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RESEARCH ARTICLE

The millennium eruption of Hekla in February 2000

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Abstract The 18th historic eruption of Hekla started on 26 February, 2000. It was a short-lived but intense event, emitting basaltic andesitic (55.5 wt% SiO_2) pyroclastic fragments and lava. During the course of the eruption, monitoring was done by both instruments and direct observations, together providing unique insight into the current activity of Hekla. During the 12-day eruption, a total of 0.189 km^3 DRE of magma was emitted. The eruptive fissure split into five segments. The segments at the highest altitude were active during the first hours, while the segments at lower altitude continued throughout the eruption. The eruption started in a highly explosive manner giving rise to a Subplinian eruptive column and consequent basaltic pyroclastic flows fed by column collapses. After the explosive phase reached its maximum, the eruption went through three more phases, namely fire-fountaining, Strombolian bursts and lava effusion. In this paper, we describe the course of events of the eruption of Hekla and the origin of its magma, and then show that the discharge rate can be linked to different style of eruptive activity, which are controlled by fissure geometry. We also show that the eruption phases observed at Hekla can be linked with inferred magma chamber overpressure prior to the eruption.

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Introduction

The Hekla volcano is situated on the south-western boundary of the Eastern Volcanic Zone (EVZ) in Iceland and is one the most active volcanoes in Iceland having, prior to the 2000 eruption, erupted 17 times during the last 11 centuries (Fig. 1). In addition to eruptions from the main volcano, at least six eruptions have occurred on the periphery of the volcano, the last in 1913 (Thorarinsson 1967; Jakobsson 1979). The recurrence rate of Hekla eruptions was around one to two eruptions per century until the 1970s, when it changed drastically. Since 1970, the volcano has erupted about every 10 years, in 1970, 1980–81, 1991 and in 2000 (Thorarinsson and Sigvaldason 1972; Grönvold et al. 1983; Gudmundsson et al. 1992; Hoskuldsson and Olafsdottir 2002).

The regularity of Hekla eruptions is also manifested in the chemical composition of its eruption products. After long periods of quiescence (a century or more), high silica magma (rhyodacite) was ejected from the volcano, as in the eruption of 1104, which followed more than 250 years of dormancy. In contrast, shorter repose periods (<30 years) ended with the eruptions of low silica magmas (andesite to basaltic andesite). Eruptions taking place along the periphery of Hekla are, however, always basaltic (Thorarinsson 1967; Jakobsson 1979).

The initial phase of each Hekla eruption is always highly explosive. The duration and magnitude of the explosive phase is directly correlated with the length of the preceding repose period. Eruption columns rising above the vent during the first hours of an eruption are

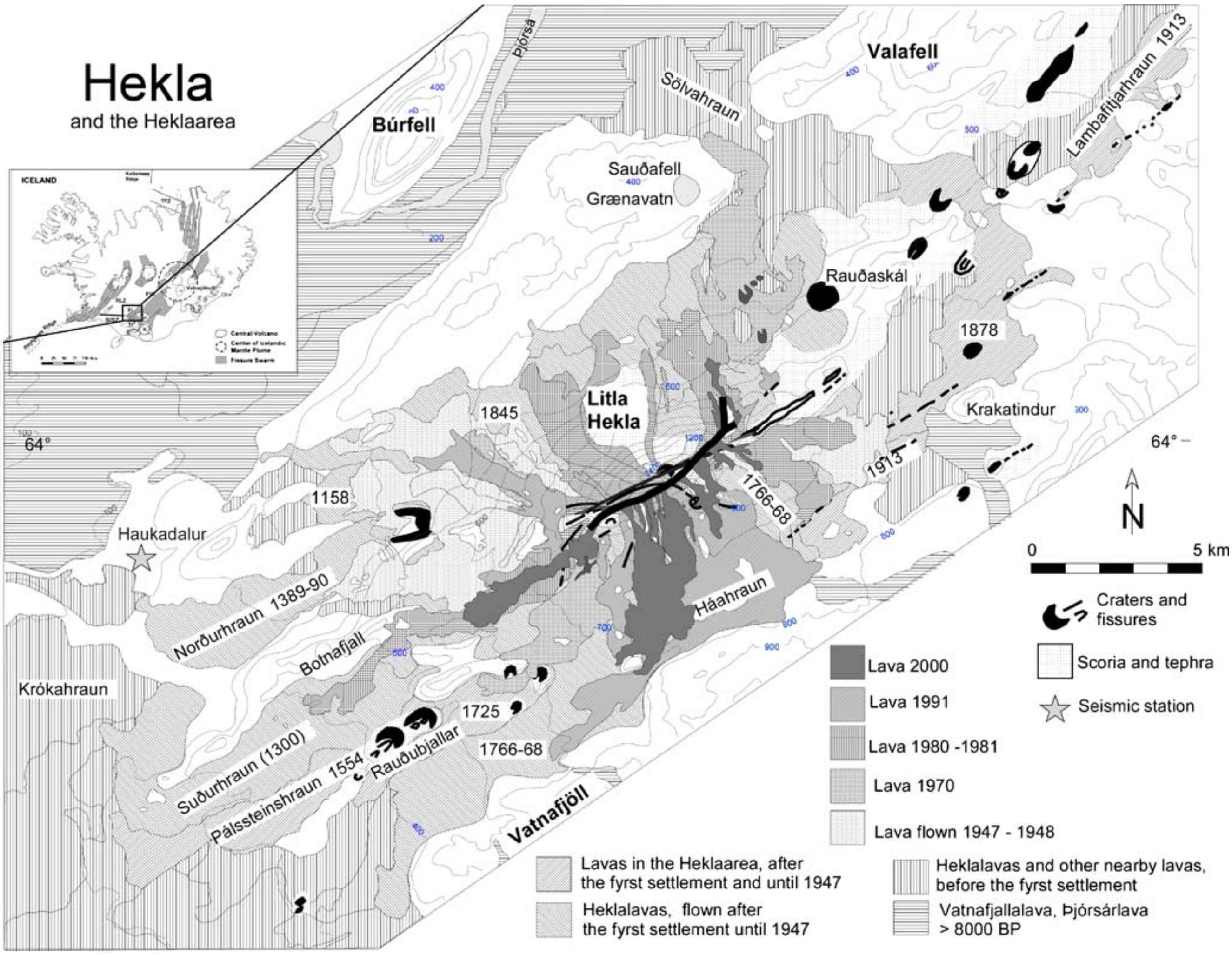

Fig. 1 Geological map of the Hekla region showing lava flows and the fissure from the eruption 2000. Also shown are lava flows formed during the 20th century. The largest historic lava flows are indicated. See Fig. 4 for more details of the lava flow and fissure segmentation. *Map inset* shows location of Hekla within Iceland; *shadowed areas* indicate active volcanic systems (modified after Thorarinsson 1967)

known to have reached 12–36 km in height (Thorarinsson 1967; Höskuldsson 2000). In the 1947 eruption, the plume reached an altitude of 32 km, and in the eruption of 1104 A.D., the eruption plume reached an altitude of about 36 km, following pre-eruption repose periods of 102 and 250 years, respectively (Thorarinsson 1967; Höskuldsson 1999, 2000). The eruption of 1947 was the first eruption of Hekla to be documented in detail (Thorarinsson 1967).

Although Hekla is known for high eruption plumes in the first stage of its eruptions, pyroclastic flow deposits, named the “Selsund” pumice, have only been reported from a prehistoric eruption that occurred some 3,900 years ago (Thorarinsson 1954; Sverrisdóttir et al. 2004). In the eruption of 1947 several floods occurred in the river Rangá and steam plumes rising sideways from Hekla were observed. The plumes were, however, interpreted to originate from warm meltwater flowing down the slopes of Hekla. Deposits formed by these flows consisted of blocks of ice and pyroclastic fragments (Kjartansson 1957; Höskuldsson 2000). Höskuldsson (2000) suggested from photographic studies of the eruption plume that the floodwater and the sideways plumes originated from column collapse and the formation of subsequent pyroclastic flows that mixed with snow and ice, as was observed in the eruption of Redoubt in 1989–1990 (Gardner et al. 1994). Descriptions from the 1980–1981 eruption also suggest that pyroclastic flows were formed at the beginning of the eruption, and similar flooding occurred in the river Rangá, north of Hekla, as in the year 1947 (Grönvold et al. 1983). In the 2000 eruption, several pyroclastic flows were generated in the beginning phase of the eruption (Höskuldsson and Olafsdóttir 2002).

Once the explosive phase is over, eruptions at Hekla become effusive. The historic eruption of 1104 is the only one in which it is certain that no lava flows formed. Sigmarsson et al. (1992) have however suggested, based up

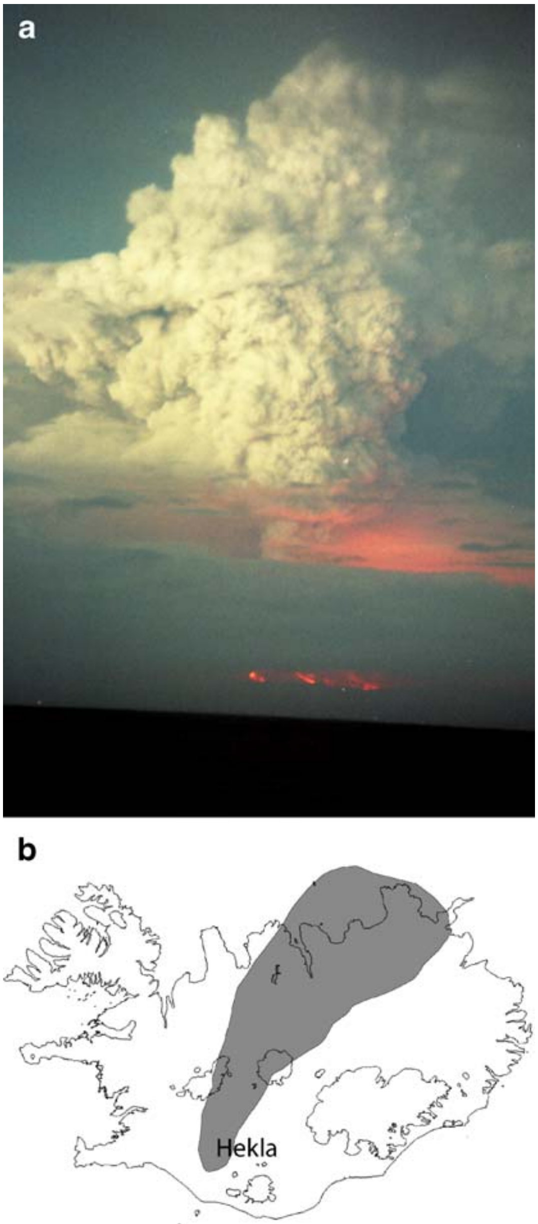

Fig. 2 **a** Photograph of the eruption plume taken on 26 February at approximately 19:20 from Vestmannaeyjar. The plume had reached into the evening sky thus it became illuminated by the sun. Below the plume, red glow from the fissure and the lava flowing down from it is visible. From this photo it is clear that at the same time as the fissure segment 2 is generating the plume, other segments have started generating lava. Photo by Sigurgeir Jónasson. **b** Schematic map of the eruption plume as it dispersed northward. Map made according to MODIS satellite data

on geochemical relations, that the dacitic lava named Háahraun (Fig. 1) was formed in that eruption. Only in the major explosive eruptions is the bulk of the erupted material tephra (Thorarinsson 1967). Many of the 18 historic eruptions in Hekla have created eruption plumes reaching altitudes of between 20 and 30 km, but still created large volumes of lava after the initial phase ceased. In the 2000 eruption, the main explosive phase was short-lived and produced a minimal amount of tephra, hence most of the erupted volume was lava.

In this paper, we describe the eruption of Hekla 2000 and its evolution from the initial explosive to the effusive phase. The eruption was in many ways different from its predecessors, forming the most aerially limited tephra fall deposit known in the vicinity of the volcano, although total eruptive volume (lava and tephra) is moderate. We also describe the physical appearance and chemical composition of the lava flows and pyroclastic flow deposits. Discussion of the relevance of these observations to the ever-shortening repose period of Hekla and the evolution of its activity within the last 30 years concludes the paper.

Eruption precursor

In 1998, H. Ólafsson at NORVOL installed devices to measure the water table in some creeks and lakes around Hekla. Lakes and springs originating in the lava fields SW of Hekla had been showing signs of a lowered water table and continued to do so until the year 2000. Similar observations were made previously, specifically prior to the eruptions in 1766, 1947, 1970 and 1980–1981 (Grönvold et al. 1983). The origins of these changes in groundwater are not fully understood, but may be associated with volcano inflation prior to eruptions since inflation of the volcano widens fissures and faults and thus increases permeability in the bedrock.

In the afternoon of 26 February 2000, P. Einarsson, from the Science Institute, University of Iceland, noticed seismic unrest at Hekla volcano. A warning was issued at about 17:20 that an eruption was imminent within the next hour. At 17:45, strain meters at the Icelandic Meteorological Office (IMO) registered a sharp decrease that was reversed at 18:17, which was thought to mark the opening of the first vents at Hekla volcano (http://hraun.vedur.is/ja/heklufrettir.html). The first observations of the eruption cloud were made at 18:20. Throughout the eruption, the IMO monitored the eruption tremor and the plume height.

Initial eruption phase and the eruption cloud

The eruption's initiation late in the afternoon made direct observations difficult because the sun had just settled below the horizon and the volcano itself was in shadow; only the upper parts of the billowing plume were clearly visible as they rose into the bright sky (Fig. 2). Photographs show a large red glow along the southern slopes of Hekla. News teams from CNN as well as local TV stations were airborne about 50 min after the eruption started. The CNN team had been stationed in Vestmannaeyjar due to the intent of the Keiko Foundation to liberate the killer whale that same day. Keiko decided to stay, but the CNN team got a front-row seat at the 18th eruption of Hekla. Video footage taken by these news teams shows intense fire fountaining along the eruptive fissure at 20:00.

A 6.6-km-long fissure opened along the length of Hekla volcano from the SW to the NE, slightly to the south of the summit area. The first visual signs of the eruption were the eruption plume billowing up to the sky and development of an eruption cloud. The height of the plume was registered by the IMO's weather radar in Reykjavik and was closely monitored throughout the eruption (Lacasse et al. 2004). Early on in the eruption, satellites orbiting over Iceland observed the plume track; those data were later supported with additional information from a NASA DC-8 research aircraft that encountered the ash plume on 28 February north of Iceland. The observations gave unique information on the evolution of the cloud as it was dispersed away from the eruption site by a strong Arctic low-pressure weather system (Rose et al. 2001; Simpson et al. 2000). The NASA DC-8 aircraft suffered severe damage due to the volcanic ash in the eruption cloud (Simpson et al. 2000).

The plume reached a maximum height of some 12 km at 18:49 (only 32 min after its initiation), indicating a rise speed of some 6.2 m/s. Once the plume had reached buoyant equilibrium, it was dispersed towards the north. Deposition of ash particles on land was recorded by local weather observation posts, which indicated a cloud dispersion rate of 30 m/s (Lacasse et al. 2004). According to Haraldsson (2001), the total volume of tephra deposited during the first phase of the eruption was on the order of 0.001 km^3, making it one of the smallest eruption clouds originated from Hekla volcano (Fig. 2).

Discharge rate

Visual observations were limited near the beginning of the eruption, but seismographs around Hekla volcano registered seismic unrest and eruption tremor throughout the eruption. The eruption plume height was also monitored by weather radar run by the IMO (http://hraun.vedur.is/ja/heklufrettir.html). Using data from the weather radar we can estimate the discharge rate for the first hour of the eruption. Having measured the variation in the eruption column

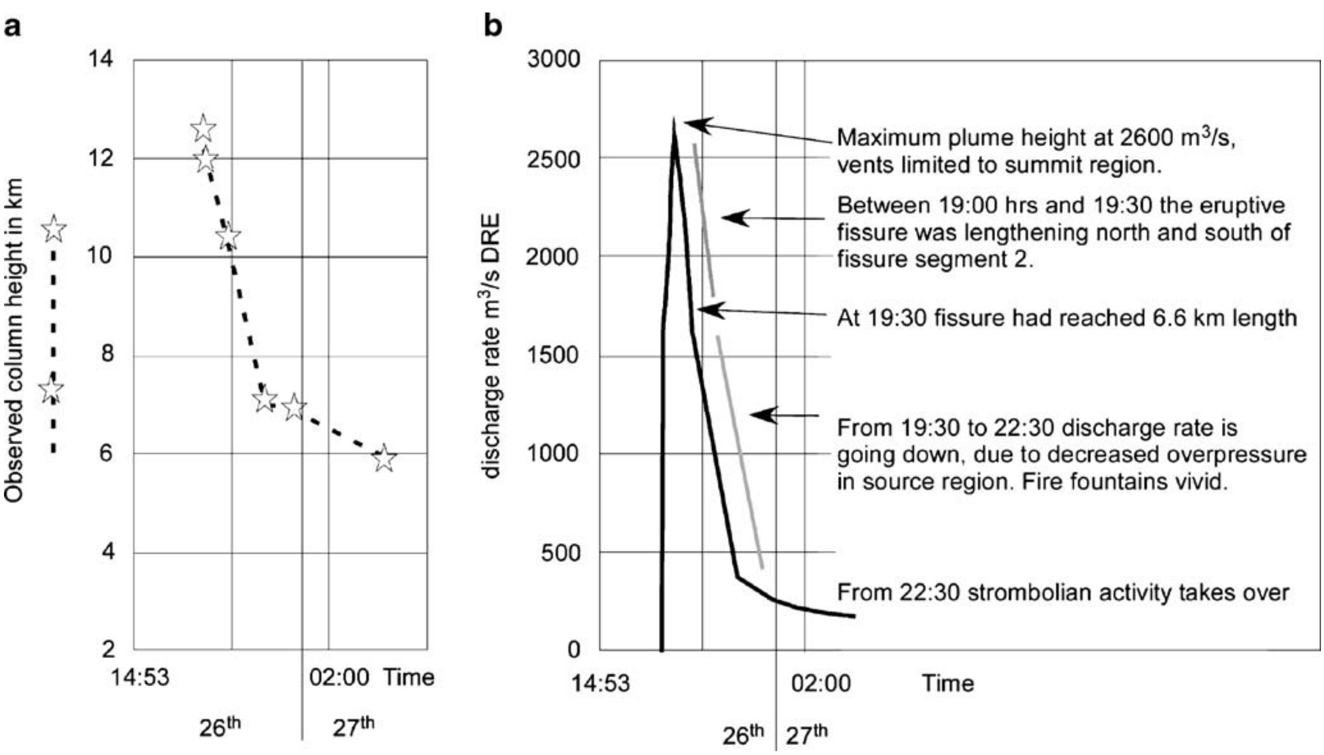

Fig. 3 **a** Observed column height from the IMO weather radar in Keflavik 142 km away from Hekla volcano. A sharp peak is attained at 19:00, after which it starts to decline. **b** Calculated effusion rate for the first hours of the eruption was according to plume height. The eruption took place along a fissure that gradually lengthened to 6.6 km. As in the Hekla eruptions 1980 and 1991, the 2000 eruption started along fissure segment 2, the summit part. Thus, the effusion rate calculated is only valid for fissure segment 2. As the fissure lengthened to the south and north, the effusion rate at segment 2 declined and eventually stopped. This is supported by observation that shows that the explosion craters of this segment are not associated with lava apron or lava flows. Between 19:00 and 19:30, the observable decreased effusion rate along segment 2 can be attributed to the lengthening of the eruptive fissure. On the other hand, once the eruptive fissure had reached 6.6 km length, the decreased eruption rate can be allocated to the decrease in overpressure at the source region

height during the first hour of the eruption, we could estimate the discharge rate for the same period of time. The eruption column height is related to the discharge rate by:

$$H_t = 1.67Q^{0.259} \quad (1)$$

H_t is the maximum eruption column height in km and Q is the discharge rate in m^3/s dense rock equivalent (Morton et al. 1956; Settle 1978; Wilson et al. 1978; Sparks 1986; Carey and Bursik 2000). Figure 3a, b show the results of calculations using Eq. (1). The variation in the effusion rate during the first hour of the eruption indicates that a sharp maximum was attained during the first few minutes, and that the maximum discharge rate (2,600 m^3/s) was attained at 18:49 on 26 February.

The results from the discharge rate calculations indicate that the initial Subplinian explosion was sustained for no more than 30 min. According to the tremor records, the discharge rate attained a sharp maximum, fluctuated for some 30 min, and then began to decline (Fig. 3b). The fluctuations in the discharge rate and its sharp decline as the vent enlarged along the whole fissure are possible reasons for column collapses and the generation of pyroclastic flows. News crews flying above and around Hekla between 19:00 and 20:00 reported several fire fountains along the eruptive fissures. The calculated discharge rate curve fits well with these observations, suggesting that fire-fountain activity was a vivid continuation of the Subplinian phase.

The segments of the eruptive fissure

Field measurements carried out in the summer of 2001 show that the eruptive fissure is divided into five discontinuous segments with a total length of 6.6 km, which cross Hekla striking from southwest to northeast. Seismicity extended as deep as 14 km during the eruption (Fig. 4), with most of the earthquakes occurring below the fissure. The south-eastern side of the summit area is faulted parallel to the fissure strike, forming a platform just below the summit crest (Fig. 5). The eruptive fissures lie in parallel along this platform, with a general NE–SW trend. At the northern end, the fissure splits into two segments, one of which strikes due north (Fig. 5). At both ends of the fissures, eruptive craters were observed to produce lava flows in the south and north. Along the entire length of the eruptive fissures a total of 39 craters were observed in the summer of 2001. Observation from Vestmannaeyjar, about 70 km south of Hekla, showed a large red glow along the entire Hekla ridge from the onset of the eruption cloud (about 19:00) until the view was obscured by weather at about 20:00. There were no indications of directional propagation of the erupting fissures from earthquake foci or direct observations. All indications are consistent with a scenario similar to that for the eruption of 1980 in which all the fissures were activated within a period of a few hours. Fissure characteristics are summarised in Table 1 and descriptions follow below.

The northern fissure segment is split into two branches. The branch that trends due north goes from 1,200 m altitude down to 900 m. At high elevation, it joins the main fissure striking NE SW, parallel to Hekla proper. The combined length of the segment is 1.5 km. Two scoria cones, rich in spatter, are at the foot of the northern branch of the fissure from which most of the lava in the north originates. The main branch has five small craters and is surrounded by an extensive spatter field. Two lava streams flow to the north from the fissure (Fig. 6) and two others to the south (Fig. 5). The segment was active for the first 3 days.

Fissure 2 starts along the main ridge at an altitude of 1,150 m and runs half way along the ridge where it then veers off to the south onto the fault platform, at some 1,300 m altitude. Along this fissure there are nine explosive and five effusive craters. All the explosive craters are at 1,300 m altitude and the largest explosive craters are about 300 m in diameter. Lithic blocks within the explosive deposits are up to 2 m in diameter (Fig. 7). The effusive craters are covered with a spatter apron. The fissure segment is 1.23 km long and the gap between fissures 1 and 2 are about 120 m. Fissure segment 2 was active on the first day of the eruption.

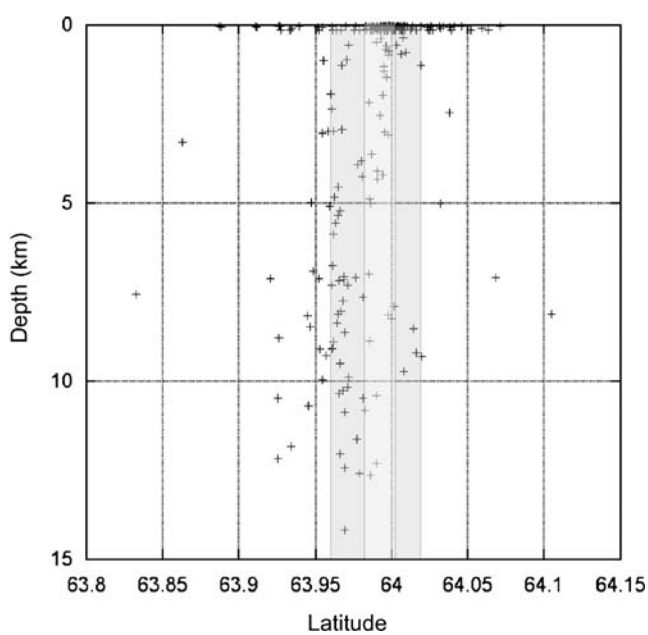

Fig. 4 Location of the main seismic events during the Hekla 2000 eruption. The deepest earthquakes were at about 14 km. Intense seismic activity towards the surface, however, clusters of activity at 0 depth is probably an artefact. *Large box* indicates topographic expression of Hekla. *Small box* indicates extension of eruptive fissure

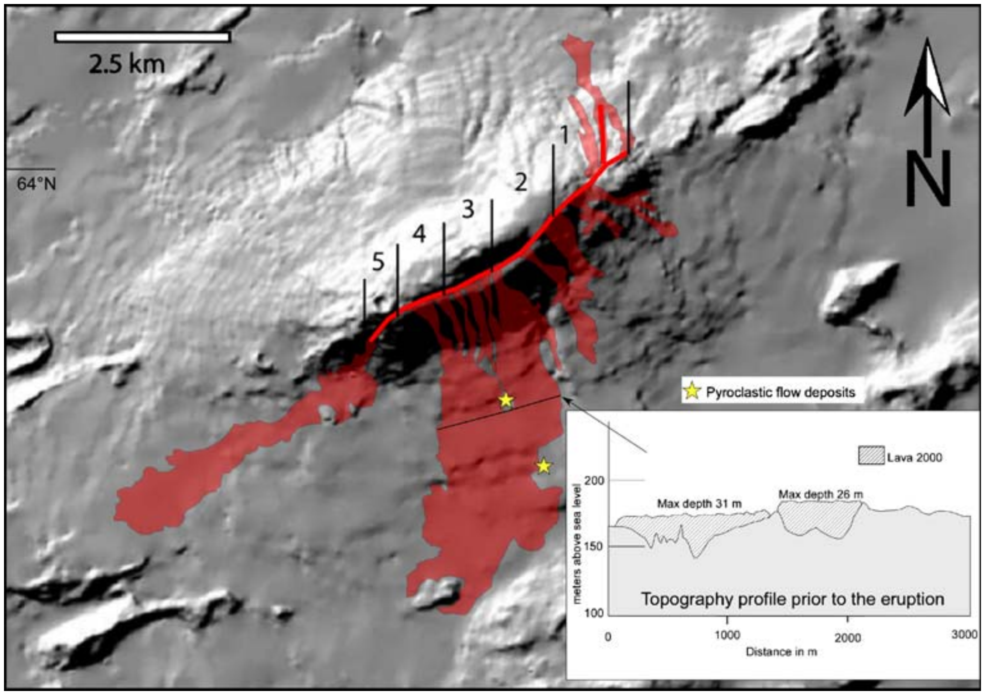

Fig. 5 Map of the lava flow formed in the Hekla 2000 eruption. The eruptive fissure crosses Hekla from south to north. The fissure divides into five segments. Segment 2 was the first to open and give rise to the Subplinian column. *Yellow stars* show the location of pyroclastic flow deposits associated with plume collapse. *Inserted figure* shows the topography in the area before the eruption and a profile measured across the lava flow field from the 2000 eruption. The lava flow is confined to lows in the topography and reaches a maximum thickness of 31 m in the western part and a maximum of 26 m in the eastern part. The figure illustrates the importance of knowing pre-eruption topography to be able to accurately assess lava volume

The gap between fissure segments 2 and 3 is 140 m. Fissure segment 3 has one explosive crater at its northernmost end at an altitude of 1,300 m. Surrounding the rest of the fissure is an extensive spatter apron that partially started to creep down slope (rheomorphic). Scoria deposits ejected onto the spatter apron indicate that the activity developed from fire fountaining to Strombolian. Lava streams stretch downhill from six effusive craters on the fissure, feeding the lava field on the southern slopes of Hekla. Segment 3 extends southwest for 0.9 km (Fig. 5), and runs along the fault platform at an altitude of some 1,300 m. The segment was active for the first 2 days.

Fissure segments 3 and 4 are separated by about 180 m. Fissure segment 4 also strikes SW-NE at an altitude of 1300 m on the fault platform. It has 4 distinct craters. Their effusive nature is clear from extensive spatter fields along the whole fissure. The uphill part of the spatter field shows evidence of rheomorphism. In flatter, spatter-covered areas along the fissure, cauldrons tens of meters wide and a couple of meters deep formed, due to snowmelt underneath the spatter. Scoria deposits cover part of the spatter field, indicating Strombolian activity in the final stage of activity. Lava issued from fissure segment 4 flowed down to the south of Hekla in four main streams (Figs. 5 and 8). The fissure segment was active for the first 4 days of the eruption.

Table 1 Segmentation and characteristics of the eruptive fissure and number of craters on each segment

Fissure	Length (km)	No. of craters	Direction of lave flow
1	1.5	7	N and S
2	1.23	14	S
3	0.89	6	S
4	0.35	4	S
5	1.66	8	SW

Figure 5 shows the location of each segment

The gap between fissure segment 4 and 5 is 350 m. Segment 5 the southernmost fissure, was active throughout the eruption. The fissure stretches along the south-eastern side of Hekla, along a NE–SW strike, from an altitude of 1,300 m down to 550 m. A total of eight craters were observed along this fissure. All craters were covered with spatter, which started to creep down the slopes. Three of the craters that are midway on the fissure segment have built up scoria cones on the spatter apron. Lava from the fissure flowed down the slopes partly along the fissure. Fissures fed the lava that flowed SW. At the southern end of the fissure, at 550 m altitude, a huge block of older lava was uplifted (Figs. 5 and 9). During a visit to this area on 3 March, we observed that lava was oozing out from the underneath of this uplifted block (Fig. 9) and sporadic Strombolian explosions at several minute intervals took place in the craters located midway on the fissure. Strombolian activity was observed in this fissure segment until 6 March.

Pyroclastic flows

During the summer of 2001 field mapping of the lava flow and the eruptive fissures took place. With much astonish-

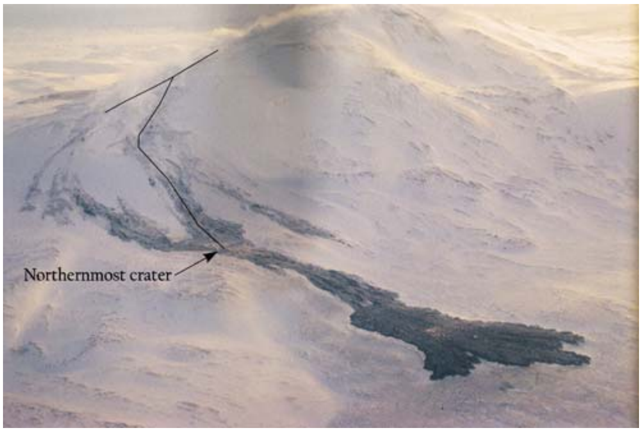

Fig. 6 Photograph of the northernmost part of the eruptive fissure, segment 1. Here the fissure splits into two braches. The main fissure alignment is indicated with a *black line* and the *arrow* points to the northernmost crater. Photo from the 2 March

ment, deposits from several pyroclastic flows were observed. Along the northern fissure, several tongues of pyroclastic deposits extend beyond the overlying lava flow. The deposits consist of a fine ash matrix with several larger cauliflower bombs ranging in size from 10 to 30 cm. Lithic fragments in the deposits range in size from 5–10 cm, consisting of fragments of older lava and welded pyroclastics.

On the southern flank of Hekla, much more voluminous pyroclastic flow deposits were observed. Part of the mapping consisted of measuring profiles across the lava flow to quantify changes in topography and thus get accurate information on lava thicknesses. The main profile crosses the "kipukas" (islands) in the lava field south of Hekla at the break in slope (Fig. 10). On these kipukas, tongues of three large pyroclastic flows were observed to partially overlap each other. The lava flow partially covers all of the deposit tongues, confirming that the pyroclastic flows were formed in the first stage of the eruption. One of the tongues formed by the pyroclastic flows had overrun part of the lava formed earlier in the eruption, which strongly suggests that the lava fountains and the volcanic plume from which the pyroclastic flows are inferred to have been derived were active at the same time.

The most prominent tongue of the pyroclastic flow deposits is close to 2 m in thickness (Fig. 11) and consists of fine- to coarse-grained ash with abundant cauliflower and bread crust bombs floating in the matrix and on the surface. The bombs range in size from 10 cm to 1.5 m. Lithic fragments comprise dense lava fragments, ranging in size from 2 to 20 cm. This deposit tongue has very abrupt sides with edges as high as 1.7 m. The head of the deposit thins out in the direction of flow. Reaching 1 to 1.7 m beyond the edge of the main deposits is a thin layer made of fine- to coarse ash, bombs and lithics. This thin layer is interpreted as the deposit of an ash cloud surge accompanying the pyroclastic flow.

In lows 3–4 km south of Hekla, pyroclastic flow deposits extend beyond the overlying main lava flow field (Fig. 5). Hence, the pyroclastic flows flowed down the same way as the lava flows. Furthermore, since their deposits are observed sticking out from underneath the lava flows, the pyroclastic flows must have been dense and confined by topography. All pyroclastic flows to the south of Hekla originated from the central area (fissure segments 2 and 3).

The lava flows

The magma erupted was basaltic andesite in composition (SiO_2 55.5 wt%). The temperature range was 1,062 to 1,136°C, with a viscosity in the range of 10^3–10^8 Pa s. The lava flows are of aa type with a typical rugged and spiny surface. Most of the lava was emplaced during the first hours of the eruption when the discharge rate was highest. Observation of the lava front on 28 March, close to Lambafell south of Hekla and about 6.2 km away from the fissure showed that the lava quickly developed a crust and remained liquid at the interior. The lava fronts built up to a height of some 10 m and then became unstable and collapsed, at which point the molten interior of the lava advanced. The lava then stopped advancing, formed a crust due to cooling and started to build up a new front.

Observations made on 3 March closer to the source of the SW lava flow field revealed pasty toothpaste lava (Fig. 12). As it came into contact with the atmosphere it quickly developed a crust due to cooling. By continuous flow of the lava away from the source the brittle crust began to compress, accumulate and form a rugged surface. As the flow progressed away from the source, the surface

Fig. 7 The largest of nine explosion craters along fissure segment 2. The crater is about 300 m in diameter and at an altitude of 1,300 m. Note that there are only explosive deposits around the crater. Neither lava apron nor lava is observed to come from the explosive craters belonging to fissure segment 2. This part of the eruptive fissure gave rise to the Subplinian column. The *person shown inside the circle* is to show the scale

Fig. 8 View towards Hekla from the south. The main lava flow field is fed by fissure segments 3 and 4. *White areas* within the lava flow field are kipukas, on which we observed the pyroclastic flow deposits. The SW lava flow field is fed by fissure segment 5. Craters along this segment are at the lowest altitude (550 m) and were active throughout the eruption. Photo is from 2 March

crust became increasingly spiny and twisted. At the time of observation, the discharge rate was 1–2 m^3/s, estimated from observation of flow in the lava channel.

Four main lava fields formed in the eruption of Hekla 2000. Two of them are small and located at the northern extremity of the volcano and the other two, which are much larger, were emplaced on the plains to the south and southwest. The main characteristics of the lava fields are summarised in Table 2.

Magma issued from the northernmost fissure (fissure segments 1 and 2) and formed lava flows on both sides of the volcano (Fig. 5). These are small lava fields made up of aa-lava. The lava is channelised down the steepest part of the slopes and in places it accumulated at the foot of Hekla, where the topography becomes flatter. Two of the lava streams halted on the steepest slope, indicating that their feed was quickly cut off. The best preserved craters are observed on the northern slope of Hekla and on the crest. In places, the magma has oozed out of the fissure without any major explosive or fire fountain activity (Fig. 9). All the lava streams feeding these two lava fields developed well-defined channels, carrying the flow down the slopes of Hekla. The area of the lava field in the north is about 0.64 km^2 (Table 2). The average thickness of the lava is about 3 m, thus its volume is estimated to be 2.0×10^{-3} km^3. Southern fissure segments issued lava covering an area of 1.3 km^2 and estimated volume of 4.0×10^{-3} km^3 (Table 2).

Lava issued from fissure segments 3 and 4 fed the large lava field on the southern slopes of Hekla (Fig. 5) through six distinct lava streams that come down the slopes of Hekla and merged to form one lava field at the foot of the volcano. The lava stream from fissure segment 3 is very prominent and fed the southernmost part of the lava field, whereas the stream coming down from fissure 4 partly joins with this stream and partly feeds the northern half of the lava field. On 28 February, several glowing lava streams were observed flowing down the slopes from fissure segment 4, but visibility was limited and no streams from fissure segment 3 were then observed. The lavas were rough aa-type. GPS measurements made at the lava front on 28 February and repeated in the summer of 2001 indicate that the front around the hill Lambafell (some 5.4 km from the eruptive fissure) had advanced some 20 m on the south side and some 70 m on its north side. Thus the lava advanced rapidly during the first 2 days of the eruption while the discharge rate was highest, then at a drastically reduced rate later, after the discharge rate continued to decline. The total area covered by the lava on the south side of Hekla is 11.05 km^2. Thickness measurements carried out in the summer of 2001 show that the lava field is up to 35 m thick in places. However, the edges of the lava stream are fairly constant in thickness, ~7–8 m. The lava edges are interpreted as boarders of the lava stream that has filled up pre-existing topographic depressions. A comparative study of the topography before and after the eruption supports this interpretation and indicates that the average thickness of the lava field is around 10–12 m, giving a total volume of this part of the lava field as 0.133 km^3 (Fig. 5, Table 2).

The lava flow field in the SW is the second largest in volume of those formed, and was fed by two main lava streams, which originated from fissure segment 5 (Fig. 5). The two lava streams merge at the foot of the volcano close to the source of the lower stream. On 3 March, lava was observed oozing out from the southernmost end of the fissure from under an uplifted block of older lava (Fig. 9). The lava continued to advance until 6 March when flow terminated in the lava channel. Field investigations indicate that the lava issued from under the uplifted block was the main feeding stream for this lava flow field (Figs. 5 and 12). The flow is a rough aa-type like the other lava flows

Fig. 9 The source of the SW lava flow field, and the southernmost part of fissure segment 5. Lava oozes out from under an uplifted block of older lava. The lava stream is at 550 m a.s.l. Photograph taken on 3 March

Fig. 10 Overview from fissure segment 3 towards the lava flow field in the south. The lava apron can be seen in the lower right-hand corner. On the kipukas in the lava flow field are pyroclastic flow deposits. A close-up of the deposits is shown in Fig. 11

formed in the eruption. At its head, the main stream divided into several advancing tongues. The tongues were then cut off as the main lava flow advanced. The lava field in the SW covers an area of 4.94 km^2. The thickness of the lava ranges from 7 m at the edges up to 25 m at its interior. Its average thickness is estimated to be 10 m, giving a total volume for this flow field of 0.049 km^3 (Table 2). The total volume of lava issued in the entire 10-day eruption is therefore around 0.188 km^3. The amount of tephra formed in this eruption is estimated as having a bulk volume of 0.001 km^3 (Lacasse et al. 2004). However, integration of the discharge-rate curve indicates that about 0.028 km^3 of tephra was ejected during the first 2 days. The discrepancy can be attributed to the volume of near vent deposits that were not considered in the Lacasse et al. (2004) analysis.

Petrology

The petrological evolution of Hekla magmas is described in the literature as either the result of fractional crystallization (Baldridge et al. 1973) or the mixing of two end members (Sigvaldason 1974). Based on isotopic studies, Sigmarsson et al. (1992) inferred that the silicic and basaltic end members are genetically unrelated. End-member compositions of the Holocene Hekla system are basaltic ferro-andesite (Iceland) and rhyodacite. Sigvaldason (1974) discussed in detail the compositional range of the Hekla rocks, but for the present discussion, the more basic compositions are of primary interest.

Most of the historic (after 1104 A.D.) Hekla rocks are hybrids of basaltic andesite with variably admixed rhyodacitic material. These hybrid rocks range in composition from basaltic andesite (53–54% SiO_2) to those with some 60% SiO_2 erupted in the initial phase of large eruptions that followed repose periods of about a century. The eruption frequency of the Hekla system changed in 1970 when a small homogeneous basaltic andesite eruption occurred after a repose period of only 23 years followed by similar eruptions in 1980–1981, 1991 and 2000. The only other known historic eruption of this type was an isolated event in 1222 after a repose period of 16 years. Chemical compositions and mineral compositions of the Hekla 2000 eruption are listed in Table 3, which illustrates the close similarity of the basaltic andesite erupted, products of which cannot be distinguished from one or another based on chemical properties.

In the following, the properties of the recent Hekla basaltic andesite are addressed in terms of their mineralogy and equilibrium conditions of the observed mineral assemblage. Based on the nearly aphyric nature of the basaltic andesite it can be concluded that its residence time in crustal holding chambers was very short. It is most likely that the Hekla magmas separate only a short time before eruption. This is in agreement with short preceding repose times and geodetic observations (Grönvold et al. 1983; Sigmundsson et al. 1992; Tryggvason 1994).

Microphenocrysts are sparse in the 2000 Hekla basaltic andesite, generally less than 5% in the quenched glasses that formed within particles emitted in the initial Subplinian column of the eruption. Plagioclase, olivine, clinopyroxene, titanomagnetite and apatite are always present but ilmenite has only been found occasionally. These microphenocrysts are homogeneous crystals that may be taken to reflect short-lived equilibrium conditions prior to eruption and/or growth/resorption during ascent of the magma. A brown quenched glass is preserved in the smallest fragments of the Subplinian ash that is the characteristic products of the initial phase of the basaltic andesite eruptions. Pyroclasts larger than about 2 mm in diameter were not quenched rapidly enough to preserve a glassy state and have an

Fig. 11 Photograph of the pyroclastic flow deposits on the kipukas indicated on Fig. 10. The *person* is standing on top of the pyroclastic flow tongue, which is about 2 m thick here. Around the main deposit tongue there is a thin apron, which is thought to have formed from an accompanying ash cloud surge

Fig. 12 View from above the termination of fissure segment 5, over the SW lava flow field. The lava is channelled along the centre of the lava flow field. In the foreground of the photo is the uplifted block shown in Fig. 9

opaque groundmass of cryptocrystalline phases, mainly plagioclase, clinopyroxene and titanomagnetite. Similarly, the basaltic andesite lavas are fine-grained rocks composed of mainly plagioclase and clinopyroxene with abundant titanomagnetite but subordinate amounts of olivine and apatite. The Hekla lavas were variably oxidized during early flow or during coalescence of lava spatter, as indicated by reddish flow-bands in lavas and in large bombs.

For the purpose of petrological modelling, the observed phases are the only milestones to guide the selection of appropriate pressure regime for calculations. Modelling with the aid of the Melts and pMelts software (Ghiorso and Sack 1995; Ghiorso et al. 2002; Asimow and Ghiorso 1998) was performed for the Hekla basaltic andesite. Modelling of this kind is an iterative process in which estimated pressure conditions are systematically explored in order to reproduce the observed mineral assemblage.

The modelling requires a quantitative knowledge of the magma's water content prior to eruption because of the significant effect the water has on the calculated liquidus temperature and mineral equilibria. The present modelling is based on the water content of glass inclusions in plagioclase from the quenched initial phase of Hekla 2000 (Table 3) measured on the ion probe facility at the Grant Institute, University of Edinburgh. The ion-probe analyses of the volatiles are normalised to titanium, which also was analysed on an electron microprobe in order to confirm that the major element composition of the inclusion is identical to that of the bulk glass of the pyroclasts. The water content of the pyroclast glass surrounding the crystals was also analysed on the ion probe. Oxygen fugacity is an intensive variable that drastically affects liquidus temperatures and crystallisation of ferromagnesian minerals. Although likely, in general, a fugacity control by the FMQ buffer (fayalite-magnetite-quartz buffer) remains only an educated guess. Chemical criteria regarding the redox state of the magma may be derived from the observed ferric/ferrous ratio of the rocks. This observation cannot, however, be taken as a conclusive indication of the initial redox state of the Hekla basaltic andesite due to obvious secondary oxidation of the sampled material. Therefore modelling was run on the FMQ buffer as well as on FMQ-1 in order to better simulate the observed mineral assemblages. The goal of the modelling was to find pseudounivariant conditions under which the observed phases, including olivine, clinopyroxene and spinel, are produced during the first 5% of crystallization. This is not possible using the FMQ buffer at the high-pressure regime but can be achieved using a FMQ-1 fugacity profile.

The results of the modelling can be summarized in the following points. At isobaric conditions, the observed pseudo-invariant mineral assemblage (three silicate phases and liquid) of the basaltic andesite, can only be simulated (pMelts) in a slightly reduced (FMQ-1) environment at about 500 MPa (16.5 km) where Ol, plag, cpx and spinel are in equilibrium at 1,061 °C. The liquid viscosity is $10^{1.9}$ Pa s and the system viscosity is 10^2 Pa s. These conditions require a very low degree of crystallinity (4.7%) in order to reproduce the observed mineral assemblage.

Several combinations of polybaric crystallization simulated by the Melts code may be visualized, but all require initial crystallization at pressures less than 650 MPa (19.8 km) and higher than 350 MPa kb (11.6 km) in order to produce olivine and clinopyroxene simultaneously at high pressures, and titanomagnetite and plagioclase at pressures of about 100 MPa. The total degree of polybaric crystallization needed to produce the observed mineral assemblage exceeds 6%.

The ascent ratio of the magma controls crystallization; a quasi-adiabatic rise can be simulated with an ascent/cooling ratio of 5.5 MPa/°C. At higher ascent ratios, the minerals will be resorbed. Our preferred model is isobaric crystallization during melt segregation followed by ascent with little or no

Table 2 Characteristics of the lava flow fields formed in the eruption of Hekla

Lava field	Thickness (m)	Area (km^2)	Volume (km^3)	No. of feeding streams
North	1.5–7 (3)	0.64	0.002	5
North–south flow	1.5–7 (3)	1.30	0.004	4
South	7–32 (12)	11.05	0.133	12
Southwest	7–25 (10)	4.94	0.049	2
Tephra			0.001	
Total	–	17.93	0.189	–

See Figs. 1 and 6 for a map of the lava. Thickness in parentheses is the mean value

Table 3 The chemical composition of Hekla rocks was analyzed at the Institute of Earth Sciences by ICP-OES on whole rock samples after lithium metaborate fusion and dissolution in a mixture of 5% nitric, 1.33% hydrochloric and 1.33% oxalic acid

	H2000	H1970	H2000-Fsp	H2000-Ol	H2000-Cpx	H2000-Mt
SiO_2	55.52	54.18	54.06	36.21	50.36	
TiO_2	2.07	2.02			0.86	19.78
Al_2O_3	14.54	14.87	28.32		2.31	3.17
FeO	11.79	12.57	0.37	35.02	13.24	70.28
MnO	0.28	0.27		0.69	0.51	0.59
MgO	2.89	2.94		27.46	14.52	3.07
CaO	6.82	7.07	10.86	0.23	17.07	
Na_2O	4.01	4.09	5.33		0.28	
K_2O	1.21	1.26	0.15			
P_2O_5	0.87	0.73				
Sum	100	100				

The Hekla 2000 analysis (H2000) represents an average of 20 samples of tephra and lava. The Hekla 1970 analysis (H1970) represents lava sampled in June 1970. Microprobe analysis of the microphenocryst of the Hekla 2000 rock was analysed on ARL SEMQ microprobe at the Institute of Earth Sciences. Analytical conditions were 15-kV accelerating voltage and 15-nA sample current. Reported values are averages of three analytical points on ten grains of each mineral. The Hekla rocks and microphenocrysts are virtually homogeneous within analytical precision. Water analysis of silicate inclusions in feldspars and of degassed glass rims on feldspars was analysed at the Ion-Microprobe facility at the University of Edinburgh. Each analysis represents duplicate analysis of inclusions and glass rims of three different mineral grains. Water content of the H2000 magma was 2.3 wt% as analysed in silicate inclusions by ion probe. Degassed magma as analysed on glass rims on separated feldspars contained 0.14% water (see text)

resorption. In any case, during ascent, the melt becomes saturated with water at about 50 MPa (about 1.5 km) at which point degassing will inevitably start, which has a drastic effect on liquidus temperatures. The measured water content of the degassed magma (0.14%) corresponds to a liquidus temperature of 1,136°C, compared to 1,062°C for the calculated pre-eruptive equilibrium.

Discussion

The eruption of Hekla in February 2000 was accompanied by all the classical precursors known for eruptions at Hekla volcano. Disturbances in the groundwater table were observed up to 2 years before the eruption started. These disturbances can probably be attributed to the inflation of the volcano prior to an eruption, resulting in changes of the hydrological gradients. Between eruptions, earthquakes are scarce at Hekla. About 1.5 h before the 2000 eruption, intense earthquake activity started, which was thought to mark the onset of magma rise towards the surface (Soosalu et al. 2005).

Earthquakes accompanying the eruption were initially small and shallow (0–4 km), but after the onset of the eruption, earthquakes extended to depths of 14 km, although they were mostly concentrated between 4 and 9 km (Soosalu et al. 2005). Ground deformation accompanying the eruption in 1980–1981 indicated a magma reservoir at a depth of some 8 km (Kjartansson and Grönvold 1983), but a detailed seismic survey did not support the existence of any substantial magma reservoir under Hekla at any depth between 0 and 14 km prior to or during the 2000 eruption (Soosalu and Einarsson 2004). Our petrological modelling suggests that if a substantial magma chamber exists under Hekla, it must lie deeper than 14 km, supporting the findings of Soosalu and Einarsson (2004). Dacitic pumice patches found in clasts of the airfall deposits could, however, originate from minor magma pockets between depths of 4 and 8 km. Accepting that the basaltic andesite originated from a depth of some 14 km, the average magma rise speed to the surface was on the order of 2.9 m/s.

The water content of glass inclusions within crystals is measured at 2.3 wt%. Such high water content in basaltic andesite suggests that the CO_2 concentration was on the order of 2,300 ppm (Dixon et al. 1995). Whereas the CO_2 exsolves readily, being fully exsolved from the magma at 3 km depth, water does not start to exsolve from the melt until at about 1.5 km depth (Dixon et al. 1995; Dixon and Stolper 1995). Volcanic glass rims around crystals show a water content of 0.14 wt% in surface sampled scoria. Thus, degassing of the magma was almost completed, and it lost about 2.16 wt% water and all CO_2 of the initial volatile content. Eruption tremor has been inferred to be associated with degassing of magma in eruption conduits (McNutt 1994; McNutt et al. 1995). An analysis of tremor in the Hekla 2000 eruption indicates that it is of shallow origin (Soosalu et al. 2005), consistent with degassing of H_2O. Exsolution of CO_2 is seemingly less violent as it takes place along the whole height of the conduit and is over at the depth of 3 km.

Although the CO_2 concentration was initially high on the basis of modelling (Dixon et al. 1995), there are indications that magma flowing towards the surface lost CO_2 to its surroundings on its way (Taylor et al. 1983; Eichelberger et al. 1986; Jaupart and Allegre 1991; Gardner et al. 1996). Observations supporting this were made in the Hekla eruptions of 1947 and 1970 and in the eruption of Eldfell on Heimaey in 1973. In all cases, pits and rivers of CO_2 gas were observed along the outer perimeter of the volcanoes during calm weather (Kjartansson 1957; Thorarinsson 1967; Einarsson 1974). Furthermore this was observed a few days into the eruptions of Hekla 1947 and Heimaey 1973 but not during the opening phase, suggesting that the CO_2 is lost in to the conduit at lower effusion rates. Thus we argue that at high discharge rates H_2O and CO_2 in the magma both contributed to the Subplinian phase of the eruption. However, as the magma overpressure decreased, the discharge rate decreased and the system reached new equilibrium. At this stage CO_2 percolated out through the fractured conduit walls during ascent and water becomes the prominent volatile in the magma at the surface, since it does not start exsolving until at about 3 km depth.

When the vent broke through to the surface, the magma was a combination of liquid, tiny crystals and compressed volcanic gas. This mixture gave rise to the short-lived Subplinian eruption plume. We did not observe any major change in original volatile content of the magma from the first magma erupted to the last. Thus variations in eruptive style throughout the eruption cannot be explained by variation in volatile content of the magma. On the other hand, inferred discharge rate changed drastically through the eruption and that can be correlated with the eruptive style. Further, we note that the explosive craters situated highest up on Hekla did not issue lava, suggesting that they ceased activity as the eruption fissure reached full length. During the last phase of the eruption, only the vents on the southernmost fissure were active. Those vents are about 550 m lower in altitude than the summit vents, and are the lowest vents along the eruptive fissures. These observations suggest that the eruptive style is controlled by whole–fissure discharge rates and hence by variations in magma reservoir overpressure under Hekla.

Jaupart and Allegre (1991) suggested from observation of Mt. Pelée and Mt. St. Helens that the principal factor affecting eruptive style was the overpressure in the magma reservoir. Further studies by Gardner et al. (1996) supported their findings. Hekla is an interesting case since its eruptive fissures not only cross the mountain but also open at different altitudes. Our studies show that as the discharge rate or overpressure in the magma chamber decreased, the eruptive activity moved to vents at lower altitudes. This is an observation consistent with the maximum rise height of the magma being controlled by overpressure in the magma chamber.

If we assume that the dike width was constant throughout the eruption, then a decreased discharge rate will have decreased the magma flow rate in the dike. Decreased flow rate will have allowed passive degassing of volatiles either through the conduit wall or up through the magma column. At the highest discharge rate (2,600 m^3/s) in the Hekla eruption the magma released about 1.2×10^5 kg water/s, while at a lower effusion rate (10 m^3/s) the water release was only 535 kg water/s. Volumetric expansion due to magmatic water release will thus have a drastic effect on exit velocity, which is of fundamental importance in eruption hazard forecasting, since exit velocity controls jet heights above vent.

The pyroclastic flow deposits observed on the southern and northern slopes of Hekla require an explanation. During the first hours of the eruption, the discharge rate reached 2,600 m^3/s, and concurrently some 1.2×10^5 kg H_2O was being released from the magma each second. Magmatic water degassing, along with calculated magma viscosity increase from 10^3 to 10^8 Pa s, produced the observed fragmentation of the magma. Thus high discharge rate, water-saturated magma and magma fragmentation contributed to the generation of the 12-km-high eruption plume, with the discharge rate being the fundamental factor (Carey and Bursik 2000). To generate a pyroclastic flow, the discharge rate and entrainment of atmospheric air must vary during the eruption to cause instability in the plume and its partial collapse. Possible changes in the geometry of the eruptive vents may have provoked plume instability, but Jaupart and Allegre (1991)

Table 4 Summary of parameters from four Hekla eruptions

Year of eruption	Max. discharge rate (m^3/s)	Volume (km^3)	Duration (days)	Average discharge rate (m^3/s)	Preceding repose period (years)
1970[2]	6,155	0.21	60	40.5	22
1980–81[3]	4,797	0.15	12	144.7	10
1991[4]	1,720	0.15	54	32.2	10
2000[5]	2,600	0.189	12	181.3	9

Data from; Thorarinsson 1967[1]; Thorarinsson and Sigvaldason 1972[2]; Grönvold et al. 1983[3]; Gudmundsson et al. 1992[4] and this study[5]
Max. discharge rate is calculated from plume height observations

pointed out that any variation in the eruptive vent is going to have minimal effects on the exit velocity and discharge rate if the vent is much smaller than the feeder dike. In the case of Hekla 2000, the largest vents were 300 m in diameter while the feeding dike was at least 14 km high. We observed a high discharge rate in the beginning and a sharp decline an hour after the onset of the eruption (Fig. 5b). This decline can be correlated with lengthening of the eruptive fissure from 1.3 km (fissure segment 2) to 6.6 km. Assuming constant magma supply from depth, the lengthening of the fissure is sufficient to affect the alimentation of the plume and the entrainment of atmospheric air in the plume region. Thus we suggest that the plume underwent a partial collapse to form pyroclastic flows due to lengthening of the eruptive fissure.

Volume estimates for eruptive products are based on direct measurements in the field. When calculating volume from field data we take into account pre eruption topography. If that were not considered the estimated volume would have been considerably smaller. The volume for the lava flow field is 0.188 km^3. Of the last four Hekla eruptions, the 2000 eruption compares most closely to the eruption in 1970 in volume. However, if we compare the inferred maximum discharge rates in the eruptions, their duration and their volume, the data from four previous eruptions are not coherent; this suggests that volumes of past Hekla eruptions could be underestimated in some cases (Table 4) due to insufficient knowledge of pre eruptive topography or that maximum discharge rate based on column height is not reliably linked with total eruption volume at Hekla volcano.

Conclusions

The 18th historic eruption of Hekla lasted for 12 days. During this time, a volume of some 0.189 km^3 of magma was emitted. The eruption started with a brief Subplinian phase, giving rise to a 12-km-high eruption plume. During the Subplinian phase, several small volume pyroclastic flows formed. As the eruption continued, activity changed to fire fountaining and then to Strombolian, ending with a quiet effusive lava phase. Magma emitted was basaltic andesite with a mineral assemblage, indicating equilibrium conditions at a depth of some 14 km. Juvenile water content of the magma was 2.3 wt%.

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