóknasvæðinu. a) Misgengi á Ógöngusvæðinu. b) og c) Sprunga með niðurföllum og niðurföll á Langadragsvæðinu. d), e) og f) Stór niðurföll og sprunga með vísbendingum um nýlegar hreyfingar á Tómasarhagasvæðinu.
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Figure 8. Earthquake locations in the study area from September 1996 to May 2011, data from the Icelandic Meteorological Office. The background is from the National Land Survey of Iceland. – Staðsetning jarðskjálfa við Tungnafellsjökul frá september 1996 til mai 2011. Gögn frá Véðurstofu Íslands. Bakgrunnsmyndin er frá Landmælingum Íslands.
from the center to the tips the deformation changes to brittle. In the fissure swarm one can find open fissures, aligned basaltic cones and faults (Kurtz et al., 2007). The fissure swarm of Tungnafellshjökull bears some of these characteristics, but nevertheless appears to be a little different. Although the volcanic system of Tungnafellshjökull is situated at the plate boundary, activity in the system has been scarce for the last ca. 10,000 years. The fissure swarm is unusually wide and short. This is one of the reasons we prefer to classify the Tungnafellshjökull system with the Central Iceland Volcanic Zone rather than the much more active Eastern Volcanic Zone.

CONCLUSIONS

1. Ground checks of fissures and faults in the summers of 2009 and 2010 revealed evidence of recent movements in the Tungnafellshjökull fissure swarm, consistent with InSAR studies of Pagli et al. (2007). Some of the evidence strongly suggest that movements occurred as recently as the spring of 2010.

2. Three types of fault structures related to movements could be differentiated. Type 1 is a step in a glacial ground moraine that normally doesn’t have any obvious features. The step thus indicates Postglacial movements. Type 2 and 3 are sinkholes or fractures on the ground. Both types indicate Postglacial movements, but type 3 has open and fresh wounds in the rim of the sinkholes and the edge of the fractures indicating movements during the last year, even as recent as the last thaw.

3. Study of the seismic activity in the period 1996 to 2011 reveals 2–3 events or episodes during which the movements may have taken place. The first episode was in 1996, during the Gjálp eruption in Vatnajökull, which was located about 35 km away from the survey area. This event was detected in SAR interferograms by Pagli et al. (2007) and probably had the largest influence on the faults in the fissure swarm. The other events are smaller, one in August 2008 and the other in November 2009.

4. The cumulative seismic moment of all these seismic events amounts to that of a single earthquake of magnitude 3.4. The total geometric moment of the observed displacements, on the other hand, is equivalent to a magnitude of at least 5.0 if released in one earthquake. This discrepancy suggests that the fault movements were not purely of tectonic origin, but rather associated with magma movements at depth.

5. The fissure swarm of the Tungnafellshjökull volcanic system is relatively short (40 km) and wide (20 km),
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if compared to other fissure swarms at or near the divergent plate boundaries of Iceland. It is considerably wider than the central volcano and thus partly bypasses it instead of extending from it. The southern branch is highly asymmetric, with all normal faults downthrown to the west. Graben structures are found in the northern branch but are small.

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