The 2011 unrest at Katla volcano: seismicity and geological context

Giulia Sgattoni[1,2,3*], Federico Lucchi[1], Páll Einarsson[2], Ólafur Gudmundsson[3], Gianfilippo De Astis[4], and Claudio Antonio Tranne[1]

[1]*Department of Biological, Geological and Environmental Sciences, University of Bologna, Bologna, Italy*

[2]*Institute of Earth Sciences, Science Institute, University of Iceland, Reykjavik, Iceland*

[3]*Department of Earth Sciences, Uppsala University, Uppsala, Sweden*

[4]*National Institute of Geophysics and Volcanology (INGV), Rome, Italy*

[*]*Corresponding author: giulia.sgattoni@unibo.it* https://doi.org/10.33799/jokull2019.69.053

Abstract — *Katla is one of the most active volcanoes in Iceland and is characterised by persistent seismicity. It is partly covered by the Mýrdalsjökull glacier and its historic activity is dominated by phreatomagmatic eruptions within the caldera associated with catastrophic glacial floods. In July 2011 a sudden jökulhlaup was released from the glacier, associated with tremor, elevated seismicity inside the caldera and a new cluster of seismicity on the south flank. This was likely caused by a hydrothermal or magmatic event, possibly a small subglacial eruption. Similar unrests occurred in 1955 and 1999. We have identified changes of the seismicity pattern coinciding with the 2011 unrest, suggesting a modification in the volcanic system. It may be speculated that if the persistent seismicity at Katla is an indication of a pressurized magma system ready to erupt, small events like those of 1955, 1999 and 2011 may trigger larger eruptions in the future. We have also conducted a pilot study of the geology of the southern flank, where the new seismicity is recorded, and identified sources for flank eruptions in the recent eruptive history of Katla. These include rhyolitic domes and surtseyan craters. Therefore, a wide range of volcanic processes have to be taken into account as possible source for the new seismicity and volcanic hazard.*

Keywords: Katla volcano, volcano seismicity, long-period earthquakes, silicic domes, flank activity

INTRODUCTION

The study of subglacial volcanoes is crucial, as magma-ice interaction can produce highly explosive eruptions and jökulhlaups (glacial floods; Major and Newhall, 1989, Gudmundsson *et al.,* 2008), but problematic, because the ice cover prevents direct observations and complicates the understanding of geophysical signals. The Katla volcanic system, in south Iceland, is a prime example. Katla hosts a large caldera covered by the Mýrdalsjökull ice cap (Figure 1) and is a peculiar volcano for its persistent seismicity also during periods of volcanic quiescence (Einarsson, 1991). It is one of the most active volcanoes in Iceland and its volcanic activity is dominated by explosive, phreatomagmatic eruptions (Óladóttir *et al.,* 2008). The last eruption to break the ice surface occurred in 1918 and the current repose time is the longest known in history (Larsen, 2000).

After the eruption of Eyjafjallajökull in 2010, scientists' attention was pointed to Katla, as several previous eruptions of Eyjafjallajökull were swiftly followed by eruptions at neighbouring Katla (Einarsson and Hjartardóttir, 2015). However, no visible eruption

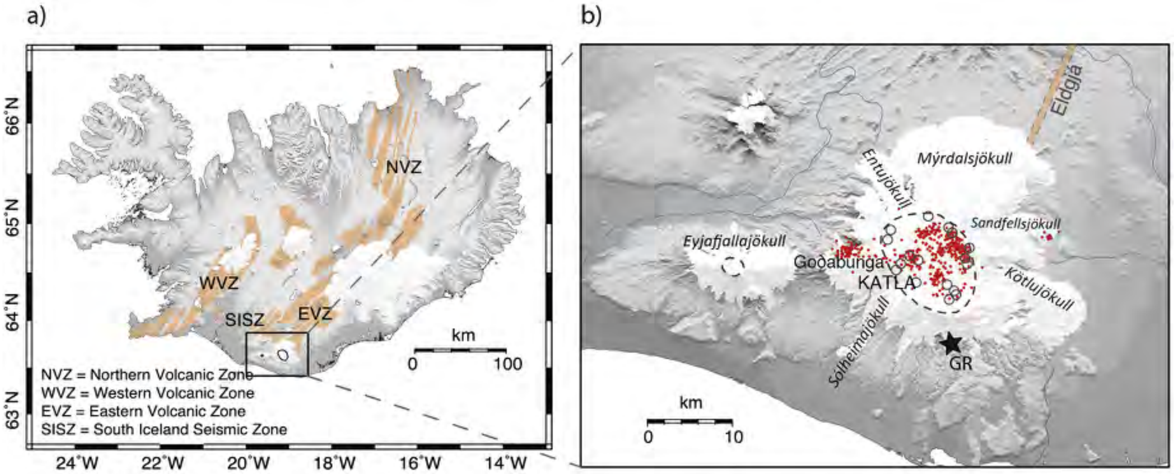

Figure 1. Map of Iceland showing volcanic systems in orange (Einarsson and Sæmundsson, 1987). In the enlarged inset, main seismic and geological features of Katla. Red dots: epicentres before July 2011, located inside the caldera and at Goðabunga. Black star: new cluster near Gvendarfell Ridge (GR) started in July 2011. It is represented with a star because of its small size, derived from relative location (Sgattoni *et al.,* 2016a,b). Dashed lines: Katla and Eyjafjallajökull caldera rims. Open circles: ice cauldrons (Guðmundsson *et al.,* 2007). White areas: glaciers. To the NE, the location of Eldgjá fissure. Topography information from the National Land Survey of Iceland. – *Kort af eldstöðvakerfum Íslands. Stækkaða kortið til hægri sýnir skjálftavirkni á Kötlusvæðinu og staði sem koma við sögu í greininni. Rauðir punktar sýna upptakastaði skjálfta fyrir 2011, að mestu innan öskjunnar og í þyrpingu vestan Goðabungu. Svört stjarna sýnir þéttu skjálftaþyrpinguna við Gvendarfell sem hófst í júlí 2011. Umfang hennar er minna en stjarnan. Slitnu línurnar sýna öskjur Kötlu og Eyjafjallajökuls, litlir hringir sigkatla í yfirborði jökulsins. Jöklar eru sýndir með hvítum lit. Eldgjá, sem er hluti eldstöðvakerfis Kötlu, er sýnd norðaustan Mýrdalsjökuls. Landslagsgögn eru frá Landmælingum Íslands.*

occurred. But in July 2011, increased earthquake activity occurred at Katla, together with a tremor burst and a jökulhlaup, the latter causing considerable damage to infrastructure. This unrest episode was similar to two others that occurred in 1955 and 1999, which some authors have interpreted as minor subglacial eruptions (Thorarinsson, 1975; Guðmundsson *et al.,* 2007). However, the interpretation is controversial, as no eruptive products were identified. The same general controversy applies to the 2011 unrest. This episode may have been related to either a geothermal event with no magma involved or a small subglacial eruption (Sgattoni *et al.,* 2017).

The seismic activity at Katla in recent decades has been concentrated in two main source areas, inside the caldera and on the west flank, at Goðabunga (Fig.1b), with the latter being much more active, at least until the end of 2004 (Sturkell *et al.,* 2006). Seasonal patterns have also been reported with different features for the two clusters (Einarsson and Brandsdóttir, 2000; Jónsdóttir *et al.,* 2009). Another cluster has been recently identified on the eastern flank of the volcano by Jeddi *et al.* (2016). Clear changes in the seismicity at Katla occurred in July 2011. The 2011 unrest was associated not only with increased seismicity inside the caldera, but also with the onset of new seismicity on the southern flank of the volcano, west of the Gvendarfell ridge (GR in Figure 2), at the glacier margin (Sgattoni *et al.,* 2016b).

Attention has therefore been recently directed towards the southern flank of Katla, which to date has not been considered a source of serious volcanic hazard, and thus its geology has been little studied. Basaltic to intermediate hyaloclastites and lavas, together with rhyolitic domes were identified by Lacasse *et al.* (2007) and Jóhannesson and Saemundsson

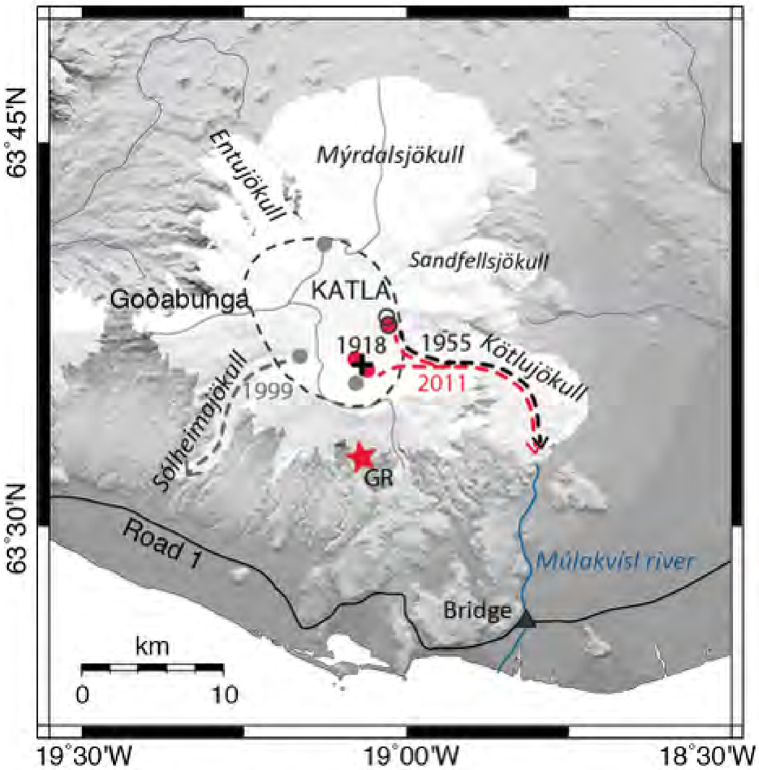

Figure 2. Recent unrest at Katla. Black cross: 1918 eruption site (Björnsson *et al.,* 2000). Black, grey and red dashed arrows: routes of 1955, 1999 and 2011 jökulhlaups, respectively. Circles with same outline or fill colors mark the cauldrons newly formed or deepened during the same unrest episode. Red star: new seismic source in the Gvendarfell area. GR: Gvendarfell ridge. Light grey lines: water divides of main outlet glaciers (Björnsson *et al.,* 2000). Topography information from the National Land Survey of Iceland. – *Yfirlitskort af nýlegum atburðum við Kötlu. Svartur kross: Gosstöðvar 1918. Svört, grá og rauð ör sýnir leiðir jökulhlaupanna 1955, 1999 og 2011. Hringir í sömu litum sýna sigkatlana sem mynduðust í jöklinum við upptök þessara hlaupa. Rauð stjarna: Upptakasvæði skjálftarununnar við Gvendarfell. GR: Gvendarfell. Ljósgráar línur: Vatnaskil helstu skriðjökla. Landslagsgögn eru frá Landmælingum Íslands.*

(2009), but no detailed description of their features is reported. We thus decided to undertake a geological survey in the area around the Gvendarfell ridge, where the new seismic cluster is located, aimed at identifying the main geological and tectonic features possibly connected with the seismic sources.

In this article, we place the 2011 unrest episode at Katla in the broader context of its geology and eruptive history. Moreover, we analyze the general changes of the historical seismicity at Katla by looking at the seismic catalogue from 1998 to 2015. We use this information to shed light on the 2011 unrest and suggest a possible interpretation.

THE KATLA VOLCANIC SYSTEM

Geological overview

Katla is located just south of the intersection between the active rifting zone of the Eastern Volcanic Zone (EVZ) and the transform boundary of the South Iceland Seismic Zone and may be classified as an intraplate volcano (Figure 1). An occasional connection with rifting in the EVZ is exemplified by the AD 934 Eldgjá eruption (Sturkell *et al.,* 2008). Katla and Eyjafjallajökull appear to be tectonically connected, as the Eyjafjallajökull E-W fissure swarm merges with the Katla radial fissure system (Einarsson and Brandsdóttir, 2000; Einarsson and Hjartardóttir, 2015).

The Katla volcanic system consists of a large central volcano mostly covered by the Mýrdalsjökull ice cap, connected to the Eldgjá fissure system extending 75 km to the northeast (Larsen, 2000; Thordarson *et al.,* 2001). The central volcano hosts a 10×14 km wide and 650–750 m deep, ice-filled caldera (Björnsson *et al.,* 2000). Three main glaciers descend from the ice cap through deep gaps in the southeast, southwest and northwest caldera walls (Figure 1b), corresponding to the three main possible paths for jökulhlaups via Kötlujökull, Sólheimajökull and Entujökull, respectively. Several ice cauldrons (at least 16) located within the caldera and at its rim are the surface expression of subglacial geothermal activity (Guðmundsson *et al.,* 2007).

A zone with reduced P-wave velocities (with its base at ∼3 km below the bedrock surface) and absent S-waves was identified beneath the Katla caldera with seismic undershooting and interpreted as evidence of a magma chamber (Guðmundsson *et al.,* 1994). This is in agreement with an aeromagnetic survey (Jónsson and Kristjánsson, 2000) and a recent tomographic study by Jeddi *et al.* (2016). A shallow magma reservoir is consistent with geobarometric analyses by Budd *et al.* (2016) that imply polybaric magma crystallization pointing to simultaneous deep and shallow magma storage. This is in contrast with previous geochemical studies by Óladóttir *et al.* (2008) suggesting the absence of shallow magma reservoirs in the current plumbing system at Katla.

The Katla volcanic system has possibly been active for several hundred thousand years (Jakobsson, 1979; Björnsson *et al.,* 2000), producing FeTi-rich alkali basalts and mildly alkali rhyolites, with very subordinate intermediate rocks (Lacasse *et al.,* 2007; Óladóttir *et al.,* 2008). Many outcrops along the caldera rims and glacier margins are composed of rhyolitic lavas (Jóhannesson and Sæmundsson, 2009; Lacasse *et al.,* 2007). The age of the caldera is unknown.

Seismicity

Despite its tectonic location outside the main rift zones, persistent seismicity has been detected at Katla since the first sensitive seismographs were installed in Iceland in the 1960s (Einarsson and Brandsdóttir, 2000). Until the 2011 unrest, this seismicity has been concentrated mostly within the caldera and immediately to the west, at Goðabunga (Figure 1). The caldera seismicity consists mostly of high-frequency and hybrid events, probably associated with subglacial geothermal activity and volcano-tectonic processes (Sturkell *et al.*, 2008). The Goðabunga cluster consists mainly of low-frequency shallow events with emergent P-waves, unclear S-waves and long low-frequency coda. These events have a controversial interpretation in the literature, either as a response to a rising viscous cryptodome (Soosalu *et al.,* 2006) or due to glacial processes such as ice-fall events (Jónsdóttir *et al.,* 2009). Recent discovery of a massive landslide of about 1 km^2 that has been active since at least 1945 at the site of the proposed cryptodome (Sæmundsson *et al.* 2020) calls for reinterpretation of the possible sources of the Goðabunga seismicity. Moreover, volcano-tectonic microearthquakes are recorded on the eastern flank of the volcano beneath the surface at around 3.5 km depth, near the tip of Sandfellsjökull glacier (Jeddi *et al.,* 2017).

The Katla seismicity also shows a seasonal variation, particularly at Goðabunga, where the seismic activity peaks in autumn. A less pronounced peak of seismicity in the caldera occurs instead during the summer (Jónsdóttir *et al.,* 2007). This seasonal correlation has been interpreted as a result of ice-load change and resulting pore pressure variation at the base of the glacier (Einarsson and Brandsdóttir, 2000) or due to enhanced glacial motion during periods of distributed subglacial water channels (Jónsdóttir *et al.,* 2009).

Holocene volcanism

The Holocene volcanic activity at Katla has been characterized by three main eruption types. The most frequent are phreatomagmatic explosive eruptions due to magma-ice interaction below the glacier that produced jökulhlaups and widespread tephra layers (0.02–1.5 km^3 volume; Thorarinsson, 1975; Larsen, 2000). At least 300 subglacial explosive eruptions are known during the Holocene, with 20 in historic times, i.e. since about 900 AD (Óladóttir *et al.,* 2005). The least common are effusive basaltic eruptions along the fissure swarm in the ice-free part of the volcanic system (8–10 in the Holocene). These include the two largest eruptions of AD 934–40 Eldgjá Fires (19.6 km^3; Thordarson *et al.,* 2001) and ∼7.7 ka Hólmsá fires ($\geq$5 km^3; Larsen, 2000). The third type of activity consists of explosive silicic eruptions from the central volcano that produced tephra fallout (<0.01–0.27 km^3; Larsen *et al.*, 2001) and probably jökulhlaups (Larsen, 2000). It is not established whether these events also generated effusive silicic products that are exposed on the volcano today. At least 12 silicic tephra layers are identified in the 1.7–6.6 ka time interval between the Hólmsá and Eldgjá fires (Larsen, 2000). A minor silicic component was erupted during the Eldgjá fires (Einarsson *et al.,* 1980), but silicic eruptions are not reported since then, possibly indicating a substantial change in the plumbing system caused by the Eldgjá eruption (Óladóttir *et al.,* 2008).

In historical times, Katla has been the most productive volcanic system in Iceland in terms of magma volume erupted (Thordarson and Larsen, 2006). It has generated observable subaerial eruptions fairly regularly at a rate of 1–3 eruptions per century, with repose periods ranging between 13 and 98 years, and averaging 47 years since AD 1500 (Larsen, 2000).

Recent activity

The last eruption to break the ice surface was an explosive basaltic eruption in 1918 that produced a $\sim$14 km high eruptive plume and tephra fallout (0.7 km^3), accompanied by a massive jökulhlaup that deposited a large volume of juvenile eruptive materials. The eruption site was located near the south rim of the caldera beneath $\sim$400 m of ice (Eggertsson, 1919; Sveinsson, 1919; Larsen, 2000).

Periods of elevated seismicity, not associated with eruptive activity, occurred at Katla in 1967 and 1976–77 inside the caldera and at Goðabunga (Einarsson, 1991). Two minor subglacial eruptions, but with no subaerial tephra emission, may have occurred in June 1955 and July 1999. The 1955 event took place near the eastern rim of the caldera (Figure 2) where two shallow ice cauldrons formed and a small jökulhlaup drained from south-east Mýrdalsjökull (Thorarinsson, 1975). In 1999, a new ice cauldron formed on the glacier (Guðmundsson *et al.,* 2007) and a jökulhlaup was released from Sólheimajökull (Sigurðsson *et al.,* 2000; Roberts *et al.,* 2003), associated with earthquakes and bursts of tremor.

From 1999 to 2004, GPS measurements on nunataks exposed along the caldera rim revealed steady uplift of the volcano, interpreted to result from 0.01 km^3 of magma accumulation (Sturkell *et al.,* 2006, 2008). Consequently, Guðmundsson *et al.* (2007) showed that increased geothermal heat output occurred in 2001–2003 based on the evolution of ice cauldrons, together with the increased seismicity and ground uplift. However, a recent study by Spaans *et al.* (2015) reported that the uplift may be due to glacial isostatic adjustment as a consequence of mass loss of Iceland's ice caps.

JULY 2011 UNREST

A significant, general increase in seismicity started at Katla in July 2011 and lasted until winter 2011. This followed a period of uplift of most ice cauldrons on Mýrdalsjökull (11–12 m at cauldron 16) between August 2010 and July 2011, resulting from water accumulation under the glacier (Guðmundsson and Sólnes, 2013).

The seismicity intensified especially in the southern sector of the caldera and culminated with a 23-hour tremor burst on July 8–9th (Sgattoni *et al.,* 2016b, 2017). No signs of eruption breaking the ice were observed, but a $\sim$18 million m^3 jökulhlaup drained from Kötlujökull and some ice cauldrons deepened in the southern and eastern parts of Mýrdalsjökull (Figure 2). The jökulhlaup swept away the bridge over Múlakvísl river early in the morning of July 9th. This coincided with a clear flood-related tremor phase lasting around 5 hours. Two main tremor sources were identified in the southern and eastern caldera, corresponding to the active cauldrons, and were interpreted to be associated with either geothermal or magmatic processes (Sgattoni *et al.,* 2017).

At the same time, a new earthquake source became active on the southern flank near the Gvendarfell ridge, at the edge of the glacier (Figure 2). This seismicity consists of long-period events with an emergent P wave and an unclear S wave, and has a peculiar temporal pattern characterized by regular inter-event times modulated by a seasonal correlation. Due to their temporal pattern and the depth distribution of the hypocentres (Sgattoni *et al.,* 2016a), they are inferred to relate to volcanic rather than glacial processes. The events locate in the shallow subsurface between 0.5 and 0.9 km depth, but the depth is marginally resolved to differ from zero. The size of the cluster inferred from relative location is on the order of 100 meters (Sgattoni *et al.,* 2016a). Both magmatic and hydrothermal processes are considered possible (Sgattoni *et al.,* 2016a,c).

EARTHQUAKE ACTIVITY 1998–2015

Catalogue data from the Icelandic Meteorological Office (IMO) give an overview of the seismic activity at Katla during the period 1998–2015, as a framework for the interpretation of the 2011 unrest episode and new seismicity. The seismic data of this catalogue were recorded by the Icelandic national seismic network (SIL) and the earthquake location obtained using a 1D SIL-velocity model (Stefánsson *et al.,* 1993). The permanent monitoring network around Mýrdalsjökull has been densified through time (Figure 3). The depth of the earthquakes is not well resolved, however, most events appear to be located at shallow depth between 0 and 5 km (Vogfjörð and Slunga, 2008).

The analysis of the catalogue shows significant changes through time in the seasonal patterns, size and location distribution of the persistent seismicity recorded at Katla since the 1970s (e.g. Einarsson and Brandsdóttir, 2000). Because the network configuration has improved through time, the magnitude of completeness of the catalogue has also improved (lowered). Here we describe the seismicity above M=1 (for the two main clusters, Caldera and Goðabunga), which is presumably below the magnitude of completeness for the whole time span we consider. However, the same features, albeit less pronounced, would also be seen by increasing this threshold to M=1.7, which is indicated as the magnitude of completeness of the Katla seismicity between 1993–2006 by Jónsdóttir *et al.* (2007). We also point out that the changes we observe in the seismicity patterns do not coincide in time with changes in the network. The following are the main features of the seismicity at Katla during 1998–2015, (Figures 4 and 5):

– The Goðabunga cluster was more active than the caldera until the first half of 2011, with around 11600 events with magnitude M_L>1 compared to 3300 inside the caldera. The most intense earthquake activity occurred during the 2000–2004 seismic crisis, after the 1999 unrest episode, when inflation was observed at Katla (Sturkell *et al.,* 2008).

– Increased seismicity at Goðabunga followed the 2010 Eyjafjallajökull eruption.

– Since July 2011, more earthquakes have occurred in the caldera than at Goðabunga, with 1610 events with M_L>1 compared to 760 at Goðabunga.

– The magnitude of the largest events at Goðabunga has been decreasing since 2009, with most events of M_L<2 as of 2010.

– The autumn seismicity peak of the Goðabunga clus-

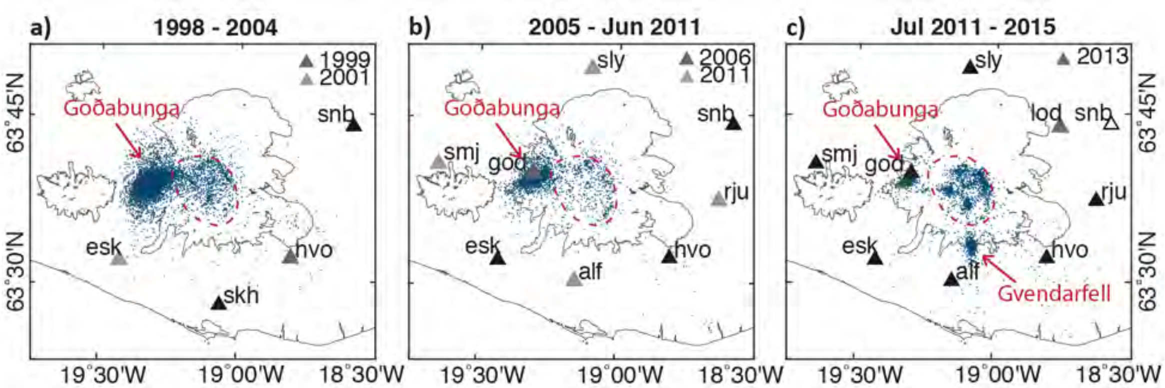

Figure 3. Earthquake locations (in blue) at Katla during 1998–2015 from the IMO catalogue. All events with magnitude M_L>1 were selected for the caldera and Goðabunga seismic clusters, and events with $M_L M_L$>M_L0 for the southern flank seismicity. Black triangles: stations operating during the whole time period of each panel. Grey triangles: stations that were deployed later. Station "snb" in (c) was substituted by "lod" in 2013. – *Skjálftastaðsetningar (bláir punktar) fyrir þrjú tímabil 1998–2015, gögn frá Veðurstofu Íslands. Fyrir skjálfta innan öskjunnar og vestan Goðabungu eru eingöngu sýndir skjálftar með* M_L *> 1. Fyrir þyrpinguna við Gvendarfell eru sýndir skjálftar með* M_L *> 0. Svartir þríhyrningar: Skjálftamælistöðvar sem gengu allt tímabilið sem sýnt er á kortinu. Gráir þríhyrningar: Stöðvar sem settar voru upp síðar. Stöðinni "snb" var skipt út fyrir "lod" árið 2013.*

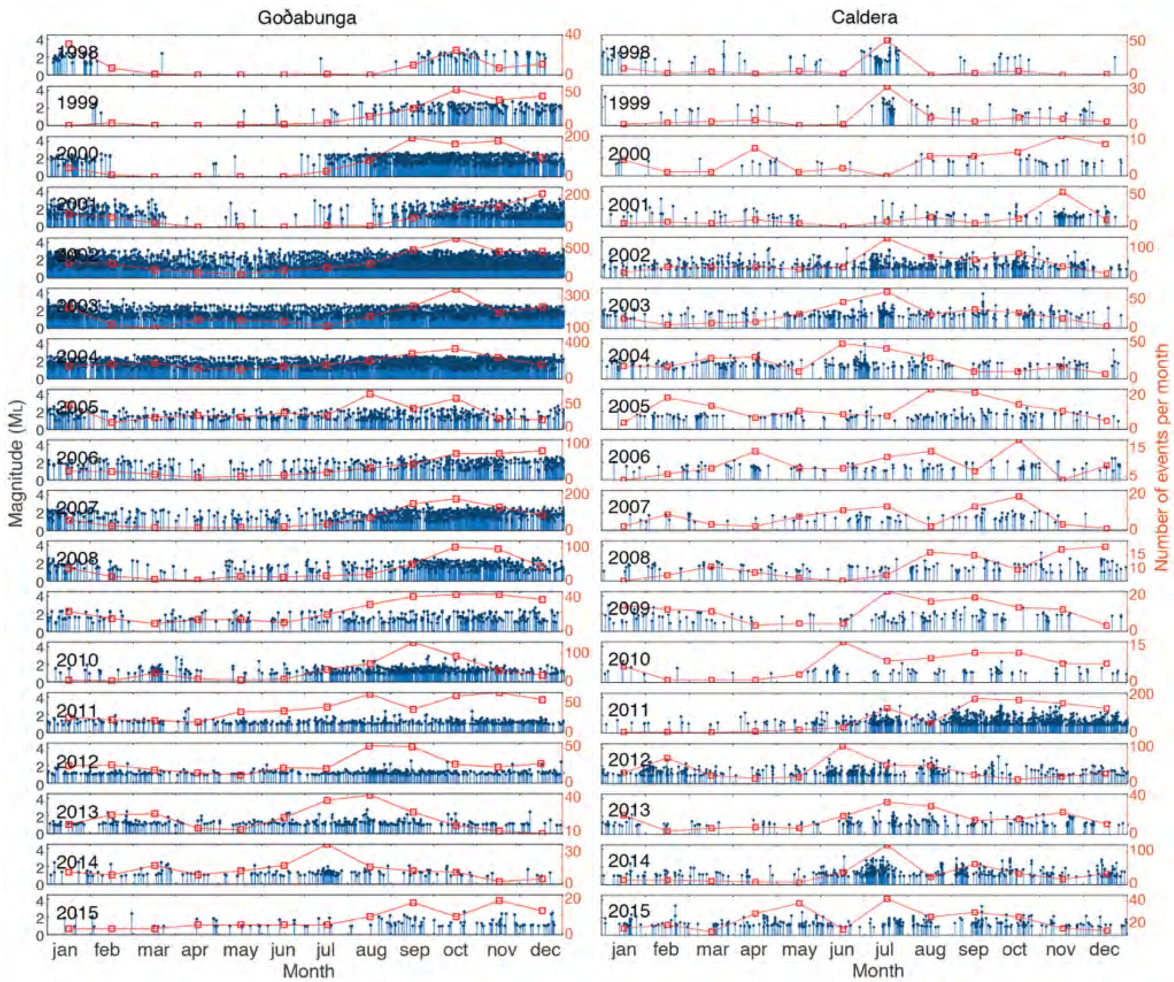

Figure 4. Magnitude-time evolution of the seismicity at Goðabunga (left) and inside the caldera (right) during 1998–2015, from IMO catalogue (events with magnitude M_L>1). – *Stærð teiknuð sem fall af tíma fyrir skjálfta í Goðabungu-þyrpingunni (vinstri) og fyrir skjálfta innan öskjunnar (hægri) á tímabilinu 1998–2015. Skjálftar með* M_L > *1. Gögn frá Veðurstofu Íslands.*

ter described by Soosalu *et al.* (2006) and Jónsdóttir *et al.* (2009) still occurs, but has gradually become less clear. In addition, this peak seems to have shifted to an earlier time of the year, probably reflecting climate and weather changes.

– The seasonal correlation of the caldera seismicity is less pronounced than at Goðabunga (as was already observed in previous studies), but, opposite to Goðabunga, it has become clearer in the past few years, especially in 2012, 2013 and 2014.

– A sharp increase of the seismicity rate inside the caldera occurred in July 2011, coinciding with the unrest episode and jökulhlaup, and continued until the beginning of 2012 with 660 events with M_L>1 and 20 with M_L>2.5.

– The Gvendarfell seismic cluster on the southern flank became active in July 2011. It includes nearly all events located on the southern flank of Katla (Figure 3), with the spread of the hypocenters due to location uncertainty. The size of the cluster is in fact very

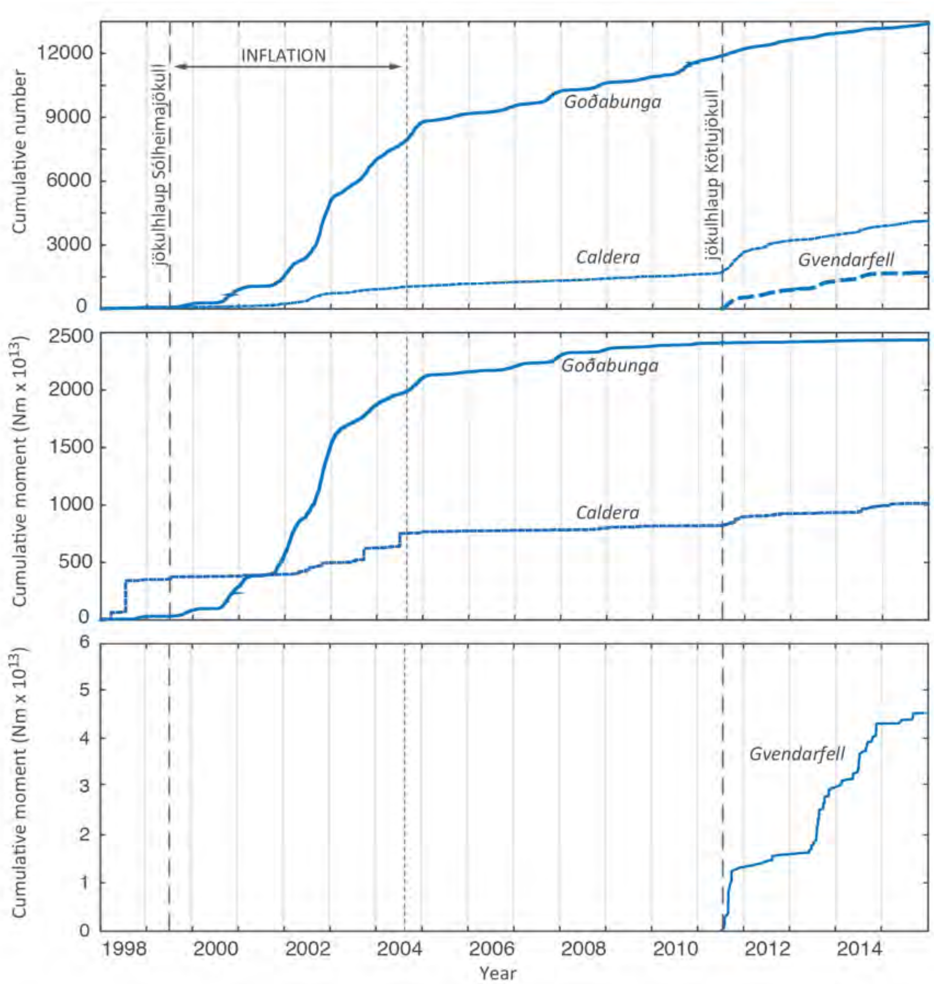

Figure 5. Cumulative number of earthquakes and cumulative seismic moment release during 1998–2015 in the Goðabunga, Caldera and Gvendarfell seismic clusters, from IMO catalogue (events with magnitude M_L > 1). The moment-magnitude relation used is $\log M_0 = 1.5M + 9.1$, where M_0 is the moment and M is the magnitude. The 1999 and 2011 unrest episodes and the inflation period are marked with dashed lines. – *Uppsafnaður fjöldi skjálfta og uppsafnað skjálftavægi skjálfta 1998–2015 í þyrpingunum vestan Goðabungu, innan öskjunnar og við Gvendarfell. Eingöngu eru teknir skjálfta með M_L > 1. Gögn frá Veðurstofu Íslands. Samband milli skjálftastærðar og skjálftavægis er: $\log M_0 = 1.5M + 9.1$, þar sem M_0 er skjálftavægið og M er stærð skjálftans. Atburðirnir 1999 og 2011 og þenslutímabilið 1999–2004 eru sýnd með strikalínum.*

small, on the order of one hundred meters (Sgattoni *et al.,* 2016a). The Gvendarfell seismicity has faded out since September 2017. The intensity of seismicity at Katla volcano as a whole has been low over a similar time scale (IMO data).

GEOLOGICAL FEATURES OF THE GVENDARFELL AREA

A geological field study was carried out outside the southern rim of the Katla caldera near the Gvendarfell ridge, in the vicinity of the new 2011 seismic cluster (Figure 6). This area is partly covered by the Mýrdals-

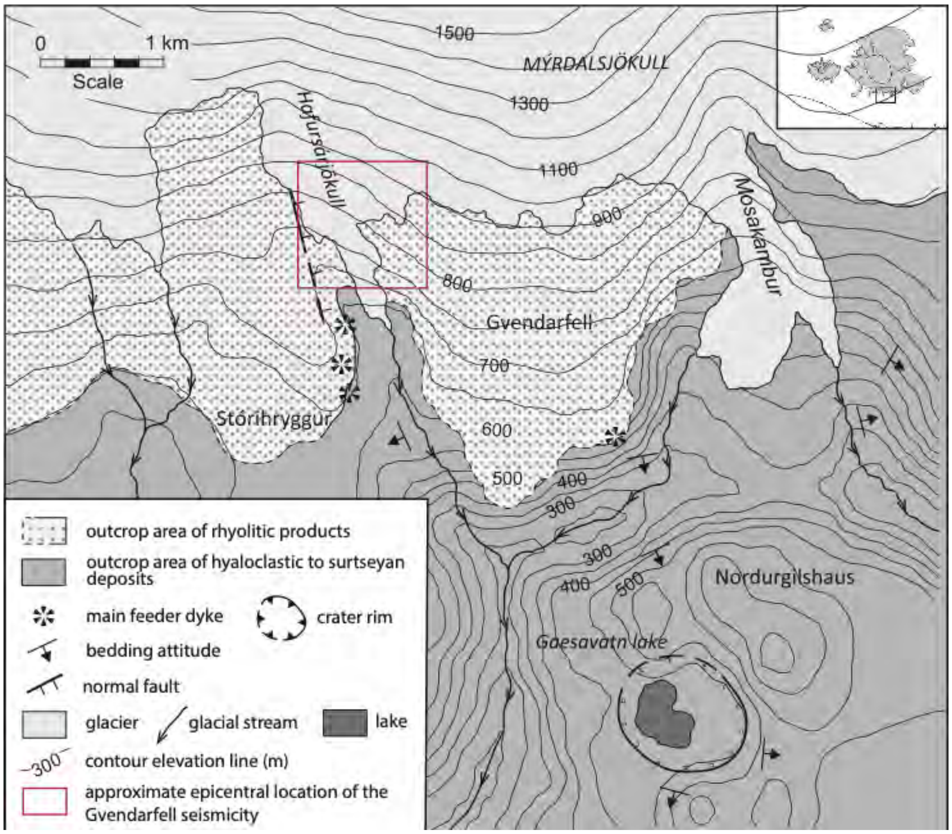

Figure 6. Schematic map of the main geological features observed in the Gvendarfell and Norðurgilshaus area. The approximate location of the Gvendarfell seismic cluster is also drawn with a red box representing the uncertainty of absolute location (Sgattoni *et al.,* 2016a,c). – *Kort af helstu jarðmyndunum svæðisins við Gvendarfell og Norðurgilshaus. Upptakasvæði skjálftanna við Gvendarfell er einnig afmarkað með rauðum ferningi. Stærð hans gefur til kynna óvissu í staðsetningu þyrpingarinnar.*

jökull glacier and the exposed region is characterized by flat-topped ridges bordered by steep ravines eroded by the fast-retreating Hafursárjökull and Mosakambur glacier streams (Figures 6, 7). We carried out a geological field study and lithostratigraphic analysis around the Stórihryggur ridge, whereas it was not possible to directly investigate the flanks of the Gvendarfell ridge. Moreover, we worked in the area around the Gaesavatn lake, to the south-east of Gvendarfell. No signs of recent volcanic or hydrothermal activity have been seen in the whole area.

A hundred-meters thick pile consisting of pale-grey rhyolitic lava lobes and domes (tens-of-meters thick) was identified on the E side of the Stórihryggur ridge. They show concentric to fan-shaped flow bands (Figure 7a) and obsidian-rich margins, embedded within pale fragmented (talus) material. The lavas are characterized by pervasive prismatic, platy and columnar jointing, which is arranged both subvertically and in fan shapes, depending upon the overall morphology of the lava. Where clearly seen, fracture spacing appears to be narrow, on the order of cm to

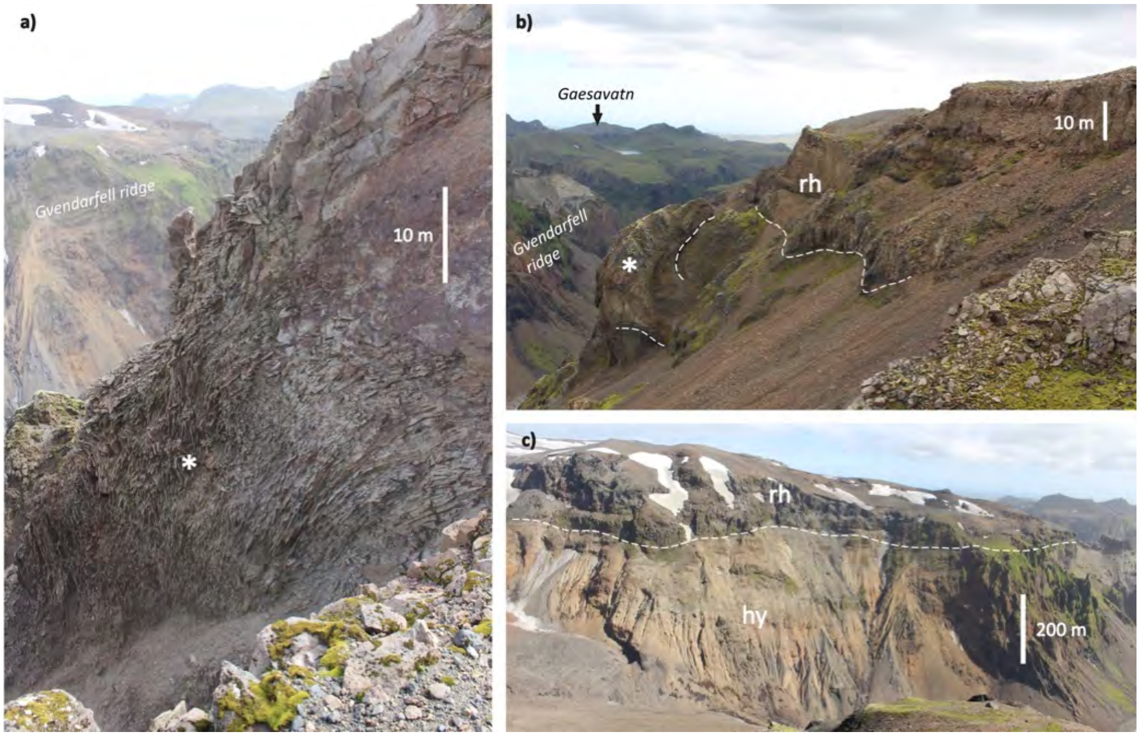

Figure 7. Rhyolitic lavas in the Gvendarfell area. a-b) Pervasively jointed rhyolitic lava lobes (*) and overlying lava flows (rh) along the eastern side of the Stórihryggur ridge. c) Panoramic view of the Gvendarfell ridge from the West with lava flows (rh) lying above yellowish hyaloclastic deposits (hy). – *Rýólít-hraun við Gvendarfell. a-b) rýólít-kubbaberg (*) og hraunlag sem liggur ofan á því (rh), í austurhlíð Stórahryggjar. c) Yfirlitsmynd af Gvendarfelli séð úr vestri, sýnir hraunlag (rh) ofan á gulleitu, súru móbergi (hy).*

tens of cm (Figure 7a,b). Some of these lava bodies display the platy jointing structure typical of lava body interiors (Forbes *et al.,* 2014).

The top of the Stórihryggur ridge consists of a 40–50 meters thick sequence of three viscous lava flow units that gently dip southwards, overlying the lava lobes/domes pile. The lava flows comprise 2–3 metre-thick zones of vertical columnar jointing and glassier texture at tops and bases, which surround a paler-coloured and more crystalline flow interior that is cut by platy fractures (Figure 7b). We collected two samples of the lava flows that were analyzed by David Budd (Budd, 2015). The chemical analysis revealed a rhyolitic composition ranging in SiO_2 from 69 to 72 wt%. Similar lithostratigraphic features are visible also in the upper portion of the Gvendarfell ridge (Figure 7c), both on its western and eastern flanks, although we could not reach the outcrops and investigate directly in the field the rock lithotypes. However, the occurrence of rhyolitic lava deposits in this area is consistent with the petrochemical study of Lacasse *et al.* (2007) and Jóhannesson and Saemundsson (2009) along the southern Katla's caldera rim.

A N-S oriented, sub-vertical cliff along the eastern cliff of the Stórihryggur ridge was interpreted as a normal fault cutting the exposed lava succession with a tens-of-meters displacement (Figures 6, 8). This is confirmed by the evidence for vertical displacement of the lava flow units on the opposite sides of the fault (Figure 8) and by its almost rectilinear and sub-vertical shape. Alternative interpretations as a glacial erosive feature or as a constructional margin of an ice-marginal lava flow (Tuffen *et al.,* 2002) are therefore considered less likely.

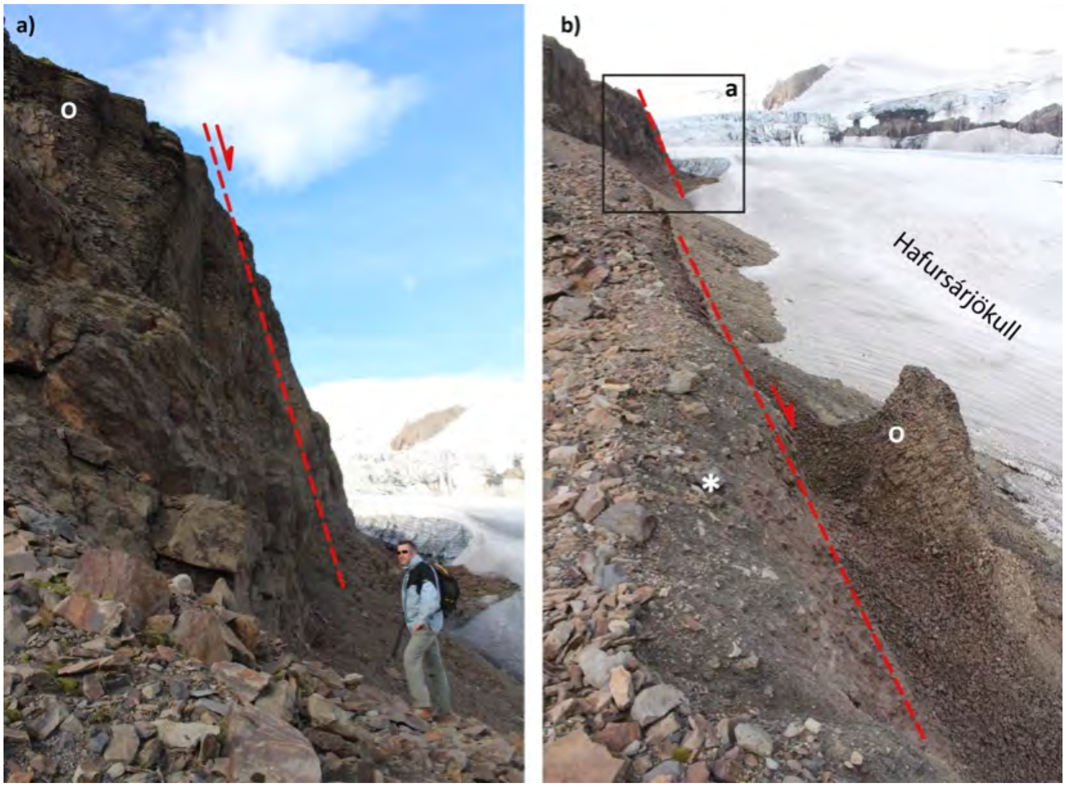

Figure 8. N-S oriented, sub-vertical normal fault along the eastern side of Stórihryggur ridge. Pervasively-jointed rhyolitic lavas (°) are exposed on the opposite sides of the fault with a tens-of-meters vertical displacement. The fault is sealed by a glacial moraine associated to the retreating Hafursárjökull glacier stream (*). – *Nærri lóðrétt siggengi með N-S strikstefnu í austurhlíð Stórahryggjar. Kubbaberg úr rýólíti sést báðum megin misgengisins. Lóðfærslan um misgengið skiptir tugum metra. Misgengið er hulið jökulurð sem tengist hörfun Hafursárjökuls.*

On both sides of the Gvendarfell ridge, in its middle-lower portion, we observed a very thick (up to ∼200–250 m), sequence of dark to yellowish volcaniclastic deposits (Figure 7c), with no base exposed. Their features resemble those of hyaloclastic deposits with palagonitized portions, although it was not possible to closely investigate them, nor the contact relationships with the overlying rhyolitic lavas. The presence of basaltic hyaloclastic deposits in this area is consistent with the petrochemical study of Lacasse *et al.* (2007) and Jóhannesson and Saemundsson (2009). Notably, a crude-layering of these deposits is visible, displaying a radial bedding attitude around the Gvendarfell ridge (Figure 6).

Similar deposits crop out in the surroundings of the Gæsavatn lake (Figures 6, 9a), to the south of Gvendarfell. There, we observed a tens-of-meters thick succession of massive to crudely-stratified yellowish lapilli-tuffs composed of dense black (basaltic) glass fragments, minor vesicular scoriae and rare lithic clasts, with several fine ash and accretionary lapilli-rich layers (Figure 9b). Low-angle cross-stratification and sandwaves (cm- to dm-scale) are visible (Figure 9c), together with a few SW-to-NE directed bomb sags (diameter <10 cm; Figure 9d). These deposits have an overall radial, gentle outward-dip around the Gæsavatn lake, also showing in the NE side of the lake an opposite dip-direction typi-

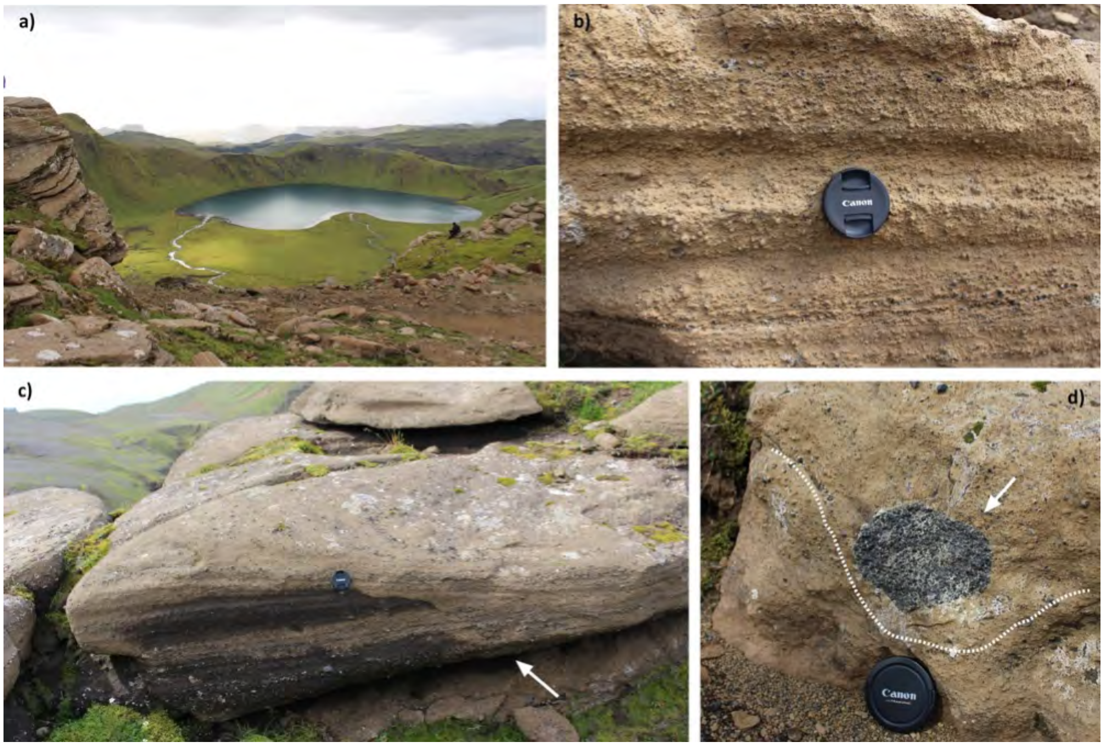

Figure 9. Volcaniclastic deposits exposed along the NE side of Gæsavatn lake (a), with accretionary lapilli-rich layers (b), low-angle cross-stratification (c) and bomb-sags (d). White arrows indicate the SW-to-NE direction of provenance of these deposits based on the bedforms shape (c) and the ballistic trajectory of the bomb sags (d). – *Gjóskulög koma vel fram í sniði norðaustan Gæsavatns (a), með lögum af öskubaunum (b), skálögóttri gjósku (c), og fallförum (d). Hvítar örvar sýna falláttina sem lesa má út úr lagskiptingunni (c) og lögun fallfarsins (d).*

cal of crater rims. Anomalous high-angle dipping (up to 70°) was observed along a tectonically-controlled ravine transverse to the sub-rounded geometry of the lake.

Volcanologic and tectonic implications

Hereafter, we attempt to draw some conclusions about the eruption types and environmental conditions of the volcanic activity in the Gvendarfell area, bearing in mind the difficulty in accessing most of the outcrops.

The most important feature observed is the occurrence of pervasively-jointed rhyolitic lava lobes and domes embedded within fragmented material, interpreted as the products of effusive subglacial rhyolitic eruptions similar to those described e.g. at Torfajökull (Tuffen *et al.,* 2001, 2008; Lescinsky and Fink, 2000), Öræfajökull (Stevenson *et al.,* 2006), Krafla (Tuffen and Castro, 2009) and Prestahnúkur volcanoes (McGarvie *et al.,* 2007). The rhyolitic lava flows at the top of the succession have a distinctive near-horizontal orientation and less pervasive jointing, similar to flat-lying lava flows in the subaerial lava cap of rhyolitic tuyas (e.g. Tuffen *et al.,* 2002). Although we were unable to inspect the flow surface textures and contact relationships in detail, we speculate that these were generated in subaerial conditions. Some of the underlying rhyolitic lava lobes may have acted as feeding points for these lava flows.

Notably, most of the feeder dykes of this lava succession are aligned approximately along a N-S direction, apparently as the continuation of the proposed fault in the E side of the Stórihryggur ridge (Figure 6). We argue that there could have been a NNE-SSW tectonically-controlled magma transport during this activity. More likely, this pattern of radial faulting and (rhyolitic) dyking is a feature of the Katla volcanic stress field (e.g. Burchardt *et al.,* 2018), not of purely tectonic activity. The presence of a number of rhyolitic intrusions around the Gvendarfell ridge is indicative of a main area of lateral magma supply and flank eruption during the eruptive history of Katla. A similar information can be derived from the general radial dip around the Gvendarfell ridge of the hyaloclastic deposits observed along its middle-lower sides.

No radiometric ages are available for these products, which makes it not possible to define chronologically the rhyolitic and tectonic activity identified along the Katla's southern flank around Gvendarfell. The proposed interpretation of lavas erupted in subglacial to subaerial environmental conditions suggests that these lavas were most likely emplaced before (or during) the Last Glacial Maximum (LGM), that occurred in Iceland around 21 ka BP (Norðdahl, 1991). This corresponds to a generic pre-Holocene age as suggested by Lacasse *et al.* (2007) and Jóhannesson and Saemundsson (2009). This is also coherent with the presence of deep ravines that were most likely eroded by retreating glacier streams after the LGM. However, the possibility that volcanic and tectonic processes have been active in the Gvendarfell area during the Holocene cannot be ruled out.

The features of the deposits exposed in the area of Gæsavatn are those of basaltic, palagonitized products of dilute pyroclastic density currents (PDC) and ballistic fallout typical of Surtseyan eruptions developed in shallow-water to subaerial conditions. Their radial outward bedding attitude describe a tuff cone structure centred on the lake, which is also consistent with the bomb sag direction and the route of PDCs inferred from the bedform shapes (Figure 9c, d). Overall, the lithologies observed here are broadly similar to those described at the Varda tuff cone in southwest Öræfajökull (Smellie *et al.,* 2016), but without complex subsidence attributed to ice block melt-out. The presence of the Gæsavatn tuff cone demonstrates that the deposits of the southern flank of Katla are not entirely of subglacial origin, as is commonly assumed (Lacasse *et al.,* 2007; Jóhannesson and Saemundsson, 2009).

DISCUSSION

The July 2011 unrest coincided with the beginning of a period of elevated earthquake activity within the caldera and the beginning of a new cluster of earthquakes on the southern flank of the volcano. Moreover, since 2011 the seismicity rate has become higher inside the caldera than at Goðabunga, opposite to previous patterns. These noteworthy changes are likely related to modifications in the volcanic system, as also indicated by slight ground deformation consistent with inflation observed with GPS between 2011 and 2012 (B.G. Ófeigsson and S. Hreinsdóttir, pers. comm.). However, it is not simple to constrain the origin of these changes, as this unrest, similarly to the 1955 and 1999 episodes, was not accompanied by direct indications of volcanic activity or a clear deformation field.

As Katla is partly covered by a glacier, it is possible that a part of its persistent seismicity is related to glacial processes, since volcanic and glacial processes can produce similar waveforms (Weaver and Malone, 1976; West *et al.,* 2010). The controversial interpretation of the Goðabunga seismic cluster is an example (Soosalu *et al.,* 2006; Jónsdóttir *et al.,* 2009). Also the ground deformation has controversial interpretations: the 1999–2004 inflation episode has been interpreted in association with either magma accumulation inside the volcano (Sturkell *et al.,* 2006, 2008) or glacial rebound (Spaans *et al.,* 2015). In this respect, we note that the ground deformation notably coincided with a seismic crisis at Goðabunga that has had no observed equals since and started after the 1999 unrest episode, when jökulhlaup and ice cauldron formation occurred. A similar trend has characterized the 2011 unrest, although with a less clear deformation pattern, and is interpreted by Sgattoni *et al.* (2017) as originating from volcano-related (magmatic or hydrothermal) rather than glacial processes. Therefore, we suggest that volcanic processes generally dominate as a source for seismic activity at Katla.

An influence of the glacial system is outlined by the typical summer peaks of seismicity occurring inside the Katla caldera. They are frequently associated with small jökulhlaups or increased water drainage from the glacier, and with changes in the chemical composition of the water discharged (Wynn *et al.,* 2015). Seasonal variations in the glacial-geothermal system may be responsible for these summer peaks, as suggested by Wynn *et al.* (2015). However, in the 1955, 1999 and 2011 unrest episodes, the jökulhlaups have been particularly catastrophic and have been accompanied by an increased seismicity rate and occasionally by tremor (in 1999 and 2011), indicating a more dramatic change in the volcanic/geothermal system than usual.

The 2011 unrest was associated with increased heat released by the volcano as indicated by the water accumulation under the glacier that started a year before (Guðmundsson *et al.,* 2014). The tremor and sudden sinking of ice cauldrons and jökulhlaup that occurred in July 2011 may have been due to a geothermal event, a volcanic (magmatic) event such as a subglacial eruption or a combination of the two, such as a shallow magma intrusion leading to increased geothermal activity. It is not straightforward to draw conclusions about whether a subglacial eruption occurred. According to Galeczka *et al.* (2015), the chemical analysis of floodwater does not show evidence that the water came into contact with magma. The analysis of the tremor conducted by Sgattoni *et al.* (2017) suggests that most of the signal is associated with volcano-related processes occurring at the sites of the active cauldrons and an additional small portion of the signal is associated with the flood itself. The duration of the tremor and the inferred flood velocity are consistent with the tremor burst having been generated by boiling phenomena and/or explosions induced by the water release from the hydrothermal system. This would imply that a geothermal source may have sufficed to generate the tremor and the flood, with no need for a magmatic event. However, the notable increase of seismic activity inside the caldera that continued for months after the jökulhlaup is hardly consistent with an exclusively geothermal event and may indicate that the unrest did involve magma, although no eruptive products were identified (Sgattoni *et al.,* 2017). Concerning this, it must be noted that, in a subglacial volcano like Katla, small eruptions may escape the geological and historical records because they are concealed by the glacier.

In addition to the tremor and increased caldera seismicity, the 2011 unrest marked also the activation of a new seismic source on the southern flank. Sgattoni *et al.* (2016b) suggested that this seismicity may be associated with a shallow hydrothermal system activated in association with the unrest episode, although no direct evidence of hydrothermal activity was found. However, a possible connection to magmatic processes cannot be ruled out. The geological study of the Gvendarfell area demonstrated that the southern flank of Katla acted as the locus of both tectonic activity and flank eruptions fed by radial dykes outside the caldera during its pre-Holocene (to recent?) history. We have identified two areas of magma ascent, corresponding to the Gvendarfell ridge and the Gæsavatn lake, which indicates that volcanic activity has already occurred close to the area where the current south-flank seismicity is recorded. Therefore, it cannot be excluded that the Gvendarfell seismic cluster is related to renewed eruptive processes. The lava bodies of silicic composition exposed in the Gvendarfell area are comparable in size to the volume occupied by the hypocenter distribution that was obtained from relative location (Sgattoni *et al.,* 2016a). Thus, the intrusion of a similar lava body should be taken into account as a possible source for the seismic events, but clearly the depth of intrusion will significantly influence the nature of associated geophysical signals. As demonstrated by Krafla central volcano, rhyolitic intrusion depths may vary from kilometres (e.g. the rhyolitic magma intercepted by IDDP-1 borehole at Krafla at a depth of 2.1 km; Elders *et al.,* 2011) to superficial intrusions beneath ice only tens of metres in thickness (Tuffen and Castro, 2009).

Our reconstruction has profound implications on Katlas's hazard potential. We in fact observed that both basaltic and rhyolitic volcanic activity outside of the caldera seems controlled by radial dykes that can cause flank eruptions of different compositions. Moreover, activity in the caldera (likely controlled by magma ascent along the ring faults) can be connected to or trigger activity outside the caldera, as observed in 2011. Inside the caldera, any surface activity (geothermal or magmatic) is influenced by ice, while magma transport to the flank can lead to subaerial activity, because the flanks are (currently) to a large degree ice-free. This deeply influences what sort of hazards can be expected at Katla in case of volcanic reactivation. In light of this, further studies are needed to better constrain the volcanic history and environment of eruptions and intrusions on the southern flank, preferably combined with radiometric dating.

The potential involvement of magma during the unrest episodes is not supported by clear signs of surface deformation in the recent activity of Katla. This might be explained by very shallow processes responsible for the persistent seismicity, sometimes evolving into real seismic crises. If, for example, a shallow magma chamber exists, as postulated by Guðmundsson *et al.* (1994) and supported by more recent studies (Budd *et al.,* 2016; Jeddi *et al.,* 2016), and the unrest episodes are related to small batches of magma reaching or approaching the surface, the associated deformation signal might be negligible and hidden beneath the glacier. In this scenario, it is important to note that the 1955, 1999 and 2011 unrest episodes occurred in different parts of the caldera, indicating that a large portion of the volcanic system has been activated recently.

Although no evidence of large-scale inflation is currently observed at Katla, the possibility that the volcano is preparing for an eruption cannot be discarded. It is not unlikely that the edifice is already in an inflated state that was reached before the deformation measurements started. At Krafla, for example, inflation of the edifice immediately followed the 1975–1984 rifting episode, and then since 1989 the volcano has been slowly deflating, but the pressure of the magma system is currently on the same order as before the rifting episode (Buck *et al.,* 2006). The scenario at Katla may be similar and rapid inflation might have occurred after the 1918 eruption. Accordingly, the persistent seismicity may reflect the processes taking place in a pressurized system persistently close to failure. The 1955, 1999 and 2011 episodes might be signs of this. If this was the case, these unrest episodes would represent important warnings, because they occurred suddenly with no precursory activity and could have triggered a larger eruption, or could do so in the future.

CONCLUSIONS

The 2011 unrest episode at Katla was characterized by a sudden jökulhlaup, tremor bursts originating at the source of the water flood (where ice cauldrons deepened), increased earthquake activity within the caldera and the appearance of a new source of persistent earthquakes on the southern flank. This marked a clear change of the long-term seismicity pattern, as outlined by the analysis of the 1998–2015 seismic catalogue, that likely highlights a modification of the volcanic system, possibly involving magma movements.

The 2011 unrest, similarly to the 1955 and 1999 episodes, was likely associated with hydrothermal processes or magma movement, possibly a small subglacial eruption. All unrest episodes were apparently accompanied by only small deformation fields. In the absence of evidence for recent large-scale recharging of a magma chamber beneath Katla, it may be speculated whether Katla is already in an inflated state, having inflated immediately following the most recent large eruption in 1918. This may be the cause of the persistent seismicity at Katla.

During a pilot study of the geology of the southern flank in the source area of the new seismicity we have found evidence that flank eruptions occurred during the pre-Holocene (to recent) history of the volcano. We have identified two sources in particular, one corresponding to the Gvendarfell ridge, and the other one to Gæsavatn lake, documenting subglacial to surtseyan, basaltic to rhyolitic volcanic activity. This highlights new scenarios for Katla's eruptive history and future activity and suggests that magmatic intrusions on its flanks should not be neglected as a potential seismic source.

Acknowledgements

The authors would like to thank the Icelandic Meteorological Office for access to catalogue data from the permanent seismic network. We thank Hugh Tuffen, whose valuable suggestions helped improve the analysis of the geological data. This work was funded by the University of Bologna, University of Iceland and Uppsala University, as a part of a joint PhD project. We thank the sheriff in Vík for logistic support. The Generic Mapping Tool (Wessel *et al.,* 2013) was used to produce some of the graphics.

Ágrip

Katla er meðal virkustu eldstöðva Íslands og hegðun hennar síðustu áratugi hefur einkennst af stöðugri skjálftavirkni. Eldstöðin er að talsverðu leyti hulin jökli og flest þekkt gos á sögulegum tíma hafa verið undir þykkum jökli innan öskju hennar. Þeim hafa því fylgt stór jökulhlaup. Í júlí 2011 varð snöggt jökulhlaup sem tók af brúna yfir Múlakvísl. Þessum atburði fylgdi óróahviða, aukin skjálftavirkni innan öskjunnar og ný skjálftaþyrping við Gvendarfell sunnan hennar. Líklegustu skýringar á þessum breytingum eru að annað hvort hafi orðið breytingar á jarðhitakerfi eða kvikuinnskot, hugsanlega lítið eldgos undir jöklinum. Svipaðir atburðir urðu 1955 og 1999. Rannsóknir á skjálftavirkninni sem fylgdi atburðunum 2011 leiða í ljós breytingar á eldstöðvarkerfi Kötlu. Leiða má rök að því að hin þráláta skjálftavirkni sé vísbending um að kvikukerfið sé undir þrýstingi, hugsanlega nálægt brotmörkum sínum og tilbúið til goss. Litlir kvikutengdir atburðir, líkir þeim sem urðu 1955, 1999 og 2011, gætu því verkað sem gikkir fyrir stærri atburði. Skjálftaþyrpingin við Gvendarfell beinir athyglinni að suðurhlíðum eldstöðvarinnar. Suðurbrún Kötluöskjunnar einkennist af súrum gosmyndunum og hraungúlum. Einnig má finna í Mýrdalsfjöllunum forna öskugíga með ummerkjum um surtseysk gos, t.d. Gæsavatn. Þessar frumathuganir benda til þess að huga þurfi að fjölbreytilegri sviðsmyndum Kötlugosa en hingað til hefur verið gert.

REFERENCES

Björnsson, H., F. Pálsson and M.T. Guðmundsson 2000. Surface and bedrock topography of the Mýrdalsjökull ice cap, Iceland: The Katla caldera, eruption sites and routes of jökulhlaups. *Jökull* 49, 29–46.

Brandsdóttir, B. and P. Einarsson 1992. Volcanic tremor and low-frequency earthquakes in Iceland. In: Gasparini P. and K. Aki (ed.) *Volcanic Seismology*, Springer Verlag, Berlin, Heidelberg, 212–222.

Buck, W.R., P. Einarsson and B. Brandsdóttir 2006. Tectonic stress and magma chamber size as controls on dike propagation: Constraints from the 1975–1984 Krafla rifting episode. *J. Geophys. Res. Solid Earth* 111, 1–15. https://doi.org/10.1029/2005JB003879

Budd, D.A. 2015. *Characterising volcanic magma plumbing systems: A tool to improve eruption forecasting at hazardous volcanoes.* PhD dissertation, Uppsala University, 42 pp.

Budd, D.A., V.R. Troll, B. Dahren and S. Burchardt 2016. Persistent multitiered magma plumbing beneath Katla volcano, Iceland. *Geochem. Geophys. Geosyst.* 17, 966–980. https://doi.org/10.1002/2015GC006118

Burchardt, S., T.R. Walter and H. Tuffen 2018. Growth of a volcanic edifice through plumbing system processes-volcanic rift zones, magmatic sheet-intrusion swarms and long-lived conduits. In: Burchardt, S. (ed.) *Volcanic and Igneous Plumbing Systems Understanding Magma Transport, Storage, and Evolution in the Earth's Crust.* Elsevier, pp. 89–112.

Eggertsson, S. 1919. Ýmislegt smávegis viðvíkjandi Kötlugosinu 1918. *Eimreiðin* 25, 212–222.

Einarsson, E.H., G. Larsen and S. Thorarinsson 1980. The Sólheimar tephra layer and the Katla eruption of $\sim$1357. *Acta Naturalia Islandica* 28, 2–23.

Einarsson, P. and K. Sæmundsson 1987. Earthquake epicenters 1982–1985 and volcanic systems in Iceland. In: Sigfússon, Þ.I. (ed.). *Í hlutarins eðli, Festschrift for Þorbjörn Sigurgeirsson.* Menningarsjóður, Reykjavík (map).

Einarsson, P. 1991. Earthquakes and present-day tectonism in Iceland. *Tectonophysics* 189, 261–279.

Einarsson, P. and B. Brandsdóttir 2000. Earthquakes in the Mýrdalsjökull area, Iceland, 1978–1985: Seasonal correlation and relation to volcanoes. *Jökull* 49, 59–73.

Einarsson, P. and Á.R. Hjartardóttir 2015. Structure and tectonic position of the Eyjafjallajökull volcano, S-Iceland. *Jökull* 65, 1–16.

Elders, W.A., G.Ó. Friðleifsson, R.A. Zierenberg , E.C. Pope, A.K. Mortensen, Á. Guðmundsson, J.B. Lowenstern, N.E. Marks, L. Owens, D.K. Bird, M. Reed, N.J. Olsen and P. Schiffman 2011. Origin of a rhyolite that intruded a geothermal well while drilling at the Krafla volcano, Iceland. *Geology* 39(3), 231–234. https://doi.org/10.1130/G31393.1

Galeczka, I., E.H. Oelkers and S.R. Gislason 2014. The chemistry and element fluxes of the July 2011 Múlakvísl and Kaldakvísl glacial floods, Iceland. *J. Volcanol. Geotherm. Res.* 273, 41–57. https://doi.org/-10.1016/j.jvolgeores.2013.12.004

Guðmundsson, Ó., B. Brandsdóttir, W. Menke and G.E. Sigvaldason 1994. The crustal magma chamber of the Katla volcano in South Iceland revealed by 2-D seismic undershooting. *Geophys. J. Int.* 119, 277–296.

Guðmundsson, M.T., Þ. Högnadóttir, A.B. Kristinsson and B. Guðbjörnsson 2007. Geothermal activity in the subglacial Katla caldera, Iceland, 1999–2005, studied with radar altimetry. *Ann. Glaciol.* 45, 66–72.

Guðmundsson, M.T. and J. Sólnes 2013. Activity at Katla and jökulhlaup in Múlakvísl river 2011 (in Icelandic). In: Sólnes J., F. Sigmundsson, and B. Bessason (eds.). *Natural Hazard in Iceland: Volcanic eruptions and earthquakes.* University of Iceland Press, 228–229 (in Icelandic).

Jeddi, Z., A. Tryggvason and Ó. Gudmundsson 2016. The Katla volcanic system imaged using local earthquakes recorded with a temporary seismic network. *J. Geophys. Res. Solid Earth* 121, 7230–7251. https://doi.org/10.1002/2016JB013044

Jeddi Z., G. Sgattoni, Ó. Guðmundsson, A. Tryggvason and B. Lund 2017. A peculiar cluster of microearthquakes on the eastern flank of Katla volcano, southern Iceland. *Jökull* 67, 1–16.

Jonsson, G. and L. Kristjánsson 2000. Aeromagnetic measurements over Mýrdalsjökull and vicinity. *Jökull* 49, 47–58.

Jóhannesson, H. and K. Sæmundsson 2009. *Geological Map of Iceland, 1:600.000. Bedrock Geology.* Icelandic Institute of Natural History, Reykjavík (1st ed.).

Jónsdóttir, K., R. Roberts, V. Phjola, B. Lund, Z.H. Shomlai, A. Tryggvason and R. Böðvarsson 2009. Glacial long period seismic events at Katla volcano, Iceland. *Geophys. Res. Lett.* 36, L11402.

Jónsdóttir, K., A. Tryggvason, R. Roberts, B. Lund, H. Soosalu and R. Böðvarsson 2007. Habits of a glacier covered volcano: seismicity and a structure study of the Katla volcano, South Iceland. *Ann. Glaciol.* 45, 169–177.

Lacasse, C., H. Sigurðsson, S.N. Carey, H. Jóhannesson, L.E. Thomas and N.W. Rogers 2007. Bimodal volcanism at the Katla subglacial caldera, Iceland: Insight into the geochemistry and petrogenesis of rhyolitic magmas. *Bull. Volcanol.* 69, 373–399.

Larsen, G. 2000. Holocene eruptions within the Katla volcanic system, south Iceland: characteristics and environmental impact. *Jökull* 49, 1–28.

Larsen, G., A.J. Newton, A.J. Dugmore and E.G. Vilmundardóttir 2001. Geochemistry, dispersal, volumes and chronology of Holocene silicic tephra layers from the Katla volcano system, Iceland. *J. Quat. Sci.* 16, 119–132.

Lescinsky, D.T. and J.H. Fink 2000. Lava and ice interaction at stratovolcanoes: use of characteristic features to determine past glacial extents and future volcanic hazards. *J. Geophys. Res.* 105(B10), 23711–23726.

Major, J.J. and C.G. Newhall 1989. Snow and ice perturbation during historical volcanic eruptions and the formation of lahars and floods. *Bull. Volcanol.* 52, 1–27. https://doi.org/10.1007/BF00641384.

McGarvie, D. 2009. Rhyolitic volcano-ice interactions in Iceland. *J. Volcanol. Geotherm. Res.* 185, 367–389. https://doi.org/10.1016/j.jvolgeores.2008.11.019.

Norðdahl, H. 1991. Late Weichselian and Early Holocene deglaciation of Iceland. *Jökull* 40, 27–50.

Óladóttir, B.A., G. Larsen, Th. Thordarson and O. Sigmarsson 2005. The Katla volcano, S-Iceland: Holocene tephra stratigraphy and eruption frequency. *Jökull* 55, 53–74.

Óladóttir, B. A., O. Sigmarsson, G. Larsen and Th. Thordarson 2008. Katla volcano, Iceland: Magma composition, dynamics and eruption frequency as recorded by Holocene tephra layers. B. Volcanol. 70, 475–493. https://doi.org/10.1007/s00445-007-0150-5.

Roberts, M.J., F.S. Tweed, A.J. Russell, Ó. Knudsen and T.D. Harris 2003. Hydrological and geomorphic effects of temporary ice-dammed lake formation during jökulhlaups. *Earth Surf. Processes Landforms* 28, 723–737.

Sæmundsson, Þ., J.M.-C. Belart, P. Einarsson, H. Geirsson, Á.R. Hjartardóttir, E. Magnússon, F. Pálsson and G.B.M. Pedersen 2020. Slope deformation above the Tungnakvíslarjökull outlet glacier in western part of the Mýrdalsjökull glacier – causes and consequences. Nordic Geological Winter Meeting, January 8-10, 2020, Oslo, Norway. Abstract Volume.

Sigurðsson, O., S. Zóphoníasson and E. Ísleifsson 2000. Jökulhlaup úr Sólheimajökli 18. júlí 1999 (The jökulhlaup from Sólheimajökull July 18, 1999, in Icelandic with English summary). *Jökull* 49, 75–80.

Sgattoni, G., Ó. Gudmundsson, P. Einarsson and F. Lucchi 2016a. Joint relative location of earthquakes without a predefined velocity model: an example from a peculiar seismic cluster on Katla volcano's south-flank (Iceland). *J. Geophys. Int.* 207(2), 1244–1257. https://doi.org/10.1093/gji/ggw331.

Sgattoni, G, Z. Jeddi, Ó. Gudmundsson, P. Einarsson, A. Tryggvason, B. Lund and F. Lucchi 2016b. Long-period seismic events with strikingly regular temporal patterns on Katla volcano's south flank (Iceland). *J. Volcanol. Geotherm. Res.* 324, 28–40.

Sgattoni, G., Ó. Gudmundsson, P. Einarsson, F. Lucchi, K.L. Li, H. Sadeghisorkhani, R. Roberts and A. Tryggvason 2017. The 2011 unrest at Katla volcano: characterization and interpretation of the tremor sources. *J. Volcanol. Geotherm. Res.* 338, 63–78. https://doi.org/-10.1016/j.jvolgeores.2017.03.028

Soosalu, H., K. Jónsdóttir and P. Einarsson 2006. Seismicity crisis at the Katla volcano, Iceland – signs of a cryptodome? *J. Volcanol. Geotherm. Res.* 153, 177–186.

Spaans, K., S. Hreinsdóttir, A. Hooper and B.G. Ófeigsson 2015. Crustal movements due to Iceland's shrinking ice caps mimic magma inflow signal at Katla volcano. *Sci. Rep.* 5, 10285. https://doi.org/10.1038/srep10285.

Stefánsson, R., R. Böðvarsson, R. Slunga, P. Einarsson, S. Jakobsdóttir, H. Bungum, S. Gregersen, J. Havskov, J. Hjelme and H. Korhonen 1993. Earthquake prediction research in the south Iceland seismic zone and the SIL project. *Bull. Seismol. Soc. Am.* 83(3), 696–716.

Stevenson, J.A., D.W. McGarvie, J.L. Smellie and J.S. Gilbert 2006. Subglacial and ice-contact volcanism at the Öræfajökull stratovolcano, Iceland. *Bull. Volcanol.* 68, 737–752. https://doi.org/10.1007/s00445-005-0047-0.

Sturkell, E., P. Einarsson, F. Sigmundsson, H. Geirsson, H. Ólafsson, R. Pedersen, E. de Zeeuw-van Dalfsen, A.T. Linde, S.I. Sacks and R. Stefánsson 2006. Volcano geodesy and magma dynamics in Iceland. *J. Volcanol. Geotherm. Res.* 150, 14–34. https://doi.org/-10.1016/j.jvolgeores.2005.07.010.

Sturkell, E., P. Einarsson, M.J. Roberts, H. Geirsson, M.T. Guðmundsson, F. Sigmundsson, V. Pinel, G.B. Guðmundsson, H. Ólafsson and R. Stefánsson 2008. Seismic and geodetic insights into magma accumulation at Katla subglacial volcano, Iceland: 1999 to 2005. *J. Geophys. Res.* 113(B03212).

Sveinsson, G. 1919. Kötlugosið 1918 og afleiðingar thess (The Katla eruption of 1918 and its consequences). Reykjavík, Prentsmiðja Gutenbergs, pp. 61.

Sæmundsson, K. 1982. Calderas in active volcanic regions in Iceland (in Icelandic). *Eldur er í Norðri*, Reykjavík, Sögufélag, 221–239.

Thorarinsson, S. 1975. Katla og annáll Kötlugosa. *Árbók Ferðafélags Íslands.* Reykjavík, 125–149.

Thordarson, Th. and G. Larsen 2006. Volcanism in Iceland in historical time: Volcano types, eruption and eruptive history. *J. Geodyn.* 43, 118–152. https://doi.org/-10.1016/j.jog.2006.09.005

Thordarson, T., D.J. Miller, G. Larsen, S. Self and H. Sigurðsson 2001. New estimates of sulfur degassing and atmospheric mass-loading by the 934 AD Eldgjá eruption, Iceland. *J. Volcanol. Geotherm. Res.* 108, 33–54.

Tuffen, H. and J.M. Castro 2009. The emplacement of an obsidian dyke through thin ice: Hrafntinnuhryggur, Krafla Iceland, *J. Volcanol. Geotherm. Res.* 185(4), 352–366.

Tuffen, H., D.W. McGarvie, H. Pinkerton, J.S. Gillbert and R.A. Brooker 2008. An explosive-intrusive subglacial rhyolite eruption at Dalakvisl, Torfajokull, Iceland. *Bull. Volcanol.* 70, 841–860.

Tuffen, H., J. Gilbert and D.W. McGarvie 2001. Products of an effusive subglacial rhyolite eruption: Bláhnúkur, Torfajökull, Iceland. *Bull. Volcanol.* 63, 179–190.

Vogfjörð, K. and R. Slunga 2008. Imaging subsurface mass movement through relative earthquake locations in the Katla volcano, Iceland, and the possible location of a magma chamber. Reykjavík, Iceland, IAVCEI General Assembly.

Weaver, C.S. and S.D. Malone 1979. Seismic evidence for discrete glacier motion at the rock-ice interface. *J. Glaciol.* 23, 171– 184.

Wessel, P., W.H.F. Smith, R. Scharroo, J.F. Luis and F. Wobbe 2013. Generic Mapping Tools: Improved version released. *Eos Trans. AGU*, 94, 409–410. https://doi.org/10.1002/2013EO450001

West, M.E., C.F. Larsen, M. Truffer, S. O'Neel and L. LeBlanc 2010. Glacier microseismicity. *Geology* 38(4), 319–322. https://doi.org/10.1130/G30606.1.

Wynn, P.M., D.J. Morrell, H. Tuffen, P. Barker, F.S. Tweed and R. Burns 2015. Seasonal release of anoxic geothermal meltwater from the Katla volcanic system at Sólheimajökull, Iceland. *Chem. Geol.*| 396, 228–238. https://doi.org/10.1016/j.chemgeo.2014.12.026.