Hazard Assessment and Risk Mitigation for Tourists at Hekla Volcano, South Iceland

Jorge Eduardo Montalvo Morales

Faculty of Earth Sciences
University of Iceland
2010

Hazard Assessment and Risk Mitigation for Tourists at Hekla Volcano, South Iceland

Jorge Eduardo Montalvo Morales

30 ECTS thesis submitted in partial fulfillment of a
Magister Paedagogiae degree in Geology

Advisor
Magnús Tumi Guðmundsson

Faculty of Earth Sciences
School of Engineering and Natural Sciences
University of Iceland
Reykjavik, 28 July 2010

Hazard Assessment and Risk Mitigation for Tourists at Hekla Volcano, South Iceland.
Hazard Assessment and Risk Mitigation
30 ECTS thesis submitted in partial fulfillment of a *Magister Paedagogiae* degree in Geology

Faculty of Earth Science
School of Engineering and Natural Sciences
University of Iceland
Sturlugata 7
107, Reykjavik
Iceland

Telephone: 525 4000

Bibliographic information:
Jorge Montalvo, 2010, *Hazard Assessment and Risk Mitigation for Tourists at Hekla Volcano, South Iceland*, Master's thesis, Faculty of Earth Sciences, University of Iceland, pp. 67.

ISBN XX

Printing: XX
Reykjavik, Iceland, 28 July 2010.

Abstract

Hekla volcano is located in South-Central Iceland at the intersection of the South Iceland Seismic Zone and the East Volcanic Zone. Hekla has erupted at least 18 times during historical times (since AD 1104). One of Hekla's main characteristics is the production of mixed eruptions, i.e., both explosive and effusive. Hekla's most common final products are of basaltic andesite composition (52 – 54 wt% SiO_2). The onsets of the eruptions at Hekla are sudden and without much warning; precursory seismic activity, which have been compared with strain data, can announce the onset of an eruption approximately 30 minutes before the breakthrough. The main hazards threatening tourists hiking to the summit of Hekla are (1) tephra fall (including ballistic) fallout, (2) pyroclastic density currents, (3) lava flows and (4) jökulhlaups or lahars. Other hazards include gas and fluorine poisoning. It is found that life- threatening situations can arise within a few minutes after the onset of an eruption out to a distance of 5 km from the summit. Warning to tourists during the short interval of seismicity before an eruption is therefore very important.

Increase in the number of tourists in this area has a positive impact on the tourist industry income due to the potential development that accompanies; however, it also represents a higher risk of casualties in the event of an eruption. It is suggested that mitigation of risk can be obtained through a combination of public and tourist education, by providing tourism providers with accurate information, by setting up warning signs at strategic places around the volcano and through information in form of pamphlets and web-based information.

ÚTDRÁTTUR

Eldfjallið Hekla er sunnarlega á miðhálendi Íslands, þar sem skerast suður-íslenska jarðskjálftabeltið og eystra eldfjallabeltið. Hekla hefur gosið að minnsta kosti átján sinnum á sögulegum tíma (frá 1104 e.K.). Eitt af merkustu sérkennum Heklu er það að gosin geta verið blönduð, þ.e. hvort sem er sprengigos eða hraunflæði. Algengast er að úr fjallinu komi andesítbasalt (52 – 54 wt% SiO_2). Heklugos gera boð á undan sér; undanfarandi skjálftavirkni sem borin er saman við þenslu gefur um það bil 30 mínútna forskot áður en gos brestur á. Það helsta sem ferðamenn verða að varast er (1) gjóska og hraunbombur, (2) gjóskuflóð, (3) hraunflæði og (4) jökulhlaups (lahars). Auk þess er hætta á gas- og flúoreitrun. Álitið er að á nokkrum mínútum eftir að gos hefst geti skapast lífshættulegar aðstæður í allt að 5 km frá gígnum. Þess vegna er afar áríðandi að ferðamönnum sé gert viðvart á þeirri skömmu stund sem líður frá því skjálftavirkni hefst og þar til gos er komið í gang.

Fjölgun ferðamanna á þessu svæði hefur hagstæð áhrif á afkomu ferðamannaiðnaðarins, en því fylgir hins vegar meiri hætta ef fjallið fer að gjósa. Mælt er með því að reynt verði að draga úr hættunni með ýmisskonar fræðslustarfsemi, bæði fyrir almenning og ferðamenn. Einnig með því að fá ferðaþjónustunni í hendur nákvæmar upplýsingar, með því að setja upp viðvörunarmerki á mikilvægum stöðum allt umhverfis fjallið, og með upplýsingum í bæklingum og á netinu.

Dedication

A mi familia…
Con grandes sacrifcios deberian venir grandes recompensas.
(To my family…
With great sacrifice should come great reward).

Table of contents.

LIST OF FIGURES.

LIST OF TABLES

Acknowledgements

I want to thank first of all Olga Morales, my Mother, because throughout the years she has been despite of everything an invaluable support for me to reach all my goals. Soy la persona mas orgullosa del mundo al poder llamarme hijo tuyo, gracias mamá. To Jón Snorri Ásgeirsson and Ágústa Harðardóttir for “adopting” me as their child and embracing me in their family. To Magnús Tumi for his advice and guidance through the process of writing this thesis and for the material provided. To Ingibjörg Jónsdóttir and Guðmundur Freyr Úlfarsson, especially Ingibjörg for the invaluable conversations and for their assistance with the ArcGIS program, which was used to produce some of the maps presented here. To Ármann Höskuldsson and Þorvaldur Þorðarson for their contribution with some visual material. To Ólafur Ingólfsson and Niels Óskarsson for their critic and experienced points of view in the many discussions. To Claudia Cabras for her patience, love and belief that things can only get better.

1. Introduction

According to the Icelandic Tourist Board (ITB – Icelandic Tourist Board, 2009), tourism represents around 5% of the country's Gross Domestic Product (GDP) and has seen a ~8.3% annual increase in the past ten years. Nature is by far the highest factor attracting tourists to Iceland (according to the ITB 70% of tourists coming to Iceland) and the majority of visitors tend to dwell in the country from 5 – 14 days. In that period of time, some tourists enjoy different hiking trails that are found in the country, e.g., the hiking trail between Landmannalaugar and Þórsmörk (the hike last on average 3 days) and other much shorter hikes, including hiking on ice or geologically active areas. In addition, the majority of the tourists (~70%) prefer to travel around the country in rented cars or coaches. More information is required but some assumptions could be made in relation to the fact that most tourists tend to visit the southern part of the country, the region where Hekla is located.

Hekla volcano is one of the areas that has, over the years, received an increasing number of visitors, although no consistent numbers are available. It is located in South-Central Iceland at the intersection of the South Iceland Seismic Zone (SISZ) and the East Volcanic Zone (EVZ). See Fig 1 and 2. The volcano's general characteristics do not permit an accurate long-time prediction of the next eruption; thus Hekla is becoming a serious concern for authorities, media, travel agencies and tourists. Hekla has erupted at least 18 times in historical times. Hekla is particular because of the mixed eruptions; nonetheless, the final products are most commonly basaltic andesite. Only once in historic times has a predominantly rhyolitic eruption been recorded at Hekla. Production of basaltic lavas is linked to eruptions in the fissure swarms outside the main edifice (Thordarson and Larsen, 2007; Höskuldsson et al., 2007). Hekla erupts in a three-stage pattern, where it shows the transition between both mechanisms in which it commonly erupts, i.e., explosively and effusively.

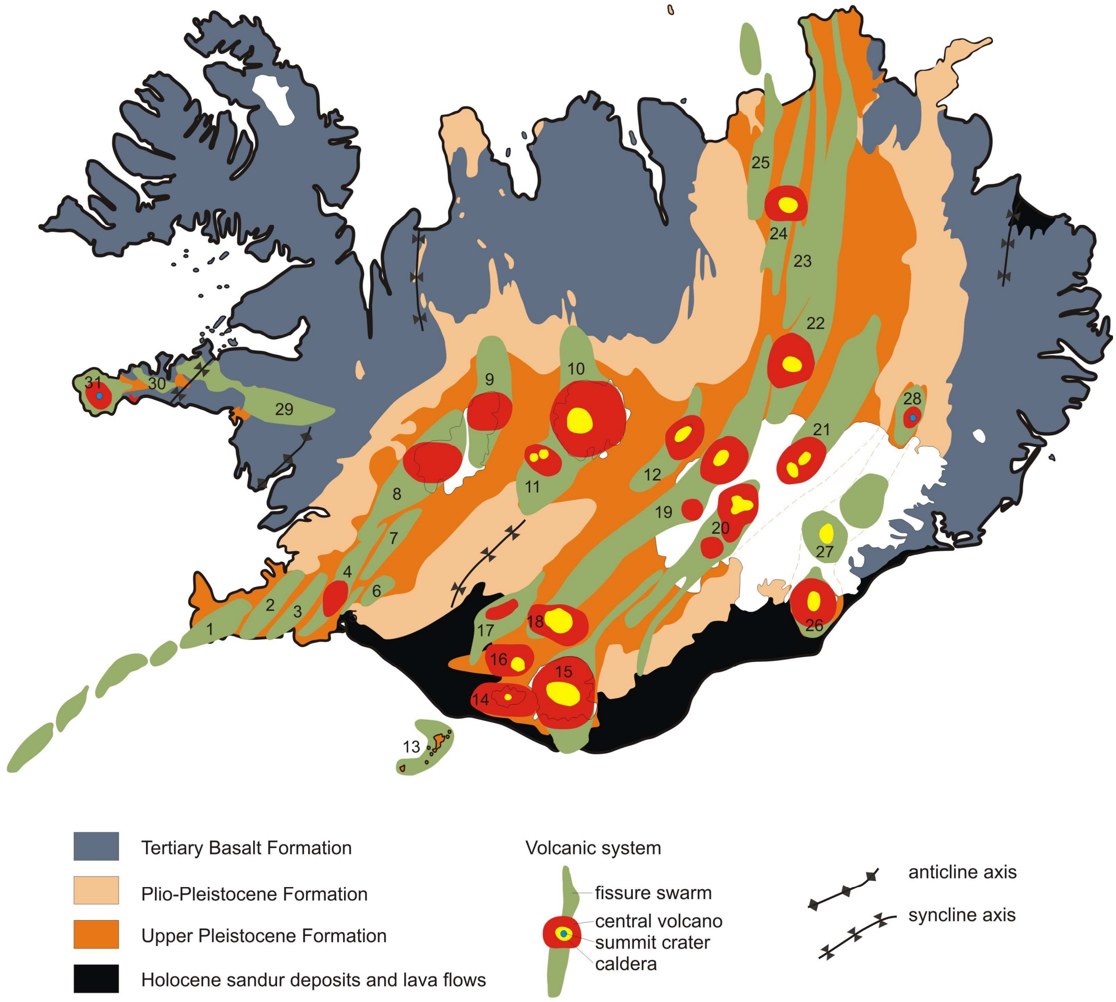

Figure 1 Volcanic systems in Iceland. Hekla volcanic system is marked by the number 17 on this map (From Thordarson and Larsen, 2007. p. 122).

There are no important settlements located close to the volcano. However, some farms are found to the South and West of the volcano. Næfurholt, southwest of Hekla, is the one closest to Hekla at ~10 km from Axlagígur crater (from 1947 eruption). Thus, this thesis is more directed to how to introduce Hekla to international tourists. In other words, one of the main objectives of this thesis is to collect, organize and present information relevant behind the mechanisms driving the eruptions in Hekla volcano with the aim of increasing awareness in this matter. This information could become essential in organizing booklets, pamphlets, or information signs. It is not intended here to propose a stop to tourism in the area but it is suggested that people are made aware of the current situation. This thesis is built up by presenting the general aspects of volcanism in Iceland, followed by the special emphasis on Hekla and the potential hazards present at this volcano; making a special effort to direct the information to the tourist population. It is hoped that this thesis can work as a guideline, instructing tourists on their own safety when visiting Hekla or other volcanically active areas, whether visiting on their own or on guided tours.

2. Geological background.

2.1. On the Volcanism in Iceland.

Volcanism in Iceland is not quite typical of island volcanism due to the special geological setting of the island. In Iceland, it is possible to find nearly all types of volcanoes and eruption styles known on Earth (Thordarson and Larsen, 2007). This characteristic is the result of the interaction between the divergent plate boundary and the mantle plume underneath the island. This interaction creates the different volcanic zones, or neovolcanic zones (Thordarson and Larsen, 2007), which are described as "belts of active faulting and volcanism" (Thordarson and Larsen, 2007. p 119). See Fig 1 and 2.

Each volcanic belt (Fig. 1 and 2) has its own characteristic components. However, most of them also share similar conditions, such as predominance of tholeiitic magmatism. Additionally, volcanoes in Iceland are classified, among others into polygenic and monogenic, depending on the recurrence of activity from the same vent (e.g., Thordarson and Larsen, 2007). Another classification is related to the geometry of the actual vent of basaltic volcanoes, whether it is circular or linear (Thorarinsson, 1981 in Thordarson and Larsen, 2007); and more importantly on the type of eruption and the volcanic environment, whether it is aerial, subglacial or submarine.

The basic and fundamental geological structures in Iceland are the volcanic systems, which are characterized by a fissure (dyke) swarm, a central volcano or both. A volcanic system in Iceland commonly has a lifetime of 0.5 – 1.5 million years (Thordarson and Larsen, 2007). Fissure swarm systems are elongated structures normally sub-parallel to the axis of the active volcanic zone that contains it. Central volcanoes are not always present, however, they mark the point of eruptive activity in that structure (Thordarson and Larsen, 2007). Thirty volcanic systems have been identified in the volcanic zones in Iceland, the sizes of which vary from ~25 to 2500 km^2 and lengths are from 7 to 200 km. Presence of central volcanoes can be observed in 19 volcanic systems in Iceland; some of which can feature more than one volcano. The presence of a central volcano could be indicative of a shallow magma chamber (Thordarson and Larsen, 2007). These central volcanoes are built by repeated eruptions from a central area, which is maintained by a persistent plumbing system (Thordarson and Larsen, 2007).

The categorization of an event, whether it is an effusive, explosive or mixed eruption, is given on the basis of the erupted material. Thus, it is an effusive eruption when more than 95% of the material is lava; eruptive when more than 95% of the material is tephra; and mixed when there is combination of both types of material and the ratio falls between those limits (Thordarson and Larsen, 2007).

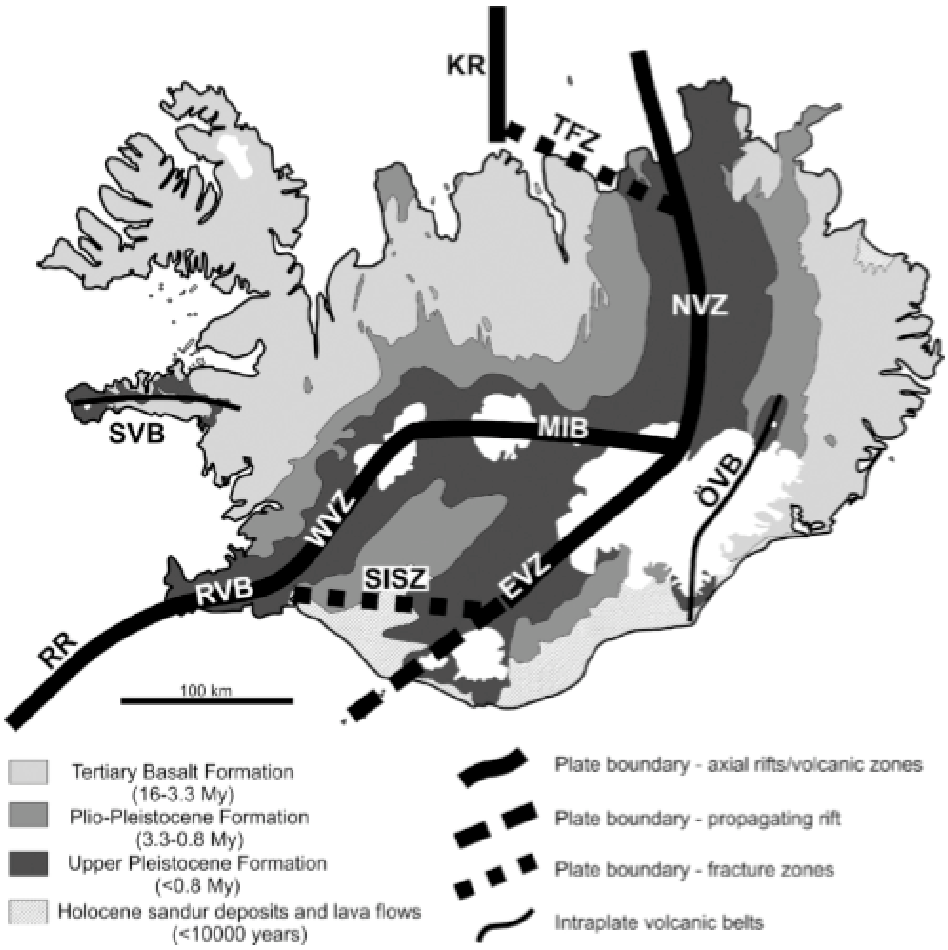

Figure 2. Map of Iceland illustrating the location of the divergent plate boundaries and the location of the volcanic zones in Iceland. Hekla is part of the East Volcanic Zone (EVZ). (From Thordarson and Larsen, 2007. p. 121).

Basaltic volcanism dominates in Iceland but in historical records there is evidence of andesite, dacite and rhyolite lavas. Explosive volcanism in Iceland occurs in three main styles: Surtseyan, Phreatoplinian and Plinian and thus representing the two main classes of explosive eruptions: magmatic (for “dry” eruptions) and phreatomagmatic (for “wet” eruptions) (Thordarson and Larsen, 2007).

Mixed eruptions are a special category. As mentioned before these eruptions show both effusive and explosive characteristics and in Iceland almost exclusively belong to andesite volcanism. These types of eruptions have been located mostly at Hekla volcano (Thordarson and Larsen, 2007).

2.2. Hekla*.*

For the preparation of this chapter a typical eruption event at Hekla was taken into consideration, i.e., the following description applies to the normal trend or fashion in which Hekla is most likely to erupt.

Hekla (Fig. 3) is located about 110 km east of Reykjavík. It stands high above the central lowlands, reaching an altitude of 1488 m.a.s.l. It is a central volcano that matches the characteristics of a stratovolcano, formed by different lava flows and material ejected from a fissure swarm oriented northeast – southwest (Thorarinsson, 1950). It is possible to observe the typical shape of a stratovolcano (i.e., a cone with 15-33° slopes) only from a certain perspective (Thordarson and Larsen, 2007). Hekla is characterized by mixed eruptions, which by definition can be both explosive and effusive and almost exclusively formed in andesite volcanism (Thordarson and Larsen, 2007).

Hekla is clearly one of the most active volcanic systems in Iceland (See Fig 1). In historical times, i.e., from the settlement time, Hekla has erupted in 23 occasions (See Table 1), out of which 18 eruptions have been restricted to the central volcano itself, whereas the other 5 occurred on fissures outside the central volcano (Thordarson and Larsen, 2007; Höskuldsson et al., 2007).

All of the eruptions in the central volcano are considered mixed eruptions (i.e., that feature both explosive and effusive activity), except for the one in 1104 AD, which was of rhyolitic composition and purely explosive (Thordarson and Larsen, 2007). Hekla produces intermediate lavas [accounting for ~95% of the intermediate lavas produced by volcanoes in the country in historical times (Thordarson and Larsen, 2007)]. The eruptions within the central volcano occur along a ~5 – 7 km long fissure that follows a southwest-northeast trend and that crosses the summit of the volcano (Höskuldsson et al., 2007).

Figure 3: *Photograph of Hekla Volcano in South-central Iceland, it reaches 1488 m.a.s.l. and the main edifice was built by repeated eruptions over the ~5 - 7 km long volcanic fissure. This picture shows the dimensions of the stratovolcano from the South flank (photograph faces North). The small map shows the location of Hekla (yellow star). Photo by J. Montalvo. Map from Thordarson and Larsen, 2007.*

These eruptions along the main fissure have produced the intermediate to silicic rocks (Sigmarsson et al., 1992). Additionally, some of the eruptions have occurred on fissures outside of the central volcano (Thordarson and Larsen, 2007; Höskuldsson et al., 2007) and which tend to erupt more basaltic lavas (Sigmarsson et al., 1992). Studies suggest the existence of a magma chamber somewhere between 8 and 14 km depth (Sigmarsson et al., 1992; Soosalu and Einarsson, 2004). Recent studies disregard the possibility of a shallow magma chamber due to the absence of geothermal activity at Hekla and the lack of small-scale seismicity (Soosalu and Einarsson, 2004).

Historical eruptions on the Hekla volcanic system

Year of eruption (A.D.)	Tephra (km^3)	Tephra DRE (km^3)	Lava (km^3)	Preceding interval (years)
Hekla central volcano				
2000	0.01	0.004	0.17	9
1991	0.02	0.01	0.15	10
1980–1981	0.06	0.026	0.12	10
1970	0.07	0.03	0.2	22
1947–1948	0.18	0.08	0.8	101
1845	0.23	0.1	0.63	77
1766–1768	0.4	0.18	1.3	73
1693	0.3	0.13	*0.9*	56
1636	0.18	0.08	*0.5*	39
1597	0.29	0.13	*0.9*	86
1510	0.32	0.14	*1.0*	120
1389	0.15	0.07	*0.5*	47
1341	0.18	0.08	*0.5*	40
1300	0.5	0.22	*1.5*	78
1222	0.04	0.02	*0.1*	15
1206	0.4	0.18	*1.2*	46
1158	0.33	0.1	0.1	53
1104	2	0.61		>230
Total	5.6	2.2	10.8	

Table 1. Information on the historical eruptions of Hekla, including only the activity on the Central Volcano. There have been 23 eruptions in total, the 5 eruptions not listed are associated to fissure swarms outside the Central Volcano. DRE= volume of material calculated as Dense Rock Equivalent. (From Thordarson and Larsen, 2007. p 141).

As can be seen in Table 1, Hekla has erupted about one to three times per century since 1100 AD. This apparent pattern, however, is different for the 20th century, in which Hekla erupted 5 times. These eruptions additionally presented another particular trend of being of less magnitude than the preceding ones (Table 1), in other words, the explosivity and magnitude (along with the silica content) of the eruptions vary considerably depending on the repose time between eruptions (Table 1); the longer the repose time the more explosive the initial stage of the eruption will be (due to higher content of silica) [Thordarson and Larsen, 2007; Höskuldsson et al., 2007; Sigmarsson et al. 1992]. However, the final lava contains about 52 – 54 wt% SiO_2, corresponding to basaltic andesite (Sigmarsson et al., 1992; Thordarson and Larsen, 2007).

Hekla follows a consistent eruptive pattern (Thordarson and Larsen, 2007). After building up the eruption, Phase 1 is marked by a subplinian to Plinian event (which are powerful convecting plumes of gas and ashes rising to several kilometers into the atmosphere), and that are characterized by high magma discharge, followed by a sharp drop in the eruption intensity, in which it can be observed a simultaneously sustained emission of tephra and lava fountains, which consequently marks Phase 2 of the eruption, which is mostly effusive (Thordarson and Larsen, 2007). Finally, Phase 3 is characterized by small Strombolian eruptions and little magma discharge (Thordarson and Höskuldsson, 2008; Thordarson and Larsen, 2007).

The initial phase of all known events is always highly explosive (Höskuldsson et al., 2007), which poses danger to travelers visiting the area that may get caught in the vicinity of the volcano during an eruption. It has been determined that the columns of erupted material ejected in this first phase have reached heights between 12 – 36 km (Höskuldsson et al., 2007), presenting considerable risk for air traffic (Gudmundsson et al., 2008). Another concern related to these eruption columns is the tendency for collapse and formation of pyroclastic density currents. One of the reasons for collapsing clouds is a variation (fluctuation) in the discharge rate observed at the vent (Höskuldsson et al., 2007).

Eruptions at Hekla commonly have no long-term precursors, such as volcanic tremor several hours before the eruption (and other than deformation of the volcanic edifice). Instead a series of magma-related earthquakes can be observed ~1 hour prior to eruption. A defined three-staged pattern has been described for the eruptions at Hekla (Thordarson and Höskuldsson, 2008; Thordarson and Larsen, 2007). As a consequence, such eruptions can produce certain volcanic hazards that can be divided into primary hazards (e.g., Pyroclastic Density Currents and Tephra fallout) and secondary hazards (e.g., gas poisoning and fluorosis); and which include overall seven main types of volcanic hazard that are a result of the style of the eruption (Frampton et al., 2000). The nature and severity of the hazards at Hekla will be discussed in more detail in Chapter 3.

The last eruption in Hekla began on the 26^{th} of February 2000 at 18:19h UT and lasted for about 12 days. It took place along the main fissure; which in this event was divided into 5 discontinuous segments (Fig 3). Also, about 39 eruptive craters were observed to produce lava flows distributed along the length of the fissure (Höskuldsson et al., 2007).

The first stage of the eruption was in fact short-lived and small amounts of tephra were produced. Calculations made by Höskuldsson et al. (2007) suggest that the subplinian eruption was sustained for about 30 minutes and the amount of tephra deposited during the eruption was ~0.01 km^3. Most of the erupted volume was produced during the effusive stage; eventually forming lava flows (Fig 4). A maximum discharge rate of 2.600 m^3/s was attained at 18:49 UT (Höskuldsson et al., 2007). This information is corroborated by seismic records and observations. That maximum was followed by a period of fluctuations in the discharge that lasted approximately 30 minutes. At the end of that fluctuating period the discharge rate began to decline (Höskuldsson et al., 2007). Evidence of pyroclastic density currents was observed in field studies carried out in the summer 2001 by Höskuldsson et al. (2007).

2.2.1. Precursors and Monitoring.

Extensive geophysical research has been carried out at Hekla and surroundings using a seismic network, strain meters and geodetic measurements. With these elements several projects have been carried out, including the location of the magma chamber underneath Hekla, which remains yet to be confirmed. Authors like Soosalu and Einarsson (2004) suggest that evidence points to the top of the magma chamber being at 8 km depth. Some of the tangible evidence is the lack of major geothermal activity on Hekla (Soosalu and Einarsson, 2004). However, some other authors suggest the magma chamber to be closer to the surface (e.g., in Linde et al. 1993). Nonetheless, Hekla has the particularity of being normally aseismic, except during volcanic events (Linde et al., 1993; Soosalu et al., 2003;

Soosalu and Einarsson, 2004), when signs of activity start ~25 – 80 minutes before the onset of an eruption (Soosalu et al., 2003).

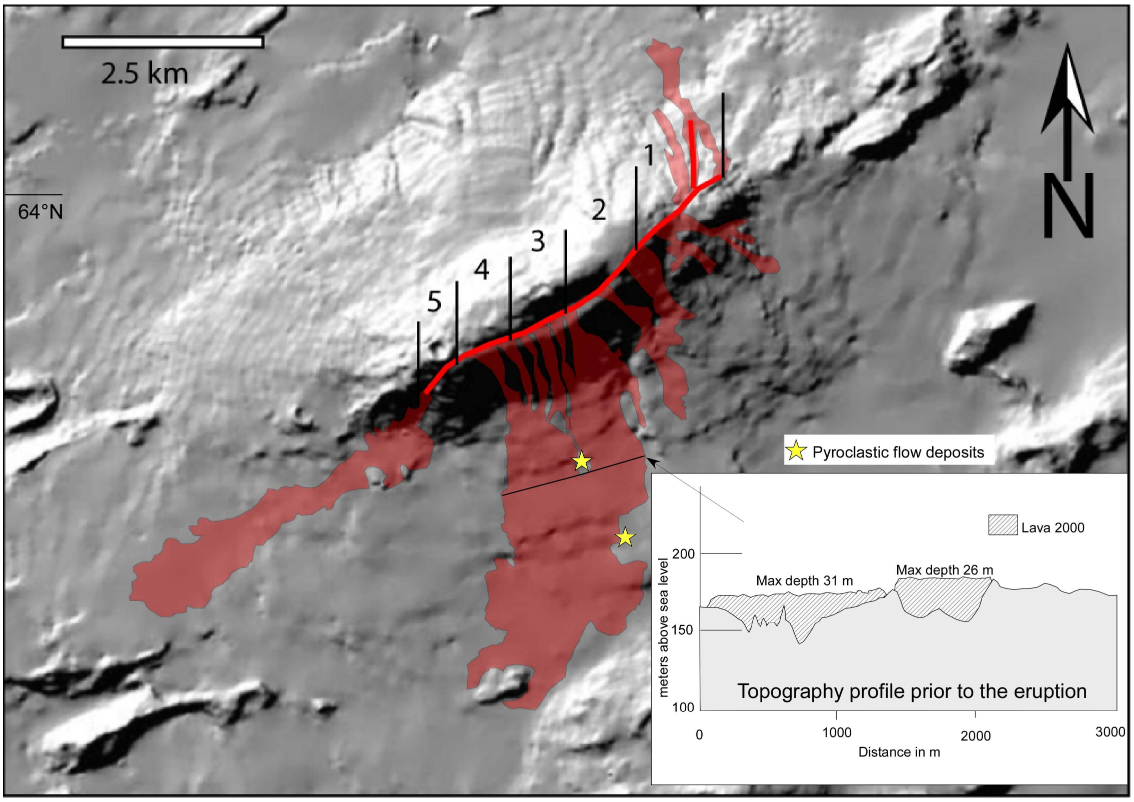

Figure 4. Image showing the division of the main eruptive fissure (continuous red line) during the eruption of Hekla in February 2000. Furthermore, the map shows the extent of lava flows produced during the eruption. Additionally, yellow stars mark the locations where Höskuldsson et al. mapped pyroclastic density currents produced in this eruption (From Höskuldsson et al., 2007. p. 174).

The connection between the depth of the magma chamber and the precursory seismic signals is established on two assumptions: a) that the tremor will be reflected or sensed if the magma flow is somewhat turbulent (Soosalu et al., 2003 and references therein), or b) if the magma source is deep, inflation of the magma chamber will not be recorded until dykes start propagating (Soosalu and Einarsson, 2004). These are some of the parameters indicating why Hekla does not show sufficient seismic activity to make long-time predictions.

Observations have been made in creeks and lakes close to Hekla showing a decrease in the water table. This drop has been explained by inflation of the volcanic edifice. However, more tangent evidence was the seismic unrest that Hekla featured only about an hour before the actual eruption (Höskuldsson et al., 2007). Strain measurements can be made in order to establish evidence of magma movement at depth (Linde et al., 1993). These results can additionally be compared to geodetic data acquired as evidence of inflation in the volcanic edifice. The theory behind this idea is that magma creates tension as it rises, by forcing its way up through the rock; this tension is the information that can be recorded in the strain meters as contraction or expansion (Linde et al., 1993).

Since normally Hekla presents no long-term pre-activity, seismic data and strain data can be of relevant importance, mainly because these data sets complement each other and are a great tool to estimate the probability of an eruption. It is important to keep in mind that commonly the detection of seismic unrest at Hekla (Höskuldsson et al., 2007) can be interpreted as the initiation of magma ascent (Linde et al., 1993).

2.2.2. Onset of a typical eruption at Hekla.

The onset of Hekla eruptions is usually marked by the appearance of seismic activity on the monitoring systems around the volcano. The earthquakes associated with volcanic activity (i.e., increasing pressure and movement of magma) are often very small and usually in swarms (Jakobsdóttir, 2008). At the last Hekla eruption in 2000, seismic unrest was noticed at 17:20h, basically one hour before the actual eruption (Höskuldsson et al., 2007). The eruption of 1991 officially started at 17:02 GMT, however, premonitory earthquakes started to be recorded at 16:30 GMT (Soosalu et al., 2003). Low-frequency volcanic tremor is directly related to the volcanic activity and commonly the detection of volcanic tremor marks the onset of the eruption and can be observed throughout the duration of the eruption (Soosalu et al., 2003). Appearance of volcanic tremor has been compared with strain measurements and these data are consistent (Soosalu et al., 2003).

The eruption itself can take place along the fissure or fissures that cross the summit of the mountain, or fissures that can open on the flanks. The way in which Hekla erupts has been divided by different authors (e.g., Höskuldsson et al., 2007; Thordarson and Höskuldsson, 2008; Thordarson and Larsen, 2007) into three phases that represent the evolution of the typical eruption at Hekla. It has to be noted that in some cases there is no visibility due to cloud cover and bad weather, thus the importance of the seismic or strain meters for constant monitoring the activity in the volcano.

2.2.3. Phase 1: Explosive Phase.

During phase 1 of Hekla eruptions, high eruption plumes may have reached altitudes up to ~36 km (Höskuldsson et al., 2007) [See Fig. 5]. Observations made with the aid of the meteorological radar of the Icelandic Meteorological Office (Veðurstofa in Icelandic) located near Keflavík showed that the volcanic plumes produced by Hekla in the 1991 and 2000 eruptions, reached the ~12 km altitude detection limit of the radar in about 10 - 30 minutes after the onset of the eruption (Larsen et al., 1992; Lacasse et al., 2004).

If a plume loses its momentum before reaching hydrostatic equilibrium it can collapse due to gravity. This collapse leads to the formation of pyroclastic density currents[1], some of which have been identified after eruptions of Hekla (Höskuldsson et al., 2007). Also, at this first stage, the ash fall takes place and possibly electric discharges (lightning) could be expected

[1] Pyroclastic density currents: Are a high-density mixture of hot, dry rock fragments and hot gases that move away from the vent that erupted them at high speeds. They may result from the explosive eruption of molten or solid rock fragments, or a mixture of both. They may also result from the non-explosive eruption of lava, when parts of dome or a thick lava flow collapses down a steep slope. The effects of a pyroclastic flow can be quite catastrophic. The temperatures of rock and gas inside the cloud can be between 200 and 700°C. Additionally, pyroclastic flows can leave deposits of loose material that in specific conditions could ultimately cause lahars (Summarized from the United States Geological Survey (USGS)'s webpage at http://volcanoes.usgs.gov/hazards/pyroclasticflow/index.php).

Subsequently, the other products of the phase I of the eruption are produced within the next 30 minutes or so after it has started. In this time range, pyroclastic density currents are very likely to start gushing down the slopes. Afterwards, within an hour the lava flows start running. Lahars and jökulhlaups can occur as the pyroclastic density currents flow down the flanks or in matter of minutes after the events.

2.2.4. Phase 2

It is not entirely clear where the boundary between Phases 1 and 2 of the eruption is, since it has been observed in some cases that the eruptive plume and lava production were simultaneously active (Höskuldsson et al., 2007). Anyway, normally once the explosive phase (i.e., Plinian or subplinian part of the eruption) has come to an end, the eruptions become typically mixed. It shows a more effusive character due to a drop in the eruption intensity. At this stage a sustained emission of ash and lava is observed (Thordarson and Höskuldsson, 2008; Thordarson and Larsen, 2007). Lava fountains normally represent the beginning of the second stage in the eruptive event at Hekla, which occasionally can occur just a few minutes after the start of the eruption, following the explosive phase (Grönvold et al., 1983). At this point there is mainly production of lava, which can last for several days or even months.

2.2.5. Phase 3

Finally, during Phase 3 of the eruption the activity is mainly reduced to Strombolian explosions and low ejection of magma from some of the craters formed during the eruption (Thordarson and Höskuldsson, 2008; Thordarson and Larsen, 2007).

Figure 5. The 28 km high eruption column produced in the Plinian eruption of Hekla in 1947. Eruptive columns produced in Phase 1 of an eruption at Hekla might have reached up to 36 km height. These columns could reach 12 km [which is the Keflavík radar top detection limit (Lacasse et al., 2004)] within 30 minutes (often around 10 min. approx.) from the onset of the eruption. Photo taken by Sæmundur Þórðarson.

2.2.6. Tourism at Hekla.

Iceland has become a popular tourist destination. Estimates indicate that more than 470.000 people from different nationalities visit Iceland every year mainly eager to experience the nature (ITB, 2009). One of the most tempting reasons to visit Iceland is the volcanic character of the island and the opportunity to see features such as geysers and other geothermal features that are not available in many other countries. Many people are also attracted by the recent volcanic history of Iceland and events such the eruptions of Surtsey, Heimaey, Krafla and Hekla.

Hekla, as most natural recreational sites, has seen a great flow of visitors, although concrete numbers are not kept by any agency on how many people actually visit Hekla, it is known that several people visit the area especially in the summer months. Based on eyewitnesses, it is known that on good summer days it is possible to see more than ~150 tourists at Hekla, and according to Almannavarnir (Civil protection department of the Icelandic Police), the majority of these tourists come to the location on rented cars. This information can be supported with the statistics from the Icelandic Tourist Board (2009). Therefore, the potential for a serious accident in the event of an eruption has increased at Hekla due to the increasing number of travelers and hikers that visit the area (Guðmundsson et al., 2008), despite of the ongoing alert for a potential eruption. Hekla volcano can be reach from different points. Skjólkvíar is the most common and best suited, since one of the roads leads directly to a parking lot in Skjólkvíar from where the climb starts. The average ascent time is about 4 hours. See Fig. 6.

Despite the fact that many tourist providers have stopped organizing tours to Hekla, visitors can still hire separately the same providers or they can simply visit the area when renting a car. The information on the potential hazards that Hekla can pose has not been communicated yet to tourists, e.g., through warning signals, pamphlets, and presentations at tourist locations around Hekla or by keeping an updated webpage where any tourist can access this information about the hazards. Tourist should be aware of the mechanisms of eruption at Hekla in order to reflect on how to act in the event of an eruption.

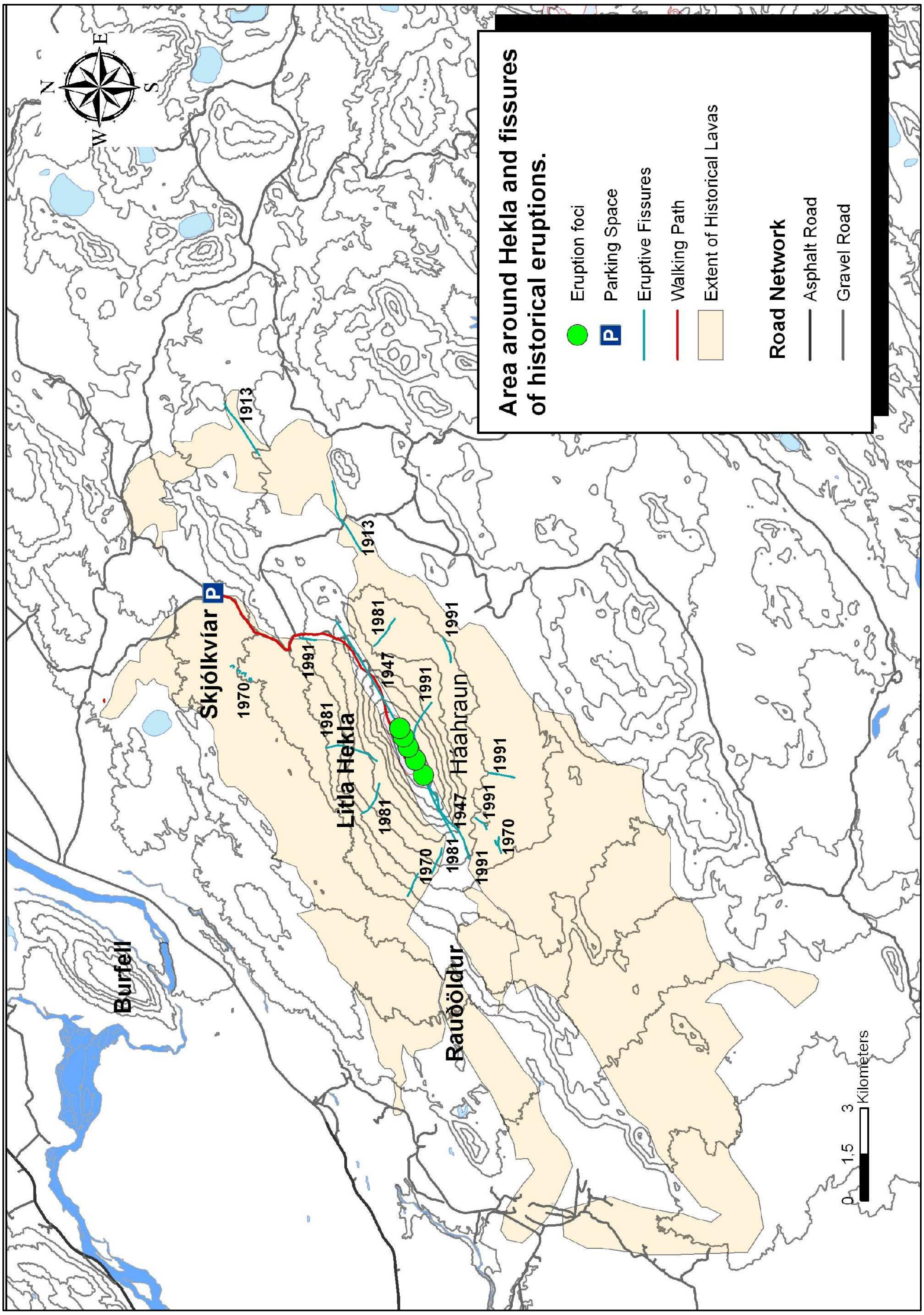

Figure 6: The area around Hekla showing the road network, most common climbing path, location of parking space and eruptive fissures from the eruptions in 1913, 1947, 1970, 1980 and 1991 (Hjartarson, 1995). The eruption in 2000 was mainly divided into five segments along the main eruptive fissure crossing the volcanic edifice (Höskuldsson et al., 2007)

3. Methods.

In this chapter a description is given of the potential hazards present at Hekla and how it can affect tourists. This was made by analyzing existent information from reports on Hekla (after recent eruptions) and defining the hazards occurring most commonly during a typical eruption. With selected information there were produced maps defining the areas that could be affected by those hazards that were previously defined. This thesis' contributes mainly with the definition of the hazards for Hekla, along with a rough grading of the level of danger (given in Table 3), the maps and possible ways to mitigate the danger for tourists at Hekla. Finally, other volcanic areas of the world will be considered for learning purposes (historic facts and response among others). Some popular tourist sites were taken into consideration for this comparison; Yellowstone National Park (Wyoming, USA) and Ruapehu, New Zealand, among others.

3.1. Definition of Main Hazards

Volcanic hazards can be divided into primary (or Main) and secondary hazards, depending on whether they can have direct consequences and pose an immediate threat to people or if they can have a longer and slower impact on the environment. Classifications of hazards include events related to volcanism and that are the result of the style and environment of the eruption. Among others classifications include tsunamis, avalanches, earthquakes, etc. (Frampton et al., 2000; Gudmundsson et al., 2008). However, not all of the volcanic hazards are relevant to Hekla. In this thesis 1) tephra fallout, 2) pyroclastic density currents, 3) lava flows and to some extent 4) lahars and jökulhlaups are regarded as main hazards for Hekla due to the swiftness and reach of their occurrence. Consequently, hazards associated with volcanic gases, and infrequent or unlikely hazards for Hekla such as earthquakes, lightning and tsunami are considered as secondary hazards.

Here after are categorized the direct events that can have more effect over a certain population (including tourists in the area) or animal stock and which are directly related to the volcanic event, i.e., the main volcanic hazards. Secondary volcanic hazards are regarded as less hazardous for people in the way that people could avoid them more easily, none the less in the long run certain secondary hazards, such as fluorine poisoning, did in the past cause famine and loss of livestock (Gudmundsson et al., 2008).

Furthermore, volcanic eruptions at Hekla and other Icelandic volcanoes pose a potentially serious threat to air traffic over the North Atlantic. An example of the consequences of aircrafts encountering the volcanic cloud of Hekla 2000 eruption is mentioned in Lacasse et al. (2004). Volcanic ash can cause extensive damage to the engines of aircrafts.

3.1.1. Tephra Fallout.

Tephra is the fragmental material produced during a volcanic eruption, and which is commonly transported by air and deposited by fallout (Larsen and Eiríksson, 2008). Including the heaviest and larger fragments called Ballistic fragments. Most volcanic eruptions produce tephra, of which the three main components are glass, crystals and lithics (Larsen and Eiríksson, 2008). Tephra fallout produced by Plinian or subplinian eruptions (Fig. 5) that have lasted for an hour to several hours can produce large deposits tens of centimeters thick in proximal areas to the eruption foci and changing wind direction can increase the area of impact (Guðmundsson et al., 2008). The way tephra is dispersed depends on several factors such as type of explosive activity, discharge rate and magnitude of the event, height of the column, wind direction and strength (Larsen and Eiríksson, 2008).

The Hekla volcanic system is responsible for a large amount of magma output in historical times and; part of it is preserved by tephra layers in soils around Iceland (Thordarson and Höskuldsson, 2008) and certain places in mainland Europe (Larsen and Eiríksson, 2008). According to estimates made by Larsen and Eiríksson (2008) over 40 km^3 of uncompacted freshly fallen tephra from Hekla have covered ca. 80% of Iceland during the Holocene (12.000 years BP – present).

Volcanic ash could have a strong impact on human health. Horwell and Baker (IVHHN booklet) worked on a pamphlet for the USGS and the University of Cambridge, among others, to present the effects of volcanic ash on people. They classify the effects into four categories: respiratory, eye, skin and indirect effects, and present a description of the symptoms that can be observed for each category. They also point out that people with chronic lung conditions and heart problems are most at risk. However, they also mention that the development of symptoms is generally dependent on factors such as duration of exposure to ash, concentration of particles in the air, proportion of fine particles in the ash, etc. Moreover, eye irritation is mainly caused by scratching (corneal abrasion) of the front of the eye and they point out that wearing contact lenses does not prevent it. Also, some conjunctivitis can be developed. Finally, ash can also cause skin irritation, which can lead to secondary infections due to scratching. They conclude advising on ways to protect and what to do if one needs to protect from ashfall.

Additionally, ballistic fragments represent a major threat due to the velocity in which they fall. Estimations point that there is ~78% probabilities of encountering ballistic fragments of 0,4 to 1 m (Max. 3,5 m) in diameter within 1 km from active volcanic foci (Hurtado and Cortes, 1997). Naturally, the probability decreases with distance but it is still quite latent even beyond 5 km (Hurtado and Cortes, 1997).

3.1.2. Pyroclastic Density Currents (PDC).

Pyroclastic density currents, as has been mentioned before in this thesis, behave similarly to avalanches (Fig. 7). PDC can be confined by topography (Höskuldsson et al., 2007) but with right density and speed they can also overcome the landscape. They flow downhill at very high velocities containing a mixture of hot, dry rock fragments and hot gases (Frampton et al., 2000). The velocity of a pyroclastic flow as it flows downhill and across the ground commonly exceeds 100 km/h (Francis, 1993 and USGS webpage reference); and the temperature in the clouds can be between 200 – 700°C.

Pyroclastic density currents have been reported in association with the central volcanoes that erupt more evolved lavas (Gudmundsson et al., 2008). In the case of Hekla, pyroclastic density currents are the result of collapsing eruptive cloud produced in the first stage of the eruption (Höskuldsson et al., 2007) during a Plinian or subplinian style eruption (See Fig. 5 and Fig. 7). Eruptive plume partial collapse can occur due to instability at the vent that affects the discharge and causes fluctuations, e.g., due to lengthening of eruptive fissure (Höskuldsson et al., 2007). These events have been recorded in the eruptive history of Hekla. Nonetheless, pyroclastic density currents and their deposits have been interpreted as flood deposits in several occasions (Höskuldsson et al., 2007; Gudmundsson et al., 2008). Pyroclastic density currents have been recorded for the Plinian eruption of 1947 and the subplinian eruptions of 1980 and 2000 (Gudmundsson et al., 2008). The deposits observed commonly consist of a fine ash matrix with several bigger particles called bombs 10 – 30 cm in size. Fragments of older lavas were also observed, 5 – 10 cm in diameter (Höskuldsson et al., 2007).

Observations made in 2001 after the most recent eruption at Hekla, indicate that some of the pyroclastic density currents were also produced when lava fountains were active, i.e., lava fountains and volcanic plume were active at the same time (Höskuldsson et al., 2007). This conclusion was reached after correlating the way a pyroclastic flow deposit overruns a previously formed lava flow. Observations also show that the pyroclastic clouds flowed down the same path as the lavas did (Höskuldsson et al., 2007).

The most prominent pyroclastic density current deposit observed by Höskuldsson et al. (2007) measured close to 2 m in thickness and which was found ~3 km from the main eruptive fissure. It contained 0.1 – 1.5 m bombs encompassed in a fine to coarse-grained ash matrix. Fragments of lithics were observed, 2 – 20 cm in size and belonging to a previous dense lava flow (Höskuldsson et al., 2007). These deposits can give an idea on how powerful the explosive event and how large the discharge might have been.

Figure 7. Photos by Hans Jurgen Beug.

This series of photographs was taken during the Hekla eruption in 1980 from a distance of about 10 km (Grönvold et al. 1983). The photographs show the evolution of a PDC produced a few minutes after the onset of the eruption. In the upper pictures it is seen the breakout of the eruption. Steam production is here due to melting of the snow (Grönvold et al., 1983) as the cloud gushes down the hill (Bottom pictures). In the bottom right picture it is seen the pyroclastic material plus the steam reaching the lower slope of the mountain. It is very likely that events like this have caused flooding, e.g., in the 1947 eruption. Anyway, pyroclastic density currents can trigger melting of the snow and ice, causing the formation of Lahars.

3.1.3. Lava Flows.

There are two main types of lavas: Pahoehoe and ‘A‘a. Both types are produced in effusive volcanic events and their differences are mostly due to differences in discharge rate (Thordarson and Höskuldsson, 2008), although they can also be affected by the magma composition and rheology. ‘A‘a lavas are characterized by the formation of spiny, glassy and rough surfaces; and represent the high-discharge end member, with rates of ≥ 100 m^3/s (Thordarson and Höskuldsson, 2008). In addition, ‘a‘a flows tend to form a sort of channel surrounding the main lava channel in order to insulate and prevent cooling of the lava. However, this transport mechanism is not very thermally efficient, therefore the lava channels are in fact not very long and the lava is not able to advance more than ca. 13 km (Thordarson and Höskuldsson, 2008; Thordarson and Larsen, 2007).

On the other hand Pahoehoe, the low-discharge end member (discharge ≤ 30 m^3/s ca.) lavas are better insulated and thus being able to cover larger distances if topography is favorable (>25 km) (Thordarson and Höskuldsson, 2008). The way these lavas advance is by building up in lobes. As the lava flows it cools down from the surface inwards. The cooler parts start to form a crust, which serves as an insulator (Thordarson and Larsen, 2007), and then when the inner pressure exceeds the resistance exerted by the crust, it breaks allowing molten material to ooze out and then start the process again. The process will be continued until there is not enough discharge to increase the pressure inside a lobe to break the crust (See Fig. 4 and 9 for example on lava flows from Hekla 2000 and 1991 respectively).

Lavas have been the main product in the last eruptions of Hekla. Lava fountains normally represent the beginning of the second stage (Fig. 8) in the eruptive event at Hekla, which on occasions can be just a few minutes after the start of the eruption, following the explosive phase (Grönvold et al., 1983). The common end composition of the lavas is that of a basaltic andesite (~55wt% SiO_2) and temperature has been estimated to be in the range of 1,062 – 1,136°C (Höskuldsson et al., 2007). Lavas within the Hekla system can be produced along the main eruptive fissure (or main volcanic ridge – See Figures 4 and 8) or through adjacent fissures away from the main volcanic ridge, and it has been observed that the explosive phase and effusion of lavas can happen simultaneously (Grönvold et al., 1983). The maximum length of the fissures can be reached within few hours, depending on how fast the system loses overpressure (Höskuldsson et al., 2007). Once the activity has decreased considerably, the effusivity starts being more and more restricted along the fissure until very close to the end it is confined to one or a few craters that formed during the eruption; at this point the activity consists of Strombolian bursts, which mark the final stage of the eruption (Höskuldsson et al., 2007).

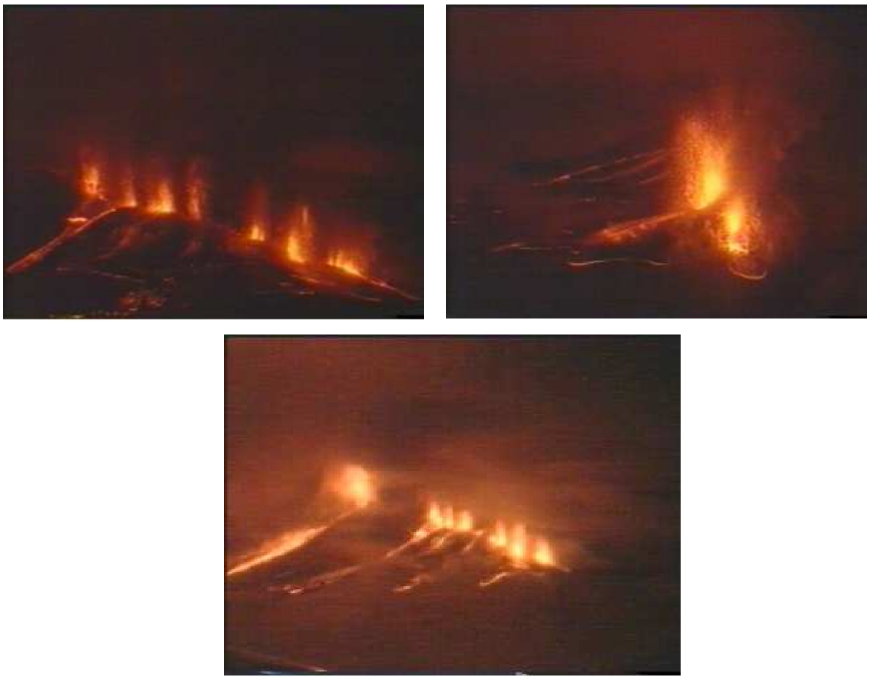

Figure 8. Photographs showing the lava fountains in full action along the main eruptive fissure which for this eruption (Hekla 2000) reached ca. 5 km in length and it was divided into 5 segments that were active at different times, the segment on top of the mountain was mainly active during the first two hours (Höskuldsson et al., 2007). Photos by Gísli Óskarsson.

The lavas erupted at Hekla, as it is common for lava flows, form an insulating crust that preserves thermal energy and the lava remains liquid in the interior, thus being able to flow for fairly long distances away from the vents. Höskuldsson et al. (2007) observed that the lavas produced in the 2000 eruption formed a protective crust that allowed them to advance for about 6 km. These lavas were of the ‘a‘a (or aa) type. The advancing of the lava is described as follows: “after the lava has formed a crust the interior remains liquid because the crust serves as a thermal insulator (Thordarson and Larsen, 2007); the lava front builds up to approximately 10 m, at this point the crust in the front becomes unstable and collapses, allowing the molten interior to advance (flow). Then, due to cooling a new crust starts to form and the cycle repeats one more time” (Höskuldsson et al., 2007).

Additionally, this tendency of the lavas to flow large distances is what ultimately could represent a threat for people even if they are hiking fairly far away from the volcano; however, it is not a major threat since one can more often observe the advance of the lava flow, and even if the flow could change direction it is commonly possible to outrun it, however a potential escape path is necessary to keep in consideration. Another event to keep in mind is the possibility of finding dammed rivers, i.e., lava flows can block and eventually dam rivers; and produce floods in some cases (Guðmundsson et al., 2008).

3.1.4. Lahars and Jökulhlaup.

These events could have a large impact on the surroundings. Nonetheless, near Hekla there are no important settlements that could be affected by floods and large floods have not occurred in Hekla eruptions (as compared to those from Grímsvötn or Katla). However, floods in the Rangá River have been reported after the eruptions in 1947 and 1980 (Kjartansson, 1951; Höskuldsson et al., 2007). Attention to this type of hazard should be paid since even if a flood is not large it can be dangerous to hikers that happen to be in its path. As has been stated before the first phase of an eruption at

Hekla involves the production of volcanic plumes, which can lead to pyroclastic density currents (Fig. 6). Furthermore, Hekla has small glaciers on the northwestern side and it is snow covered in winter. Thus, rapid melting could occur when pyroclastic density currents come in contact with the snow and ice.

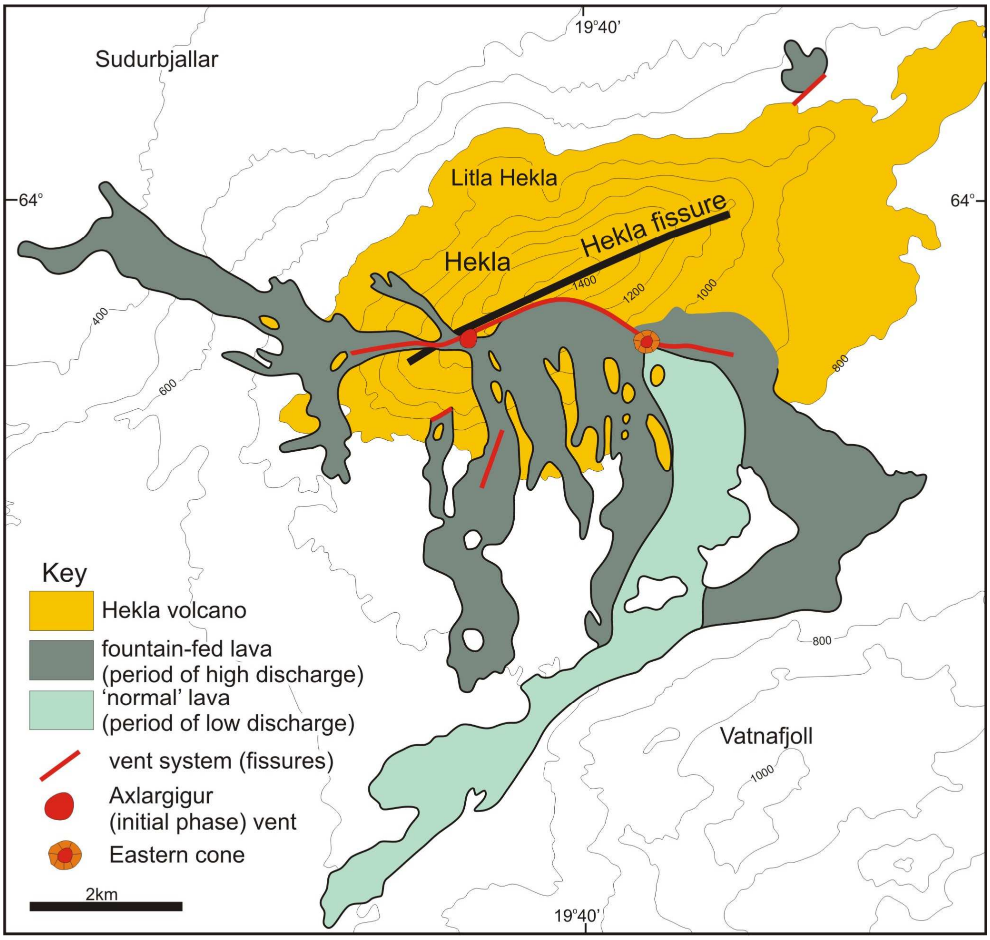

Figure 9. The vent system and lava flows formed in the eruption of Hekla in 1991. (From Thordarson and Larsen, 2007. P 135).

Lahars are a mixture of volcanic debris and water flowing down the slopes of volcanoes and which often follow a volcanic eruption where pyroclastic density currents had been produced (Lavigne and Thouret, 2000). Lahars can be mudflows, with a sediment concentration of 20 – 60% by volume; or debris flows, where the sediment concentration is often greater or equal to 60%

volume (Lavigne and Thouret, 2000). Both types contain so much rock that the internal strength would be sufficient to rip apart constructions. Lahars flow in pulses (as a surge or series of surges) driven by gravity, and their speed and discharge overpass greatly that of a common stream flow and the sediment transport capacity is quite big due to buoyancy, dispersive pressure and amount of cohesive clay and silt (Lavigne and Thouret, 2000). An extreme example in recent events is the lahar that destroyed a town (Armero) and killed more than 20.000 people in central Colombia in 1985 following a small volcanic eruption in the Nevado del Ruiz volcano.

Jökulhlaups, on the other hand, are glacial outburst floods produced more often by water dammed under a glacier that is released suddenly, producing high discharge rates. The common mechanism driving the jökulhlaup results from water accumulating for a certain amount of time in a depression or even a lake under a glacier. The origin of the melting of water in most of the cases is due to subglacial geothermal activity continuously melting the ice, the water accumulates in a subglacial lake and is then drained out (Gudmundsson et al., 2008). Evidence of the impact of jökulhlaups can be found on most of Iceland's south and southeast coast (especially areas close to Mýrdalsjökull and Vatnajökull), where the landscape has been reshaped and land even extended into the ocean by numerous jökulhlaups.

Hekla nowadays possesses two small glaciers on the NW slope (Fig. 10), which have retreated a great deal since the beginning of the 20th century (Hjartason, 1995). Helgi Pjeturss and Guðmundur Kjartansson were two of the first people to describe and study the glaciers at Hekla in the first decades of the 20th century. Since then not much has been done to study the actual state of the glaciers (Hjartarson, 1995). Descriptions of the glaciers and their location can be found on Hjartarson (1995) and Kjartansson (1945). A map from Landmælingar Íslands from 1986 shows a glacier extending down from the top and passing right north of Lítla-Hekla (to the East) and reaching almost down to Móhnúkar.

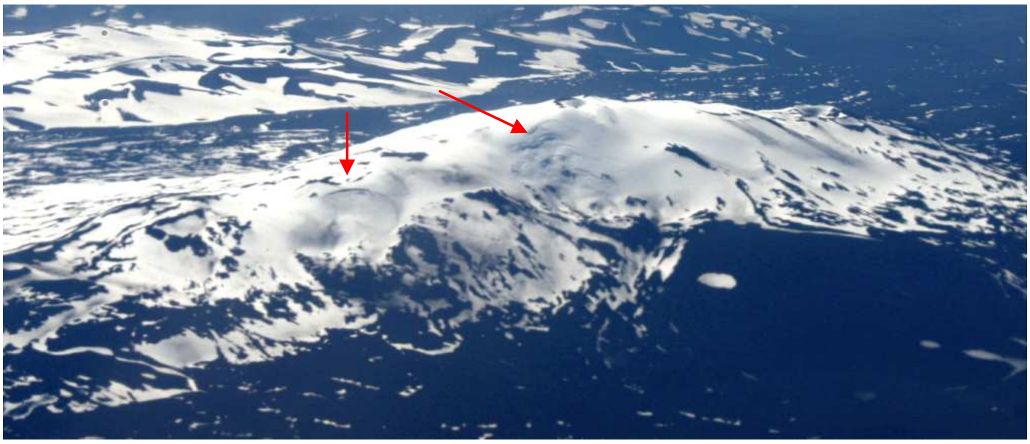

Figure 10. The remaining glaciers at Hekla. The photograph was taken from the North. Photo: Magnús Tumi Guðmundsson, June 2008.

It has been difficult to monitor and measure the production of Lahars or Jökulhlaups at Hekla. Nonetheless, descriptions from the Hekla eruption in 1947 are available. These descriptions were gathered by Guðmundur Kjartansson, where he tries to make a recount on the flood that occurred at the start of the eruption. For his description, he relies on interviews made to the people that live in farms in the area around the volcano. It is essential to remember that there are no major settlements (i.e., towns or villages) around Hekla and the only inhabitants on the area live in scattered farms along the river Rangá (Kjartansson, 1951).

After conducting extensive research, he concluded that the "*Hlaup*" as he calls the event, must have happened only 20 minutes after the onset of the eruption. He assumes also a rapid and extreme melting of the snow and ice that were covering Hekla (or at least part of it), accompanied by a large discharge, all happening in a short period of time (Kjartansson, 1951). Fast and wide melting occurring a few minutes after the beginning of the eruption might support the idea of a lahar produced by pyroclastic density currents. Kjartansson is, however, unable to reach a strong conclusion in his report. Nonetheless, he manages to contribute with discharge measurements. The discharge of this flood was moderate; it measured 123 m^3/s at Hella, located 61 km south of the volcano (Kjartansson, 1951).

As a conclusion, the flood produced in the Hekla eruption in 1947 was in all likelihood produced after pyroclastic density currents rushed down the volcano, melting the snow and ice and mixing with the volcanic products. Kjartansson also mentions that historical records describe similar floods after eruptions at Hekla in 1766 and 1845.

3.2. Secondary Hazards.

There are also other hazards that are commonly taken into consideration. However, they do not apply, or apply in a rather secondary basis at Hekla due to the environment. Some of these other hazards include lightning, which has been observed and reported (Hutchinson, 1983). Earthquakes can be considered a volcanic hazard but in an indirect way since the magnitude of volcanic earthquakes is commonly not large enough to cause extreme damage (Guðmundsson et al., 2008). However, seismic activity could trigger landslides or mass movement that in a way could become dangerous as well for tourists.

3.2.1 Volcanic gases.

Volcanic gases represent a serious threat associated with volcanism, however, danger due to volcanic gases at Hekla has not been reported to affect humans and poisoning has been limited to livestock and fish. Several different types are found at volcanoes, however, they occur at varying rates and concentrations. Volcanic gases include: Carbon dioxide (CO_2), which is heavier than air and thus sinks and accumulates in lower areas. For this reason, in the event of strong gas activity people are advised to avoid depressions, such as holes, etc. Excess concentrations of CO_2 can cause dead to fish in lakes, rivers or creeks after an eruption (Sigurðarson, S. from

Matvælastofnun[2]). Another common gas is Hydrogen sulfide (H_2S), which has a very characteristic smell (like rotten eggs). It is very toxic for humans in large concentrations. However, at large concentrations, when it has become life threatening, the smell is not perceived anymore (Sigurðarson, S. Matvælastofnun[2]). Other poisonous gases that could be produced by a volcano are Hydrochloric acid (HCl), Sulfur dioxide (SO_2) and even Sulfuric acid (H_2SO_4); all are highly corrosive and can cause damage to the skin (Sigurðarson, S. Matvælastofnun[2]).

3.2.2. Fluorine in Hekla's magma.

Tephra fallout can be the cause of a secondary hazard. Ash from Hekla is known to carry fluorine, which has been measured to be between 300 – 4500 ppm in freshly fallen ash (Sigurðarson, S. Matvælastofnun[2]). The fluorine attached to the ash grains can be transferred to crops and water reserves in very little time, leading to contamination that could eventually cause fluorosis (fluorine poisoning). Sigurðarson presents two ways in which a living being could be poisoned with fluorine; one is by respiration and the other is by ingestion. Either way, the fluorine can be transported into the blood and spread throughout the body (Sigurðarson, S. Matvælastofnun – See footnote 2). The effects can be somehow dependent on each individual and do not necessarily need to be the same for animals or people. Common symptoms of fluorosis include damage of the bones, where fluorine reacts with the calcium bonding them together. Additionally, fluorine can cause a depletion of calcium in the blood. If inhaled, it can also cause irritation and inflammation of the respiratory track, leading to very serious lung problems, which could ultimately cause dead. If ingested, it can cause pain, irritation and inflammation of the digestive system causing defecation with traces of blood (also diarrhea). There could also be some damage to the kidneys when fluorine is not evacuated from these organs. Some other characteristics of "short-term" poisoning are drooling, running nose, cough, difficulty of breathing, vision

[2] Report found on the webpage of the Icelandic food and veterinarian authority http://www.lbs.is/Uploads/document/yd_eydublod/ahrif_eldgosa_a_dyr.pdf (last accessed on July 25th, 2010).

deficiency or even blindness, loss of appetite, some degree of paralysis, and loss of conscience (Sigurðarson, S. Matvælastofnun – See footnote 2).

3.3. *Comparison with other volcanoes.*

Volcanism is a worldwide phenomenon, and where there is a volcano, there usually are interesting sites to observe and therefore the area has visitors. The number of people visiting different volcanoes around the world is very variable. Furthermore, there are several areas in the vicinity of a volcano that are fairly populated. Most of the work already done in risk assessment is mainly aimed at preserving life of people in these areas. However, forecasting explosive eruptions for prevention purposes still remains a young science (Baxter et al., 2008). Extensive research and modeling has been carried out to extend the knowledge in order to improve crisis planning and management when volcanoes like Vesuvius, Mount St. Helens, Pinatubo and others enter another unrest period (Baxter et al., 2008).

Yellowstone National Park (Wyoming, USA) is a popular tourist destination, visited every year by ca 3 million people from all over the world. At this site, extensive monitoring is performed with participation of basically every member staff of the park (Christiansen et al., 2007). The reason is that at any moment, depending on the season between 70.000 and 100.000 people could be affected, in the event of a hazardous situation (Christiansen et al., 2007). Nonetheless, it is always emphasized that in a hazardous situation, the event could affect larger areas outside the park boundaries (Christiansen et al., 2007), meaning that more people could be affected, even if the areas around the park are sparsely populated. The biggest towns in the vicinity of Yellowstone National Park are Cody and Jackson Hole, Wyoming, both with a population over 8.000. Gardiner and West Yellowstone, Montana, are located just at the North and Western entrances, respectively. The sum of the population of both towns is about 2000 people. The most common hazards to mitigate at Yellowstone are hydrothermal explosions with at least 26 explosions since the park was formed in 1872 (Christiansen et al., 2007).

Yellowstone is also a very volcanically active area and different types of volcanic eruptions are likely to occur within the park. Estimates of the location and type of eruption have been made. However, accuracy is difficult to estimate due to the long repose times, i.e., no volcanic eruption has occurred in the past 70.000 years in Yellowstone or its vicinity (Christiansen et al., 2007).

In Mount St. Helens (Washington, USA) scientists defined zones of hazard during the volcanic unrest of May 1980; access of public and forestry workers to the areas around the volcano that were more likely to be impacted by pyroclastic density currents and floods (or lahars) was restricted (Baxter et al., 2008). However, this area was far smaller than the actual affected area in the eruption of 1980 (Baxter et al., 2008). On Mount Pinatubo (Philippines), scientists had issued a hazard map, where extreme worst-case scenarios were displayed. Nonetheless, it was also decided to proceed with the evacuation of people who they considered were most at risk. Scientists worked with rescue organisms to help people to evacuate the potentially affected area (Baxter et al., 2008). Luckily, the decision and actions came at the right moment because evidence uncovered later on, showed that the eruption was in fact larger than they had imagined (Baxter et al., 2008).

Mount Ruapehu (New Zealand) shares some similarities with Hekla in the way that both have intermediate lava composition, the periodicity in which it has erupted in the 20th century is also fairly high. Mount Ruapehu is also a popular tourist place and one of the ski locations in New Zealand. Ruapehu has been monitored constantly, especially since the 1996 eruption (Weinstein and Patel, 1997). With the information provided by scientists, the ministry of civil defense classifies the risk and evasive action is followed, according to the status of risk of the volcano (Weinstein and Patel, 1997). However, no real evacuations have been performed for Mt. Ruapehu, rather just closure of the ski fields during the eruption of 1996 (Weinstein and Patel, 1997).

In Iceland two other volcanoes, Eyjafjallajökull and Katla, have been under constant special monitoring, with more particular emphasis on Katla for the potential direct effects that it could have at the South coast including the towns of Vík and Hvolsvöllur (Guðmundsson et al., 2005). A detailed assessment of risk has been made by a group of scientists in Iceland where they list and describe the situation and models for a potential eruption at Mýrdalsjökull (Katla Volcano) or Eyjafjallajökull. Especial attention is paid to the production of Jökulhlaups. Nonetheless, these volcanoes are under constant observation, with measurements of ground deformation, changes in seismic and geothermal activity, etc. (Guðmundsson et al., 2005). Despite this, people in the area seem to live calmly and in special relation with the volcano, despite the fact that in case of an eruption starts showing signs they will have a warning about one (1) hour before the onset (Guðmundsson et al., 2005).

4. Results.

Within the following analysis, a typical Hekla eruption was assumed, with a subplinian to Plinian initial phase lasting at most a few hours, followed by production of lava fountains and eventually to low magnitude Strombolian eruption. The main hazard is associated with the explosive phase (subplinian – Plinian). Despite the severity of most of the volcanic hazards listed above only some of them represent an important direct threat to tourists who are present in the vicinity of Hekla in the moment of an eruption. The hazards were given a level of danger (Table 3) and those with higher level require special consideration due to their severity. Table 2 presents a list and characteristics of the hazards.

Low level of danger means that the probability of being harmed is rather low. Also it means that the specified hazards do not pose an immediate threat to people, unless people are particularly exposed to them. On the other hand High (or very high) levels of danger are given to those hazards that occur in every eruption and that are life threatening to people, and from which the probabilities of survival are very slim, if people are directly exposed.

Based on the assumption that the opening phase will be marked by a Plinian or subplinian type of explosive activity sustained for up to a few hours, followed by production of lava fountains and lava flows, the maps (Figs 11 – 13) show the areas that would be affected by the High danger hazards of tephra fallout, pyroclastic density currents and lava flows within a certain time from the onset of the eruption. These maps are based on the information gathered from observations of eyewitnesses and other scientific documents (Grönvold et al., 1983; Hutchinson, 1983; Hjartarson, 1995; Höskuldsson et al., 2007), compiled in the ArcGIS program. When producing the maps and calculating the information, finer details, such as the effects of terrain are not explicitly taken into account, but indirectly they do since the mountain's shape and form affect the definition of hazard zones.

Table 2. Table of the main Hazards at Hekla and their swiftness.

Type of Hazard	Occurrence	Level of Danger	Onset after eruption	Speed	Duration	Reach
Earthquakes / Seismic Tremor	Always	None - Low	Precursors, between 23 – 80 min. before eruption.	—	Throughout the eruption	—
Lightning	Rare	Low - Medium	Associated with production of tephra. 10 – 60 min[1]	—	—	—
Tephra fallout	Always	Medium - High	10 – 60 min depending on distance from the source. [1, 2]	Transported ~ 45 – 70 km/h. [2, 9]	~ 2 hours [2] ~ 5-6 hours but the bulk falling in the first 2 hours [9]	Depending on wind conditions, it could reach ~330 km in 5 hours [3]
Ballistic fallout	Always	High – Very High	Few minutes after the onset of eruption. [5]	—	—	>5 km [11]
Pyroclastic density currents	Very Often - Always	Very High	Few minutes after the onset of eruption. [5]	>80[7] – 360[1] km/h.	A few seconds. [1]	~ 3 – 4 km. [5]
Lava flows	Very Often - Always	High	~ 3 min – 1 hour. [5, 9]	Depending on the slope. ~ 1 – 10 km/h. [6]	Several days or even months. [2, 5]	Max. extent of historical lavas: ~10 km from the source.
Lahars (or Jökulhlaup)	Often – Very often. [4]	Medium – High	Few minutes after the start of the eruption. [1, 4] ~ 20 min after the onset of eruption. [4]	~ 25 km/h. [8, 9]	Depending on volume of water but it has been documented ~ 1 – 1.5 h. [4]	Approx. 60 km in the first hours. But confined to channels[4]
Gas poisoning	Often	Low to humans – High to animals. [10]	First hours after the eruption, related to tephra fallout. [10]	—	Depending on weather conditions and precipitation.	Depending on weather conditions.

References on Table 2:

1) Hutchinson, 1983.
2) Gudmundsson et al., 1992.
3) Larsen et al., 1992.
4) Kjartansson, 1949.
5) Höskuldsson et al., 2007.
6) http://volcanoes.usgs.gov/hazards/lava/index.php (Accessed 04FEB10).
7) http://volcanoes.usgs.gov/hazards/pyroclasticflow/index.php (Accessed 20FEB10).
8) http://volcanoes.usgs.gov/hazards/lahar/ruiz.php (Accessed 04FEB10).
9) Grönvold et al., 1983.
10) Williams-Jones and Rymer on Encyclopedia of Volcanoes, 2000.
11) Hurtado and Cortes, 1997.

Table 3. Definition of Levels of Danger

Low	Little possibility of death or serious injuries
Medium	Considerable possibilities of death or serious injuries
High	Death or serious injuries more likely if people are directly hit.
Very High	Likelihood of Death is high if people are directly hit.

Fig. 11 shows the total area that can theoretically be affected by pyroclastic density currents produced by volcanic column collapse within 5 minutes from the onset of an eruption, estimated from observations and reports of recent eruptions. The impact of pyroclastic density currents will be mostly confined to the volcanic edifice and lower slopes, about 5 km away from the main volcanic foci on top of the mountain. Note that a great part of the walking path leading up the mountain from Skjolkvíar (the location of the parking lot) falls under this area. Pyroclastic density currents can be deadly, not only because of the speed they can reach (commonly >80 – 360 km/h) and their composition, but also for the temperatures of the cloud (>300°C) (Baxter et al., 2008). Pyroclastic Density Currents can be expected to occur any time during the explosive phase.

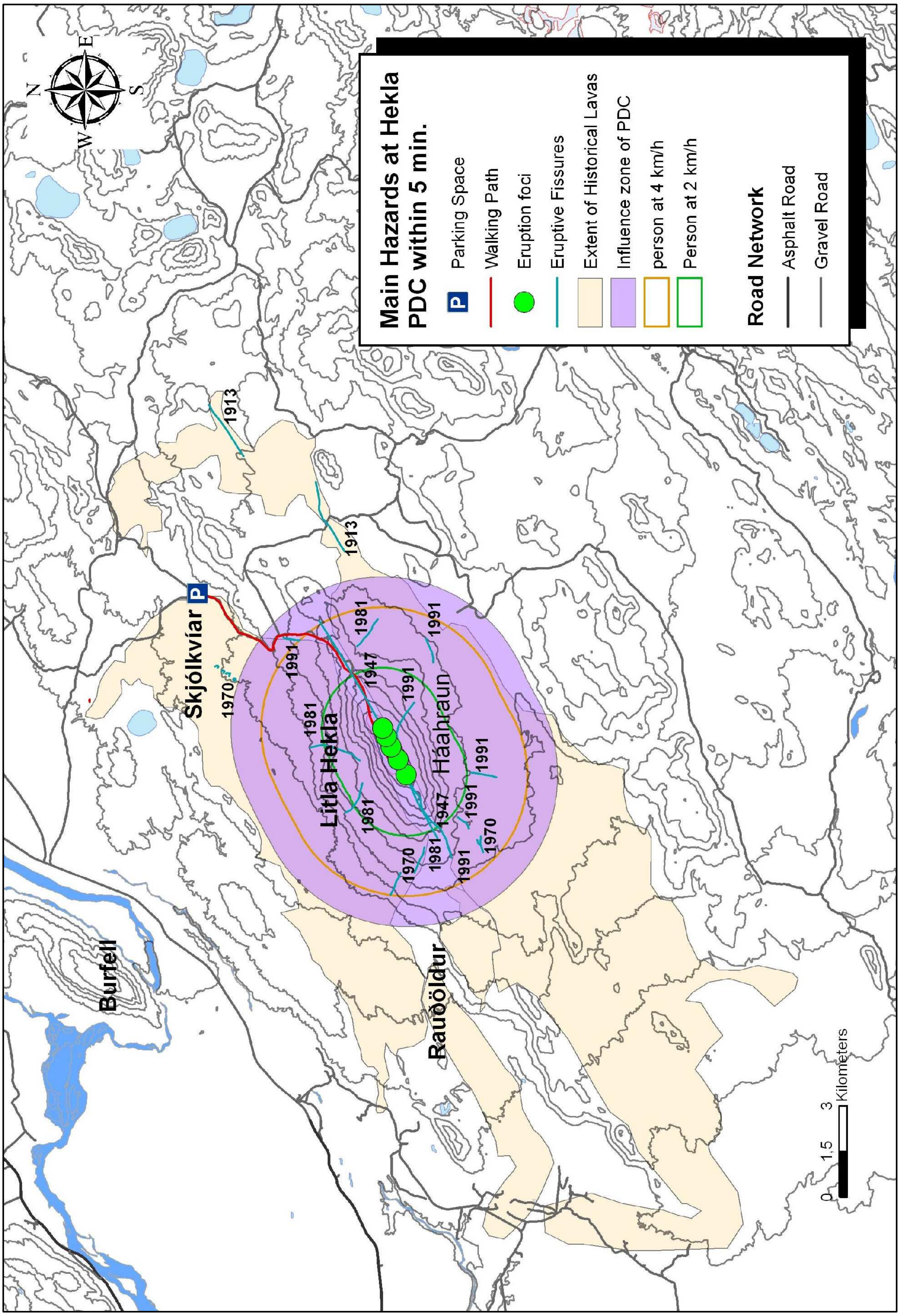

Figure 11: *Area that could be affected by Pyroclastic Density Currents (PDC) within the first 5 minutes after the onset of the eruption. Also, the distance covered by people descending from the ridge of Hekla after one hour assuming two different speeds (2 and 4 km/h).*

Fig. 12 shows the area that can potentially be affected by tephra and ballistic fallout approximately 10 minutes after the onset of the eruption. Once again, estimations have been made from the observations and studies made on recent eruptions. There are several aspects that make these phenomena quite dangerous, e.g., of being hit by a rock fragment (ballistic impact) or inhale the ash particles. Note how spread the cloud could be in such a short time. Fallout in the proximal areas can be quite considerable (tens of centimeters) and could last for a few hours. It will be accompanied by ballistic fallout, most likely including lithic fragments. This phenomenon is highly dependent also in wind direction, so people caught on the volcano should be advised to pay attention to the wind trajectory to avoid trying to escape in the downwind direction.

Fig. 13 shows the area marking the potential maximum reach of lava flows within 10 minutes after the flow of lava starts, estimated from reports of recent eruptions. The onset of lava formation could occur ~3 to 60 minutes after the start of the eruption. One of the most dangerous events during this stage is the formation of eruptive fissures because it commonly happens quickly and it cannot be established by monitoring measurements where exactly or which fissures will open first or which trend they are going to follow. Nonetheless, commonly the first fissure to open is the main eruptive fissure crossing Hekla including part of the summit. Most of the lava formation happens at these eruptive fissures. Thus, any tourist being near by a forming or eruptive fissure can be at risk of being burnt.

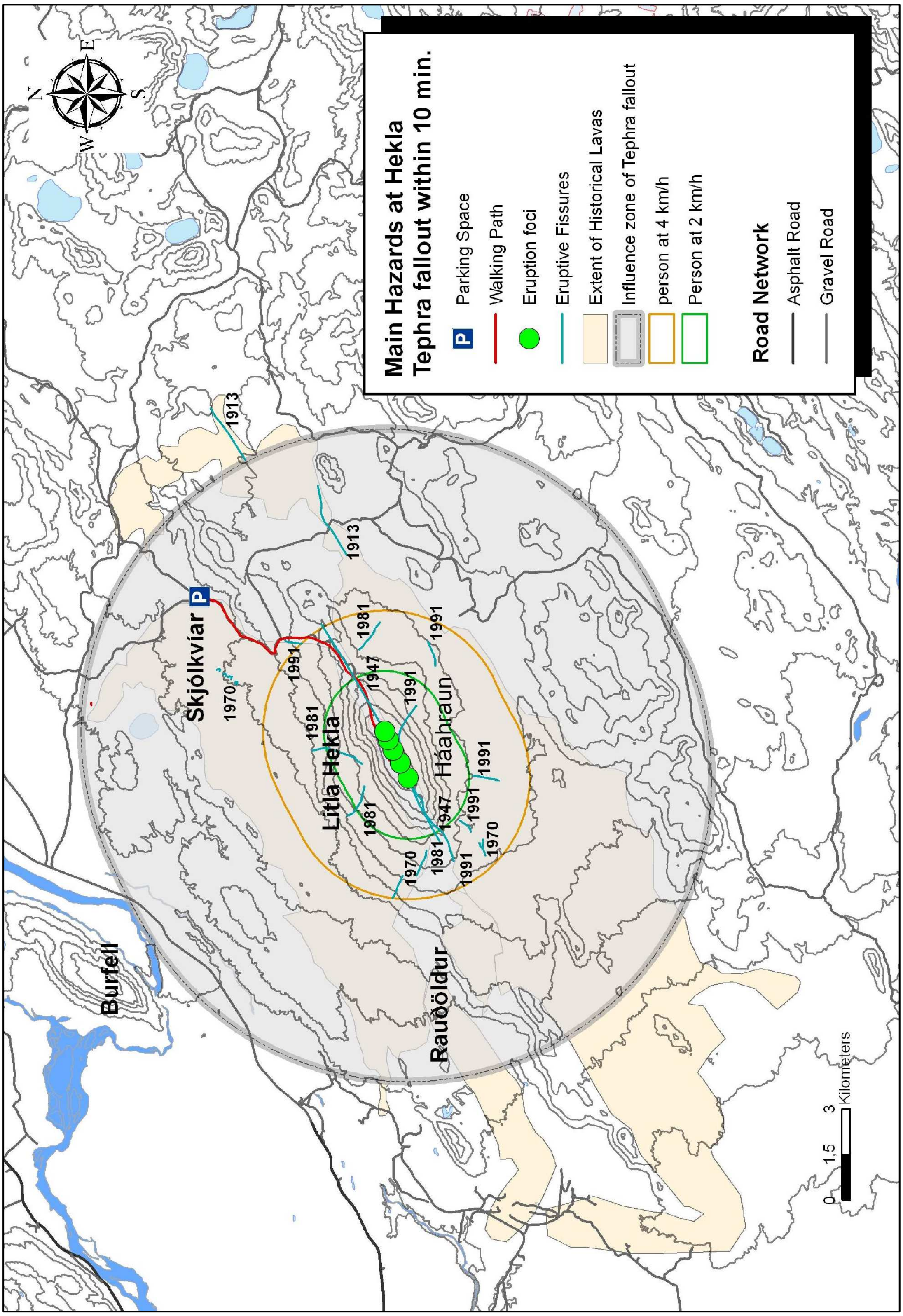

Figure 12: *Hazard map for tephra fall showing the area that would be most likely affected by tephra fallout within 10 minutes from the onset of the eruption. Also, the distance covered by people descending from the ridge of Hekla after one hour assuming two different speeds (2 and 4 km/h).*

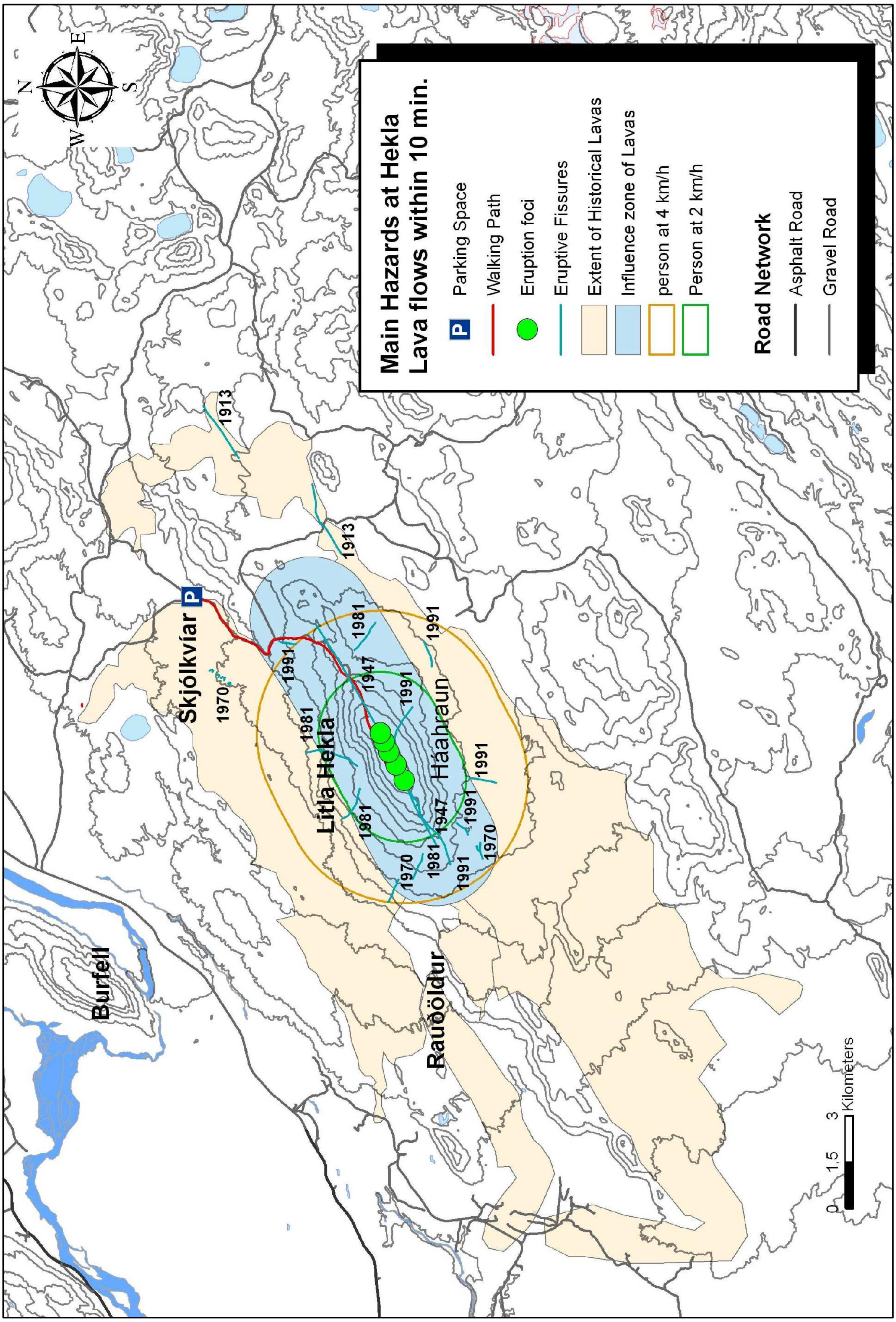

Figure 13: Hazard map for lava flows showing the maximum reach of lavas ~10 minutes after onset of lava formation. Lava production can start ~3 – 60 minutes after the eruption starts. Also, the distance covered by people descending from the ridge of Hekla after one hour assuming two different speeds (2 and 4 km/h).

4.1. Suggestions (Mitigation)

Hekla as a volcano needs to be taken seriously and full attention should be paid in order to ensure the security of people traveling to or through the areas impacted by eruptions. One of the least expensive mechanisms to increase awareness and prevention of volcanic disasters might be the handling of information. Little effort has been made to inform tourists about the potential danger present in the vicinity of some volcanoes in Iceland. It is true that civil protection organisms do their best to advert people from visiting high-risk areas and still people go. Nonetheless, it is believed that this is the result of poor exchange of information between the "transmitters" (i.e., tourist providers, civil protection, etc.) and the "receptors" (i.e., tourists).

Several methods have been proposed in order to keep a specific state of alert in the mountain but costs and maintenance are a further issue. However, constant monitoring is kept by the Veðurstofa (Icelandic Meteorological Institute) with the seismic and strain meter network around the area. Additionally, a webcam has recently been put into function at Búrfell, which points directly to the volcano (Images from this webcam can be seen at www.ruv.is/hekla/). Moreover, for monitoring purposes and also for gaining information, it is also possible to follow the activity on the Icelandic Meteorological Institute's webpage (vedur.is).

Systems to alert about the imminence of an eruption in the area of the volcano have been also proposed and it is believed that these proposals should not be entirely disregarded. One of the systems suggested here consists of a series of sirens positioned along the main trails that lead to the summit of Hekla. There might be factors that point to the inefficiency of this system such as the weather; in bad weather conditions, e.g., fast winds and possibly rain or a combination of both, the sirens are not likely to be heard.

What's more, Sigurður Harðason, an electrician from Kópavogur (capital region, Iceland), suggested a system consisting of blinking lights to warn the tourists in case of unrest in the volcano. However, once again adverse climatic conditions make this system likely not to be efficient; some of those conditions could be fog, for example. Furthermore, in order to install these systems there should be a union or company willing to cover the charges of installing and maintenance. Another suggestion was, with the aid of the Icelandic phone companies, to locate and send a short message (sms) to all the mobile phones located in the area of Hekla to alert them to the unrest in the volcano. However, it is possible that the telecommunication system might fail due to oversaturation of the network (Bird et al., 2010).

For example, in Katla, which is another quite active volcano in the southern region of Iceland and which represents a serious threat as well, many measures have been taken in order to advise the tourists visiting the area (including Þórsmörk), on the west side of the volcano. One of the differences between locations, i.e., between the area around Katla and Hekla is the number of people that might be affected.

On one hand, around the area where Katla is located there are more inhabitants than around Hekla, not only people living in farms but also towns or villages such as Vík í Mýrdal (Population ca. 300). On the other hand, Þórsmörk is a very popular hiking and camping destination, especially during the summer months. The exact number of tourists is also hard to estimate, especially those coming for just one day. During the summer, wardens are stationed in mountain huts in the area. Some of their responsibilities is to manage accommodation facilities and to warn tourists in the event of an eruption in Katla, e.g., they have been instructed and trained to fire flares and warning maroons, which at the moment are the only mean to alert that an eruption has started (bird et al., 2010).

Eruption Emergency Guidelines are available for Katla in a pamphlet with detailed information about the volcano and the potential crisis, along with the phenomenon and nature of the danger. Also, It has a fairly detailed description on the procedures to follow in the event of an eruption. It is also available in different languages (Icelandic, English, French, German, Danish and Spanish).

A similar pamphlet can be made out for Hekla, with a short description of the mechanisms of eruption, putting special emphasis onto the explosive character at the onset of the eruption and the fact that warning signals are given just shortly before the onset. Also, a description of the main hazards, their level of danger and effects, along with a map showing the total areas that could be affected by those hazards. As for example, in Fig. 14.

Furthermore, hazard and emergency response information signs have been located in mountain huts and key points along hiking trails (Bird et al., 2010). These information signs include short information on Katla along with the products and characteristics of the eruptions, a hazard map of the area showing which are the areas of higher risk of jökulhlaups, and a short description of the procedures that should be followed when an eruption occurs. It is also pointed out to the radio stations that most likely will give information on the events. Additionally, these information signs are presented in 6 languages (Icelandic, English, French, German, Danish and Spanish).

This sort of information signs would be useful also for Hekla using similar components. As an example, for Katla the best assessed hazards are jökulhlaups, which are fairly rare at Hekla, thus some of the information that the signs need to contain must be what to do during tephra fallout, for example. The signs somehow should also advice people to keep some masks in their hiking equipment in case they are caught in heavy ash fall. Helmets would also be advisable to be used but not all tourists will be so well prepared. First of all and most importantly, it is important to design a risk plan in order to advise people on what to do and then establish exactly what information should be included in the signs.

It might be possible that with the aid of some stakeholders these brochures and pamphlets can be produced and distributed in places where tourists could stop on the way to Hekla, e.g., gas stations, restaurants, etc. Furthermore, these pamphlets should be available at tourist information offices and hotels, as well as car rental companies, since most of the tourists that visit the area do not go on organized trips, rather on their own (ITB, 2009), and these visitors, in my respect, are the ones who need more awareness and information.

Commonly tourism employees can play an important role in cases of emergency even though they might also lack enough information on the hazards and response procedures (Bird et al., 2010). It is possible that in the event of an eruption, tourists will need to rely on their own. It is not possible to offer drills to know exactly how to react upon an eruption. Nonetheless, adequate dissemination of hazard, risk and emergency response information could improve the preparedness of tourists to deal with volcanic events (Bird et al., 2010). Therefore, it might be useful also to open a visitor center for Hekla, so that information can be given and displayed at all times and where people can refer to in case of doubt.

Furthermore, information signs should be placed at intersections of the routes that lead to Hekla. In some of the areas where people might get a clear view of the volcano and where they could stop for a while to read about the volcano, e.g., as has been done in sites like south Iceland in the area affected by the earthquakes in 2000. But most importantly, signs should be placed in the parking lots at the base of the volcano, to increase the chance that the information will be delivered to the targeted population (Fig. 15).

As mentioned before, it is suggested that these signs (and pamphlets) should contain 1) a map of the area, showing the access routes and some possible or suggested escape routes, 2) the basic information on the mechanisms of the eruption at Hekla, 3) a brief description of the main hazards possible to be encountered at Hekla, 4) a map showing the whole area that could be impacted by the main hazards [such as Fig 14], and 5) a list of radio stations and phone numbers where tourists can receive more information on the on-going eruption. The information in the pamphlets and signs should be translated into several languages, as it has been done for Katla. It could also be ideal if the radio stations would broadcast the information in more than just the Icelandic language.

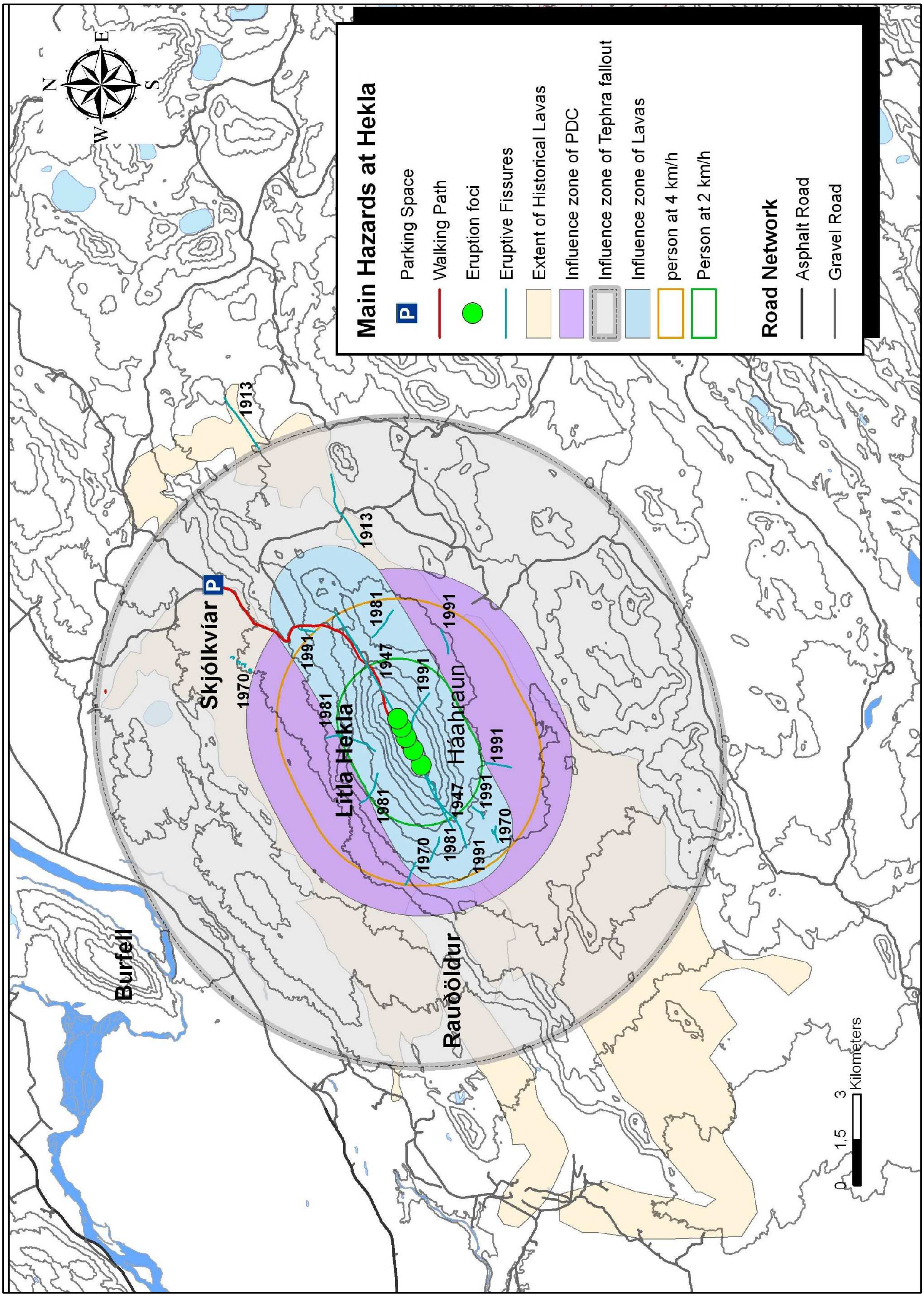

Figure 14. *The area around Hekla that could be affected by all the main hazards defined for this volcano. The influence zone of the hazards is defined within 5 – 10 minutes after the onset of the eruption. This map can serve as an example for information signs and pamphlets.*

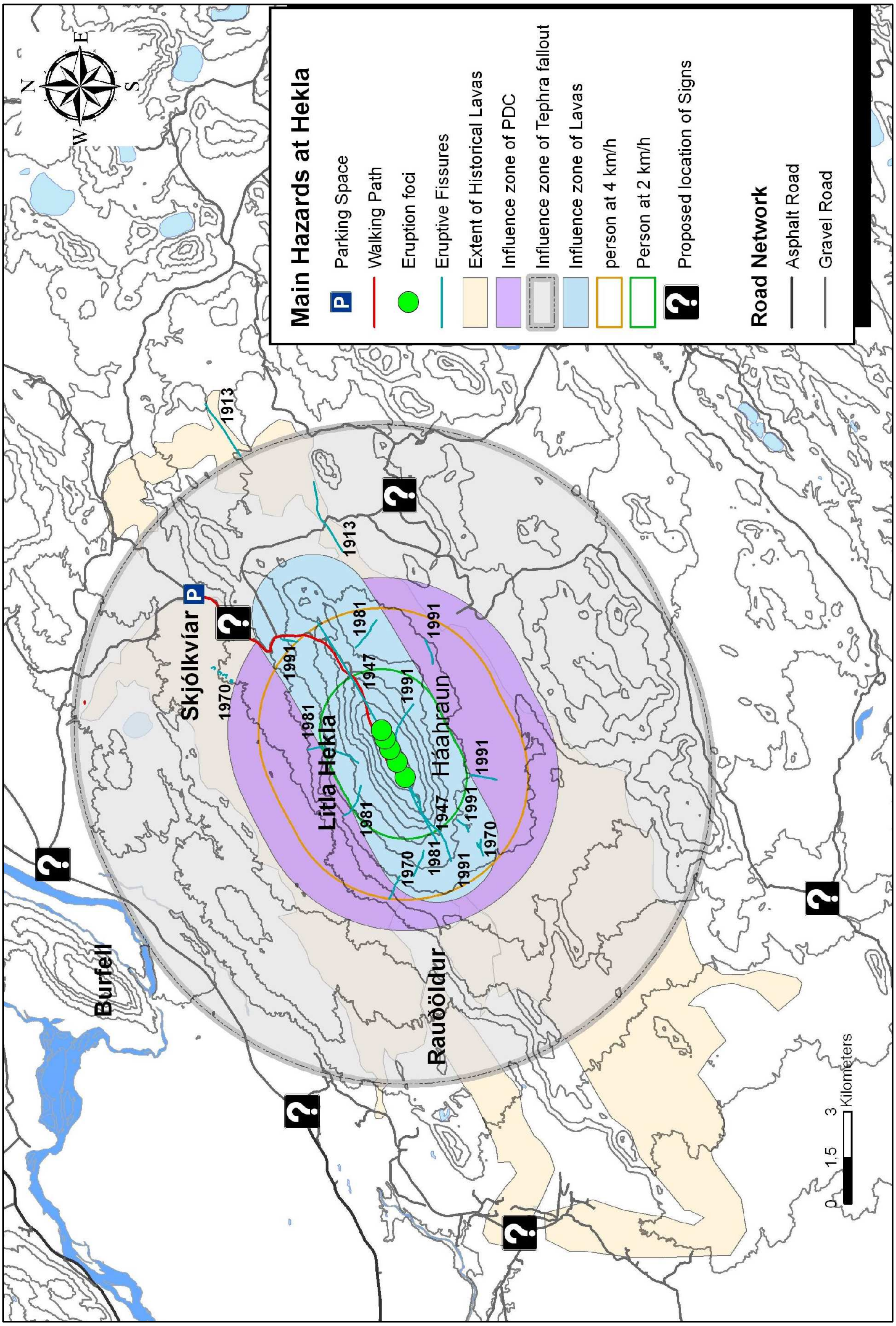

Figure 15. *Map defining the main hazards affecting the area around Hekla and the proposed location of information signs.*

4.2. Dissemination of knowledge on volcanic hazards at Hekla.

There are various ways to achieve effective dissemination of volcanic hazards. One is by compiling documents where people is more involved, i.e., contemplating the possibility of using educational models in order to transmit the information and make people think about the options available in order to create some level of awareness in the targeted group. It is important to understand that it is not possible to educate the tourists prior their arrival, however, it is believed that it is important to make tourist operators more aware of the potential danger at stake in the places they are planning to visit with the tourists. Tour providers need to be more involved in knowing what options are available to spread the relevant information a normal tourist might need in order to enhance his/her chances of escaping unharmed, in case of an emergency.

The information can be passed on in the school for guides (Leiðsöguskólinn) or the multiple training that most providers, including mountain guides, receive regularly. Additionally, they could collaborate to keep that information updated and see how their experience can help to see and put forward that information from different perspectives or approaches. For example, by defining which method might be most successful in increasing awareness and understanding among tourists. How could tourism providers break those pre-judgments that tourists might have about volcanic hazards and that could ultimately blurry the relevant knowledge? Because as Bird et al. (2010) state: “knowledge of a natural hazard does not just include information about the phenomenon and its hazardous processes but also an understanding of the characteristics and behaviour of those processes”.

Furthermore, they can update information posted on the internet, translated into different languages so regular people intending to come to Iceland start getting informed, once again, that information should make people aware, not scare them. This includes that the information has to be prepared from a multicultural perspective, keeping in mind that the potential receivers of that information come from several backgrounds (e.g., different countries in the world and speak different languages), thus in order not to end up averting people from visiting the country, assessment managers need to find what would be the most direct and easiest way for tourist to understand the message they are trying to transmit, in this case, the information on hazards at Hekla.

As mentioned before, the relevant information should also be available at hotels, gas stations and car rental companies, which for example, should be aware and pass the information to the tourists who come seeking for their services. They also should be able to advise on theoretically plausible escape routes, for tourists that get caught up in an eruption.

4.3. Potential scenario.

To give an idea of how volcanic hazard may work for an average tourist, the following scenario is presented to illustrate and reflect upon the need to inform, based on the belief that information might be the most inexpensive way to mitigate the potential threat at Hekla. The intention here is also to make people reflect, and help in the future to come up with more ideas to increase mitigation or preparation for a potential eruption. Of course several questions will remain unanswered on as how to react in the eventual case of being in the mountain during an eruption. Maybe we will have to wait for the next eruption to be able to answer some of them.

Imagine a family that comes for a summer experience here in Iceland. The parents have saved money and take their children to see the nature of Iceland. They come to Reykjavík on a sensational summer: great temperature, acceptable winds and weather conditions. After spending a couple of days in the capital; it is time to pick up the car they have booked many months before, when they were planning the trip.

Once they have hit the road, following the track that they have already set up due South and East. On the plans was a visit the most renowned places of southern and central Iceland, among others Hekla. The family did not receive any special announcement or warning when they rented the car nor at the gas station in Selfoss, where they stopped. With this sense of security and adventure they found their way to Hekla. When they reached Hekla, they realized there were other groups of visitors in the area, for several cars and couple of buses parked at the base of the mountain.

They begin their ascent up to the top, without suspecting that there could be an eruption during their visit. They don't notice any sign advising precaution at the parking lot. They know that Hekla is an active volcano for the stories they have read before. The weather is perfect for photographs, so their ascent is slow; stopping at any chance possible to take pictures and see the lava formations around the mountain.

Couple of hours after they have started their climb they hear a loud bang followed by a roaring sound, pretty much like the jet engine of a plane (Hutchinson, 1983). They noticed that most of the tourists start running down the mountain, when they saw a column of steam rise from the top of Hekla (Hutchinson, 1983). On a natural own-preservation instinct they turn back down. However, a big dark column of material was hanging almost on top of them. It was difficult to judge how big it might have been. In a matter of a few minutes ash starts falling around them along with volcanic bombs. They started to fear because they were still only half way to the parking lot. They felt how their bodies gained weight due to the ash collecting on their clothes (Hutchinson, 1983).

Some more minutes passed and they saw a big and strident mass rushed down the hill, breaking through the clouds and covering the whole slope in a matter of just 10 seconds (Hutchinson, 1983) a few kilometers away from them. Did they have an idea of what this was? They were not much concerned about what it was at that moment, they were more concerned about getting off the mountain and look for shelter.

Suddenly, they noticed a different sound coming from the mountain. The roaring noise had stopped but now there was a rumble accompanied by detonations with a few seconds interval (Hutchinson, 1983). People who were already at the parking lot preparing to leave noticed that there was a red glow coming from the top of the mountain. A few minutes later glowing lava started pouring down the slopes. Luckily, the family made it on time to the car and without any information for escape purposes, they decided just to speed away along the same road that led them there, hoping that it hadn't been blocked by any of the events that they witnessed. They turned on the radio to hear the news and hoping to receive information on what to do, but all they heard was a typical news reporter voice speaking in Icelandic.

The event obviously could not have been prevented, but would this situation have been different if they would have received some information about the mechanics of the volcano, potential danger, etc., e.g., at the gas station in Selfoss? Or if they would have seen a sign presenting the mechanics of the eruptions at Hekla and their products, along with a suggested escape route at the start of the trail leading up Hekla? What if they would have got a text message advising danger 30 minutes before everything started? What if there were some alarms that would have gone off 30 minutes before the eruption? It is my belief that these are some of the points that are necessary to keep in mind. Would these have matter for the tourist family or all the other tourists that were in the area at that moment?

5. Discussion.

Volcanic eruption predictions for disaster mitigation are not very well developed (Baxter et al., 2008) but important improvements have been made and better understanding is being reached. Different countries approach differently the potential disasters, thus the reasons for constant monitoring and the way this is done vary considerably. Another important varying factor is related to the number of people in danger within a certain range from a given volcano. Some volcanoes have a large population in their vicinity posing a big dilemma for authorities and the scientific community. Evacuation plans and volcanic crisis management is also different from country to country. Many aspects are considered when organizing a committee to handle these assessments. Amazingly, most of the decisions fall into the hands of politicians (Baxter et al., 2008; Weinstein and Patel, 1997) thus the question whether other interests (e.g., personal interests) may come into the formula when decision-making arises.

There are several economic factors that affect also the preparation and / or evacuation (if needed) of an area of high volcanic risk. It seems also quite variable the way authorities would respond upon such an event. Prevention is one of the apparent best ways to avoid fatalities, and management and presentation of the information might be one of the best ways to ensure or increase awareness and develop appropriate programs for emergency management, even if this task represents a big challenge (Bird et al., 2010).

Although the total number of people that have perished in volcanic eruptions and volcano-related events is considerable (Gudmundsson et al., 2008), natural disasters have not claimed a big toll in Iceland in recent years. Only two people have died in circumstances related to volcanic eruptions in the last 60 years. The last person to die because of a volcanic eruption died in the eruption in Vestmannaeyjar in 1973, when this person entered and remained in a house where poisonous gases had accumulated. A naturalist perished during the volcanic event of Hekla in 1947, when he was hit by a falling block lava while taking pictures or samples. This lack of dead tally in recent decades makes people somehow rest assure, however, in my opinion the fact that it has not happened yet does not mean it could not occur; and something we have learnt is that volcanoes can still behave with a certain factor of uncertainty.

With increasing tourists visiting the Southern part of Iceland, the risk of consequences on people has also increased; people involved in tourism (including tourists themselves) cannot be oblivious to the potential situation. Relevant information on the mechanisms of eruption for Hekla, potential dangers, impact zones, etc. should be spread, because it is necessary to prepare for future eruptions and the probability of providing total protection to all the tourists that could visit the area is actually not very large for different reasons (Infrastructure, transportation, etc.). Tourists can overestimate their knowledge about hazards and thus overestimate their sense of safety (Bird et al., 2010). Therefore, it is imperative that people (not only tourists but also tourism providers) understand the phenomena and their consequences in order to create a better approach to the information increase awareness of the resources available (Bird et al., 2010) to protect everybody.

For Hekla volcano, one of many popular tourist destinations in Iceland, lack of information for people visiting the volcano seems to be a reality. This could be counteracted among others with more promotion of the monitoring webpages as sources of information (Bird et al., 2010), as well as presenting more of the relevant information in English, e.g., information related to the hazards for a specific area.

Fortunately, no tragedies have occurred in this volcano. Nonetheless, international experience should be taken into account to think that it could actually happen here. Hekla is visited every year by an uncertain number of tourists, and although there are no specific data, according to people working in the area the number could be of hundreds on good summer days. Many tourist operators have ceased organizing tours to Hekla (as of 2010), however, it is still possible to hire some charter services to the volcano. Warnings have been issued about indications that the volcano is entering another unrest period, however, those warnings are not correctly delivered to the public. Apparently there are no information signs in the area or in potential tourist stops close by (e.g., gas stations on the way) alerting people of the nature of the hazard or the consequences. In this regard, it might be useful to establish a well-organized visitor's center, for example in Hrauneyjar or

Selfoss, where one of the main topics is Hekla, and where the information would be distributed to the tourists either by pamphlets, posters or even videos.

Tourist providers could manage information and increase confidence by distributing the information and getting more acquainted with the warning systems and emergency response procedures (Bird et al., 2010). However, most of the people visiting Hekla do not go on guided tours, making them quite vulnerable in not receiving the relevant information. Also, most of the tourists visiting Icelandic locations could be foreigners, thus it would be ideal that at all times the information should be available in more than just the Icelandic language.

Information has to be based on scientific facts but presented from a multicultural perspective in order to ensure that the message will reach all the groups and not just those who can understand the scientific or technical language. This task can be even more complicated if it is considered that tourists come additionally from many cultural, economic and social backgrounds (Bird et al., 2010), making necessary the implementation of multicultural approaches and different approaches to present the same element of danger. For example, some people might be keener to observe pictures and read little text while some others prefer to read a lot. In this case, it is conceivable that both persons receive a similar message about the hazards from these two different methods.

6. Conclusions

Hekla volcano has erupted at least 18 times in historical times. The last eruption was on February 26th 2000. Iceland natural landscapes attract every year a large number of tourists who are looking for adventure. Some of the destinations growing in popularity include active volcanoes. Iceland so far (or at least not in recent years) has not suffered from a volcanic crisis where thousands or hundreds of people have lost their lives; however, Iceland is not exempt to that situation. With increasing number of people visiting active areas and with increasing activity in some areas, e.g., Hekla, the probabilities of having a tourist volcanic crisis are higher than before. Thus attention should be paid to continue monitoring the relationship between volcanism and tourism and, analyze the information in order to have a clearer idea on how to respond.

Predicting a volcanic eruption is still very difficult and it is believed that the best way to avoid crisis is by informing and preparing the people to identify and face the hazards that are likely during a volcanic eruption at Hekla volcano. One of the outcomes of this study was the definition of the main hazards at Hekla. A hazard map has been made defining the potential risk areas during the beginning of a typical Plinian or subplinian Hekla eruption. These hazards and their potential reach in the first 5 – 10 minutes of an eruption are:

1. Pyroclastic density currents (PDC), reach 5 km.
2. Tephra fall, including ballistics, reach of tephra ~ 10 km.
3. Lava flows, reach 2 km.

Better information should be put in place, not only around Hekla but also for other volcanically active areas that are commonly visited by tourists. Katla is a good example for the extensive studying that has been carried out there. There are important differences between the two volcanoes, nonetheless, what has been done at Katla (e.g., erecting information signs, preparing emergency guidelines and trying to assess the education of people towards volcanic hazards n the tourist destinations around Katla), could work as a guideline for Hekla.

Promoting and implementing the information on the Internet might be an invaluable starting tool. As pointed out by Bird et al. (2010) “good education campaigns stimulate people to ask further questions and search for more knowledge”. Such knowledge should be aimed to increase an appropriate response in the event of a volcanic eruption or if a warning is issued (Bird et al., 2010).

Strategies should be made to expand knowledge and distribute the information about volcanic hazards at Hekla among the tourists. Tourist providers need to be more involved in the security of their employees and the people they serve.

It might also be useful to assess the knowledge of volcanic hazards among the people visiting the area, as it has done for example around Katla (Bird et al., 2010). This could open a new window in how to improve the transmission of the information; as Bird et al. (2010) say: “risk mitigation efforts must incorporate the human dimension of risk alongside the physical assessment of volcanic hazards”. Furthermore, information collected here, the maps and tables produced and some of the ideas might be of help to the pertinent organisms for producing evacuation plans and risk mitigation strategies relevant to Hekla and its surroundings.

Finally, as a conclusion of this study it is shown that it is necessary to adopt measurements in order to prevent a serious situation at Hekla. Tourism cannot be stopped and people need to increase their awareness, in order to increase their chances of survival in the event of an emergency. It is important to organize a way to produce and erect information signs around Hekla, at the parking space, in the hiking trail leading up the mountain. It is also necessary to produce pamphlets and distribute them, making them available in several potential tourist stops on the way to Hekla but also in hotels, tourist information offices, car rentals, etc.

References

Ásgeirsson, P. Á. Hálendishandbókin, ökuleiðir, gönguleiðir og áfangastaðir á hálendi Íslands. Önnur útgáfa. 2004.

Baxter, P.J.; Aspinall, W.P.; Neri, A.; Zuccaro, G.; Spence, R.J.S.; Cioni, R.; Woo, G. Emergency planning and mitigation at Vesuvius: A new evidence-based approach. Journal of Volcanology and Geothermal Research 178 (2008) 454 – 473.

Bird, D.K.; Gisladottir, G.; Dominey-Howes, D. Volcanic risk and tourism in southern Iceland: Implications for hazard, risk and emergency response education and training. Journal of Volcanology and Geothermal Research 189 (2010) 33 – 48.

Christiansen, R.L.; Lowenstern, J.B.; Smith, R.B.; Heasler, H.; Morgan, L.A.; Nathenson, M.; Mastin, L.G.; Muffler, L.J.P.; Robinson, J.E. Preliminary assessment of volcanic and hydrothermal hazards in Yellowstone National Park and vicinity. (2007) U. S. Geological Survey Open-file Report 2007-1071, 94 p.

Frampton, S.; Chaffey, J.; Hardwick, J.; McNaught, A. Natural Hazards. 2nd. Edition. Hodder & Stoughton. London. 2000.

Francis, P. Volcanoes. A Planetary Perspective. Oxford University Press Inc. New York, NY. USA. 1993.

Grönvold, K.; Larsen, G.; Einarsson, P.; Thorarinsson, S.; Sæmundsson, K. The Hekla Eruption 1980 – 1981. Bull Volcanol (1983) 46: 349 – 356.

Gudmundsson, A.; Oskarsson, N.; Grönvold, K.; Sæmundsson, K.; Sugurdsson, O.; Stefansson, R.; Gislason, S.R.; Einarsson, P.; Brandsdottir, B.; Larsen, G.; Johannesson, H.; Thordarson, Th. The 1991 eruption of Hekla, Iceland. Bull Volcanol (1992) 54: 238 – 246.

Guðmundsson, M.T.; Elíasson, J.; Larsen, G.; Gylfason, Á.G.; Einarsson, P.; Jóhannesson, T.; Hákonardóttir, K.M.; Torfason, H. Yfirlit um hættu vegna eldgosa og hlaupa frá vesturhluta Mýrdalsjökuls og Eyjafjallajökli. In Hættumat vegna eldgosa og hlaupa frá vestanverðum Mýrdalsjökli og Eyjafjallajökli. Ríkislögreglustjórinn. Háskólaútgáfan. 2005.

Guðmundsson, M.T.; Larsen, G.; Höskuldsson, Á.; Gylfason, Á.G. Volcanic hazards in Iceland. Jökull. No. 58. Pg. 251-168. 2008.

Hjartarson, Á. Á Hekluslóðum. Árbók ferðafélags Íslands. 1 – 236. 1995.

Horwell, C.; Baxter, P. The health Hazards of volcanic ash. A guide for the public. Booklet found on the International Volcanic Health Hazard Network (IVHHN) webpage (http://ivhhn.org/ - Observed last on 24th of January 2010).

Hurtado, A.D.; Cortes, G.P. Third version of the hazard map of Galeras Volcano, Colombia. Journal of Volcanology and Geothermal research. 77 (1997) 89 – 100.

Hutchinson, I. P. Upphaf eldgossins í Heklu 1980. Náttúrufræðingurinn. 52 (1 – 4), bls. 175 – 183. 1983.

Höskuldsson, Á.; Óskarsson, N.; Pedersen, R.; Grönvold, K.; Vogfjörð, K.; Ólafsdóttir, R. The millennium eruption of Hekla in February 2000. Bull Volcanol (2007) 70: 169-182.

Icelandic Tourist Board. Report: Tourism in Iceland in Figures. October 2009.

Jakobsdóttir, S.S. Seismicity in Iceland: 1994 – 2007. Jökull. No. 58. Pg. 75 – 100. 2008.

Kjartansson, G. Hekla. Árbók ferðafélags Íslands. 1 – 155. 1945.

Kjartansson, G. Water floods and mudflows. In Einarsson, T.; Kjartansson, G. and Thorarinsson S. eds. The eruption of Hekla 1947 – 1948. Vísindafélag Íslendinga. Reykjavík. 1951.

Lacasse, C.; Karlsdóttir, S.; Larsen, G.; Soosalu, H.; Rose, W. I.; Ernst, G. G. J. Weather radar observations of the Hekla 2000 eruption cloud, Iceland. Bull Volcanol (2004) 66: 457 – 473.

Landmælingar Íslands. (1986) Uppdráttur Íslands, blað 57, Hekla. Staðfræðikort 1:100.000. Reykjavík. Landmælingar Íslands.

Larsen, G.; Vilmundardóttir, E.G.; Þorkelsson, B. Heklugosið 1991: Gjóskufallið og gjóskulagið frá fyrsta degi gossins. Náttúrufræðingurinn 61 (3 – 4), bls. 159 – 176, 1992.

Larsen, G.; Eiríksson, J. Holocene tephra archives and tephrochronology in Iceland – a brief overview. Jökull. No. 58. Pg. 229-250, 2008.

Lavigne, F.; Thouret, J.C. Lahars: deposits, origins and behaviour. Bulletin de la societe geologique de France. (2000) Vol. 171, Issue: 5, pg: 545 – 557.

Linde, A. T.; Agustsson, K.; Sacks, I.S.; Stefansson, R. Mechanism of the 1991 eruption of Hekla from continuous borehole strain monitoring. Nature: Oct 21, 1993; 365: 737 – 740.

Sigmarsson, O.; Condomines, M.; Fourcade, S. A detailed Th, Sr and O isotope study of Hekla: differentiation process in an Icelandic Volcano. Contrib Mineral Petrol (1992) 112: 20-34.

Sigurðarsson, S. Áhrif eldgosa á dýr. Report initially written for the Icelandic Food and Veterinarian authority (Matvælastofnun), however, found on the webpage of the National Commissioner of the Icelandic Police, Civil protection department: Information on natural hazard due to Hekla volcano (http://www.almannavarnir.is/displayer.asp?cat_id=260).

Soosalu, H.; Einarsson, P. Seismic constraints on magma chambers at Hekla and Torfajökull volcanoes, Iceland. Bull Volcanol (2004) 66: 276 – 286.

Soosalu, H.; Einarsson, P.; Jakobsdóttir, S. Volcanic Tremor related to the 1991 eruption of the Hekla volcano, Iceland. Bull Volcanol (2003) 65: 562-577.

Thorarinsson, S. The eruption of Mt. Hekla 1947 – 1948. Bulletin of Volcanology, Vol. 10, Number 1, Pg. 157 – 168, December 1950.

Thorarinsson, S. Volcanic areas of the Holocene (Jarðeldasvæði á nútíma). Náttúra Íslands, 2nd ed. Almenna bókafélagið. Reykjavík, pg. 81 – 119. 1981.

Thordarson, T.; Höskuldsson, Á. Postglacial volcanism in Iceland. Jökull. No. 58. Pg. 197-228. 2008.

Thordarson, T.; Larsen, G. Volcanism in Iceland in historical time: Volcano types, eruption styles and eruptive history. Journal of Geodynamics 43 (2007) 118–152.

Watson, I.M.; Realmuto, V.J.; Rose, W.I.; Prata, A.G.; Bluth, G.J.S.; Gu, Y.; Bader, C.E.; Yu, T. Thermal infrared remote sensing of volcanic emissions using the moderate resolution imaging spectroradiometer. Journal of Volcanology and Geothermal research. Vol. 135, Issues 1 -2, 15 July 2004, Pg. 75 – 89.

Weinstein, P.; Patel, A. The Mount Ruapehu eruption, 1996: a review of potential health effects. Australian and New Zealand Journal of Public Health

1997, Vol. 21, No. 7, pg. 773 – 7.

Williams-Jones, G.; Rymer, H. Hazards of Volcanic gases. On Haraldur Sigurdsson Encyclopedia of Volcanoes. Academic Press. 2000.

United States Geological Survey (USGS) webpage. http://volcanoes.usgs.gov/hazards/pyroclasticflow/index.php (Pyroclastic Flows - Observed last on September 2009).

United States Geological Survey (USGS) webpage. http://vulcan.wr.usgs.gov/Glossary/Lahars/description_lahars.html (Lahars - Observed last on January 23, 2010).

United States Geological Survey (USGS) webpage. http://volcanoes.usgs.gov/hazards/lava/index.php (Volcanic Hazards - Lava Flows - Observed last on February 4, 2010).

United States Geological Survey (USGS) webpage. http://volcanoes.usgs.gov/hazards/lahar/ruiz.php (Volcanic Hazards - Lahars - Observed last on February 4, 2010).