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RESEARCH ARTICLE

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Earthquake activity related to the 1991 eruption of the Hekla volcano, Iceland

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Abstract The 1991 eruption of the Hekla volcano started unexpectedly on 17 January. No long-term precursory seismicity was observed. The first related activity was a swarm of small earthquakes that began approximately half an hour before the eruption. Intensive seismicity, both earthquakes and volcanic tremor, accompanied the violent onset of the eruption. Almost 400 events up to M_L magnitude 2.5 were recorded during the first few hours. During the later phases of the eruption, the earthquake activity was modest and the main volcano-related seismic signal was the persistent volcanic tremor. The tremor died away, together with the eruption on 11 March, and Hekla was seismically quiet until the beginning of June 1991, when a sudden swarm of numerous small shallow earthquakes occurred. This activity is atypical for Hekla and is interpreted to be a failed attempt to resume the eruption.

Keywords Earthquakes · Hekla eruption 1991 · South Iceland seismic zone · Volcanic tremor

Introduction

Hekla, one of Iceland's most active volcanoes, is situated at a rift-transform intersection, where the South Iceland seismic zone joins with the Eastern volcanic zone (Fig. 1). The products of the Hekla volcanic system range from basalts through basaltic andesites to dacites and rhyolites (Jakobsson 1979). The Hekla volcano itself is a ridge-shaped, ~1,500-m-high edifice (Fig. 2) built up around a fissure system with an ENE trend. The more acidic products are issued from the central volcanic edifice, the basaltic products from the fissure swarms or rifts on either side. In spite of the proximity to the divergent plate boundary, Hekla is not petrologically a typical rift zone volcano but more akin to the group of volcanoes in the volcanic flank zone south-east of the junction between the South Iceland seismic zone and the Eastern volcanic zone (Fig. 1). The flank zone has been interpreted as a propagating rift extending into the Eurasian plate (Einarsson 1991; Guðmundsson et al. 1992).

The Hekla volcano appears to be changing its eruptive pattern. Since the major eruption of 1104 A.D., and until the 1947 eruption, the pattern was characterized by relatively large eruptions about twice a century (Þórarinsson 1967). During the last few decades, on the other hand, there have been smaller eruptions of about 150×10^6 m^3 occurring about every 10 years, i.e. in 1970, 1980–1981, 1991 (Guðmundsson et al. 1992) and 2000. At the same time, there seems to be a tendency for the most recent eruptions to take place on a radial fracture pattern in addition to the main Hekla fissure that splits the volcanic ridge lengthwise (Fig. 2). These changes in the Hekla eruptive behaviour are noteworthy and may signal a lasting change in the plumbing system of the volcano.

Besides being a dangerous volcano, Hekla is notorious for its lack of detectable precursory effects. So far, the only detected physical changes before Hekla eruptions have been volumetric strain signals (Linde et al. 1993) and swarms of small earthquakes (Brandsdóttir and Einarsson 1992) about half an hour before the outbreak. No long-term or intermediate-term precursory effects have ever been detected for certain.

The 1991 eruption and the newly installed digital seismograph system in the area, the SIL system (Stefánsson et al. 1993), offered an opportunity to study the seismic activity during a Hekla eruption. In the study presented here we look for a possible prelude to the eruption in the seismicity, describe the earthquake activity accompany-

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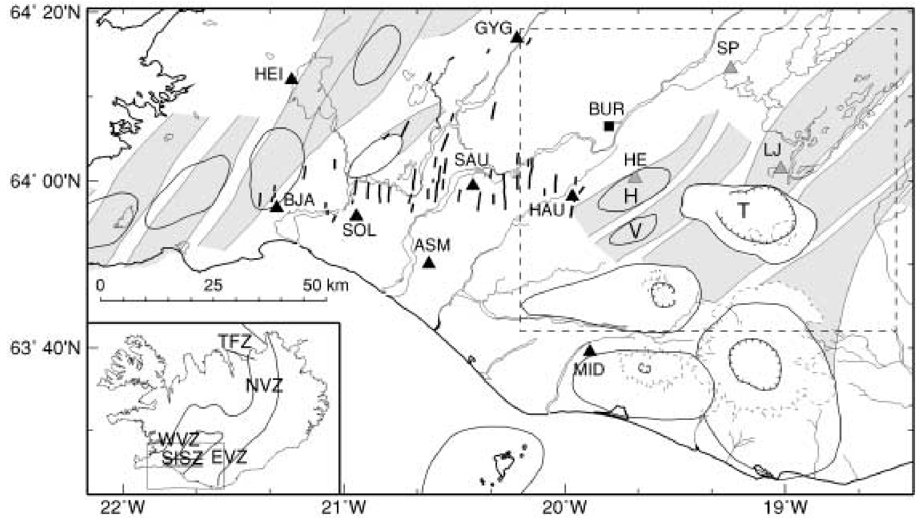


Fig. 1 Index map of the Hekla area (*dashed quadrangle*). *Black triangles* are the digital South Iceland Lowland (SIL) seismograph stations and *grey triangles* the analogue stations. *Black square* is the strain station BUR (Linde et al. 1993). *Thick black lines* are the faults of the South Iceland seismic zone. The central volcanoes are outlined, their fissure swarms are *shaded grey* (Einarsson and Sæmundsson 1987) and the calderas are *hatched* (Jóhannesson et al. 1990). Central volcanoes referred to in the text are: *H* Hekla; *V* Vatnafjöll; *T* Torfajökull. *Short dashed lines* mark the glaciers. The *smaller index map* shows the locations of the areas related to the plate margin: *WVZ* Western; *EVZ* Eastern and *NVZ* Northern volcanic zones, *SISZ* South Iceland seismic zone and *TFZ* Tjörnes fracture zone

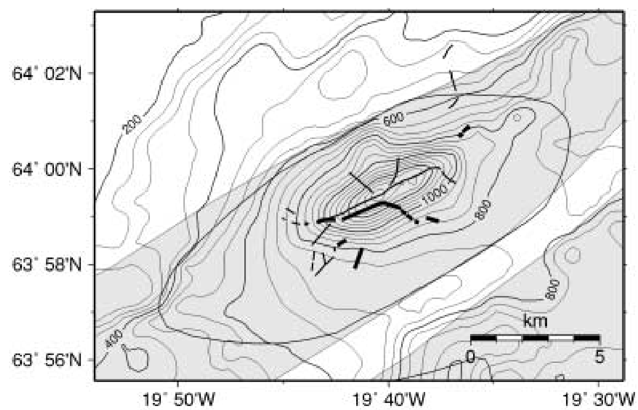


Fig. 2 Generalized picture of eruptive sites at Hekla in eruptions of 1970, 1980–81 and 1991. The 1991 fissures are shown with *thicker lines* than the others. Fissures are taken from Ţórarinsson (1970), Grönvold et al. (1983), a map of the Hekla region (1989) and Guðmundsson et al. (1992). The outlines of Hekla central volcano with its fissure swarm (*grey*) are shown. *Contour lines* are at 50-m intervals

ing the onset of the eruption, and attempt to relate the eruptive activity to earthquakes that occurred during and immediately after the eruption. We show how the structure of the volcano is linked to two N–S-striking faults or crustal weaknesses that resemble the bookshelf faults of the transform zone to the west: the South Iceland seismic zone. In a previous paper (Soosalu and Einarsson 1997) we described and quantified the background seismicity of the region around the volcano to which the present results can be compared.

Data analysis

Our study area encompasses Hekla, and includes the volcanoes Torfajökull and Vatnafjöll, and the eastern part of the South Iceland seismic zone (Fig. 1). The main bulk of the data used for this study come from the SIL network: a system of eight digital, three-component seismographs that became operational in 1990, some 8 months prior to the Hekla eruption. The system provides automatically, and in semi-real time, hypocentral locations and focal mechanisms for local seismic events (Stefánsson et al. 1993). Magnitudes (M_L) are calculated from the amplitude and the distance of the event. Hekla is located at the edge of the digital seismic network. Therefore, the location accuracy could be improved considerably by augmenting the SIL data by data from three analogue stations (HE, LJ and SP) operated in the vicinity of Hekla. Station HE is located on the flank of Hekla, in a strategically important place, but is very difficult to maintain. The station was frequently out of order, including most of the time of the eruption. Station SP was a rather insensitive station. Station LJ is located east of Hekla and north of Torfajökull Volcano. It has provided a consistent record of the seismicity of the region since it was installed in 1985. The seismic events were relocated using the location program Hypoinverse (Klein 1978). A more detailed description of the location procedure is given by Soosalu and Einarsson (1997).

Our study period was 13 months, beginning in June 1990, only shortly after the SIL system became operational. Thus the period includes almost 8 months of pre-eruption activity, the eruption itself and 4 months after it. The detection threshold of the network is consistent throughout this time (about M_L 1), possibly with an exception of the first weeks where it might have been

Table 1 Summary on the number of the observed seismic events in subregions during the study period. The high frequency and low frequency events of Hekla and Torfajökull have separate columns. *SISZ* South Iceland seismic zone. Only the earthquakes in the final event list are included in the calculations. Events that were seen only on the paper seismograms of the stations HE and LJ are shown in parentheses. The activity at Hekla proper in general, and during 1–2 June, is shown separately in *italics*. *T* Volcanotectonic; *V* volcanic

Period	Hekla–Vatnafjöll		*Hekla proper*		Torfajökull		SISZ	Other	Total
	High freq.	Low freq.	*High freq.*	*Low freq.*	High freq.	Low freq.			
June 1990–16 Jan. 1991	2	–	–	–	11	(38)	7	2	22
17 Jan. 1991	380	–	*380*	–	1	–	–	–	381
18 Jan.–11 March 1991	14 (>30[a])	(1)	*9 (>30[a])*	*(1)*	10	–	2	3	29
12 March–30 June 1991	50	1 T (51)	*35*	*1 T (51)*	9	1 V (41)	19	–	80
1–2 June 1991			*28 (>70)*	*(3 V)*					
In total	446	1			31	1	28	5	512

[a] Swarm of small Hekla events, 11 March

Table 2 Summary on the magnitudes of the observed earthquakes in the subregions. Magnitudes of the events at Hekla proper are shown separately in *italics*. *Mmax* Maximum local magnitude; *Mcorr* local magnitude of a single earthquake that has a corresponding amount of seismic energy release as all of the seismic events in each subregion during each period

Period	Hekla–Vatnafjöll		*Hekla proper*		Torfajökull		SISZ		Other Mmax
	Mmax	Mcorr	*Mmax*	*Mcorr*	Mmax	Mcorr	Mmax	Mcorr	
June 1990–16 Jan. 1991	1.51	1.57	–	–	2.07	2.36	1.14	1.37	2.05
17 Jan. 1991	2.55	3.40	*2.55*	*3.40*	1.12	1.12	–	–	–
18 Jan.–11 March 1991	2.63	2.70	*1.87*	*2.12*	2.40	2.62	1.00	1.08	0.70
12 March–30 June 1991	1.71	2.20	*1.71*	*2.13*	1.71	1.99	1.94	2.06	–
1–2 June 1991			*1.71*	*2.05*					
Total	2.63	3.43	*2.55*	*3.41*	2.40	2.74	1.94	2.09	2.05

slightly higher. The event list contains 512 events, 22 of which occurred prior to the eruption (1 June 1990–16 January 1991), 410 during it (17 January–11 March 1991) and 80 after it (12 March–30 June 1991). A summary on the number of the earthquakes throughout the study period is shown in Table 1, and a summary on the magnitudes of the events in Table 2. It shows the maximum sizes of observed earthquakes, and the calculated sizes of single earthquakes with the same amount of released seismic energy as in the seismicity in each subregion during each period.

In this paper we consider a hypocentre 'well-located' if its location fulfils the criteria of the root mean-square travel-time residual (rms) ≤0.2 s, horizontal standard error (erh) ≤1.0 km, vertical standard error (erz) ≤2.0 km and largest gap between observing stations ≤180°. In some of the figures we also plot epicentres with lower quality (rms ≤0.2 s, erh ≤2.0 km, erz ≤5.0 km, gap ≤230°).

The seismicity preceding the 1991 Hekla eruption

Only 22 earthquakes, with local magnitudes (M_L) from 0.5 to 2.1, were observed in the study area during the period from the beginning of June 1990 until 16 January 1991. The best-located epicentres are in Fig. 3 and hypocentres in Fig. 4. The map shows the main features of the seismicity, although the accuracy of the locations was not the best in these early months of the SIL network. The most striking feature is the lack of seismicity at Hekla and Vatnafjöll. Only two events, with magnitudes 1.5 and 1.1, were located at Vatnafjöll, the latter one was too inaccurate to be plotted on the map. Hekla itself did not show any signs of seismic activity during this half-year period prior to the eruption.

The Torfajökull central volcano east of Hekla was the most active area prior to the Hekla eruption, both in regard to the number of events and to their magnitudes. The located earthquakes were of the ordinary high frequency type and were clustered in the western part of the caldera. This activity at Torfajökull has a similar pattern as the seismicity observed in the post-1991-eruption time (Soosalu and Einarsson 1997). Low frequency volcanic earthquakes, often occurring in swarms, are also common at Torfajökull. However, prior to the Hekla eruption, we observed very few low frequency events at Torfajökull. On the records of the analogue station LJ, immediately north of Torfajökull, there were ten or less low frequency events per month in May–October 1990, and none from November 1990 to the onset of the Hekla eruption. The last intense swarm of Torfajökull low frequency events prior to the Hekla eruption was recorded over a year earlier, between 22 and 26 November 1989. Then there were tens of events per day on the seismograms of LJ. The maximum, of over 100 events per day, occurred on 23 November.

The easternmost section of the South Iceland seismic zone (Fig. 1), a 70-km-long transform zone expressed by bookshelf faulting on transverse faults, is included in our study area. A handful of earthquakes were observed there in the months preceding the Hekla eruption. The

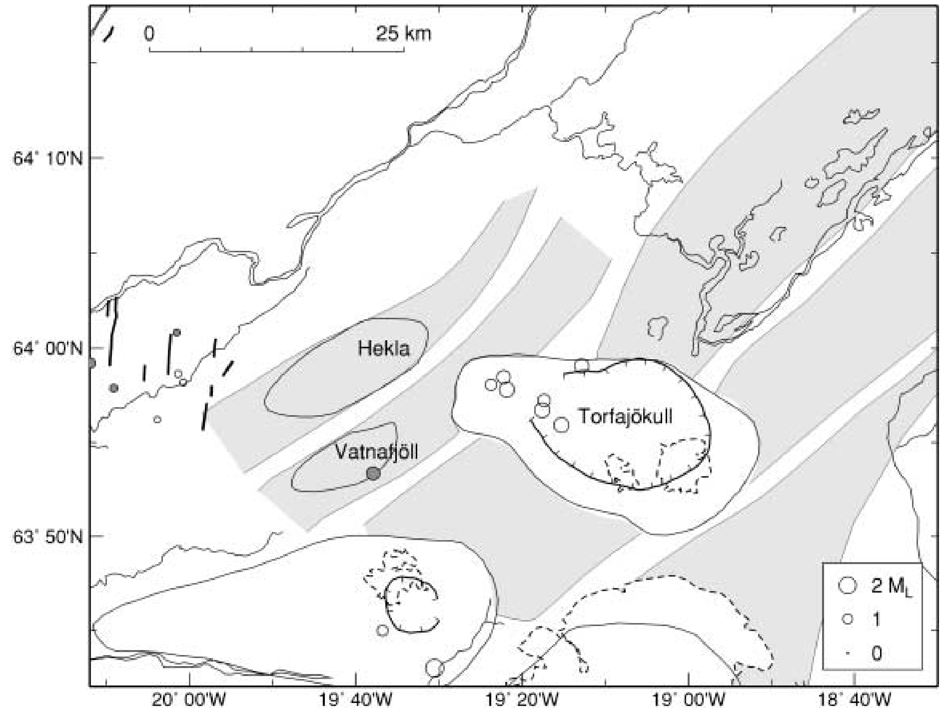


Fig. 3 Earthquakes in the Hekla region prior to the eruption, 1 June 1990–16 January 1991. 'Well-located' events (rms ≤0.2 s, erh ≤1.0 km, erz ≤2.0 km and gap ≤180°) are marked with *grey dots* and events fulfilling less strict location criteria (rms ≤0.2 s, erh ≤2.0 km, erz ≤5.0 km, gap ≤230°) are drawn with *open circles*. *Other symbols* are same as in Fig. 1. The *inset* shows the sizes of events of corresponding M_L magnitudes

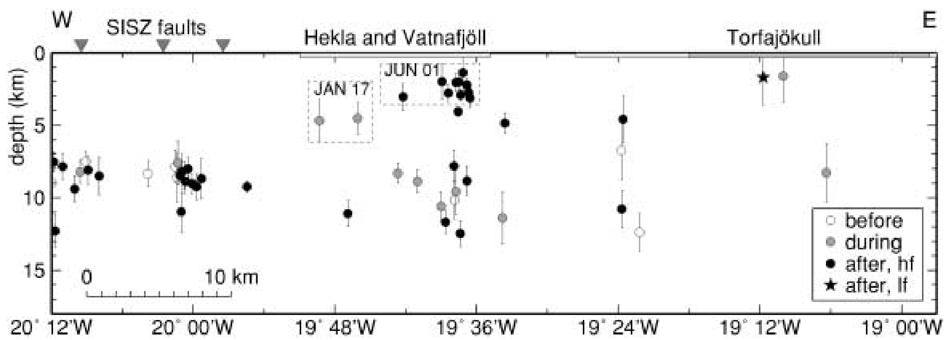


Fig. 4 Vertical cross section of the study area from South Iceland seismic zone to east edge of the Torfajökull caldera (between latitudes 63°48.6′–64°05′N), seen from south and without vertical exaggeration. Plotted are earthquakes in June 1990–June 1991. The location criteria are rms ≤0.2 s, erh ≤2.0 km, erz ≤2.0 km, gap ≤230°. *Open circles* show events before the Hekla eruption (June 1990–16 January 1991), *grey dots* during it (17 January–11 March 1991) and the *black dots* after it (12 March–June 1991). The *dots* represent ordinary high frequency tectonic earthquakes and the *star* shows a low frequency volcanic event. *Vertical error bars* are shown. *Inverted triangles* show the surface locations of the South Iceland seismic zone faults. The locations of the central volcanoes are shown with *grey bars*, the location of the Torfajökull caldera with a *darker grey shade*. *Dashed quadrangles* surround the events of 17 January and 1 June swarm

earthquakes in this area occurred at typical locations (Fig. 3) and had typical depths of about 8 km (Fig. 4). No unusual seismicity was observed in this area.

The lack of seismicity of Hekla itself and its immediate vicinity during the 7.5 months prior to the eruption is conspicuous. No earthquakes were located there during that time. This quiescence is not exceptional, however, as the longest period without earthquakes there during July 1991–October 1995 was over a year. Possible small pre-eruption events at Hekla may have been missed because the analogue station HE on its flank was out of order for several months prior to the eruption.

On 11 January, about a week before the onset of the Hekla eruption, the digital seismograph station HAU 15 km west of Hekla recorded 13 small seismic events. They originated near this station and most of them had strikingly similar waveforms with prominent surface waves, which indicated shallow origin. In spite of their temporal relation to the coming eruption, we consider it likely that they are frost-cracking events rather than real earthquakes. Such events are frequently observed by Icelandic analogue seismograph stations when the conditions are favourable for frost cracking, i.e. the temperature is well below the freezing point and decreasing rapidly, the weather calm with clear skies, little or no snow cover and, in many cases, the ground frozen after a period of thaw (Einarsson 1990). Three lines of evidence support our theory. (1) The temperature and snow cover observations of the nearby weather stations, run by the Icelandic Meteorological Office, show that the condi-

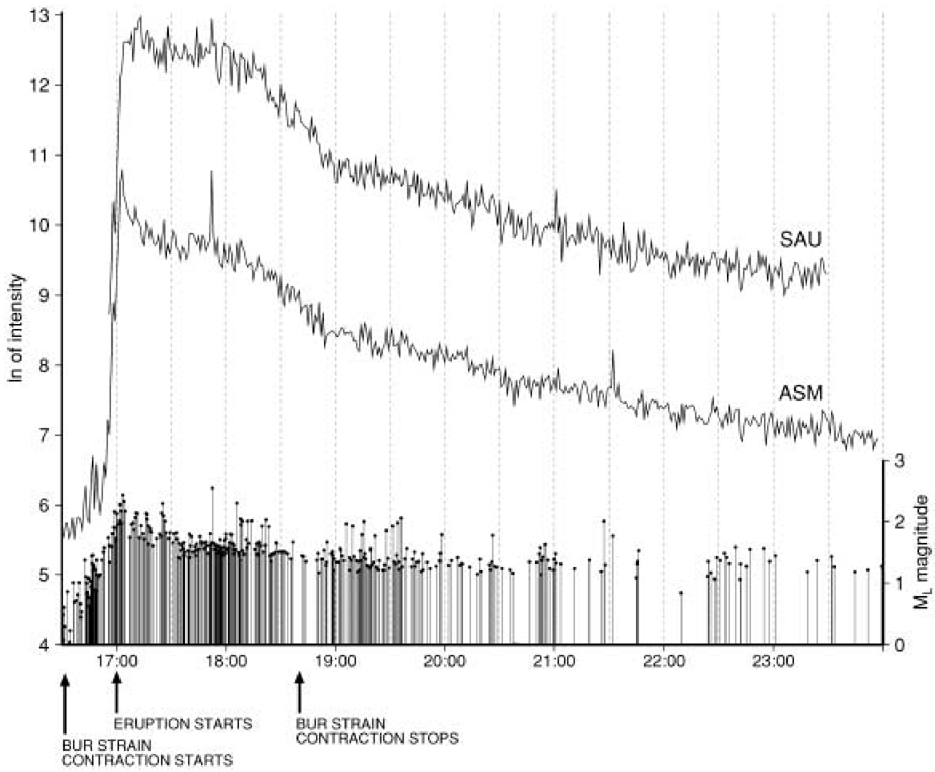


Fig. 5 Temporal distribution of the earthquakes related to the onset of the Hekla eruption with their M_L magnitudes (*scale on the right*). The time extends from 16:30 h on 17 January 1991, until midnight. For comparison, tremor intensity observation curves at the stations SAU and ASM are shown. As the tremor contains chiefly low frequencies, the intensity graphs were made for the bandwidth 0.5–5 Hz. The intensity is calculated as averaged energy over 60-s intervals, and its ln logarithm is plotted (*scale on the left*). The start and stop of the strain signal of station BUR showing the intrusion (Linde et al. 1993) and the onset moment are shown with *arrows*

tions were suitable for frost-cracking to occur. (2) The analogue station LJ recorded innumerable events with typical frost-cracking appearance during that day. (3) The digital station SAU, 35 km away from Hekla, observed one near event very similar to the ones of HAU.

Seismicity during the eruption 17 January–11 March 1991

The first evening

The crust under Hekla started to show signs of awakening only about half an hour before the volcanic material came into sight. The first earthquakes were observed at 16:30 h GMT (Fig. 5), and strain records of a local strain-meter network started to show a signal that was interpreted to be caused by an advancing intrusion under Hekla (Linde et al. 1993). According to Guðmundsson et al. (1992), the eruption itself began at 17 h. The seismicity soon grew very intense, numerous events followed each other at short intervals that were, on occasions, less than a minute in duration. The very first earthquakes were small, with magnitudes (M_L) around 1 or less. The magnitudes became larger, up to about 2, towards the onset of eruptive activity at about 17:00 h. After this culmination, the magnitudes remained at the same level for some tens of minutes and started, subsequently, to decrease slightly. The largest observed event was of magnitude 2.5 and occurred at 17:52 h on 17 January.

Volcanic tremor appeared on the seismograms during the first minutes of the eruption. To begin with, it was visible as a few-seconds episode of low frequency movement between the frequent earthquakes. In a few minutes it grew to be the dominant factor in the recordings, which made picking the earthquake phases somewhat troublesome. We discuss the volcanic tremor related to the Hekla eruption in detail in a separate study (Soosalu et al., in preparation).

In total, it was possible to identify 380 events at the Hekla Volcano from 16:30 h until midnight. Their M_L magnitudes varied from 0 to 2.5. None of the events is well-located, for various reasons. Volcanic tremor disturbed the arrival-time readings, particularly on the records of the analogue stations LJ and SP. The nearest SIL station, HAU, was down and the analogue station HE on Hekla itself was out of order. Most of the events were recorded by only two SIL stations, SAU (35 km W of Hekla) and ASM (50 km SW of Hekla).

The amplitude of the tremor affected the threshold magnitude of the observed Hekla earthquakes. The tremor was at its highest during 17–18 h, then decreased sharply until 19 h, and more gently after that. In Fig. 5, the detected events at ~17:00–18:00 h are all about 1.5 or larger in magnitude. Later on, the threshold magnitude of the earthquakes was about 1. Although both the locations and the magnitudes of the earthquakes are only estimates they give a qualitative impression of the abundant seismicity related to the start of the eruption. All the Hekla events that were recorded on 17 January by three or more stations are plotted in Fig. 6. The locations are very approximate. The main problem was that most of the events are outside the network. The horizontal error bars give only some estimate for the accuracy, and the vertical errors are generally larger.

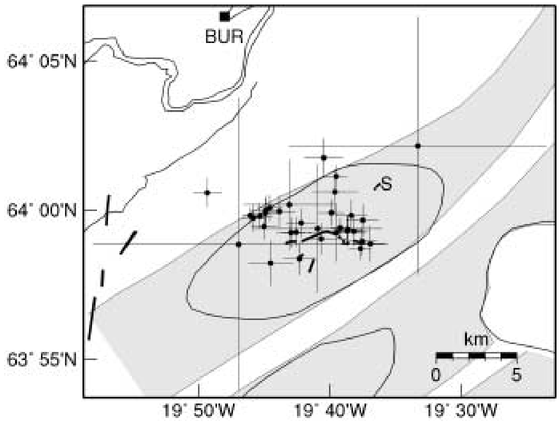


Fig. 6 Locations of the Hekla earthquakes on 17 January, observed by three or more stations, 33 in total. None fulfils the criteria for 'well-located' events. Eruptive sites at Hekla are shown with *thick black lines*, the main crater with a *cross*, both are taken from Guðmundsson et al. (1992). *S* Skjólkvíar. *Black bars* at about 20°W are the easternmost faults of the South Iceland seismic zone. The strain station BUR is shown with a *black square*

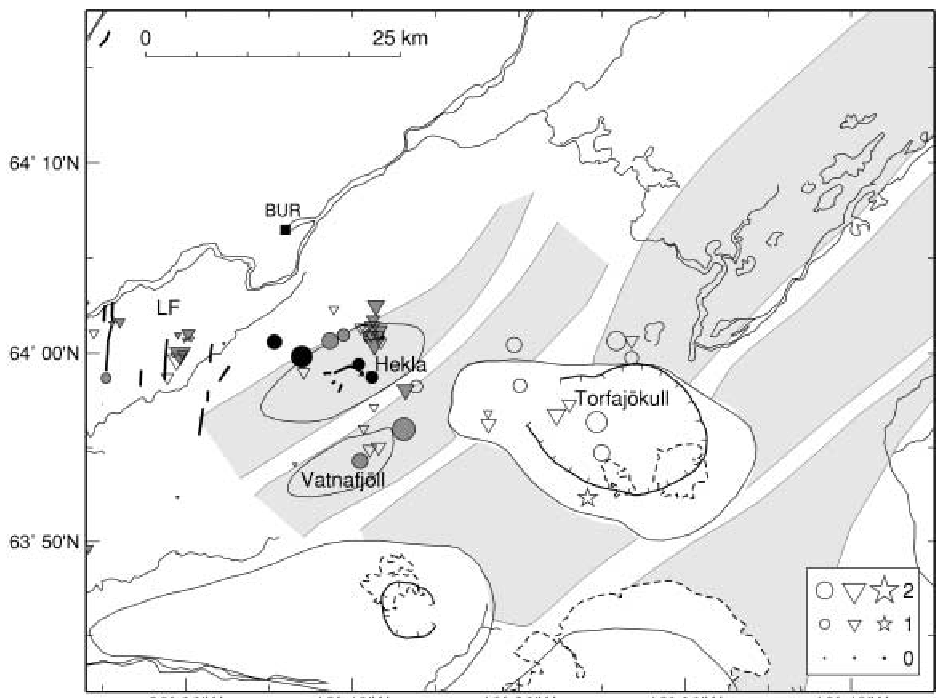
Fig. 7 Earthquakes in the period 17 January–30 June 1991. The location criteria for *open* and *grey symbols* are the same as in Fig. 3. *Dots* are events that occurred during the Hekla eruption. *Black dots* are earthquakes on 17 January, and they fulfil the looser location criteria. *Open circles*, and the more accurately located *grey dots* are events that occurred during the Hekla eruption on 18 January–11 March. *Inverted triangles* show earthquakes after the Hekla eruption on 12 March–30 June 1991. The analogue station HE on the flank of the volcano had recorded all the plotted post-eruption Hekla events. All of them, except one on 16 April (64°01.39′N, 19°37.55′W, depth 4 km, M_L 1.4) belong to the swarm of earthquakes at the beginning of June 1991. The *star* is a low frequency earthquake in June 1991. *LF* Leirubakki fault. The *inset* shows the M_L magnitude scale for the events

Four events have more precise locations and are plotted with black dots in Fig. 7. The larger ones occurred at 17:52 and 21:31 h, and are also in Fig. 4, at about 5 km depth. The smaller events with less accurate depths (black dots on Hekla in Fig. 7) occurred prior to the eruption. Kristín Vogfjörð and Sigurður Th. Rögnvaldsson (personal communication) studied four other Hekla earthquakes before the start of the eruption using seismic records of SIL stations and the presence or absence of depth phases. Their depth estimates were about 3 km.

The first earthquakes at 16:30–17:00 h, before the onset of the eruption, were small and tended to grow bigger with time (Fig. 5). Their hypocentres are not well determined, thus temporal development of the depths of the earthquakes is not known. They may mark the intrusion of magma towards the surface, but can also reflect changes of the general stress field in the area. The quick start of Hekla eruptions has also been evident during previous eruptions. In 1970, seismographs recorded earthquakes about 25 min before the eruption (Einarsson and Björnsson 1976). In 1980, the associated seismicity started approximately 20 min before the eruption onset (Grönvold et al. 1983).

During the first hour of the eruption, fissures were opening and propagating (Guðmundsson et al. 1992). Intense seismicity, both tremor and earthquakes, accompanied the volcanic activity (Fig. 5). Until 20 h on 17 January, 308 earthquakes were observed, some 60 of which preceded the eruption. The earthquake activity decreased distinctly after 20 h; the time interval between observed subsequent events grew longer, and they became smaller in magnitude.

All the Hekla earthquakes on 17 January, as far as it was possible to discern, can be classified as normal high frequency brittle-failure earthquakes with clear S phases. Actually, the higher frequency content was used for visual



picking of the events from the continuous low frequency volcanic tremor. Separate low frequency volcanic earthquakes were not found or were masked by the tremor.

The seismicity during the eruption after the onset day

The eruptive activity of Hekla was most powerful during the first 11 hours, when the effusion rate may have been as much as 2,000 $m^3 s^{-1}$. In the first day, several fissures were active in a radial pattern in the SW–SE part of the volcano. The average effusion rate during the first 2 days was about 800 $m^3 s^{-1}$ (Guðmundsson et al. 1992). The volcanic tremor continued after midnight with a declining trend until 04:00 h on 18 January, when it levelled off. On 19 January, all the effusive activity had concentrated to one fissure that was ESE from the summit of Hekla, down the flank where it formed a large cinder cone (Guðmundsson et al. 1992).

The earthquake activity at Hekla and Hekla–Vatnafjöll area was very modest during the eruption. No earthquakes were recorded at Hekla on 18 January. The SIL network detected three earthquakes at Hekla on 19 January, one of which was well-located in the northern part of Hekla at a depth of 9.6 km. On 19 January–21 February, 14 (five well-located) events with magnitudes between 1.1 and 2.6 were observed (Fig. 7): nine of them (three well-located) occurred at Hekla proper. The depths of all these events were between 8 and 12 km (Fig. 4). After 21 February until the end of the eruption, no earthquakes were located in the Hekla–Vatnafjöll area. However, the analogue station HE on the flank of the volcano observed a swarm of about 30 small events on 11 March, before noon. We suggest they were caused by conduit collapse when the volcanic activity ceased.

The depths of the Hekla events after 19 January were about 8–12 km, and were similar to typical events in the eastern part of the South Iceland seismic zone and in the Hekla–Vatnafjöll area observed in July 1991–December 1996 (Soosalu and Einarsson 1997). All the earthquakes seen by the SIL network during the eruption at Hekla and its vicinity were high frequency tectonic events with distinct S phases; none of them looked like low frequency volcanic earthquakes. Station HE started working on 24 February, but its gain was set low because of the volcanic tremor and, therefore, we could not detect local low frequency earthquakes, if there were any.

The seismic energy that was released in the observed earthquakes in the Hekla–Vatnafjöll area during the eruption was approximately 8.7×10^9 J, which corresponds to a single earthquake of magnitude 3.4, calculated with the formula: $\log E = 11.8 + 1.5 * M_L$. Most of this energy, 8.0×10^9 J, was released in the first hours of the eruption on 17 January. This period alone corresponds to a magnitude 3.4 earthquake.

The SIL system observed ten high frequency tectonic earthquakes at Torfajökull during the Hekla eruption, none of which was well-located. Their M_L magnitudes varied between 1.4 and 2.4. The analogue seismograph LJ did not show any signs of low frequency seismicity at Torfajökull during the Hekla eruption. In the South Iceland seismic zone only two ordinary small earthquakes were recorded during the Hekla eruption.

Seismicity between March and June 1991

In the period 12 March–30 June 1991, after the cessation of the Hekla eruption, the SIL network observed 80 earthquakes in our study area, 17 of which were well-located (Fig. 7). The Hekla–Vatnafjöll area was seismically peaceful until the end of May 1991. All the observed earthquakes there were small (M_L –0.1–1.6), and were located on the north–south lineament cutting the eastern flank of the volcano, which we identified in the seismicity of 1991–1996 (Soosalu and Einarsson 1997). One Hekla event with a rather poor location had a low frequency appearance similar to the Hekla events in February 1993–December 1996. All the others were ordinary high frequency earthquakes, with depth estimates of 4–12 km (Fig. 4). Some small low frequency events, about 10 to 30 per month, were seen on the seismograms of the analogue station HE, and were probably originated at Hekla. No swarms of low frequency events were observed at Hekla, however.

An unusual swarm of small high frequency earthquakes started suddenly at Hekla on 1 June 1991, at 15:35 h, and continued until 01:14 h on 2 June. The SIL network observed about 30 events (four well-located) with magnitudes of 0.6–1.7, and the analogue station HE at Hekla recorded more than 70 additional small events. The swarm was continuous: the events followed each other typically at intervals of some minutes. The released seismic energy of this activity was 7.5×10^7 J, corresponding to a magnitude 2.05 earthquake. These events were concentrated in the northern part of the volcano (Fig. 7), and the obtained depths for well-located events were mainly in the uppermost 3 km (see Fig. 4). The earthquakes at Hekla proper are normally observed to be much deeper: at 8–12 km. The location of the small Skjólkvíar lava (Fig. 6), which erupted on 17–18 January, is in the same area as the earthquake swarm of June 1991. The main activity of the 1970 eruption also occurred in the north part of Hekla (Þórarinsson 1970).

The analogue station HE (and LJ quite faintly) observed three volcanic-looking events on 1 June: two very near each other at 17:26 h and a third one 10 min later. Their appearance is similar to so-called hybrid events (Chouet 1996, p. 310), i.e. they have a high frequency onset, but continue with a low frequency wavetrain. Their amplitudes look similar to those of high frequency events of approximately magnitude 1 in the same seismogram. We did not notice any continuous volcanic tremor on 1–2 June. After this, the Hekla region was practically quiet seismically until the end of June.

The seismicity at Torfajökull was at ordinary background levels after the Hekla eruption; the magnitudes of the ten observed events were between 0.5 and 1.7. There were no indications of increased seismicity related to the eruption. Later, in the second half of 1991, intense swarms of low frequency volcanic earthquakes occurred at Torfajökull, which we speculated were somehow connected with the volcanism at Hekla (Soosalu and Einarsson 1997). No such swarms were observed in March–June 1991. In total we noticed about 40 small local low frequency events on the LJ seismograms in March–June. One event (M_L 1.3), on 20 June, could be located at the southern edge of the Torfajökull caldera (Fig. 7).

The eastern end of the South Iceland seismic zone appeared rather active after the Hekla eruption. Until the end of June 1991, 19 events (11 well-located) of magnitudes –0.3–1.9 were observed at depths of 6–12 km. Most of the activity occurred near the Leirubakki fault (Fig. 7) in April 1991. Stefánsson et al. (1993) reported that increased seismic activity was observed in the seismic zone and its surroundings after the Hekla eruption until the end of June 1991. The activity at the eastern end of the zone could be a part of this phenomenon.

Conclusions and discussion

The 1991 Hekla eruption started practically without a warning, as both the related seismic activity and the strain signal reflecting an intrusion travelling towards the surface (Linde et al. 1993) were observed only half an hour before the onset of the eruption (Fig. 5). Possibly small seismic events could have been observed somewhat earlier, if the station HE on the volcano or the digital station HAU had been available. The next Hekla eruption occurred between 26 February and 8 March 2000. By contrast, both stations HE and HAU operated normally, and the first small eruption-related earthquakes were recorded almost 80 min before its onset (Einarsson 2000; Stefánsson et al. 2000). However, the seismic observations did not provide any obvious data for a long-term prediction for volcanic activity at Hekla.

The earthquakes at the onset of the eruption reflect the movement of the magma at depth. Because of the inaccuracy of the event locations we could not trace any migrating front of hypocentres ahead of an intrusion. However, preliminary results for the 2000 eruption, for which we have good seismic data, do not show such a migration. Moreover, at the onset of the 2000 eruption, the very first small earthquakes occurred near the surface and, thus, are more likely to be associated with changes in the general stress field than directly with the magma. In light of the observations of this event it also appears that the magma channels and fissures can open quite aseismically and that the earthquakes occur in response to stress field changes.

After the onset hours of the eruption, the earthquake activity at Hekla was modest and the principal eruption-related seismic signal was the continuous volcanic tremor. The lack of earthquake energy release suggests that the stress field did not change much or adjust quickly after the magma conduits had reached their final extent.

Hekla appears to have a dual nature in a seismic sense: on one hand seismicity is ruled by the tectonics of the South Iceland seismic zone and, on the other hand, by the volcano's internal processes. The seismic zone is the dominant factor during the non-eruptive periods. The few Hekla earthquakes and the events in the Hekla–Vatnafjöll area typically occur at 8–12 km depth and have a tendency to occur along two N–S lineaments similar to the activity of the seismic zone faults to the west. This study gives additional evidence for the two N–S lineaments of seismicity in the Hekla–Vatnafjöll area, which resemble the activity in the South Iceland seismic zone faults. The western one, which marks the fault lineament of the 1987 Vatnafjöll earthquake (Bjarnason and Einarsson 1991), at 19°46′–19°48′W, was practically aseismic both before the 1991 eruption and during it, and also in the following months. It is possible that most of the stress here had already been released in the magnitude 6 1987 earthquake. This lineament was again seismically active during July 1991–December 1996 (Soosalu and Einarsson 1997). Another fainter hypocentral fault lineament crossing Hekla and Vatnafjöll about 5 km east of the former fault was identified in the 1991–1996 data. The Hekla–Vatnafjöll seismicity was concentrated in this area during the January–March 1991 eruption, and in the following months. The June 1991 earthquake swarm near the Skjólkvíar fissure is also elongated in the direction of this lineament, and also the main eruptive site of the 1970 eruption by Skjólkvíar (three bars by northern edge of Hekla in Fig. 2) follow this trend (Þórarinsson 1970).

The volcano-related seismicity of Hekla occurs primarily at the beginning of the eruptions. Numerous small earthquakes occur when the general stress field is adjusting to intruded magma and the opening of eruptive fissures. However, the most persistent volcano-related seismic signal at Hekla is the volcanic tremor, which starts when the magma reaches the surface and continues, although with a diminishing trend, until the end of the eruption. The earthquakes during later phases of the eruption, after the violent onset, are few and tend to follow the pattern of the South Iceland seismic zone seismicity.

The earthquake sequence at Hekla at the beginning of June 1991 is an abnormal occurrence for this otherwise aseismic volcano. Also, the small depth of these events is atypical. One possible interpretation for the shallow earthquakes at Hekla is that they are signs of an attempt to resume the eruption, but that for some reason failed. It is possible that the magma channels in the Skjólkvíar area were still to some extent prepared for a second period of eruption. Also, in earlier times, Hekla has continued its eruption after a quiescence, e.g. the activity of 1980 resumed in 1981, about 8 months later (Grönvold et al. 1983). Moreover, some hybrid earthquakes were observed that could be signs of movement of magma. We studied the temporal distribution of the depths of the June earthquakes in order to see if there was an advancing front of earthquakes ahead of an ascending intrusion, but the data were too poor to show any such trend. However, such a front does not necessarily exist, according to the observations of the onset of the February 2000 eruption. The deformation measurements at the strain station BUR in the vicinity of Hekla (e.g. Fig. 1) do not confirm any intrusion in June 1991 because no intrusion-related strain signal, similar to the one on 17 January, was seen (Kristján Ágústsson, personal communication). One can speculate if these earthquakes were caused by stress adjustment of the crust prior to an intrusion that never started propagating.

The earthquakes were few at Hekla in the study period, except at the onset of the eruption on 17 January 1991 and during the earthquake swarm on 1 June 1991. No Hekla events were observed in the last 7 months prior to the eruption. Almost 400 small earthquakes, corresponding together to seismic energy of a magnitude 3.4 event, were recorded in the first few hours of the eruption. The swarm of about 100 events in June 1991 released energy equal to a magnitude 2 event. After the 1991 eruption, the last earthquake at Hekla proper was observed on 25 August 1991 (M_L 1.3). All the events at Hekla in 1991 were ordinary high frequency earthquakes, except one M_L 0.3 low frequency event on 11 April. After a quiescence of 1.5 years, in February 1993, occasional small events started to occur at Hekla. All of them had low a frequency appearance, but clear S phases (see Soosalu and Einarsson 1997). Such earthquakes were observed until March 1999. Since 1991, high frequency Hekla earthquakes occurred again in February 1998 and July 1999. The significance of the change in the frequency content of the Hekla events is not clear.

Several studies have attempted to chart the location of the magma chamber of Hekla by different methods (e.g. Kjartansson and Grönvold 1983; Sigmundsson et. al 1992; Linde et al. 1993; Tryggvason 1994); the depth estimates for the centre of the chamber have varied between 5 and 9 km. The locations of the earthquakes during the onset of the 1991 eruption were not well enough determined to be of use in locating the magma chamber. The short time interval of 30 minutes between the onsets of seismic and volcanic activity would point to a not very deep magma source. Kristín Vogfjörð and Sigurður Th. Rögnvaldsson (personal communication) observed shallow origins for earthquakes immediately before the eruption. Preliminary analysis of earthquakes at the onset of the 2000 eruption shows that the seismicity started with very small shallow earthquakes in the first tens of minutes and, after that, the events also had deeper foci, mainly at 5–9 km. An advancing front of earthquakes could not be located. Seismicity seemed to occur simultaneously within a large volume.

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References

Bjarnason IŢ, Einarsson P (1991) Source mechanism of the 1987 Vatnafjöll earthquake in South Iceland. J Geophys Res 96: 4314–4324

Brandsdóttir B, Einarsson P (1992) Volcanic tremor and low-frequency earthquakes in Iceland. In: Gasparini P, Scarpa R, Aki K (eds) Volcanic seismology. Springer, Berlin Heidelberg New York, pp 212–222

Chouet BA (1996) Long-period volcano seismicity: its source and use in eruption forecasting. Nature 380:309–316

Einarsson P (1990) The Látrar Poltergeist, a case of frost-cracking (in Icelandic with English abstract). Náttúrufræðingurinn 60: 75–80

Einarsson P (1991) Earthquakes and present-day tectonism in Iceland. Tectonophysics 189:261–279

Einarsson P (2000) The seismograph station on Litla-Hekla and the 2000 eruption (abstract, in Icelandic). Geoscience Society of Iceland, Spring meeting 2000

Einarsson P, Björnsson S (1976) Seismic activity associated with the 1970 eruption of volcano Hekla in Iceland. Jökull 26:8–19

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

Grönvold K, Larsen G, Einarsson P, Ţórarinsson S, Sæmundsson K (1983) The Hekla eruption 1980–1981. Bull Volcanol 46:349–363

Guðmundsson Á, Óskarsson N, Grönvold K, Sæmundsson K, Sigurðsson O, Stefánsson R, Gíslason SR, Einarsson P, Brandsdóttir B, Larsen G, Jóhannesson H, Ţórðarson Ţ (1992) The 1991 eruption of Hekla, Iceland. Bull Volcanol 54:238–246

Hekla, special map 1:50,000 (1989) Icelandic Geodetic Survey, Reykjavík

Jakobsson SP (1979) Petrology of recent basalts of the Eastern Volcanic Zone, Iceland. Acta Naturalia Islandica 26:1–103

Jóhannesson H, Jakobsson SP, Sæmundsson K (1990) Geological map of Iceland, sheet 6, South Iceland, 3rd edn. Icelandic Museum of Natural History and Iceland Geodetic Survey, Reykjavík

Kjartansson E, Grönvold K (1983) Location of a magma reservoir beneath Hekla volcano, Iceland. Nature 301:139–141

Klein FW (1978) Hypocenter location program Hypoinverse. US Geol Surv Open-file Rep 78-694

Linde AT, Ágústsson K, Sacks IS, Stefánsson R (1993) Mechanism of the 1991 eruption of Hekla from continuous borehole strain monitoring. Nature 365:737–740

Sigmundsson F, Einarsson P, Bilham R (1992) Magma chamber deflation recorded by the global positioning system: the Hekla 1991 eruption. Geophys Res Lett 19:1483–1486

Soosalu H, Einarsson P (1997) Seismicity around the Hekla and Torfajökull volcanoes, Iceland, during a volcanically quiet period, 1991–1995. Bull Volcanol 59:36–48

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

Stefánsson R, Ágústsson K, Guðmundsson GB, Þorbjarnardóttir BS, Einarsson P (2000) A successful prediction and warning of an eruption in the Hekla volcano, Iceland (Abstract). AGU 2000 Spring Meeting. Eos 81:5442

Þórarinsson S (1967) The Eruption of Hekla 1947–1948. I. The eruptions of Hekla in historical times, a tephrochronological study. Soc Scientiarum Islandica, Reykjavík, pp 1–170

Þórarinsson S (1970) Hekla, a notorious volcano. Almenna bókafélagið, Reykjavík

Tryggvason E (1994) Observed ground deformation at Hekla, Iceland prior to and during the eruptions of 1970, 1980–1981 and 1991. J Volcanol Geotherm Res 61:281–291

Wessel P, Smith WHF (1998) New, improved version of the Generic Mapping Tools released. Eos 79:579