INSTITUTE OF SEISMOLOGY
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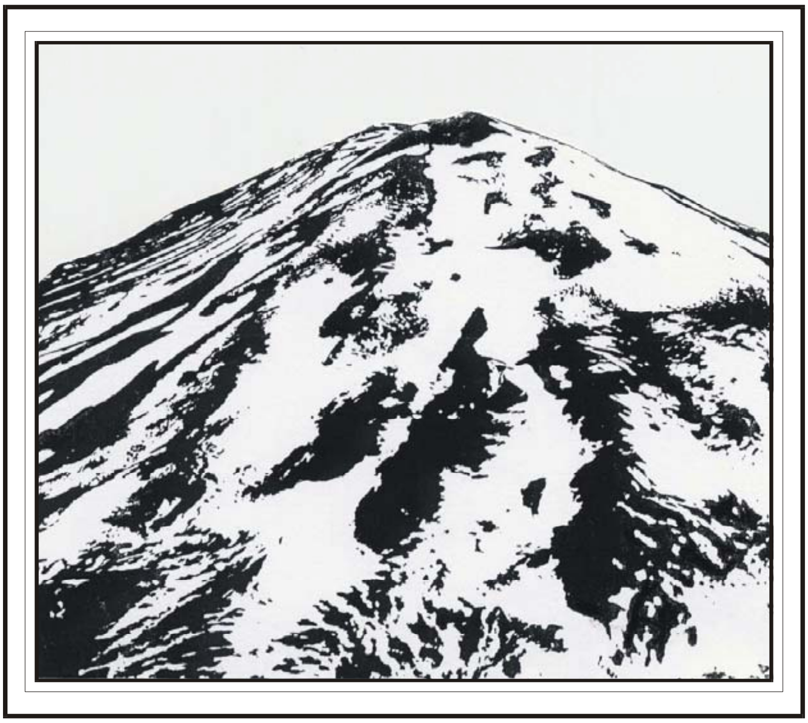

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Academic Dissertation

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To Hekla, with Respect
and
to the Memory of My Father

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Abstract

The volcano Hekla is located in south Iceland at the junction of a transform segment, the South Iceland seismic zone, and a ridge segment, the Eastern volcanic zone, of the Mid-Atlantic plate boundary. It is one of Iceland's most active volcanoes and has erupted at least 18 times during historic times. In the last years Hekla has had a tendency to have rather small eruptions approximately once in a decade, the latest occurring in 1991 and 2000.

The 1991 Hekla eruption took place in 17 January – 11 March, and was accompanied by abundant seismicity. Prior to the eruption no earthquakes were observed for several months, but a swarm of small earthquakes commenced about half an hour before the eruption itself. In total almost 400 events up to local magnitude 2.5 were observed during the first hours of the eruption. These events ceased after a few hours, and at later times of the eruption only few earthquakes occurred.

Low-frequency volcanic tremor, in the frequency band of 0.5-1.5 Hz and with major spectral peaks at 0.7-0.9 Hz started simultaneously with the eruptives reaching the surface. The tremor was the persistent seismic signal related to the eruption and continued throughout it. It was very violent during the first hours, the explosive phase of the eruption, but decreased later in amplitude. The tremor was likely closely related to degassing and thus probably has an origin near the surface.

An intense swarm of small shallow earthquakes occurred at Hekla on 1 June 1991. This is abnormal behaviour, as typically Hekla is aseismic during non-eruptive periods, and likely was a failed attempt to resume the eruption.

During later, non-eruptive times only few earthquakes occurred at Hekla and its vicinity. Their locations form two approximate N-S lineations transecting Hekla and the Vatnafjöll volcano south of it. They had hypocentres mainly at the depth of 8-13 km and followed the pattern of the seismicity of the South Iceland seismic zone west of Hekla and Vatnafjöll. Thus Hekla has a dual seismic nature, volcano-related during eruptions and transform-related during non-eruptive times.

The most persistent seismicity in the Hekla region during the non-eruptive periods was observed east of it, at the Torfajökull volcano, which is a major rhyolitic centre with a caldera and intense high-temperature geothermal activity. Numerous small earthquakes occurred in the west part of the volcano. They formed a spherical distribution around an aseismic volume, with a centre at the depth of 8 km and a diameter of 4 km. This volume was interpreted as a cooling magma chamber.

Torfajökull is also a source of low-frequency events, often occurring in swarms. Only few of them could be located, pointing to origin in the south and east parts of the caldera. These events may be some kind of indication of active magma there.

Seismic records of local earthquakes with ray paths transecting Hekla and/or Torfajökull were studied for finding signs of anomalous S-wave attenuation, which may indicate the existence of magma volumes under these volcanoes. These rays scanned Hekla at the depth of 8-14 km, partly also at 4-8 km and 14-16 km. Western Torfajökull was covered at 4-14 km, eastern and southern Torfajökull at 6-12 km. Only a small fraction of seismic records had clear indications of S-wave attenuation. Thus distinct evidence of molten volumes could not be found, neither under Hekla nor under Torfajökull. Most of the seismic rays piercing the cooling magma chamber in the west part of Torfajökull had S-waves, which indicates that this volume does not contain large batches of molten magma.

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Earthquake catalogue for the Hekla-Torfajökull area, May 1990 – December 1996

Introduction

This thesis consists of the following papers:

I Soosalu, H. and Einarsson, P., 1997. Seismicity around the Hekla and Torfajökull volcanoes, Iceland, during a volcanically quiet period, 1991-1995. *Bulletin of Volcanology*, 59:36-48.

II Soosalu, H. and Einarsson, P., 2002. Earthquake activity related to the 1991 eruption of the Hekla volcano, Iceland. *Bulletin of Volcanology,* 63:536-544.

III Soosalu, H., Einarsson, P., and Jakobsdóttir, S., 2003. Volcanic tremor related to the 1991 eruption of Hekla volcano, Iceland. *Bulletin of Volcanology*, 65:562-577.

IV Soosalu, H. and Einarsson, P., 2003. Seismic constraints on magma chambers at Hekla and Torfajökull volcanoes, Iceland. *Bulletin of Volcanology*, DOI 10.1007/s00445-003-0301-1.

The purpose of this work is to describe, analyse and interpret the seismic activity related to the eruption of the Hekla volcano that occurred in 17 January – 11 March 1991. Both the earthquakes and the volcanic tremor accompanying this event are studied. As continuous seismicity is a characteristic phenomenon in volcanic areas, it is necessary to map first the normal background level of seismicity in a non-eruptive time before the eruption-related seismicity can be identified. Such a study is made for Hekla and its surroundings, using a 4-5-year period following the 1991 eruption. A rectangular area around Hekla (63°42'–64°18' N, 18°30'–20°12' W) is used as the study area throughout the whole study period, from June 1990 to October 1995, and a smaller area around Hekla (63°48'–64°05' N, 19°25'–19°56' W) until December 1996. Together with Hekla the area covers two other volcanoes, Torfajökull to the east and Vatnafjöll to the south, and the eastern end of the South Iceland seismic zone, a transform zone of the Mid-Atlantic plate boundary. In this thesis also a seismic study is made for setting constraints to possible locations of the Hekla magma chamber, and the magma chamber of Torfajökull.

Paper I surveys the background level of seismicity at Hekla and in surrounding areas in a period, July 1991 – October 1995 (until December 1996 at Hekla and its immediate vicinity), when no eruptive activity was ongoing. This non-eruptive period was chosen as it is the first one for which digital seismic data are available. With the aid of this information the seismicity directly related to the 1991 Hekla eruption can be extracted. The most seismically active area turned out to be the Torfajökull volcano east of Hekla. Continuous seismicity was observed in the east end of the South Iceland seismic zone, which was included in the study area. Hekla was observed to be almost aseismic during this non-eruptive period. Its seismicity was not volcano-related, but reflected the transform tectonics of the South Iceland seismic zone together with the earthquake activity at the Vatnafjöll volcano south of Hekla.

Paper II deals with the earthquake seismicity at Hekla and in its vicinity during June 1990 – June 1991, a period including the Hekla eruption in 17 January – 11 March

1991. Nothing unusual in seismicity in this area was observed prior to the eruption. Earthquake activity in the surroundings was within normal limits, both with regard to number and sizes of the events, and areal distribution. No earthquakes were observed at Hekla until only half an hour before the onset of the eruption. An intense swarm of small earthquakes, up to local magnitude 2.5 was observed in the first hours of the eruption. Only few events were observed at Hekla during later phases of the eruption. In the beginning of June 1991 there occurred a sudden swarm of numerous small shallow earthquakes at Hekla. This is very atypical activity, and probably was a failed attempt to resume the eruption.

Paper III presents the volcanic tremor related to the 1991 Hekla eruption. The tremor was the continuous seismic expression of the eruption, as it started and faded out together with the volcanic activity. The tremor was by far most vigorous during the first hours of the eruption characterized by explosive activity, and declined later. The spectral analysis of tremor data in the first hours showed that the tremor spectrum had a characteristic band at low frequencies, 0.5-1.5 Hz and a dominating peak at 0.7-0.9 Hz. The tremor appears to be closely related to degassing and apparently has a shallow source.

Paper IV gives constraints on the existence of molten material under the volcanoes Hekla and Torfajökull. A set of local earthquakes, observed by the Icelandic digital seismograph network was used as the material of this study. They had 663 seismic rays that were travelling under Hekla and Torfajökull. Observations on S-wave arrivals at the seismic stations were made – whether they looked ordinary, had been clearly attenuated or were missing. It was assumed that magma somewhere in the path of the seismic ray can be a cause for shear wave attenuation. Only a tiny fraction of seismic records showed that the S-wave had clearly attenuated or was missing. Thus no definite signs of considerable molten volumes were found with this method, neither under Hekla nor under Torfajökull.

Seismic activity related to volcanoes

Seismic studies give important information on physical processes occurring at volcanoes and on the structures of their magma chamber systems. Seismic measurements can be used for volcano monitoring, forecasting eruptions and estimating sizes of eruptions in progress (McNutt 2000).

A variety of earthquake signals can be observed at volcanoes. According to the duration they can be divided into transient, earthquake-like events and continuous, long-lasting tremor (Chouet 1996; McNutt 2000). Typically the volcano seismicity increases prior to or during an eruption, and the events are mainly shallow, at less than 10-km depth (McNutt 2000).

High-frequency or volcano-tectonic earthquakes are thought to be caused by shear failure on faults, similarly to ordinary tectonic earthquakes. At volcanoes they tend to occur in swarms of events of rather similar sizes, not in mainshock-aftershock sequences, as is typical for earthquakes elsewhere. High-frequency earthquakes have clear P- and S-wave arrivals, are short in duration and have dominant frequencies at 5-15 Hz (McNutt 2000).

Low-frequency or long-period earthquakes are seismic events characteristic of volcanoes, related to magma and/or geothermal fluids and having a narrow frequency band within 1-5 Hz, most typically in 2-3 Hz (McNutt 2000). The exact mechanisms causing the low-frequency earthquakes are still not entirely understood, and they may be generated by different processes at different volcanoes. The proposed source models range from an opening and resonating crack when the magma is ascending towards the surface (Chouet 1996) to existence of pressure transients within the fluid-gas mixture causing resonance phenomena within the magma itself (e.g. Seidl et al. 1981). The low-frequency events often have emergent P-waves and lack S-waves.

Some earthquakes have characteristics of both high-frequency and low-frequency events, and are called hybrid earthquakes. They have a high-frequency onset, but the latter part of the event is similar to a low-frequency event (Lahr et al. 1994; Chouet 1996). They are thought to represent a mixture of processes, such as an earthquake occurring next to a fluid-filled cavity and setting it into oscillation (McNutt 2000).

Introducing broadband seismometers, with the ability to record ground shaking down to 0.016 Hz frequency, into volcano seismic measurements has revealed a new type of events at some volcanoes (McNutt 2000). Very-long-period events with frequencies of 0.05-0.3 Hz and shallow depths, associated with either eruptions or vigorous fumarolic activity, have been detected at some volcanoes, e.g. Kilauea (Ohminato et al. 1998) and Stromboli (Falsaperla et al. 1994). Explosive eruptions are accompanied by explosion earthquakes and many of them are characterized by the presence of an air-shock phase on the seismogram (McNutt 2000).

Distinct long-duration seismic signals caused by surficial effects, such as rockfalls, pyroclastic flows and lahars, can be observed at volcanoes (McNutt 2000). However, low-frequency volcanic tremor, which can last from minutes to days or longer, is the continuous seismic signal intrinsic to volcanoes. The tremor has been observed to have a spectrum within the frequency band of 1-9 Hz at various volcanoes (McNutt 1994); Hekla tremor is in the lower end of this range with its characteristic frequencies at 0.5-1.5 Hz. Various explanations for the cause of volcanic tremor has been proposed. Some models explain the tremor as the result of resonant effects produced by the geometry of volcanic conduits. Turbulent motion in the vapour-gas-magma mixture causes the oscillation of volcanic pipes (e.g. Seidl et al. 1981; Ferrick et al. 1982). Other models suggest that volcanic tremor is produced by vibrations of tensile, fluid-filled, jerkily or suddenly opening cracks (Aki et al. 1977; Chouet 1981). In such models the excess pressure in the fluid generates the trembling. This modelling has been refined by adding active participation of the fluid in the form of degassing (Chouet 1985). As the frequency content of the tremor is similar to that of low-frequency earthquakes it is often concluded that tremor is consisting of a series of low-frequency events close in time (McNutt 2000).

Volcanic tremor is a sign of high activity at a volcano and almost every eruption is accompanied by it (McNutt 2000). On the other hand, at some volcanoes tremor can be observed also in non-eruptive times (McNutt 1994) and changes in its characteristics, such as amplitude or frequency content, can be used for predicting impending eruptions.

Volcanoes typically are sources of persistent background seismicity. Thus it is important to distinguish between the normal activity level with its characteristics and changed patterns in seismicity that may lead to an eruption. Many successful eruption forecasts have been made by observing an increase in seismicity compared to the previously measured level (McNutt 2000). The time scale for foretelling an approaching eruption varies between volcanoes. For example, a long-term change in seismic behaviour was observed preceding the 1991 Pinatubo eruption (Harlow et al. 1996). A short-term, 50-60 minutes, prediction could be given prior to the 2000 eruption of Hekla, based on experience gained on seismic behaviour and strain changes in the 1991 eruption (Einarsson 2000; Stefánsson et al. 2000).

Geological setting of the Hekla area

Iceland is a unique landmass situated astride the Mid-Atlantic ridge. Its geology is characterized by the interplay of the spreading of the mid-oceanic plate boundary and a hot spot, which has a centre located under the NW part of the Vatnajökull glacier. The North American plate and Eurasian plate separate from each other at the speed of approximately 2 cm/year. The plate boundary is slowly dragged to NW but is displaced back on the hot spot by ridge jumps occurring with few-million-year intervals. The plate boundary in Iceland is located inside the neovolcanic zone, a chain of active volcanoes, which traverses the middle part of Iceland (Fig. 1). In the south it has two branches, the Western volcanic zone and the Eastern volcanic zone, which are connected by a transform, the South Iceland seismic zone. In the north there exists a single zone, the Northern volcanic zone. North of Iceland the plate boundary is displaced to the west by another transform, the Tjörnes fracture zone (Fig. 2).

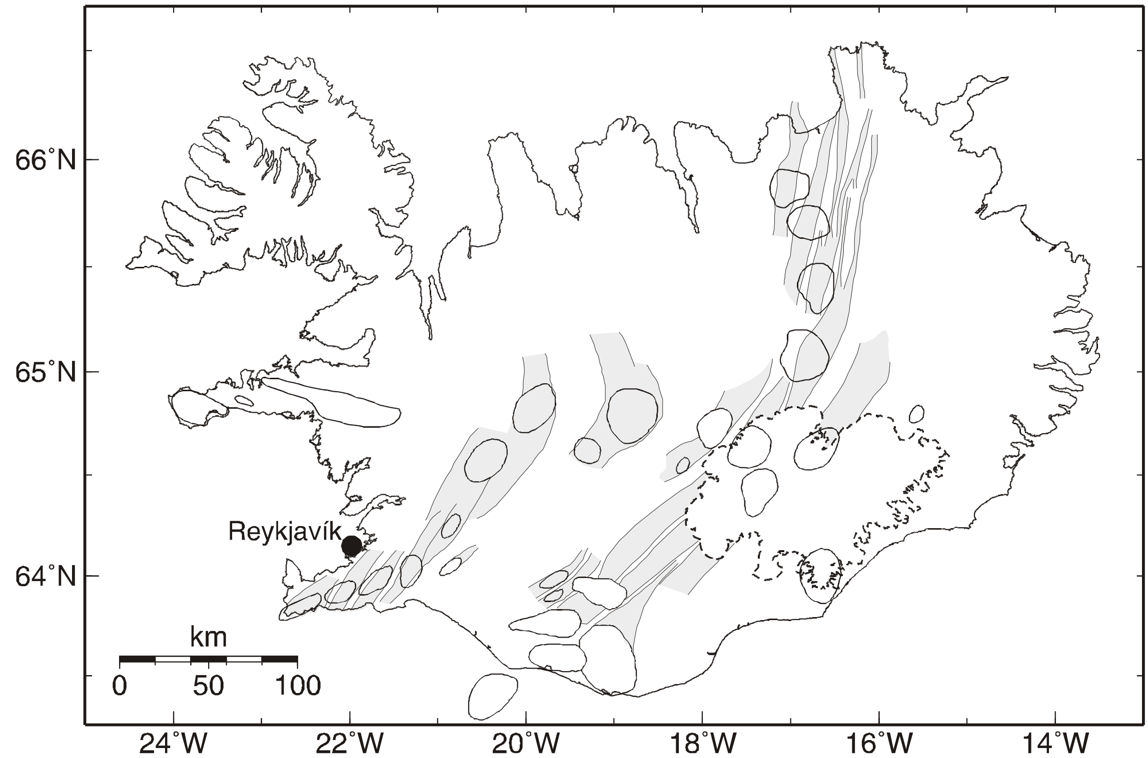

Fig. 1 The map of Iceland. The central volcanoes of the neovolcanic zone are circled and their fissure swarms shaded gray (Einarsson and Sæmundsson 1987). The Vatnajökull glacier is outlined with dashed line. All the figures are drawn using the Generic Mapping Tools program (Wessel and Smith 1998).

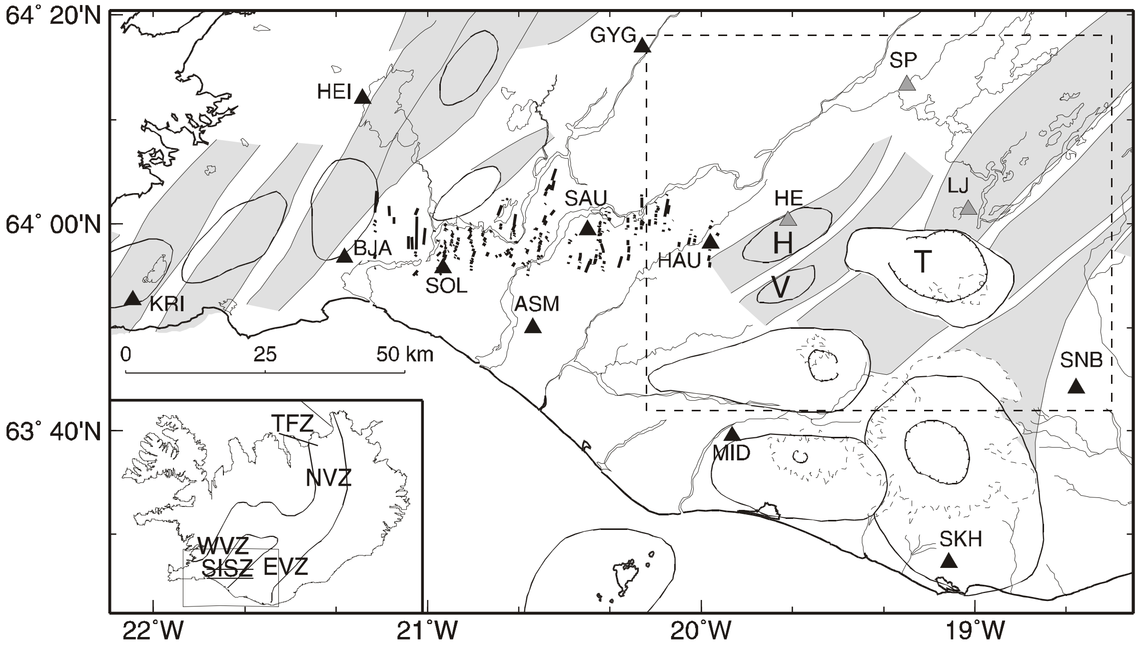

Fig. 2 The study area (dashed rectangle) and the seismograph network. Black triangles are the digital SIL seismograph stations and grey triangles the analogue stations. The central volcanoes are outlined, their fissure swarms are shaded grey (Einarsson and Sæmundsson 1987) and the calderas are hatchured (Jóhannesson et al. 1990). Named central volcanoes are: H = Hekla, V = Vatnafjöll, T = Torfajökull. Thick black lines are the faults of the South Iceland seismic zone. Their locations have been updated in recent years and they are here drawn more accurately than in the maps of the papers I-IV. Short dashed lines mark the glaciers. Smaller index map shows the locations of the Western (WVZ), Eastern (EVZ) and Northern (NVZ) volcanic zones, the South Iceland seismic zone (SISZ), and the Tjörnes fracture zone (TFZ).

The volcanism within the neovolcanic zone is expressed by volcanic systems, which consist of a central volcano – the location of the highest productivity – and a fissure swarm transsecting it (e.g. Jakobsson 1979; Björnsson and Einarsson 1990). The central volcano Hekla in south Iceland is an elongate ridge in the ENE-WSW direction, formed by repetitious eruptions and reaching the altitude of 1490 m above sea level. The recent eruptions have had a tendency to take place on a radial fracture pattern in addition to the main Hekla fissure that splits the volcano lengthwise. The fissure swarm of Hekla extends to NE and SW of the summit. The central volcanoes next to Hekla, and also studied in this thesis, are Torfajökull in the east and Vatnafjöll in the south (Fig. 2).

Torfajökull is a major rhyolitic complex, 450 km^2 in area, rising about 500 m above the surrounding basaltic landscape. It has a 12-km-diameter caldera (Sæmundsson 1972, 1982), and an outstanding high-temperature geothermal field (McGarvie 1984). Torfajökull has fissure swarms stretching to NE and SW of the central volcano. The latest eruption in the Torfajökull area occurred at the end of the fifteenth century (Larsen 1984). The Vatnafjöll central volcano south of Hekla does not have any caldera or geothermal areas. The fissure swarm of Vatnafjöll is elongate in the NE-SW direction, parallel to the fissure swarm of Hekla. No eruptions are known to have occurred in Vatnafjöll during the last 1100 years (Bjarnason and Einarsson 1991).

Hekla is located in a tectonically special area, at the junction between the South Iceland seismic zone and the Eastern volcanic zone, the east branch of the chain of active volcanoes crossing the middle of Iceland (Fig. 2). North of Hekla and Torfajökull the volcanic zone is characterized by rifting activity and in south it has the nature of a non-rifting flank zone. At the location of Torfajökull rifting is propagating towards southwest (Óskarsson et al. 1982).

Hekla is not a typical rift zone volcano, due to this special plate tectonic setting and due to its peculiar petrology. The products of the Hekla volcanic system range from basalts through basaltic andesites to dacites and rhyolites (Jakobsson 1979). The more acidic products are issued from the volcanic edifice, the basaltic products from the fissure swarms or rifts on either side. Petrologically Hekla is more akin to the group of volcanoes in the volcanic flank zone to the southeast.

Hekla is one of the most active volcanoes in Iceland and has erupted at least 18 times since Iceland was colonized in the ninth century (Guðmundsson et al. 1992). Since the major eruption of 1104 AD and until the 1947–48 eruption the pattern was characterized by relatively large eruptions about twice a century (Þórarinsson 1967). Within the last decades Hekla has appeared to be changing its eruptive pattern. Smaller eruptions with about 150 million m^3 of eruptives have been occurring about every ten years, i.e. in 1970, 1980–81, 1991, and 2000.

Hekla is known to be virtually aseismic during non-eruptive periods (Einarsson 1991). Moreover, no long-term or intermediate-term precursory seismicity has been observed before Hekla eruptions. During the latest Hekla eruptions small earthquakes have been recorded only about 25-80 minutes before the onset of the eruption itself (Einarsson and Björnsson 1976; Grönvold et al. 1983; Guðmundsson et al. 1992; Einarsson 2000; Stefánsson et al. 2000).

The South Iceland seismic zone is a 70-80-km long and 10-15-km wide zone in the South Iceland lowland. It acts as an E-W transform, but is characterized by abundant seismicity on N-S right-lateral strike-slip faults, and events up to magnitude 7.1 can occur (Einarsson 1991; Stefánsson et al. 1993). The earthquakes have a tendency to deepen towards east: in the westernmost part of the zone they are typically located in the uppermost 6 km and in east the typical depths are 6-12 km. The east end of the seismic zone, about 15 km in width, is included in the study area.

Hazards caused by Hekla eruptions

Hekla is doubtless the most notorious volcano in Iceland because of its high activity and destruction caused by its eruptions. It forms a potential hazard for various human activities, some of which is directly related to the explosive onset characteristic of Hekla eruption regardless of its size, and some of which can occur in later phases of the eruptions or even after them. Added understanding of the behaviour and eruption mechanism of Hekla is essential for preventing any loss or damage as a consequence of its eruptions.

As the Hekla eruptions start suddenly and violently they can be an immediate risk for aviation safety. Aircraft traffic close to Iceland is busy, as on average about 250 jet planes per day fly across the Icelandic Oceanic Control Area (Sveinbjörnsson 2001), and the eruption plumes of Hekla can proceed to high altitudes in a very short time (e.g. Larsen et al. 1992). The risk for aircrafts is not restricted to the initial ascending plume only, as was observed on 28 February 2000, when the volcanic particles of the eruption cloud of Hekla ejected two days earlier caused damage to the engines of a NASA research aircraft (Pieri et al. 2002).

Though Hekla is located in the uninhabited highland, it is a major tourist attraction and its surroundings are a popular hiking area in the summer time. In case of an impending eruption, even if a successful prediction can be made (as in the case of the 2000 eruption, see Stefánsson et al. 2000) a very short time for warning is probable. Very likely people close to the volcano observe little or no symptoms before the very start of the eruption, as was e.g. experienced by Hutchinson (1983) who was unfortunate enough to be next to Hekla, doing geological mapping, when the 1980 eruption started and he narrowly escaped unharmed. With his companion he had climbed to the top of Hekla some two weeks earlier, seeing no alarming signs.

Unfortunately the explosive onset part of the Hekla eruptions is understandably the most dangerous one. Though in smaller eruptions this phase is short-lasting and less violent than in the large ones, even then volcanic bombs can be ejected to distances of a few kilometres and tephra fall can badly deteriorate the visibility (Hutchinson 1983) and hinder eventual evacuating. Hekla is at least to some extent covered in snow and ice throughout the year. At least in the eruptions of 1766, 1845, 1947 (Kjartansson 1951) and 1980 (Hutchinson 1983) meltwater mudflows were observed, and during the 1947 eruption there was a considerable, though short-lasting, flood in the Ytri-Rangá river that has its source north of Hekla. The fords in the river became impassable and dead fish were observed (Kjartansson 1951). In addition, Höskuldsson and Ólafsdóttir (2002) report clear evidence of pyroclastic flows formed in the 2000 Hekla eruption.

Hekla eruptions can also be a long-term nuisance, especially for farming. The tephra of Hekla has high fluorine content and can be carried also to such parts of Iceland that are distant from the volcano. The tephra precipitates to pastures and can cause fluorine poisoning to the grazing livestock. For example, Sigurðsson and Pálsson (1957) observed symptoms of fluorosis in sheep as a consequence of the 1947-48 eruption. They also noted that fine-grained tephra is more dangerous than coarse-grained, on one hand because it has more surface for the fluorine to be adsorbed on and, on the other hand, is more likely unnoticed devoured by animals. Currently, in case of an eruption, precautions against this phenomenon are made.

If the tephra fall is abundant, it can form a deep layer on the farmland, destroy the crop and in the worst case lead to abandoning farms as has happened during the Icelandic history (Þórarinsson 1967). In the 1947-48 eruption grassland was suffering from initial tephra fall altogether in 98 farms, and water-supplies and hydro-electric installations were failing in many farms because the streams were chocked by pumice (Þórarinsson 1954). Curious phenomena occurred after this eruption, starting in the spring of 1948 (Kjartansson 1957). Contamination of groundwater in brooks and lowering of water level were observed. A more malign occurrence was the formation of “death valleys” when carbon dioxide seeping from the ground gathered in depressions in calm weather. Several sheep and smaller wild animals suffocated in these places.

The utility of seismology in studying Hekla

Though Hekla is a famous volcano, it has been little studied seismologically before the 1991 eruption. Research based on observations of analogue seismometers exist for the

1970 (Einarsson and Björnsson 1976) and the 1980-81 eruptions (Grönvold et al. 1983), but at those times the seismometer network was not as dense as today. In 1970 the closest station was at 80 km distance and in 1980 at 22 km. An analogue seismometer was installed on the flank of Hekla first in the spring 1981, after the eruption.

Because of apparent aseismicity of Hekla during non-eruptive times prospects are not very good for long-term predictions of the eruptions based on changes in the patterns of the seismicity. However, the seismicity has been observed to start shortly prior to the latest eruptions, and this gives essential tools for successful short-term predictions. Observations of the seismic activity during one eruption of Hekla give information on characteristics of eruption-related seismicity at Hekla in general, and help in understanding eruption mechanisms of Hekla. Though Hekla may be seismically a rather unusual volcano, knowledge gained at Hekla is to some extent applicable in the seismic studies of volcanoes anywhere in the world.

Mapping the magma plumbing system of Hekla can give additional information on eruptive behaviour of Hekla. Though the location of the magma chamber has been estimated in a few geophysical studies (Kjartansson and Grönvold 1983; Eysteinsson and Hermance 1985; Sigmundsson et al. 1992; Linde et al. 1993, Tryggvason 1994) no seismic research on the deep structure of Hekla and its magma source has been made so far.

The SIL network

This study bases principally on seismic data gathered by the digital stations of the SIL (South Iceland Lowland) network (Fig. 2), maintained by the Icelandic Meteorological Office. The SIL network was initiated as a Nordic seismological project in 1988, with the purpose of making earthquake prediction research in the South Iceland seismic zone (Stefánsson et al. 1993). Originally the network consisted of eight digital three-component stations in the lowland area, and later the network has been expanded also to other parts of Iceland. The SIL system locates and determines focal parameters of local earthquakes automatically and in semi-real time. As the study area is located at the edge of the original SIL network, three permanent analogue stations in the vicinity of Hekla have been used in addition to get a good station coverage for the whole area.

All the earthquakes that could be located well (with the location criteria: root mean square travel time residual (rms) is ≤ 0.2 s, horizontal error (erh) ≤ 1.0 km and vertical (erz) ≤ 2.0 km, and largest gap between observing stations $\leq 180°$) are plotted in the map in Fig. 3. The hypocentral distribution of these events is shown in Fig. 4.

Hekla seismicity prior to the 1991 eruption (Paper II)

No earthquakes whatsoever were located at Hekla or its immediate vicinity during the period from June 1990 to half an hour before the start of the eruption on 17 January 1991. On the other hand, Hekla was seismically not abnormally quiet during this period, as long intervals between earthquakes are typical there (Einarsson 1991). Thus no long-term or intermediate term precursories prior to the 1991 eruption were observed, and this eruption could not have been predicted using seismic data.

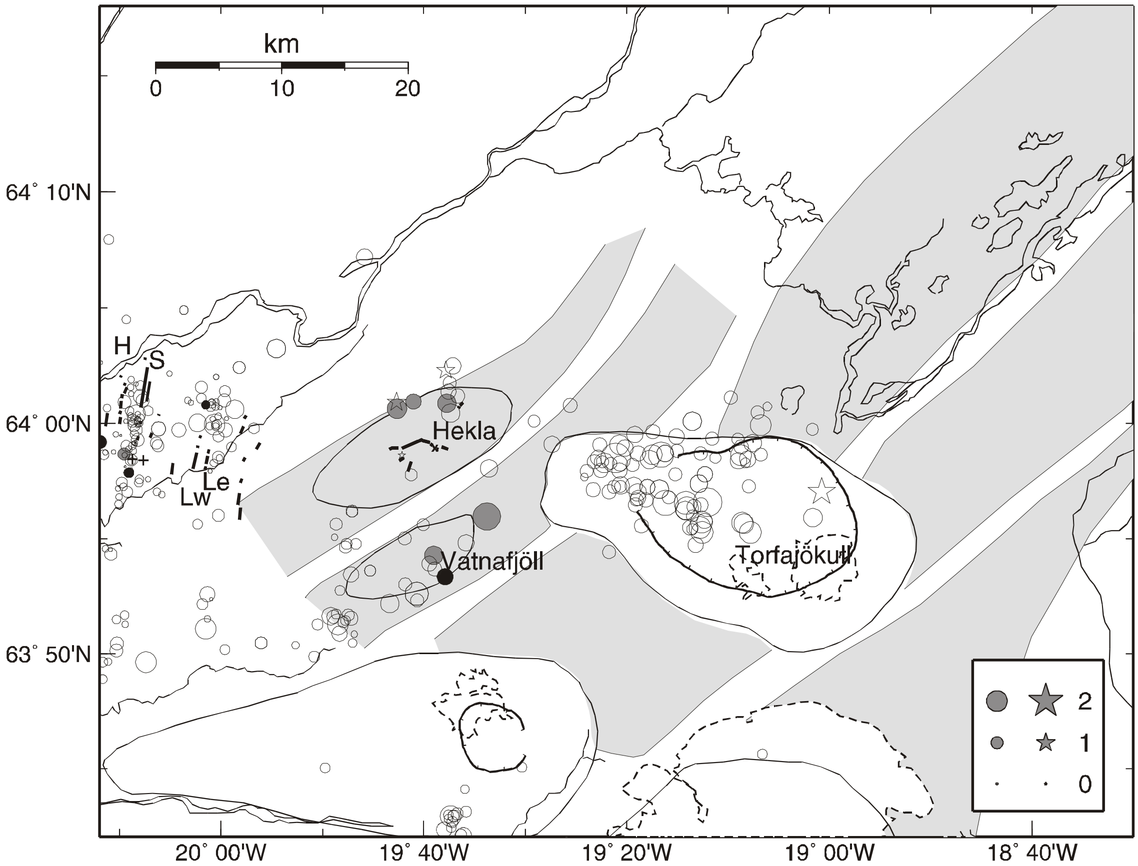

Fig. 3 All the well-located earthquakes. Black symbols are earthquakes that have occurred before the 1991 Hekla eruption, grey symbols events that occurred during the eruption, and open symbols after the eruption. Dots denote ordinary high-frequency earthquakes and stars low-frequency earthquakes. The inset shows the sizes of events of corresponding local magnitudes (M_L). Fissures of the 1970, 1980-81 and 1991 Hekla eruptions are shown. H-Hellar fault, S-Skarðsfjall fault, Lw-western Leirubakki fault, Le-eastern Leirubakki fault. Two crosses in the middle of the Hellar fault are well-located earthquakes with no M_L magnitude defined.

Seismic behaviour of Hekla during the 1991 eruption (Papers II and III)

The first precursory earthquakes related to the 1991 eruption were observed at 16:30 GMT, on 17 January, half an hour before the beginning of the eruption. The earthquakes were very small, mainly with local magnitudes between 0 and 2, and they increased in size towards the onset of the eruption. The largest event, with local magnitude (M_L) 2.5, occurred at 17:52. In total 380 events were detected during the first hours, some 60 of which before the onset of the eruption. Continuous volcanic tremor started at 17:02, together with the eruptive activity. It increased in amplitude very rapidly, within minutes, and became the dominant feature in the seismograms, effectively masking the earthquakes. The tremor remained most vigorous during the first hour of the eruption, and subsequently declined, sharply for an hour and later more gently. The tremor spectrum had a narrow frequency band of 0.5-1.5 Hz and a dominant peak at the frequencies of 0.7-0.9 Hz. It consisted mainly of surface waves and seemed to be closely related to degassing.

The initial earthquake swarm died around the midnight of 17 January, and at later phases only few earthquakes were observed at Hekla. The tremor, instead, was the persistent volcano seismic signal, which continued throughout the eruption, dying together with it around the noon of 11 March. In the very end a swarm of small earthquakes was observed by HE, the analogue seismograph station on the flank of Hekla. They likely represent the conduit collapse after the volcanic activity had ceased.

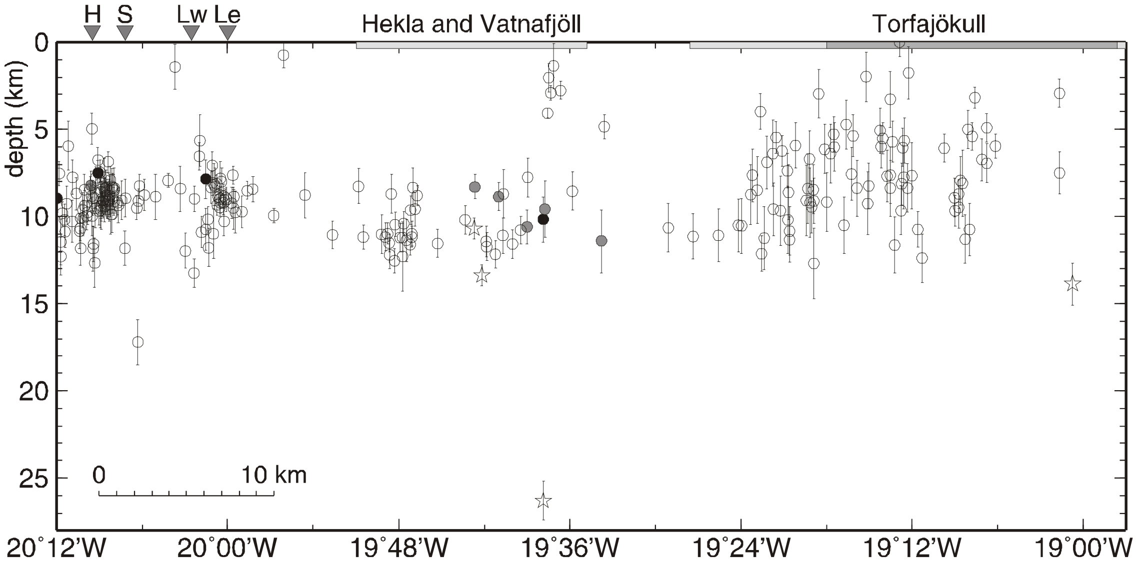

Fig. 4 Vertical cross section of the study area from South Iceland seismic zone to east edge of the Torfajökull caldera (between latitudes 63°48.6'-64°05'N), seen from south and without vertical exaggeration. Plotted are all the well-located earthquakes at these latitudes. Black symbols are earthquakes that have occurred before the 1991 Hekla eruption, grey symbols events that occurred during the eruption, and open symbols after the eruption. Dots denote ordinary high-frequency earthquakes and stars low-frequency earthquakes. Inverted triangles show the surface locations of the South Iceland seismic zone faults: H-Hellar fault, S-Skarðsfjall fault, Lw-western Leirubakki fault, Le-eastern Leirubakki fault. The locations of the central volcanoes are shown with grey bars, the location of the Torfajökull caldera with darker grey shade.

Seismicity at Hekla after the 1991 eruption (Papers I and II)

After the eruption Hekla and its immediate vicinity were seismically peaceful until the end of May 1991; only few little earthquakes occurred. An unusual swarm of small earthquakes (maximum magnitude 1.7) started suddenly at Hekla on 1 June 1991 and lasted almost half a day. The SIL network observed about 30 earthquakes, and the analogue station HE on the flank of the volcano some 70 more. The events were shallow, the obtained depths mainly being in the uppermost 3 km. The analogue stations HE and LJ observed three volcanic-looking events within this swarm, similar in appearance as hybrid events (Chouet 1996).

The study of the seismicity in the non-eruptive period of July 1991 – December 1996 revealed that the earthquakes at Hekla and Vatnafjöll are loosely clustered in two N-S lineations, similar to the faults of the South Iceland seismic zone. One of the lineations cuts the SW parts of the volcanoes and the other one the middle-NE parts of them. The earthquakes occur typically at 8-13 km depth. One event was located at the considerable depth of 26 km.

After June 1991 Hekla itself was seismically quiet for more than a year. Later sporadic small earthquakes started to occur, and their local magnitudes were typically under 1. The earthquakes at Hekla proper had peculiar appearance: they consisted only of low frequencies but had clear S-waves, similar to ordinary earthquakes. One such event, which was rather poorly located, occurred also in April 1991. In contrast, the earthquakes during the eruption and in the months following it – except the three volcanic looking events on 1 June 1991 – were ordinary in appearance.

Torfajökull seismicity (Papers I and II)

Most intensive seismic activity in non-eruptive times in the surroundings of Hekla is observed at the Torfajökull volcano. Rather high and persistent seismicity has been known to be characteristic for its western part (Einarsson 1991). During the whole study period about 200 events, up to local magnitude 2.8 were located in the Torfajökull area. Most epicentres are in the western part of the caldera and northwest of it. Hypocentres are spread in an approximately spherical volume from the surface down to about 14 km. The densest hypocentral cluster is at about 5-12 km. This hypocentral volume of Torfajökull shows an interesting spatial pattern with respect to seismic energy release. The volume has a roughly spherical shape, but inside is a volume devoid of earthquake sources in the NW part of the caldera.

Besides the ordinary earthquakes the low-frequency earthquakes are common at Torfajökull (Brandsdóttir and Einarsson 1992). The activity of low-frequency events is not temporally continuous. It may be quiet for days or even for months, and suddenly the activity can increase to innumerable small events occurring in swarms lasting from one to a couple of days. Low-frequency earthquakes were most frequent from July 1991 to July 1992, common number of events being ten to several tens per day. The highest peak occurred on October 29-31, 1991, with 40, 280 and 300 events per day, respectively. During later years smaller swarms and sporadic single low-frequency events continued to be observed. These low-frequency events are difficult to locate, because they typically are small in size, their P-waves characteristically emergent and the S-waves are unclear. Only a couple of such events were reliably located in this study, in the south and east parts of the caldera.

Seismicity of the South Iceland seismic zone faults

The easternmost section of the South Iceland seismic zone, next to Hekla, was included in the study area. The seismicity there, both during eruptive and non-eruptive times of Hekla is clustered in two elongate N-S lineaments, roughly at longitudes 20°W and 20°10’W. Small earthquakes, up to local magnitude 2 were frequent in this area, and over 190 were observed in the study period. They occurred typically in the depth range of 6-12 km. The events were located between the latitudes of 64°08’ N and 63°49’ N, but were most abundant around the latitude of 64°N, where surface faults exist.

Magma chambers of Hekla and Torfajökull (Paper IV)

A seismic ray method was used to scan the possible locations of the magma chambers of both Hekla and Torfajökull. The material of this study was 118 local earthquakes observed by the SIL network and located in Paper I. In total 663 seismic rays transecting Hekla and/or Torfajökull were examined in order to find signs of anomalous S-wave attenuation caused by molten material in the ray path. The seismic rays almost exclusively did not show signs of attenuation under these volcanoes, and thus no prominent magma bodies were found with this method. 650 of the seismic records had normal-looking S-wave arrivals that fitted to the travel time calculations. Only six records showed signs of clearly attenuated S-waves and seven cases were uncertain.

The volumes that could be scanned in this study were restricted by the distribution of earthquakes and the seismometers. Hekla volcano was covered well at 8-14 km depth, its southern part also at 4-8 km and 14-16 km. Western Torfajökull had a good coverage of seismic rays at 4-14 km, eastern and southern Torfajökull at 6-12 km. Outside these areas there were not enough data to draw definite conclusions regarding the existence of magma. Also, the resolution of this method was restricted to volumes of dimensions larger than about 800 m.

Discussion

As no earthquakes were observed at Hekla during several months prior to the 1991 eruption, a long-term seismicity-based prediction for the eruption could not have been possible. However, based on experience gained in the 1991 eruption, and in the preceding eruptions in 1970 and 1980-1981, a short-term prediction is a realistic objective. This was confirmed with a successful prediction and warning about sixty minutes before the 2000 eruption, which was to a high extent identical to the 1991 eruption – seismically, in the eruptive manner, and in regard to the amount of produced material. The prediction could be made using the knowledge of the initial earthquake swarm and strain observations related to an incipient intrusion (Einarsson 2000; Stefánsson et al. 2000). Thus monitoring seismic activity is in a crucial role in foretelling Hekla eruptions.

During non-eruptive times the seismicity at Hekla is very scarce and it does not have an apparent correlation to Hekla as a volcano. Instead, the area around Hekla and the Vatnafjöll volcano in south forms seismically a unity. The earthquakes in this area cluster loosely in two N-S lineations and occur mainly at 8-13 km depth, similarly to the distribution of the seismicity in the east end of South Iceland seismic zone.

A magnitude 5.9 (M_W) earthquake occurred in the SW part of Vatnafjöll in 1987. Its fault plane solution showed right-lateral strike-slip faulting on a N-S striking fault, i.e. characteristics of the South Iceland seismic zone earthquakes (Bjarnason and Einarsson 1991). It was thus found that “bookshelf faulting”, the seismicity pattern of the seismic zone continues to east as far as to western Vatnafjöll, some 10 km further east than the surface expressions of the seismic zone. Part of the earthquakes in our data set occurred on the same lineation as the major Vatnafjöll earthquake with its fore- and aftershocks. Another N-S lineation can be sketched further east, through the middle parts of Hekla and Vatnafjöll. The five fault plane solutions that we gained for this area are primarily of the strike-slip type, as well. Our study confirms the observations of Bjarnason and Einarsson

(1991) that the South Iceland seismic zone tectonics extend well into the volcanic zone, according to our observations all the way to the longitude of 19°40’ W.

The depths of most of the earthquakes in the initial swarm on 17 January 1991 are not well constrained because of lack of close observing seismograph stations. Kristín Vogfjörð and Sigurður Th. Rögnvaldsson (pers.comm.) estimated depths of four earthquakes before the start of the eruption to be about 3 km. Preliminary studies of the 2000 eruption also indicate that a large portion of the earthquakes before the eruption broke out were shallow. It is likely that the initial earthquakes are related to stress changes caused by the intruding magma reaching the surface, but are not forming a propagating front close to the tip of the intrusion.

A sudden swarm of at least hundred shallow earthquakes at Hekla on 1-2 June 1991 is an unusual occurrence. It likely was a failed attempt to revive the eruptive activity after its cessation on 11 March, similarly to the case of the August 1980 eruption, which continued after several months of quiescence in April 1981. The June 1991 earthquake swarm was not accompanied by a strain signal indicating a start of an intrusion, as was observed in January 1991 (Kristján Ágústsson 2000, pers. comm.). Interestingly, the 1980-1981 eruption was similar in this sense. In the initial phase of the eruption on 17 August 1980 an intrusion-related strain signal was observed, but not when the eruption continued on 9 April 1981 (Ragnar Stefánsson 2003, pers. comm.). An additional observation in favour of an attempt of resuming the eruption is the three hybrid-looking earthquakes recorded by the analogue station HE on the flank of Hekla. Such events may somehow be associated with magma. This is the only occurrence so far of volcanic-looking earthquakes observed at Hekla.

After the burst of seismicity in June 1991 Hekla was quiet for more than a year before the activity typical for non-eruptive times continued. The earthquakes were few, and had an unusual low-frequency appearance. However, at every seismic station a clear S-wave arrival could be observed. This points to brittle failure in the crust, not to the volcanic origin of the earthquakes. Apparently the reason for the low-frequency appearance is that the crust was still hot and weak after the eruption, and broke under low stress drop.

The earthquake cluster in the west part of Torfajökull is distributed around an aseismic volume with a centre at 8 km depth and a diameter of 4 km. This volume is located near the sites of the latest eruptive activity at Torfajökull some five hundred years ago. We have interpreted this to be a magma chamber, around which the small earthquakes are caused by cooling and cracking at its edges, with the aid of geothermal fluid. This interpretation is supported by the persistent nature of the activity, its spatial correlation with geothermal activity, and the spatial pattern of hypocentres and density of released seismic energy. The aseismic volume at the centre of the hypocentral cluster is at a relatively high temperature, above the brittle-ductile transition, but below the solidus.

Low-frequency earthquakes are frequent at Torfajökull and occur typically in swarms. In the whole study period the swarm activity was by far highest in July 1991 – July 1992, after the Hekla eruption. This led us to suggest some kind of connection between these two volcanoes. The few locations we were able to determine for the Torfajökull low-frequency earthquakes point to origin in the south or east part of the caldera. They may be expressions of the existence of active magma there.

The earthquakes in the east end of the South Iceland seismic zone mainly occur within two N-S lineations. The seismicity is highest in the area of mapped surface faults (approximately 10 km in length), but in total the epicentral lineaments are considerably longer, about 20-30 km. Our observations are in harmony with the boundary element calculations of Hackman et al. (1990) which imply that the South Iceland seismic zone faults have to be longer than observed on the surface, or the zone cannot accommodate the required transform deformation. Nearly all the hypocentres are concentrated at 6-12 km depth, with a peak at 8-10 km. This is a part of a general pattern of earthquake depths within the seismic zone, the hypocentres get deeper towards the east (Stefánsson et al. 1993).

We interpreted the earthquake lineations of the seismic zone to be associated with the Hellar fault (in the west) and the Leirubakki fault (in the east) that are visible on the surface (Einarsson and Eiríksson 1982). However, the hypocentres are displaced about 1 km east from the faults at the surface, and thus the faults should be dipping approximately 80°. Recent field mapping has revealed two formerly unknown faults, Skarðsfjall fault east of the Hellar fault (Einarsson et al. 2002; Fig. 3) and a fault east of the Leirubakki fault (Einarsson et al. 2003). The faults in the Leirubakki area are currently named as the western (formerly known) and the eastern (newly found) Leirubakki fault (Fig. 3). The recently mapped faults are located above our earthquake lineations and are more likely origins of them.

Our magma chamber study did not show clear evidence for eventual molten material under Hekla and Torfajökull. According to our seismogram observations there is no space for considerable magma volumes in the regions we could cover. Our study in Paper I revealed a cooling hot volume in the west part of Torfajökull. The S-waves of the seismograms with ray paths transecting this volume were mainly not attenuated. According to these observations this volume is so hot that it is in a ductile state, but it cannot be molten to a considerable extent. We located a few low-frequency earthquakes in the south and east parts of Torfajökull in this work. Our recent studies point to that these events are concentrated in the south part of Torfajökull caldera. These events may indicate batches of magma there, but more careful research has to be done on this topic.

We did not find evidence for molten material under Hekla above 14 km depth, in the volumes that can be scanned with our seismic rays. We have almost no seismic rays transecting Hekla in the uppermost 4 km, and thus cannot draw conclusions about the existence of a magma chamber there with this method. However, a shallow magma chamber at Hekla seems unlikely because Hekla is lacking the expressions usually associated to a shallow chamber, geothermal activity and persistent seismicity.

Geophysical studies of Kjartansson and Grönvold (1983), Eysteinsson and Hermance (1985), Sigmundsson et al. (1992), Linde et al. (1993) and Tryggvason (1994) have been outlining the magma chamber of Hekla and its depth estimates have been at 5-9 km. Our material shows that if molten material exists at these depths it has to be a small chamber. Guðmundsson et al. (1992) proposed a conceptual model of the volcanic system of Hekla, in which it is underlain by a compositionally stratified, extensive magma chamber. Our results show that this kind of model cannot be correct.

Conclusions

The seismicity at Hekla is quite unique and has a dual nature. In non-eruptive times the seismicity is rather scarce and the few earthquakes that do occur are not related to the volcano itself. Instead, they follow the pattern of seismic activity of the South Iceland seismic zone in the west.

No earthquakes were observed at Hekla or its immediate vicinity during the half-year period before the 1991 eruption, and thus no long-term prediction of it based on seismicity could have been made. The related seismicity started with a swarm of numerous small earthquakes increasing in size towards the onset of the eruption. They become observable about half an hour before the eruption started and continued throughout the first hours. In total about 400 earthquakes were detected. The largest event had a local magnitude of 2.5. In total the initial swarm released seismic energy corresponding a single earthquake of magnitude 3.4. Only few earthquakes occurred in the later phases of the eruption.

Low-frequency volcanic tremor entered the seismograms simultaneously with the onset of the eruption. It was most violent during the first hours, continued throughout the eruption and faded away together with it. The tremor had frequencies that were in the low end of what has been observed at various volcanoes of the world. During the first hours the characteristic frequency band of the tremor was 0.5-1.5 Hz and it had a few dominant peaks, at 0.7-0.9 Hz. The tremor started first when the eruptive conduit was open to the surface and thus was related to degassing. Large amount of seismic surface waves revealed by particle motion analysis points to shallow origin of the tremor. No low-frequency volcanic earthquakes were observed during the 1991 Hekla eruption. If any of them occurred they must have been mixed with the tremor.

A sudden earthquake swarm occurred in the beginning of June 1991, two and half months after the cessation of the eruption. Within this swarm three volcanic-looking earthquakes were recorded but no volcanic tremor was detected. The swarm is interpreted as evidence of a failed attempt to resume the eruptive activity, in the same manner as the eruption in 1980-1981.

Observations on the seismicity related to the 1991 Hekla eruption did not reveal any signals or patterns, which could be used for a long-term prediction. However, with seismograph stations close enough, the initial earthquake swarm related to the onset of an eruption can be detected soon after it begins, and with a combined use of seismicity and strain observations it is possible to foresee the eruptions in the short-time scale, approximately within an hour.

When Hekla was not erupting Torfajökull was the most active area seismically. Small high-frequency earthquakes were continuously observed in the west part of the volcano. They clustered around an aseimic body, which was interpreted as a cooling, but solified magma chamber. Low-frequency earthquakes were frequent, as well, at Torfajökull and they did not have a spatial or temporal relation to the high-frequency earthquakes. Most likely they concentrate in the south part of the Torfajökull caldera.

The eastern end of the South Iceland seismic zone was also continuously seismically active and the earthquakes clustered in two north-south lineations, which can be associated to surface faults. The seismic lineations continue farther both to the north and to the south than the mapped surface faults.

No positive results on considerable magma chambers at Hekla or Torfajökull could be found with the seismic ray method. In the uppermost 4 km at Hekla the data are scarce, but a shallow magma chamber of Hekla does not seem very likely. The dataset excludes the existence of a large batch of magma under Hekla at 4-14 km. The cooling magma chamber in the west part of Torfajökull does not seem to be molten any more, at least not to a great extent, as vast majority of the seismic rays crossing it did not show evidence of S-wave attenuation. South part of the Torfajökull caldera is the locus of low-frequency earthquakes and they may be somehow related to active magma. However, evidence of S-wave attenuation was not found in this area.

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