Reviewed research article

Seismicity observed under the Snæfellsjökull volcano

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Abstract — The Snæfellsnes peninsula in western Iceland is characterized by Pleistocene volcanism dominated by alkalic magmatism across an extinct (> 6 Ma) axial rift zone of the Mid-Atlantic Ridge. Although Iceland has an extensive seismic coverage, no systematic seismic monitoring is in place on the Snæfellsnes peninsula. In this paper, we present results of a three months field campaign in the Snæfellsnes peninsula and show for the first time that the region is (micro) seismically active in the depth range of 8–15 km. We identified and located a total of 29 seismic events that occurred in close proximity of the Snæfellsjökull volcano, with most events clustering beneath the volcano in swarm sequences. We propose that seismicity is associated with fluid-induced fracturing related to one or more magmatic reservoir(s), which may be elucidated in future seismic campaigns. Our observations are the first step towards the understanding of the plumbing system of the Snæfellsjökull volcano.

INTRODUCTION

Volcanic and seismic activity in Iceland are driven by the interaction of the Mid-Atlantic Ridge and the Icelandic Plume (Einarsson, 2008, Jakobsdóttir, 2008; Mjelde *et al.*, 2008). Seismicity concentrates along the Mid-Atlantic Ridge cutting through Iceland and separating the north-American and Eurasian plates. Seismic activity is particularly intense in the South Icelandic Seismic Zone (SISZ) and in the Tjörnes Fracture Zone (TFZ) (see inset in Figure 1), which are two transform fracture zones that accommodate the offset of the Mid-Atlantic Ridge (Stefánsson *et al.*, 2006; Stefánsson *et al.*, 2008). The axial rift was located in the Western Fjords (WF) at 15 Ma and then moved east towards the Icelandic plume, intercepting the Snæfellsnes peninsula and the Skagi peninsula around 7 Ma (Martin *et al.*, 2011).

Previous studies of the Snæfellsnes peninsula focused on constraining the evolution of the neovolcanic zone and dating volcanic activity (Jóhannesson, 1980, 1982a,b; Hardarson and Fitton, 1991; Kokfelt *et al.*, 2009; Martin and Sigmarsson, 2010; Martin *et al.*, 2011, and references therein). Figure 1 shows the outlines of volcanic systems found on the Snæfellsnes peninsula. Sigurdsson (1970) and Jóhannesson (1982b) pointed out the existence of WNW-ESE trending en-echelon lineaments identified by the alignment of volcanic structures and vents. Interestingly, the orientation of these lineaments is perpendicular to en-echelon patterns observed in the neighbouring Western Volcanic Zone and in the South Icelandic Seismic Zone.

The Snæfellsnes peninsula hosts three volcanic systems that form the Snæfellsnes Volcanic Belt (SVB). The central volcano Snæfellsjökull is located on the westernmost tip of the peninsula (Figure 1) and its last rhyolitic explosive eruption has been dated to 1750 BP by Steinþórsson (1967). Located fur-

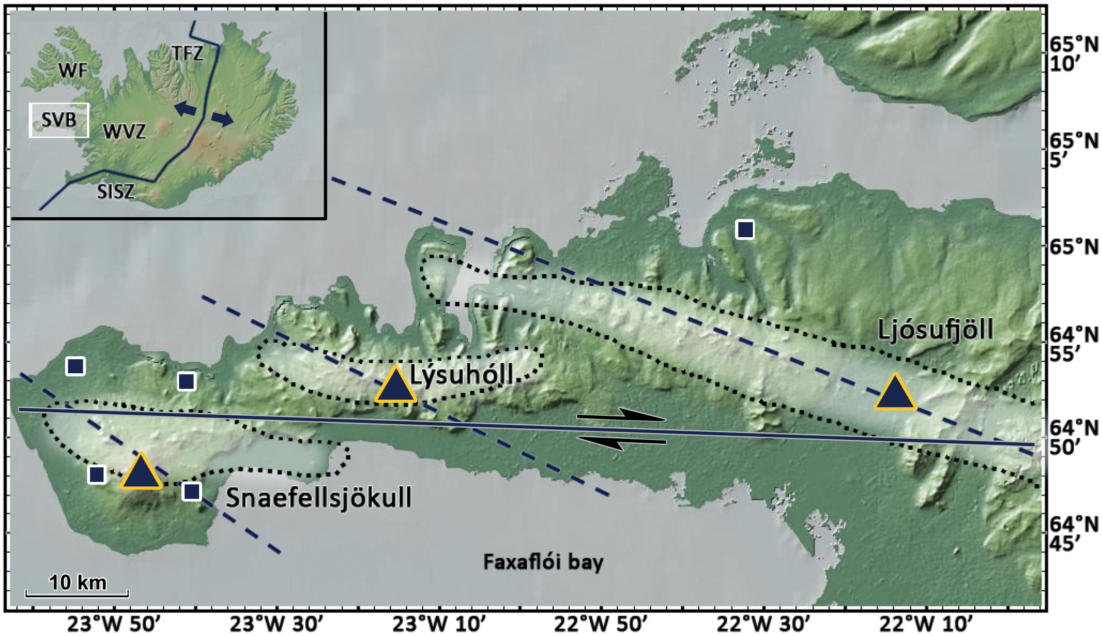

Figure 1. Map of the Snæfellsnes peninsula showing the Snæfellsjökull, Lýsuhóll, and Ljósufjöll volcanic centers (triangles) as well as the orientation of geological lineaments described by Sigurdsson (1970) (dashed lines). The shaded regions mark distributions of volcanic systems in the region. The location of the inferred transcurrent fault is indicated by the east-west trending solid line. The positions of our seismic stations are denoted by squares. – *Kort sem sýnir eldstöðvakerfin á Snæfellsnesi, sem kennd eru við Snæfellsjökul, Lýsuhól og Ljósufjöll (þríhyrningar og punktalínur), sem og línur gegnum gýgaraðir, sem Haraldur Sigurðsson lýsir í grein sinni frá 1970 (strikalínur). Staðsetning austur-vestur brotalínu, sem nefnd er í sömu grein er sýnd með heilli línu. Staðsetning jarðskjálftastöðvanna er gefin með ferningum.*

ther east is the Lýsuhóll (or Helgrindur) volcanic system which was active during the Holocene while the Ljósufjöll volcanic system marks the easternmost extension of the SVB. Here the 1050 BP Rauðhálsar event took place, which is the most recent volcanic eruption in the SVB (Flude *et al.*, 2008; Jóhannesson, 1982a). However, the reason why the Snæfellsnes peninsula features rejuvenated volcanism with the observed alignment remains unknown.

Geophysical data in the region are sparse when compared to geological and geochemical data. Little is known about the deep structure of the Snæfellsnes peninsula. Based on recordings from the HOTSPOT experiment both Allen *et al.* (2002) and Du *et al.* (2002) report a crustal thickness of about 15–20 km for the Snæfellsnes, which is the thinnest crust on Iceland. Darbyshire *et al.* (2000) estimated the Moho depth underneath the Snæfellsnes to 20–24 km. There is no record of historic seismicity on the Snæfellsnes. Also, no data are available about present day seismicity in this part of Iceland because the South Iceland Lowland (SIL) network is not designed to detect "low-magnitude events" occurring beneath the Snæfellsnes peninsula. Only during the HOTSPOT experiment in 1996–1998 a seismometer was placed near Snæfellsjökull. Therefore, we performed a seismic campaign to determine whether any seismicity occurs in this region near the volcanic centers.

Seismicity has previously been reported from many other central volcanoes on Iceland, e.g. Askja (Soosalu *et al.*, 2009) and Eyjafjallajökull (Tarasewicz *et al.*, 2012) and also from long-dormant volcanoes such as Hrómundartindur, Hofsjökull or Öræfajökull (Jakobsdóttir, 2008). The observed seismic activity typically occurs in swarms and epicenters are densely clustered around magma reservoirs or dyking volumes. Hypocentral depths of volcano related seismicity reach down to 34 km but events are mostly clustered within 2–6 km depth (Jakobsdóttir, 2008).

This paper reports the results of our three-months field campaign and identifies for the first time the occurrence of seismic activity beneath the Snæfellsjökull volcano.

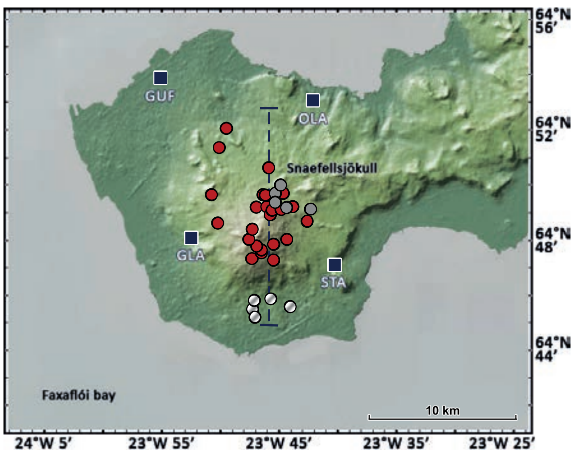

Figure 2. Spatial distribution of the recorded seismic events around the Snæfellsjökull volcano. The locations of the seismometers are denoted by blue squares and the dashed line marks the cross section that is used for the plot of Figure 3. – *Dreifing jarðskjálfta undir Snæfellsjökli. Staðsetning jarðskjálftamælanna er sýnd með bláum ferningum, en strikalínurnar marka staðsetningu þversniðsins á 3. mynd.*

DATA AND METHODS

We deployed five Trillium 240 broadband seismometers on the Snæfellsnes peninsula from July to September 2011, with the locations shown by squares in Figures 1 and 2. Since our primary objective was to determine the existence of seismic activity beneath the Snæfellsjökull volcano, we deployed four stations in the westernmost part of the peninsula, distributed 5 to 12 km distant from the volcano. We installed our fifth seismometer approximately 21 km northwest of the Ljósufjöll volcanic complex because our second objective was to determine if seismicity occurs between the Snæfellsjökull and the eastern parts of the peninsula. The stations around Snæfellsjökull were deployed either on lava flows or on hyaloclastic rocks. Data were recorded at a sampling rate of 100 Hz. The recordings were manually inspected for seismic events, which were located from hand-picked P- and S-wave arrivals using the HYPOCENTER code (Lienert and Havskov, 1995) and the 1D SIL velocity model introduced by Stefánsson *et al.* (1993) (see Table 1). We considered only events showing a S-wave arrival on the OLA, GLA and STA stations (see Figure 2; GUF recordings were dominated by large background noise and are excluded from this study) and that at least allow for one P-wave pick at any of the three stations. We used the ObsPy toolbox (Beyreuther *et al.*, 2010) for data processing.

Table 1. 1D velocity model used for this study, based on Stefánsson *et al.* (1993) with 1.74 as v_p/v_s ratio. – *Einvítt hraðalíkan notað til skjálftastaðsetninga við Snæfellsjökul.*

Depth km	v_p km/s
0	3.53
1	4.47
2	5.16
3	5.60
4	5.96
6	6.50
9	6.73
20	7.20

RESULTS

During three months of continuous recording, we identified and located 29 seismic events that were not listed in the Icelandic seismic catalogue. Numerous other microseismic events were also detected but are not included here because the low signal to noise ratio prevented reliable epicenter determinations. Nominal epicenter uncertainties for the reported 29 seismic events range from ±0.5 km to ±3.5 km in both Longitude and Latitude but are likely underestimated. However, uncertainties in the phase picking additionally contribute to scattering of the epicenter locations, since P-wave picks were not available for all stations. The respective locations are shown as red circles in Figure 2. The observed seismicity clusters beneath the southern and north-eastern flanks of Snæfellsjökull volcano, respectively with some additional events ranging towards the lower lands in the North-West. Red circles in Figure 2 denote epicenters located by phase picks on OLA, GLA and STA recordings. Additionally, few seismic events showed clear arrivals on both GLA and STA but could not be identified at OLA due to large background noise. The respective phase arrivals on GLA and STA allow for two possible epicenter locations that are shown as grey circles (shaded and solid) in Figure 2. However, the potential epicenter locations towards the south (marked as grey shaded) fall outside the volcanic complex, whereas the alternative locations (grey solid) are within the cluster at the north-eastern flank of the volcano and appear more plausible. We therefore suggest that these events belong to the same seismic source volume and are located within the north-eastern flank of Snæfellsjökull as well.

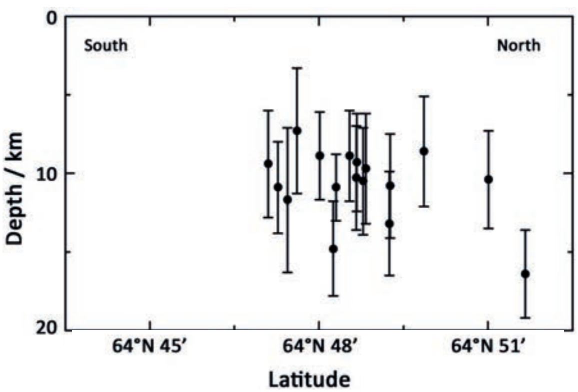

Figure 3. Cross section along the Snæfellsjökull volcano as marked by the dashed line in Figure 2, showing the depth of the seismic events as a function of latitude. Uncertainties in the determination of the depth are indicated by error bars and range from ±3 to ±5 km. – *Snið gegnum Snæfellsjökul eftir strikalínum á 2. mynd. Sniðið sýnir dýpi skjálfta sem fall af norðlægri breidd. Óvissan í dýptarútreikningum er ±3 til ±5 km.*

The dashed line in Figure 2 represents the trace of the profile shown in Figure 3. Although hypocenter depths are not well-constrained (the nominal depth error ranges from 3 km to 5 km deep) and weak P-waves complicated phase picking (see below) we observe that most of the seismic activity originates from depths of 9 to 13 km. Still, the poorly constrained hypocenter locations do not allow us to identify significant changes in depth. Note that including only three seismometers with the given geometry and unclear P-arrivals render the resulting depths highly uncertain and thus the hypocentral depth might be much shallower than stated here (Tarasewicz *et al.*, 2011). The actual seismic wave velocities underneath the Snæfellsnes peninsula are likely to deviate from the 1D SIL velocity model used for this study. We therefore checked how hypocentral depths are affected by different P-wave velocities.Yang and Shen (2005) report a low velocity anomaly in the Snæfellsnes area while in the same region Allen *et al.* (2002) observe slightly higher wave velocities in the upper crust. Thus, we reduced and enhanced P-wave velocities by 0.25 km/s at all depths of the 1D model. Reduced wave velocities result in hypocenters raised to shallower depths by about 600–1000 m, while increased velocities would place them about 200–1000 m deeper. Thus, the effect is of the same order as the uncertainties on the depth.

Figure 4 shows the waveform and the spectrogram of the strongest seismic event (M_l 1.1) recorded on July 18^{th} 2011, located beneath the Snæfellsjökull volcano. The picks for phase arrivals of the P- and S-wave are marked by solid red lines and are identical with the theoretically calculated arrival times for the given hypocenter. Figure 4a shows waveforms bandpass filtered at 4–12 Hz where the signal-to-noise ratio is best, while for the same reason the spectrograms shown in Figure 4b were generated from $f > 3$ Hz highpassed data. The signal is dominated by frequencies between 2–12 Hz and is most prominent at 5–6 Hz. In general, waveforms of all recorded seismic events are comparable and show a similar low-frequency content. Except for the M_l 1.1 event the magnitude range of the measured seismicity is between M_l -0.5 and 0.7. Generally, S-wave arrivals

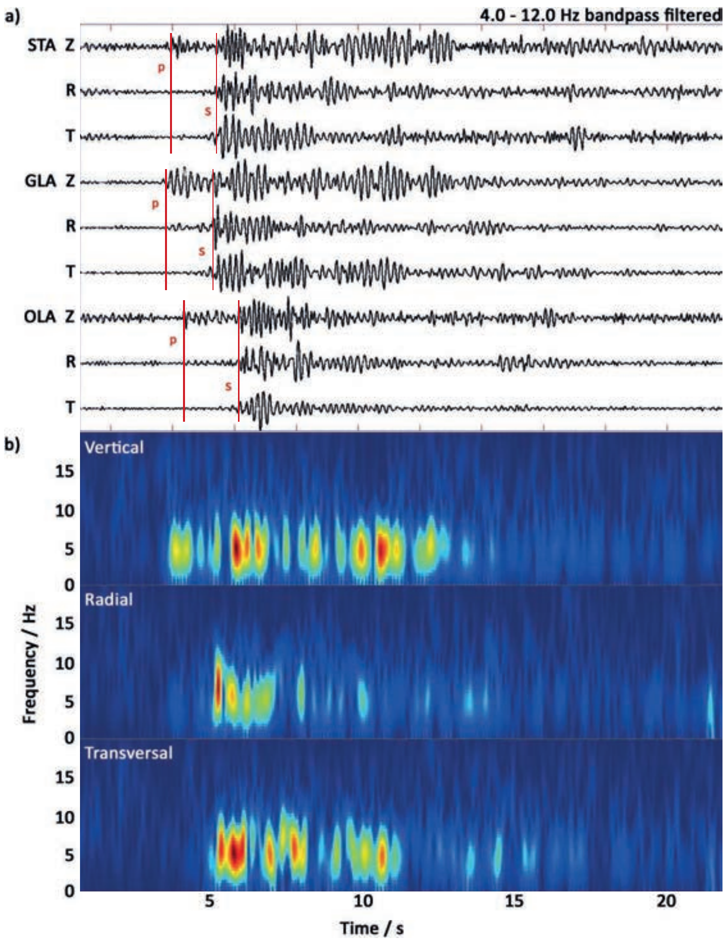

Figure 4. a) Seismogram of the M_l 1.1 event on 18 July 2011 showing vertical (Z), radial (R) and transversal (T) components as recorded by three different stations (see Figure 2 for station labeling). For a better visualization data are bandpassed with a filter between 4–12 Hz where the signal-to-noise ratio is best. Picks for the phase onsets are marked by solid red lines. b) Spectrogram of the same event as recorded on the GLA station after instrument correction. The data displayed in the spectrograms was highpass-filtered for $f > 3$ Hz so the plot is not dominated by low frequency noise. – *Línurit af skjálfta 18. júlí 2011, stærð M_l 1,1. a) Lóðrétt (Z), geislalæg (R) og þverstæð (T) hreyfing á stöðvum ATA, GLA og OLA (2. mynd), á tíðnibandinu 4–12 Hz, en á því bili er hlutfallið á milli merkis og bakgrunnssuðs best. Aflestur P- og S-bylgjufasa er sýndur með rauðum strikum. b) Tíðnigreining af sama skjálfta á GLA, eftir leiðréttingu fyrir tækjasvörun. Tíðnum neðan 3 Hz var sleppt, þar sem lágtíðnisuð yfirgnæfir merkið.*

were much more prominent than P-wave arrivals. The latter are often not well pronounced and pose one of the major uncertainties in the determination of the hypocentral depth.

Seismicity at Snæfellsjökull tends to cluster in time and space. A total of 10 events were recorded between 19^{th} and 22^{nd} of August 2011 and another 9 events occurred during 12 hours on September 6^{th}. While seismic activity in July and August is rather uniformly distributed, the September events predominantly belong to the north-eastern cluster.

The events recorded near the volcano were too small to be detected by the fifth seismometer located 60 km away near the Ljósufjöll volcanic complex. On this distant seismometer we could not identify clear signals of microseismicity like those measured with the stations close to the Snæfellsjökull volcano. However, we did record signals that could be of seismic origin but due to the lack of nearby seismic stations it is not possible to identify the nature of these events.

DISCUSSION

We show evidence of ongoing seismic activity beneath and around the Snæfellsjökull volcano. We can not rule out seismic activity in other parts of the Snæfellsnes peninsula, because our network was specifically designed to detect seismicity around Snæfellsjökull. The similarity in waveforms for many of the measured events suggests a common source mechanism and might point to much tighter spatial clustering than observed by the epicenter distribution. The spatial distribution of the epicenters and depths of approximately 10 km indicate a magmatic origin for the seismic activity. Lava flows around the Snæfellsjökull have been mapped by Jóhannesson (1981). The southern cluster of seismic events falls into the area that was active during the most recent central caldera eruption of Snæfellsjökull which covered the southern flanks of the volcano. Similarly, seismicity in the north-eastern cluster might originate from the magma source that was active during the 4000-5000 BP eruptive phase. Few seismic events were located north-west of the volcano where young flows associated with local craters have also been found. Still, a denser seismometer network is necessary to investigate the spatial clustering of hypocenters with more detail.

Two models for the geometry of the plumbing system of the Snæfellsjökull have been proposed by Kokfelt *et al.* (2008) based on isotope data of volcanic rocks. The first model suggests a stratified and long-lived magma chamber of conical shape, while the second model proposes a simultaneously evolving plumbing system made of smaller and isolated magmatic bodies of at least 3-4 km^3 each. Both models have in common that older and more evolved magmas are situated at shallower depths beneath the central summit, while younger magmas are located at greater depths below the flanks of the volcano. We identify three potentially separate sources of seismicity on the Snæfellsjökull volcano, with two main clusters on the southern and north-eastern flanks, respectively and few events located in the lower lands north-west of the volcanic edifice (Figure 2). The origin of seismicity is in agreement with both models proposed by Kokfelt *et al.* (2008) and suggests that the plumbing system of the Snæfellsjökull volcano extends from about 8 to 13 km depth. However, uncertainties on epicenters and depth are too large to rule out either of the two suggested scenarios. Based on seismic and geodetic data, magma chambers beneath active Icelandic volcanoes are confined to the upper crust (Brandsdóttir and Menke, 2008; Mitchell *et al.*, 2013).

The absence of high frequency components in the waveforms and the swarm-like appearance of seismicity suggest that seismic activity could be associated with fluid processes. However, seismicity that has been associated with fluid-induced mechanisms at e.g. Eyjafjallajökull (Tarasewicz *et al.*, 2012) or Upptyppingar (White *et al.*, 2011) volcano shows higher frequencies and is termed to be of volcano-tectonic origin. Similar low-frequency bands have been observed at Askja volcano but were interpreted as a result of absorption of high frequencies by Soosalu *et al.* (2009). Additionally, the frequency content of the signals we measure underneath Snæfellsjökull is too high and the signal duration too short to be purely fluid-related such as long period events (Chouet, 1996). Regarding the thin crust of approximately only 15–20 km under the Snæfellsnes, our estimated hypocentral depths may fall within the normally ductile part of the crust. White *et al.* (2011) argue that brittle failure within the ductile regime can be generated by high strain rates induced locally by magma movement. We therefore propose that seismic activity underneath the Snæfellsjökull volcano reflects hybrid events that involve brittle failure in combination with fluid-related processes. Although scattering and absorption of the seismic waves may contribute to the absence of higher frequency signals, we favour the scenario where seismicity is related to fluid-induced brittle failure in the deeper part of the crust.

Sigurdsson (1970) suggested that seismic and volcanic activity in the SVB could be increasing as present day spreading rates are comparable to the late Pleistocene ones which might have formed the en-echelon alignment of volcanic structures (Árnadóttir *et al.*, 2009). In this case one would also expect tectonic events at shallower depths that follow the orientation of the inferred transcurrent fault. However, the origin of recent volcanism and its distribution along the Snæfellsnes peninsula is poorly understood and the proposed fault remains hypothetical. The installation of continuous GPS stations associated with a larger array of permanent seismic stations could help to determine the current tectonic deformation of the Snæfellsnes peninsula and to reveal the origins of its rejuvenated volcanism.

CONCLUSIONS

We conducted a seismic campaign to ascertain whether or not the Snæfellsnes is seismically active. We found seismicity that clusters in time and space beneath the Snæfellsjökull volcano and originates from depths of 8 to 15 km. The seismic events show magnitudes from M_l -0.5 to 1.1 and are mainly located underneath the southern and north-eastern flanks. We propose that the seismic activity reflects hybrid volcanic events and is related to movement of fluids within the ductile part of the crust under Snæfellsjökull volcano.

Our results are the first to show seismic activity underneath the Snæfellsjökull volcano. However, a denser seismic network is necessary to draw more specific conclusions about the origin of the seismicity. Future investigations should include continuous seismic and GPS measurements along the peninsula. This will allow more robust interpretations of the geology of the Snæfellsnes peninsula, the Snæfellsjökull volcano in particular, and will help to better constrain present day activity and its relationship to Icelandic tectonics.

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ÁGRIP

Eldstöðvakerfin á Snæfellsnesi hafa verið útundan hvað varðar vöktun á jarðskjálftum. Fram til ársins 2011 er ekki vitað um neina jarðskjálfta staðsetta undir Snæfellsjökli. Sumarið 2011 voru settir upp fimm jarðskjálftamælar á Snæfellsnesi á vegum jarðvísindamanna frá Bonnháskóla, Þýskalandi. Fjórir mælanna voru staðsettir umhverfis Snæfellsjökul, en sá fimmti við Álftarfjörð, norður af Ljósufjöllum (1. mynd). Mælarnir voru reknir í þrjá mánuði, frá júlí til september. Alls voru 29 jarðskjálftar staðsettir undir Snæfellsjökli á þessu tímabili (2. mynd). Nokkrir atburðir sáust til viðbótar, sem ekki var hægt að staðsetja. Virknin var mest í tveimur hrinum, tíu jarðskjálftar mældust frá 19. til 22. ágúst og níu jarðskjálftar á 12 klukkustundum þann 6. september. Staðsetningar gáfu um 10 kílómetra dýpi, þ.e. frá 8 kílómetrum niður á 15 kílómetra (3. mynd). Skjálftarnir voru allir mjög smáir, sá stærsti um M_l 1,1 að stærð, en sá minnsti M_l -0,5. Vegna þess hve litlir jarðskjálftarnir voru sást enginn þeirra á mælinum við Álftarfjörð og að sama skapi sáust hugsanlegir skjálftar við Ljósufjöll ekki á mælunum við Snæfellsjökul. Enginn skjálfti var því staðsettur við Ljósufjöll. Af mælunum við Snæfellsjökul var sá við Gufuskála mjög ónæmur og sáust engir jarðskjálftar á þeim mæli vegna bakgrunnshávaða. Vegna smæðar sinnar voru sumir skjálftanna aðeins greinanlegir á tveimur mælum. Fyrir þá skjálfta var staðsetningin undir jöklinum valin. Nauðsynlegt er að gera frekari jarðskjálftamælingar á svæðinu og gagnlegt væri að mæla samtímis mögulegar færslur á svæðinu með GPS-mælingum.

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