Reviewed research article

Historical lava flow fields at Hekla volcano, South Iceland

Gro Birkefeldt Møller Pedersen[1,2*], Jorge Montalvo[1], Páll Einarsson[1], Olga Kolbrún Vilmundardóttir[3], Friðþór Sófus Sigurmundsson[3], Joaquín Muñoz-Cobo Belart[1,4], Ásta Rut Hjartardóttir[1], Fadi Kizel[5,6], Rose Rustowicz[1,7], Nicola Falco[8], Guðrún Gísladóttir[1,2,3] and Jón Atli Benediktsson[5]

[1]*Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland*

[2]*Nordic Volcanological Center, University of Iceland, Reykjavík, Iceland*

[3]*Institute of Life and Environmental Sciences, University of Iceland, Reykjavík, Iceland*

[4]*Laboratoire d'Etudes en Géophysique et Océanographie Spatiales, Centre National de la Recherche Scientifique (LEGOS–CNRS), Université de Toulouse, Toulouse, France*

[5]*Faculty of Electrical and Computer Engineering, University of Iceland, Reykjavík, Iceland*

[6]*Department of Mapping and Geo-Information Engineering, Technion-Israel Institute of Technology, Haifa, Israel*

[7]*Department of Electrical Engineering, Stanford University, California, USA*

[8]*Lawrence Berkeley National Laboratory, California, USA*

[*]*Corresponding author: gro@hi.is; grobirkefeldt@gmail.com*

Abstract — *Hekla volcano is known to have erupted at least 23 times in historical time (last 1100 years); often producing mixed eruptions of tephra and lava. The lava flow volumes from the 20th century have amounted 80% to almost 100% of the entire erupted volume. Therefore, evaluating the extent and volume of individual lava flows is very important when assessing the historical productivity of Hekla volcano. Here we present new maps of the historical lava flow fields at Hekla in a digital format. The maps were produced at a scale of 1:2000–10000 using a catalogue of orthophotos since 1945, acquired before and after each of the last five eruptions, combined with field observation of stratigraphy, soil profiles, tephra layers and vegetation cover. The new lava flow maps significantly improve the historical eruptive history of Hekla, prior to the 1947 eruption. The historical lava flow fields from Hekla cover ∼233 km^2 and the lavas reach up to 16 km from Hekla volcano. Flow lengths up to 20 km are known, though lava flows only travelled up to 8–9 km from Hekla in the last 250 years. Identified historical vents are distributed between 0 and 16 km from Hekla volcano and vents are known to have migrated up to 5 km away from Hekla during eruptions. We have remapped the lava flow fields around Hekla and assigned the identified flow fields to 16 eruptions. In addition, ca. 60 unidentified lava units, which may be of historical age, have been mapped. It is expected that some of these units are from known historical Hekla eruptions such as the 1222, 1341, 1510, 1597, 1636 and potentially even from the previously excluded eruptions such as 1436/1439.*

Keywords: Hekla volcano, lava flow fields, historical eruptions, tephrochronology

INTRODUCTION

Hekla is one of the four most active volcanoes in Iceland and has erupted ∼23 times since the settlement of Iceland in CE 874 (Thorarinsson, 1967; Larsen *et al.*, 2013). Its activity made a huge impact on the surrounding landscape changing the vegetation patterns, the depositional/erosional environments and affecting the human settlement since the occupation of Þjórsárdalur (Thorarinsson, 1967; Hreiðarsdóttir *et al.* 2015). Farms were abandoned, destroyed or affected during Hekla eruptions by earthquakes, tephra fall or lava flows during CE 1104, 1300, 1389, 1436, 1510, 1693, 1725, 1845 and 1947–1948 eruptions (Thorarinsson, 1967; Dugmore *et al.*, 2007; Hreiðarsdóttir *et al.*, 2015).

Hekla is located in the rift-transform intersection between the South Iceland Seismic Zone, SISZ, and the Eastern Volcanic Zone, EVZ (Figure 1). The bookshelf faults typical for the SISZ extend into the

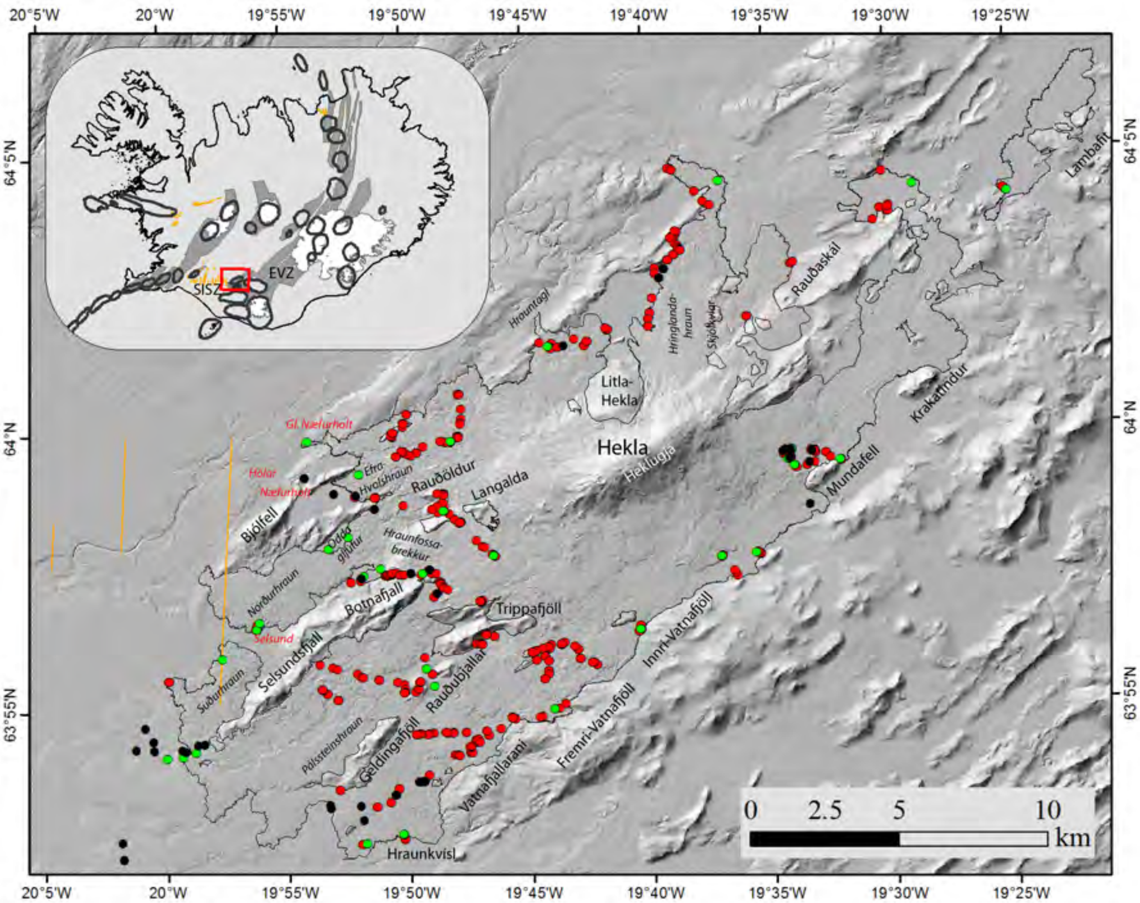


Figure 1. Hekla's historical lava fields (black outline) and local place names. Location of field data: stratigraphic relationships (red), vegetation and soil transects (green) and tephra profiles (black) are shown as dots. Faults are orange. The inset of Iceland shows volcanic systems (fissure swarms in gray, central volcanoes in black and faults in orange) according to Einarsson and Sæmundsson (1987). SISZ and EVZ stands for the South Iceland Seismic Zone and Eastern Volcanic Zone. The red frame denotes the Hekla area. Background shows hillshade from smoothed lidar DEM, with gaps filled with TDX DEM (Pedersen *et al.*, in prep., Rizzoli *et al.*, 2016). – *1. mynd. Hekla og nágrenni. Söguleg hraun eru með svörtum útlínum. Staðsetning mælistaða á vettvangi; jarðlagatengsl (rauðir punktar), gróður og jarðvegssnið (grænir punktar) og öskulagasnið (svartir punktar). Íslandskortið sýnir sprungusveima (dökkgráir flákar), megineldstöðvar (svartir hringir), og aðrar sprungur (appelsínugular línur), samkvæmt gögnum frá Páli Einarssyni og Kristjáni Sæmundssyni (1987). SISZ táknar Suðurlandsskjálftabeltið og EVZ er Austurgosbeltið. Rauði ramminn sýnir staðsetningu stóra kortsins. Hæðarlíkanið í bakgrunni er samsett úr lidar og TDX gögnum (Pedersen o.fl., í vinnslu; Rizzoli et al., 2016).*

region south of the Hekla volcanic system, and have been responsible for significant earthquake activity in the area with a M7 as its most recent major event in 1912 (Bjarnason *et al.*, 1993; Soosalu and Einarsson, 2005; Einarsson, 2015). The architecture of Hekla volcanic system features a fissure swarm and a central volcano, which are the two principal components characterizing volcanic systems in Iceland (Jakobsson, 1979b; Saemundsson, 1978). The fissure swarm extends 60 km SW-NE and is mainly defined by Holocene vents and steep-sided subglacially erupted hyaloclastite ridges, whereas only few grabens can be found. The central volcano is superimposed on the basaltic basement and includes a 5–6 km elongated, steep-sided ridge, which is oriented parallel to the fissure swarm and rises 700–800 m above the surrounding lava plains reaching an elevation of 1490 m a.s.l. This elevation varies temporally due to volcanic eruptions creating and destroying vents and thereby modifying the topography along the main fissure (Heklugjá), which historically has been described to split the ridge during eruptions. The vents during the 20th century had more complex opening than a single fissure splitting the ridge in two (Larsen *et al.*, 2013) and we therefore refer to vents on Hekla ridge, rather than Heklugjá since exact locations of vents during historical times are mostly unknown.

In Holocene times Hekla's activity has been typified by its mixed eruptions initially producing explosive sub-plinian to plinian phase that result in tephra deposits followed by fire fountaining, strombolian activity and typically ending with an effusive phase producing lava (Thorarinsson, 1950; 1967; Thordarson and Larsen, 2007; Höskuldsson *et al.*, 2007).

The composition of eruptive products at Hekla central volcano ranges from basaltic andesite to rhyolitic (SiO_2∼53%–75%), while the fissure swarm erupts basalt (SiO_2∼46%–49%) (Thorarinsson, 1967; Jakobsson, 1979a; Sverrisdóttir, 2007; Thordarson and Larsen, 2007). Since the geochemistry of the lavas from the fissure swarm is substantially different from Hekla central volcano it has been argued that the fissure swarms are fed directly by a deeper source below the fissures themselves, while Hekla central volcano is fed from a shallower, zoned magma reservoir resulting in chemically zoned eruptions (Thorarinsson, 1967; Gudmundsson *et al.*, 1992; Sigmarsson *et al.*, 1992). The degree of chemical variability has been shown to depend on the length of the preceding repose period, making the initial eruptive product more evolved after a long repose period than a short period (Thorarinsson, 1967; Sigmarsson *et al.*, 1992). However, this classical model of vertical feeding of the eruptions on the fissure swarm is challenged by data from recent events. First of all, the magma chamber under Hekla appears to be at depths exceeding 10–15 km (Sturkell *et al.*, 2013; Geirsson *et al.*, 2012; Ófeigsson *et al.*, 2011) based on the source of pressure variations during last eruptions. This is in accordance with wave propagation studies beneath Hekla which failed to show evidence for a substantial, shallow level magma chamber (Soosalu and Einarsson, 2004). Secondly, the Eyjafjallajökull 2010 eruption showed that both basaltic eruptions on the flank and more evolved magma at summit eruptions can be centrally fed (Sigmundsson *et al.*, 2010). Both Krafla 1975–1984 (e.g., Buck *et al.*, 2006) and Bárðarbunga 2014 (Sigmundsson *et al.*, 2015; Guðmundsson *et al.*, 2016) showed clear evidence for lateral propagation of basaltic dikes from the central volcano into the fissure swarms. It therefore seem very likely that basaltic fissure swarms of Hekla could be centrally fed from a density stratified magma system beneath the main edifice.

In Hekla eruptions during the 20th century the lava flow volumes make up between 80–100% of the entire erupted volume (Pedersen *et al.*, 2018) indicating that lava yield is very important for assessing the productivity of the Hekla volcano. However, there are few studies focused on the effusive history of Hekla, and few attempts have been made to provide a detailed map of the historical activity (Kjartansson, 1945; Thorarinsson, 1967; Jakobsson, 1979a; Montalvo, 2013; Kaldal *et al.*, 2018). This maybe due to the inaccessibility of the lava fields, the high resurfacing rates making the lava mapping a non-trivial task and the challenge to determine the ages of the lava flow fields.

We present new maps of historical lava fields of Hekla using a temporal archive of remote sensing data stretching back to 1945, allowing observations of the flow fields before and after the five latest eruptions (1947–1948, 1970, 1980–1981, 1991, 2000). These data, in combination with field observations of stratigraphy, soil profiles, tephra layers and vegetation cover have allowed significant improvement in the map of historical eruptive activity of Hekla.

It is the hope that this historical lava flow map in a digital format will serve as basis to improve our understanding of historical Hekla eruptions, facilitating the dating of the lava flow fields and serve as a foundation for comparing their geochemical and petrological characteristics.

DATA

The data used for this study are divided into 3 categories; remote sensing data, field data and historical sources. The remote sensing data consist of orthophotos and digital elevation models (DEMs) from 1945–1946, 1960, 1979, 1984–1987, 1998, 2004 and 2015. An overview of the data sets is compiled in Table 1.

The creation of the DEMs from old historical stereo-images is described in Pedersen *et al.* (2018) using the methodology from Magnusson *et al.* (2016). These data sets were important to delineate the flow boundaries. In particular, the orthophotos from 1945–1946 and 1960 were crucial for mapping the older lava flows, since they reveal the flow fields before the emplacement of the 1947–1948 and younger flow fields.

The field work was carried out over six weeks in 2015, 2016 and 2018 and included mapping and checking stratigraphic relationships derived from the remote sensing data (Figure 1). Soil profiles were recorded down to 30 cm in vegetation sampling sites while specific tephra profiles were recorded down to 120 cm depth logging the thickness and color of tephra layers. Where possible, tephra layers were assigned to specific eruptions based on comparison with previous work (Thorarinsson, 1967; Larsen *et al.*, 2013). Two tephra marker layers were particularly important; (a) The double-colored V-871 tephra layer also called the settlement layer because it approximately marks the time of the settlement of Iceland (Larsen, 1984; Grönvold *et al.*, 1995) and the 1510 Hekla tephra layer (Thorarinsson, 1967). The soils forming on the historical lava flows are of volcanic origin and here we distinguish between andic soils and vitric soils. Vitric soils are mostly composed of tephra and the parent material is largely unaltered since emplacement. Andic soils have brown or reddish brown color, are finer grained and imply that pedogenic processes have altered the parent volcanic material over time accumulating organic matter and forming clay minerals (Arnalds, 2015; Arnalds and Óskarsson, 2009; Mankasingh and Gísladóttir, 2018). This distinction is important as the time needed to form andic soils is counted in centuries or decades at best, while thick vitric soils can form over the course of one eruption. Plant colonization on lava fields is time dependent although other environmental factors play a role. Therefore, vegetation cover composition was analyzed in order to retrieve information regarding the chronology of the lava fields (Vilmundardóttir *et al.*, 2018).

The historical sources include annals, which primarily are medieval texts and they span from eyewitness accounts to contemporary accounts from remote places to oral histories written down centuries later. The reliability of the source can vary through time depending on whether the information is based on first hand, second or third-hand accounts (Table 2).

Place names and taxation documents from church inventories provided information regarding farm abandonments, some of which were due to lava emplacement or heavy tephra fall (*e.g.* Guðmundsson, 1952; 1954; Brynjólfsson, 1959; Hreiðarsdóttir *et al.*, 2015). Thoroddsen (1925) made an invaluable compilation of historical accounts, which Thorarinsson (1967) evaluated based on his current knowledge of volcanic eruption and tephra dispersal. Fifty years have passed since Thorarinsson's contribution, and here we re-evaluate Hekla's historical activity based on a new assessment of Hekla's historical lava flows.

METHODS

The mapping was conducted manually in geographic information system (GIS) software at a scale of 1:2000–10000. The remote sensing data were compiled in GIS which provides mapping tools making it possible to delineate lava units. The initial mapping conducted by Montalvo (2013) was based on the

Table 1. Overview of remote sensing data sources used for mapping the historical lava flows at Hekla. – *Yfirlit yfir fjarkönnunargögn sem notuð voru til að kortleggja söguleg hraun frá Heklu.*

Acquisition	Source	Data (Resolution and m/pixel)	Reference
23 Sep. 1945 and 20 Sep. 1946	Aerial photographs	Ortho (1) + DEM (10)	Pedersen *et al.*, 2018
20 July 1960 and 4 Aug. 1960	Aerial photographs	Ortho (0.5) + DEM (5)	Pedersen *et al.*, 2018
1 Aug. 1979	Aerial photographs	Ortho (0.5) + DEM (5)	Pedersen *et al.*, 2018
23 Aug. 1984 and 8 Aug. 1987	Aerial photographs	Ortho (0.5) + DEM (5)	Pedersen *et al.*, 2018
15 July 1992	Aerial photographs	Ortho (0.5) + DEM (5)	Pedersen *et al.*, 2018
10–12 Aug. 1998	SAR	Amplitude image (5)+ DEM (5)	Dall, 2003; Magnússon, 2003
1 Aug. 2006	Aerial photographs	Ortho (0.5)	Samsýn ehf.
30 July 2014 and 29 Aug. 2015	Aerial photographs	Ortho (0.5)	Loftmyndir ehf.
Mosaic 2011–2013	TanDEM	DEM (12)	Rizzoli *et al.* (2016)
29 Aug. – 4 Sep. 2015	Aerial photogr. and lidar	Ortho (0.2) + DEM (1)	Pedersen *et al.*, in prep.

orthophotos provided by the company Samsýn ehf. in 2006 and full polarimetric SAR images from the EMISAR campaign (Table 1) using previous maps as a guide (Kjartansson, 1945; Thorarinsson, 1967). This work served as an important baseline for remapping the area with the new data sets generated by Pedersen *et al.* (2018). These data sets (Table 1) along with generated differential DEMs (Pedersen *et al.*, 2018) enabled improved and detailed mapping of the lava flows from the 20th century. Furthermore, they aided mapping of early historical flows which were partly covered by the flow fields from the 20th century. Discrepancies between the initial work by Montalvo (2013) and the new analysis, based on the historical orthophotos, were checked during fieldwork, where the contacts between the lava fields were mapped and their stratigraphic positions were evaluated. Discrimination of lava units relied mainly on the stratigraphy, morphology of the flows and to some extent the vegetation. The delineation of the flow front is subject to error because offsets in the subsurface topography can be transferred to the lava flows which have been emplaced on top, creating pseudo-flow fronts within a lava flow. Morphological features that can be traced across such pseudo-flow fronts are key to identifying them, but for older lava flows with thick vegetation such flow morphologies may be very subdued or completely hidden. In some cases, vegetation community reveals the internal lava morphologies or indicate different successional stages and can therefore be used for pseudo-flow front identification. Furthermore, soil profiles have been used to differentiate between real flow fronts and pseudo-flow fronts.

In the cases of the lava flows erupted from 1845–2000 the entirety of the flow field could be traced from front to the vent due to the temporal resolution of the data set. The 1766–1768 lava field could be traced from flow front to vent except in the region of the western flow fields that may have been covered by the 1845 lava flow. The older fissure eruptions (1725, 1554, 1389) are also fairly well mapped; because they are located further away from Hekla which lowers the resurfacing rate (see Discussion) and therefore they can be mapped almost in their entirety from vent to flow front. However, for the pre-1766–68 lavas originating from vents located on Hekla ridge, only parts of individual lava flows could be mapped because they have been buried by later lava flows, and some lava flows only remain as undefined kīpukas in between other historical flows.

Assigning ages to the lava flow units has been done with variable certainty. The ages of the 1845–2000 lava flow fields are certain, and likewise with the lava flows from the 1766–68 eruption due to the above mentioned reasons regarding the temporal resolution of the data set. The location of older fissure eruptions (1725, 1554, 1389) is based on descriptions from historical sources, and interpretations from Kjartansson (1945) and Thorarinsson (1967). The age and areal extent of the lava flow fields erupted from Hekla ridge before the 1766–1768 eruptions are in many cases uncertain because of their patchy exposure, and include the 1693, 1300, 1206 and 1158 lava fields. There are historical eruptions which are known to have produced lava flows, but have not been identified in the field (*e.g.* 1597 and 1636), while for other eruptions

Table 2. Overview of information from historical sources mentioning eruptions in Hekla based on Thorarinsson (1967). Uncertain eruptions are marked with a question mark before the year. Contem., Mt. and. Eve. are abbreviations for contemporary, mount and evening, respectively. – *Tafla 2. Yfirlit yfir söguleg gögn um Heklugos, byggt á gögnum frá Sigurði Þórarinssyni (1967). Spurningarmerki framan við ártölin tákna eldgos sem óvíst er að hafi átt sér stað.*

Year	Month	Date	Time	Duration	Lava	Location	Contem. Sources	Annals / Other historical sources.
1104	winter	?	?	?	?	Fire in Mt. Hekla	None	Annals regii, Gottskálksannáll, Lögmannsannáll, Oddaverjaannáll.
1158	Jan.	19	?	?	?	Fire in Mt. Hekla	None	Annales regii, Anneles Reseniani, Gottskálksannáll, Höyers annáll, Lögmannsannáll, Oddaverjaannáll / Hungrvaka.
1206	Dec.	4	?	?	?	Fire in Mt. Hekla	Yes	Annales regii, Lögmannsannáll, Skálholtsannáll / Guðmundar saga biskups, Páls saga biskups.
1222	?	?	?	?	?	Fire from Mt. Hekla	None	Annales Regii, Flateyjarannáll, Gottskálksannáll, Oddaverjaannáll, Skálholtsannáll / Guðmundar saga biskups.
?1294	?	?	?	?	?	Fire in Mt. Hekla	None	Oddaverjaannáll.
1300	July	11/13	?	12 months	?	Fire in Mt. Hekla	Yes	Annales Regii, Annales vetustissimi, Gottskálksannáll, Höyers annáll, Lögmannsannáll, Skálholtsannáll / Laurentius saga.
1341	May	19	9	?	?	Fire in Mt. Hekla	Yes	Annales Regii, Flateyjarannáll, Gottskálksannáll, Skálholtsannáll.
1389–1390	?	?	?	1389–1390	Yes	Eruption fissure moved from Mt. Hekla to the woods above Skarð	Yes	Flateyjarannáll, Gottskálksannáll, Lögmannsannáll, Oddaverjaannáll.
?1436/ 1439	?	?	?	?	?	Fire came up in Mt. Hekla	None	Setbergsannáll / Biskupaannálar.
1510	July	25	?	?	?	Fire in Mt. Hekla	None	Setbergsannáll / Biskupaannálar.
1554	May /June	3	9	6 weeks	?	Fissures SW of Mt. Hekla	Yes	Flateyjarannáll, Setbergsannáll / Biskupaannálar.
?1578	Nov.	1	?	?	?	?	None	Árbækur Espólín V.
1597	Jan.	Early	Early eve.	> 6 months	Yes	Fire in SE part of Hekla. Many fires in the mountain at once.	Yes	Annalium in Islandia farrago, Fitjannáll, Kjósarannáll, Vatnsfjarðarannáll / Oddur Einarsson from Skálholt; Björn Jónsson from Skarðsá.
?1619	July	End	?	?	?	Fire in Mt. Hekla / Eastern mountains	Yes	Setbergsannáll, Skarðsárannáll, Vatnsfjarðarannáll / Árbækur Espólín VI, Gísli Oddson from Skálholt, Arngrímur Jónsson the Learned.
1636	May	8th / 15th	20/ 22	12 months	?	Hekla began to burn fires. Many craters.	Yes	Annalium in Islandia farrago, Ballarárannáll, Fitjaannáll, Setbergsannáll, Skarðsárannáll, Vatnsfjarðarannáll.
1693	Feb.	13	18–20	7–10 months	Yes	Hekla exploded. Litla Hekla destroyed during the eruption	Yes	Fitjaannáll, Hestsannáll, Mælifellsannáll, Sjávarborgarannáll / Árni Þorvarðsson from Þingvellir, Oddur Eyjólfsson from Holt, Þorlákur Þórðarson from Skálholt, Daði Halldórsson from Steinsholt.
1725	April	2	?	Spring	Yes	Fires N and S of Hekla. Lava close to settled parts of Rangárvellir	Yes	Hítárdalsannáll, Mælifellsannáll, Ölfusvatnsannáll / Þorsteinn Magnússon from Rangárvellir, Árbækur Espólín IX.
?1754			?	3 days	?	West of Hekla	Yes	/ Eggert Ólafsson and Bjarni Pálsson.
1766–1768	April	5	3:30	24 months ca.	Yes,	Summit ridge of Hekla. Lava SSW, N, E	Yes	Desjarmýrarannál, Höskuldsstaðaannáll, Annálar Sveinn Sölvason / Einar Jónsson from Skálholt, Hannes Finnsson.
1845	Sep.	2	9	7 months	Yes	Two main craters in the SW part of Mt. Hekla. Lava flowed W and N of Hekla	Yes	/ Jóhann Björnsson from Kirkjubær, Oddur Erlendsson from Þúfa, Páll Melsted from Hjálmholt; Robert Bunsen from Germany, W. Sartorius von Waltershausen from Germany, A. des Cloizeaux from France, J. C. Schythe from Denmark.
1878	Feb.	27	18–19	2 months	Yes	Close to Krakatindur	Yes	Thoroddsen, 1925.
1913	April	25	6	24 days	Yes	Lambafit and Mundafell	Yes	Bárðarson, 1930.
1947	March	29	6:41	13 months	Yes	Yes	Yes	*e.g.* Thórarinsson, 1976.
1970	May	5	21.23	2 months	Yes	Yes	Yes	*e.g.* Thórarinsson and Sigvaldason, 1972.
1980	Aug.	17	13:27	3 days	Yes	Yes	Yes	*e.g.* Grönvold *et al.*, 1983.
1981	April	9	2	7 days	Yes	Yes	Yes	*e.g.* Grönvold *et al.*, 1983.
1991	Jan.	17	17:05–17:07	53 days	Yes	Yes	Yes	*e.g.* Gudmundsson *et al.*, 1992.
2000	Feb.	26	18:20	12 days	Yes	Yes	Yes	*e.g.* Höskuldsson *et al.*, 2007.

(*e.g.* 1222, 1341, 1510) it is unknown if lava was produced. However, based on eruptive habits of Hekla it is reasonable to believe that these eruptions indeed produced lava flows. Finally, there are reports of eruption-like activity (*e.g.* in 1294, 1436/1439, 1578, 1619 and 1754), which Thorarinsson (1967) doubted to be eruptions at Hekla (Table 2).

RESULTS

The historical lava fields from Hekla and its fissure swarms cover ca. 233 km^2 of which it is expected that proximal regions of Hekla may have been resurfaced more than ten times. Two maps of historical lava flow fields have been produced, one including all historical flow fields and one excluding the lava flow fields from 1947–2000 (Figures 2 and 3). This has been done because extensive resurfacing has taken place during the 20th century hiding the stratigraphic relationships which could be observed before the 1947–1948 eruption. These maps exist in digital format and are available through the EMMIRS landscape portal (http://emmirs.is/landscape-portal/ : use chrome or firefox internet browsers). Here the reader is able to visually inspect the lava flow outlines in detail with historical orthophotos as a background. Furthermore the maps will be available through the CEDA repository and the Catalogue of Icelandic volcanoes (http://icelandicvolcanos.is/).

Below we focus on each of the lava units prior to 1947, as eruptions during 1947–2000 have been described (e.g. Thorarinsson, 1970; 1976; Thorarinsson and Sigvaldsson, 1972; Grönvold *et al.*, 1983; Gudmundsson *et al.*, 1992; Höskuldsson *et al.*, 2007; Pedersen *et al.*, 2018). Unidentified lava flow field units, which are likely to be of historical age will be mentioned in the end of this section.

The eruption of 1913

An eruption began on a 5 km long fissure at Mundafell, 3–6 km east of Hekla on April 25 at about 6h, preceded by vigorous earthquake activity for three hours (Bárðarson, 1930). The earthquakes were widely felt, the strongest in Reykjavík at the distance of 120 km. About 10 hours later another eruptive fissure, about 5 km long, opened up at Lambafit, 11–16 km northeast of the first (Figure 4). Both fissures produced basaltic lava with only minor ash. The eruption on the first fissure apparently only lasted about 24 hours, but the second one remained active until May 19 (Bárðarson, 1930). The product is transitional basalt (∼46 wt% SiO_2) (Thorarinsson, 1967) and the volume is estimated 0.02 km^3 (Montalvo, 2013). The 1913 eruptive fissures formed adjacent to and flanks the 1878 fissure system. Together these fissures form an en-echelon fracture system with northeast-southwest trend.

The eruption of 1878

The eruption began on February 27 accompanied by strong earthquake activity. Continuous activity was felt in the neighboring areas from 15h until 5h the following morning (Thoroddsen, 1925). Earthquakes were felt at least as far as 75 km from the eruption site. The fissure system was near Krakatindur, about 4–6 and 7–10 km east of the summit of Hekla and 23 km from the nearest inhabited area. Glow was seen at 18–19h and appears to have increased strongly around 20 h following a strong earthquake. After that the seismicity gradually decreased but the visible fire slowly increased. During the night light could be seen from Reykjavík at a distance of 120 km. Two columns of smoke and ash were observed, but on February 28 a third column was seen rising from another active area, followed by some ash-fall in the neighboring districts. Other than this the eruption was mostly effusive. The eruption site was first visited on March 17. Flowing lava was seen but by then the activity had dwindled considerably. The lava stopped flowing in the beginning of April but small explosive activity was observed until May. The eruption occurred along two fissures, arranged en-echelon and the total length of the fissure system is about 7 km (Figure 4). The lava composition was transitional basalt (∼47 wt% SiO_2) (Jakobsson, 1979a) and the estimated volume erupted was 0.03 km^3 (Montalvo, 2013).

The 1845 lava flow field

Apart from the 1947–2000 eruptions, the 1845 eruption is the best described activity from Hekla as there are detailed historical accounts available (Table 2). Lavas were observed at the foot of Hekla ridge on

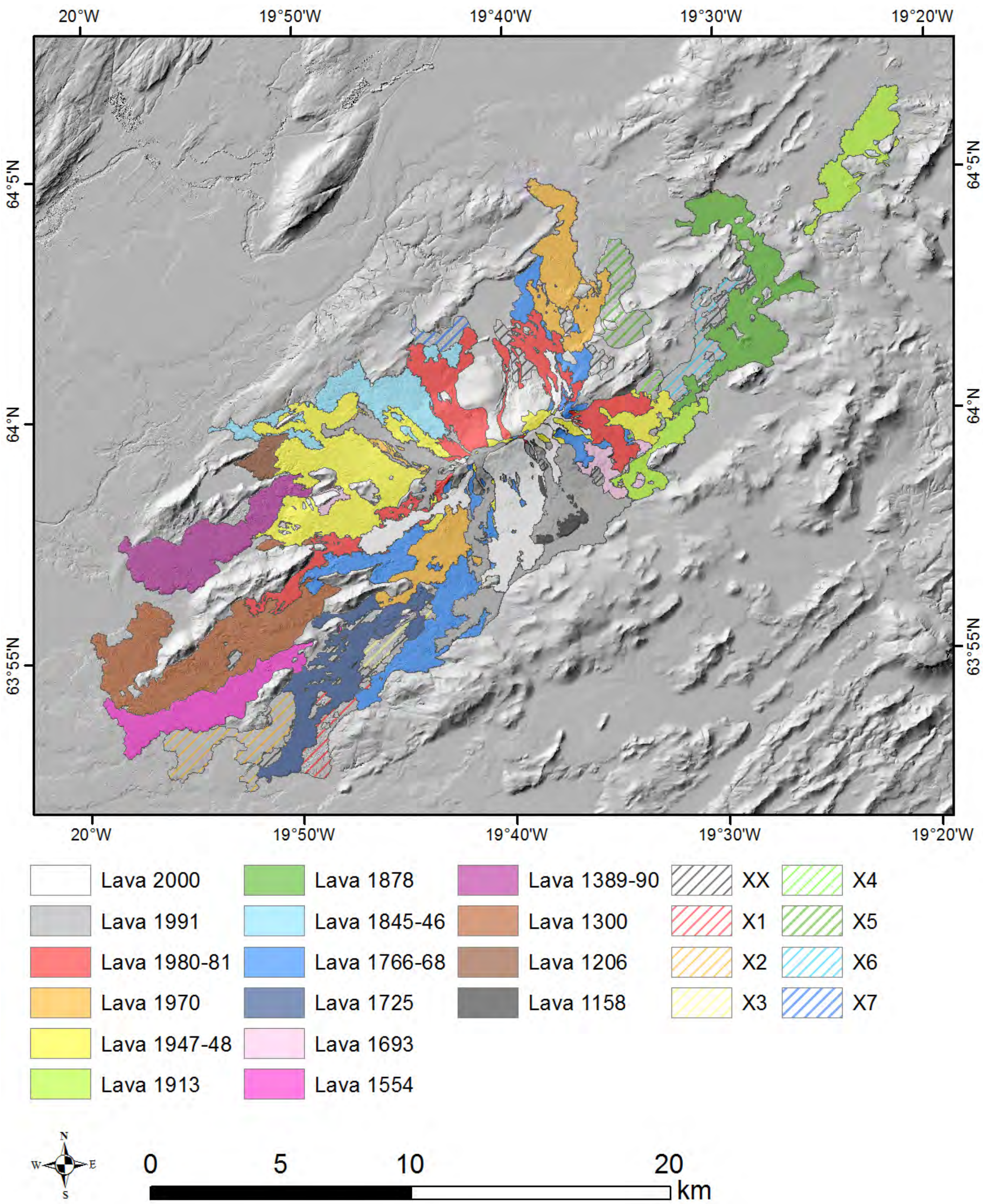


Figure 2. Map of historical lava flow fields as they are exposed after the 2000 eruption. Historical lava fields of unknown age are marked with X. Background shows hillshade from smoothed lidar DEM, with gaps filled with TDX DEM (Pedersen *et al.*, in prep., Rizzoli *et al.*, 2016). – *2. mynd. Kort af Hekluhraunum frá sögulegum tíma, eins og þau sáust á yfirborði eftir eldgosið í Heklu árið 2000. Hraunflákar af óþekktum aldri eru merktir með X, þeir eru líklega einnig frá sögulegum tíma. Hæðarlíkanið í bakgrunni kortsins er samsett af lidar gögnum, og TDX hæðarlíkaninu þar sem göt eru í lidar gögnunum (Pedersen o.fl., í vinnslu; Rizzoli o.fl., 2016).*

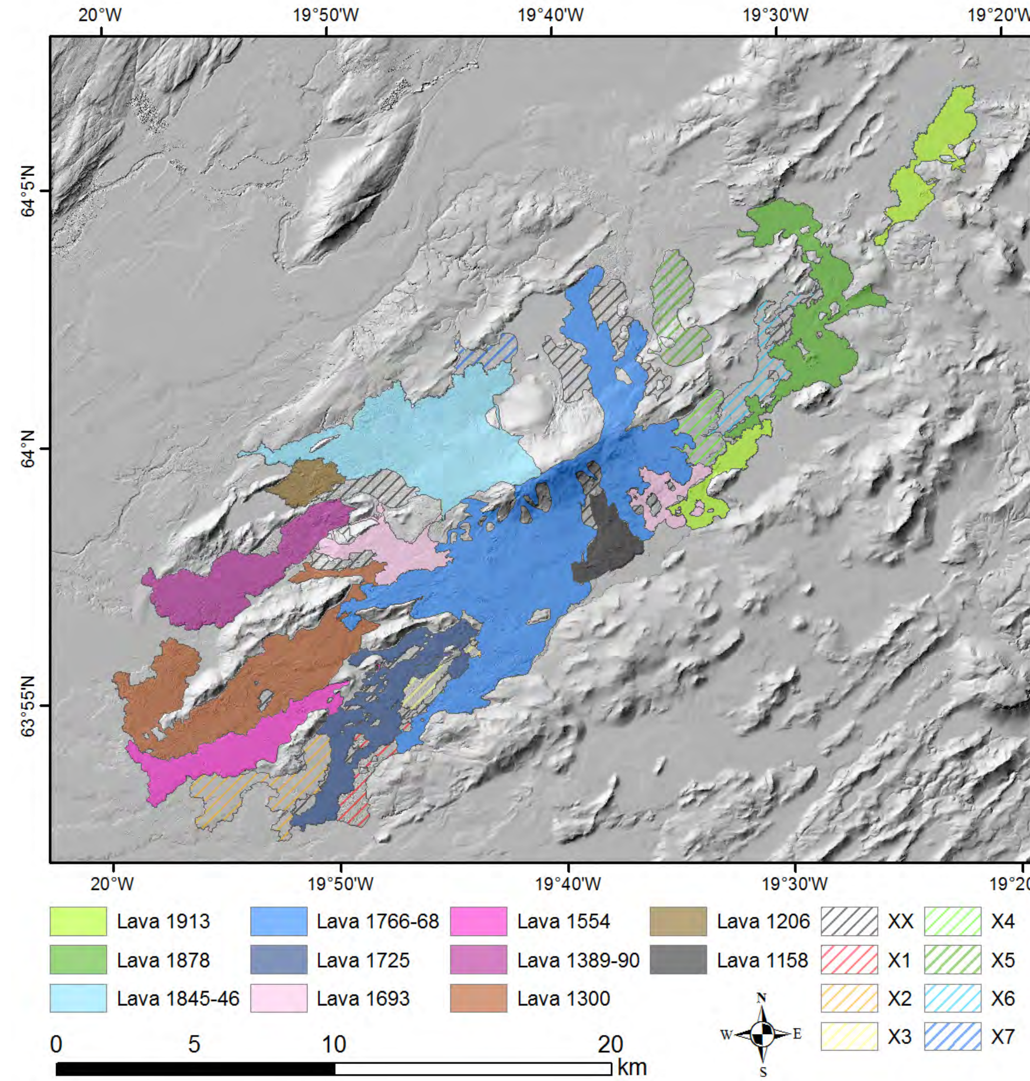


Figure 3. Map of historical flows by the time 1945–1946. Lava fields with unknown age are marked with X. Background shows hillshade from smoothed lidar DEM, with gaps filled with TDX DEM (Pedersen *et al.*, in prep.; Rizzoli *et al.*, 2016). – *3. mynd. Kort af hraunum frá sögulegum tíma samkvæmt loftmyndum frá árunum 1945–1946. Hraunflákar af óþekktum aldri eru merktir með X, þeir eru líklega einnig frá sögulegum tíma. Hæðarlíkanið í bakgrunni er samsett úr lidar og TDX gögnum (Pedersen o.fl., í vinnslu; Rizzoli o.fl., 2016).*

September 2, after dense tephra fall cleared from the region. It was reported that lava continued to flow until the end of the 7-month long eruption, with some potential pauses in activity between November 13–30, 1845, January 25-March 2 and March 23–24, 1846. The last glow was observed on March 31, while "fire-vapor" is described until April 9, 1846. The lava from this eruption caused the abandonment of the farmstead at Gl. Næfurholt (Figure 4) and detailed descriptions of the activity of the flow field exist (Schythe,

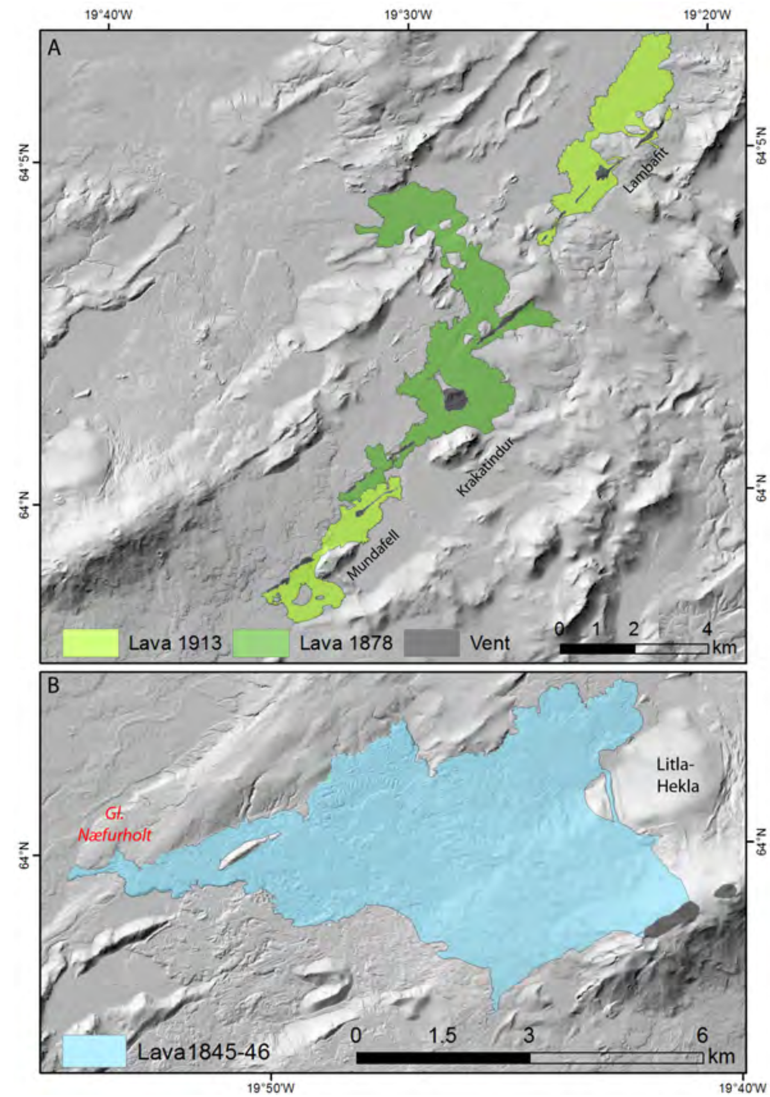


Figure 4. A. Map of the lavas of the eruptions of 1878 and 1913. The vents are marked with black polygons. B. Map of the lava field from 1845. Background shows hillshade from smoothed lidar DEM, with gaps filled with TDX DEM (Pedersen *et al.*, in prep.; Rizzoli *et al.*, 2016). – *4. mynd. A. Útbreiðsla hrauna frá gosunum 1878 og 1913. Gígar eru sýndir svartir. B. Útbreiðsla hraunsins frá 1845. Hæðarlíkanið í bakgrunni er samsett úr lidar og TDX gögnum (Pedersen o.fl., í vinnslu; Rizzoli o.fl. 2016).*

1847; Thorarinsson, 1967). Two vents are visible from the orthophotos taken in 1945–1946, both are located on the southern end of the Hekla ridge, south of Litla-Hekla. The majority of the lava flow seems to have been erupted from the southernmost fissure, which is in accordance with Kjartansson (1945). The flow front is well defined because the lava appears brighter on the othophotos than the surrounding flows due to the moss cover, which unlike the older lavas has not been covered by tephra. Our map of this lava flow is identical with previous maps of the eruption (Kjartansson, 1945; Thorarinsson, 1967).

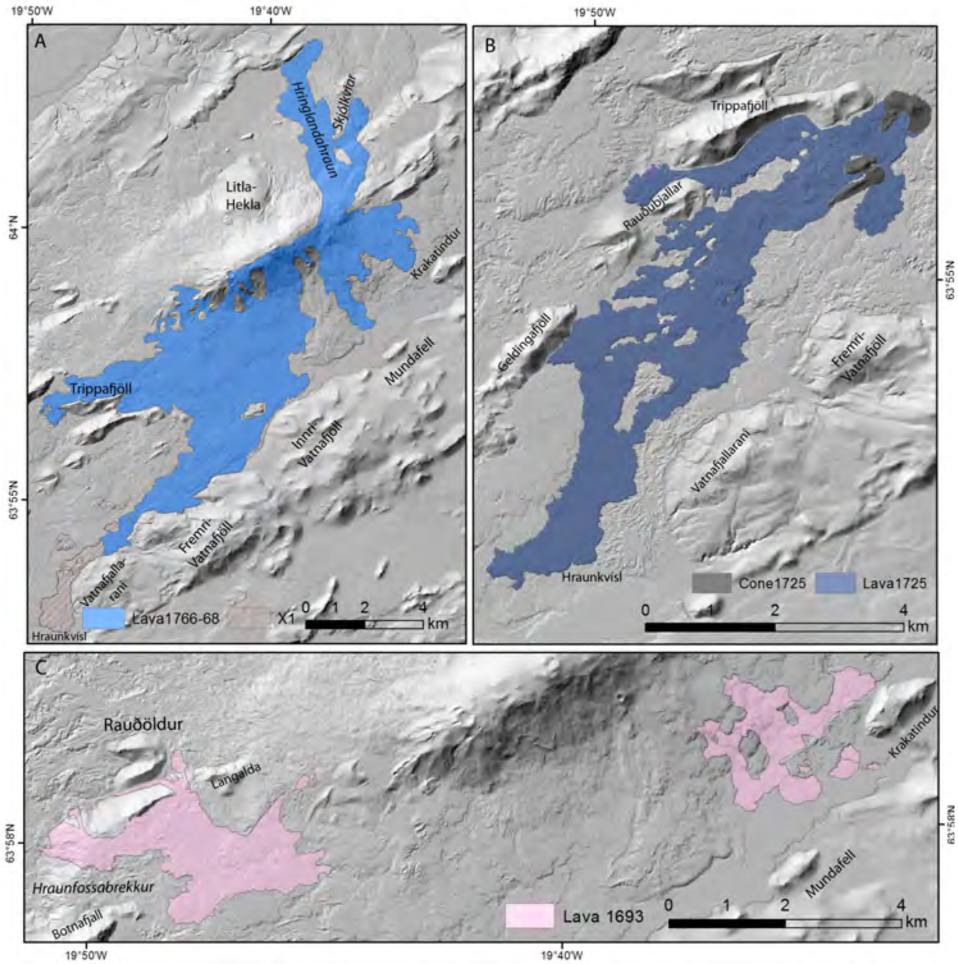


Figure 5. A. Map of the lavas of the 1766–1768 eruption. B. Map of the lava field from 1725. The vents are marked with black polygons. C. The extent of the exposed 1693 lava flow field before 1947. Background shows hillshade from smoothed lidar DEM, with gaps filled with TDX DEM (Pedersen *et al.*, in prep.; Rizzoli *et al.*, 2016). – *5. mynd. A. Útbreiðsla hrauna frá árunum 1766–1768. B. Útbreiðsla hraunsins frá 1725. Svartir flákar tákna gígana sem hraunið rann úr. C. Útbreiðsla hraunsins frá 1693, eins og það sást á loftmyndum áður en hraunið frá 1947 rann yfir það. Hæðarlíkanið í bakgrunni er samsett úr lidar og TDX gögnum (Pedersen o.fl., í vinnslu; Rizzoli o.fl. 2016).*

The 1766–1768 lava flow field

Fairly detailed accounts exist of the 1766–1768 eruption from eyewitnesses (Table 2). They describe two initial main vents producing flows to the south-west (Figure 5A), which were constrained by the northern part of Vatnafjöll in early April 1766 (Thorarinsson, 1967). Half a year later, lava flow activity is reported to the west, south and east towards Krakatindur, suggesting that at least one new vent opened in the northern end of Hekla ridge on Sep. 19, 1766. No flow activity is reported from November 1766 until March 18, 1767, when another vent seems to have opened on the northern end of Hekla ridge producing flows to the north. It is unclear how active the eruption was after March 1767, although there are accounts of observed fire in May 1767 and in March/April 1768.

Based on the orthophotos from 1945–1946 it seems that most of the 1766–1768 flow field is preserved and only minor flows may have been buried by the 1845 eruption (Figures 3 and 5A). We therefore interpret the flows described heading to the west as the flow along Trippafjöll. The flow fronts north and north east are well defined, while the flow to the south is less clear with numerous and very complex flow morphologies. Previous maps (Kjartansson, 1945; Thorarinsson, 1967) extended the flow south to Hraunkvísl and the southern tip of Vatnafjallarani, whereas Jakobsson (1979a) and our work interpret the flow stopped at the northern part of Vatnafjallarani 3.3 km further north.

Our assessment is based on (1) stratigraphic relationships revealing that the 1725 lava flow superposes the flow lobe (X1) extending to Hraunkvísl (Figure 5A) and (2) significantly different soil profiles between the 1766–1768 and this flow lobe (X1). In this area vegetation and soil is heavily influenced by the 1947–1948 tephra and possibly the 1845 tephra, we found sparsely vegetated, tephra covered lava field, 40 cm vitrisol with little sign of soil formation. However, we discovered a 50 cm soil profile on the X1 flow lobe with 10–20 cm andosol below the Hekla 1947–1948 and Katla 1918 tephra indicating that this flow is older than the 1766–1768 lavas (Figure 6).

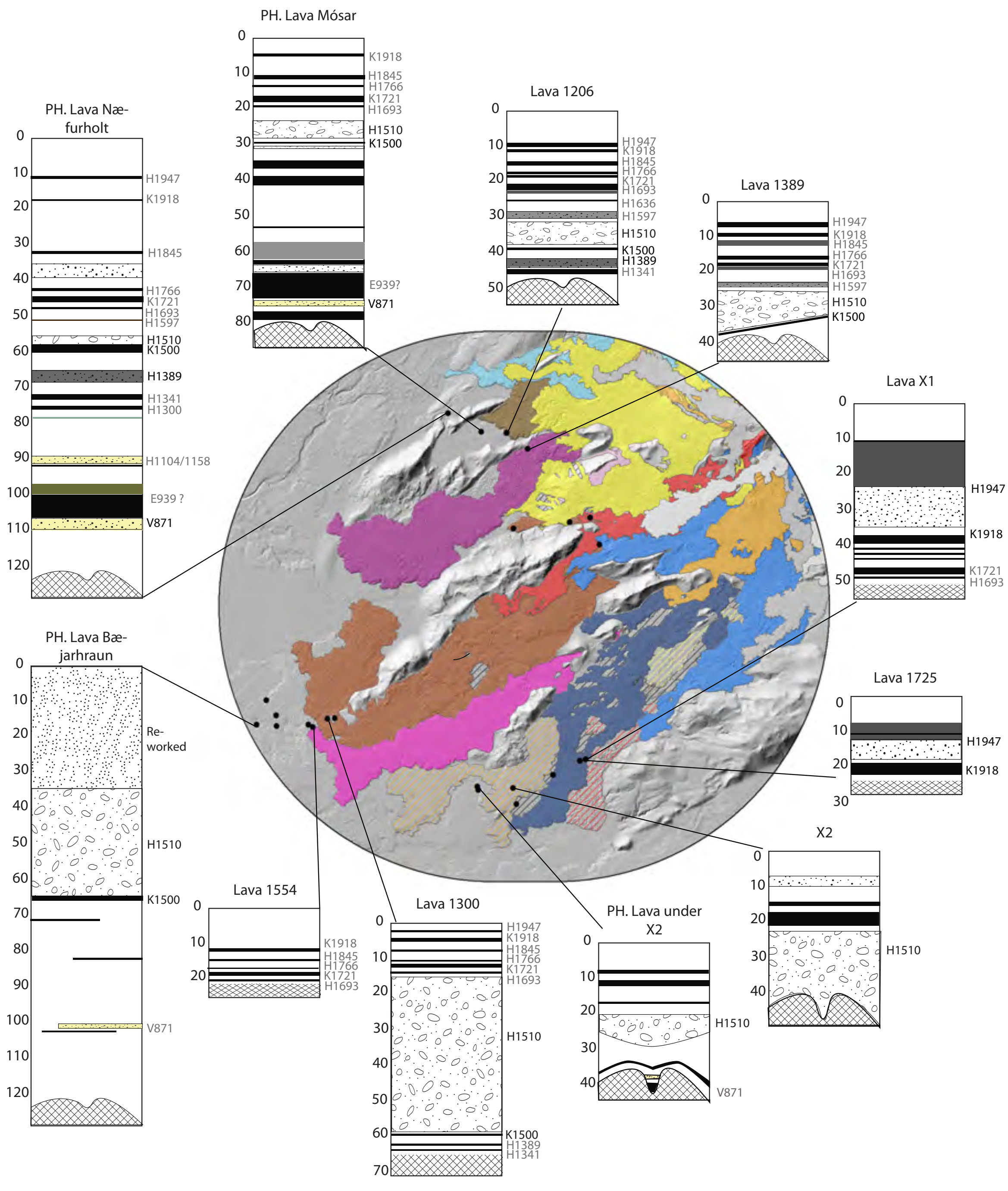
The 1725 lava flow field

The historical references of the 1725 eruption state that on April 1 or 2 multiple earth fires came up north and south of Hekla outside of the ridge itself, and describe lava extending towards the settled parts of Rangárvellir, southwest of Hekla. The eruption lasted through the spring which may suggest a 4 to 8-week eruption. The exact location of the fires is unknown, but Kjartansson (1945) suggested the vent at Trippafjöll (Figure 5B) as a potential source.

We mapped the flow field extending from the vent 1–1.5 km east of Trippafjöll to Hraunkvísl. The lava field overlies the 1554 lava flow from Rauðubjallar (also called Vondubjallar), and is overlain by the 1766–1768 lavas (Figure 5). Previously, the 1725 flow field has been mapped as a 6 km long flow (Thorarinsson, 1967; Montalvo, 2013), while our analysis extend the flow field another 4–5 km to the south based on thorough mapping of internal morphological features in order to identify pseudo-flow fronts. The soil profiles on this lava field contain Hekla 1947–1948 and Katla 1918 tephras deposited in a soil extending down 30 cm which also could fit the lava being from 1725 (Figure 6). Finally, this unit is one of the youngest looking lava flows from Hekla fissures of unknown age (the locations of the 1878 and 1913 fissure eruptions are known) and it therefore seems reasonable to assign this lava flow field to 1725.

However, the number of active vents in Trippafjöll area is uncertain. A vent 1.0–1.2 km south east of Trippafjöll could have been active in the very beginning of the eruption and later partly buried by the lavas from a vent upstream, however the vent could have been active in a previous eruption (Figure 5B). Furthermore, it is unclear if other fissures elsewhere may have been active. There are other unidentified lava flows from fissure eruptions, which are likely to be of historical age. For instance, the flow field next to Rauðaskál (Figures 2 and 3) which is heavily buried in the tephra from 1970–2000 eruptions as well as the 1766–1768 tephra (see X5 in the section of unidentified kīpukas). Other potential sources could be in

Figure 6. Overview of soil profiles on the lavas SW of Hekla. Background shows hillshade from smoothed lidar DEM, with gaps filled with TDX DEM (Pedersen *et al.*, in prep.; Rizzoli *et al.*, 2016). Tephra layers are colored according to their approximate appearance in the field, except for very coarse tephra layers such as *e.g.* H1510. The lava in the bottom of the profile is marked with a hatched signature. Uncertain ages are written in gray, while reliable ages are in black. Hekla, Katla, Veiðivötn, Eldgjá and prehistorical are denoted H, K, V, E and PH, respectively. – *6. mynd. Yfirlit yfir jarðlagasnið í hraunum suðvestur af Heklu. Hæðarlíkanið í bakgrunni er samsett úr lidar og TDX gögnum (Pedersen o.fl., í vinnslu; Rizzoli o.fl., 2016). Öskulög eru lituð í samræmi við útlit í mörkinni, og mjög grófkornuð öskulög, eins og H1510, eru táknuð með mynstri. Hraunin neðst í sniðum eru merkt með köflóttu mynstri. Óviss aldur hrauna er ritaður með gráum stöfum, en þekktur aldur er ritaður með svörtum stöfum. H=Hekla, K=Katla, V=Veiðivötn, E=Eldgjá, PH=forsöguleg hraun.*


PH. Lava Mósar
K1918
H1845
H1766
K1721
H1693
H1510
K1500
E939?
V871
PH. Lava Næ-furholt
H1947
K1918
H1845
H1766
K1721
H1693
H1597
H1510
K1500
H1389
H1341
H1300
H1104/1158
E939 ?
V871
Lava 1206
H1947
K1918
H1845
H1766
K1721
H1693
H1636
H1597
H1510
K1500
H1389
H1341
Lava 1389
H1947
K1918
H1845
H1766
K1721
H1693
H1597
H1510
K1500
Lava X1
H1947
K1918
K1721
H1693
PH. Lava Bæ-jarhraun
Re-worked
H1510
K1500
V871
Lava 1725
H1947
K1918
X2
H1510
Lava 1554
K1918
H1845
H1766
K1721
H1693
Lava 1300
H1947
K1918
H1845
H1766
K1721
H1693
H1510
K1500
H1389
H1341
PH. Lava under X2
H1510
V871

Vatnafjöll, or from the fissures close to the 1878 eruption (see X6 in the section of unidentified kīpukas).

The 1693 lava flow field

From the historical descriptions, it is clear that this 7–10-month long eruption produced a sizeable lava field spreading from multiple vents along Hekla ridge towards the north, south and west. Thorarinsson (1967) assigned the lava tongue east of Rauðöldur to the 1693 eruption based on the finding of Katla 1721 tephra (Figure 5C). The orthophotos from 1945–1946 allow us to expand this flow field upslope to the plateau between Langalda and Botnafjall, but it is covered in the proximal areas by the 1766–1768 and 1845 lavas (Figures 3 and 5). Thorarinsson (1967) also mapped 1693 lava flows north east of Hekla extending towards Mundafell, and indeed some fairly young looking lavas are buried there beneath the 1766–68 flows. Adhering to Thorarinsson's interpretation, this section of the lava flow was also mapped based on the orthophotos from 1945–1946 allowing us to connect some of the lavas which became disconnected kīpukas after the emplacement of the 1947–1948, the 1980 and the 1991 lava flows. Our field observations do not provide any conclusive evidence for the ages of these lava flows, since Katla 1721 tephra could not be identified, however the stratigraphy of these units (below 1766–1768 and above the 1300 and 1389 lavas) do not contradict Thorarinsson's (1967) suggestions.

The 1554 lava flow field

According to descriptions this eruption occurred farther forward from Hekla, which based on the local terminology means seaward, i.e., towards the sea, which is to the south of Hekla. Three fires were described to be seen from Hólar (Figure 1) in the evening of the first day of the eruption and reported to have lasted six weeks. Kjartansson (1945) suggested that Rauðubjallar (Vondubjallar) south of Trippafjöll is the source of this eruption since the Flateyjarannáll describes the site as two hills with a ravine between them (Figure 7A). Thorarinsson (1967) agreed with this suggestion mentioning that this lava flow had to be younger than the 1510 eruption, due to the lack of 1510 tephra on the flow (which is called Pálssteinshraun). The lava flow also overlies the 1300 lava flow field, but is buried by the 1725 lavas, which is in accordance with this interpretation (Figure 3). Interestingly, a tephra deposit has accumulated westward of Rauðubjallar and the tephra is still readily remobilized eroding and affecting the vegetation cover on the 1300 lava field. The orthophotos from 1945–

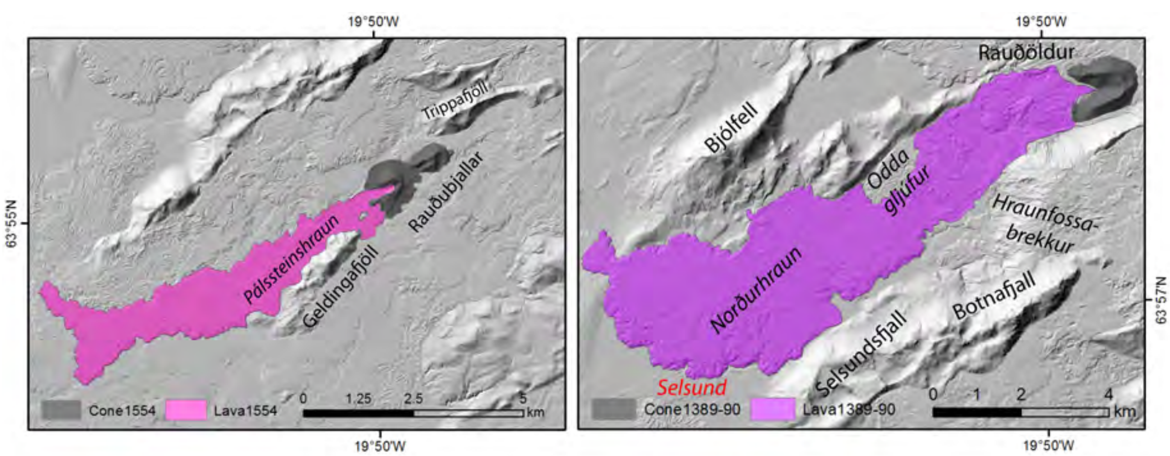


Figure 7. A. Map of the lavas of the 1554 eruption. B. Map of the lava field from 1389. The vents are marked with black polygons. Background shows hillshade from smoothed lidar DEM, with gaps filled with TDX DEM (Pedersen *et al.*, in prep., Rizzoli *et al.*, 2016). – *7. mynd. A. Útbreiðsla hrauna frá eldgosinu árið 1554. B. Útbreiðsla hrauna frá 1389, gígarnir eru táknaðir með svörtum flákum. Hæðarlíkanið í bakgrunni er samsett úr lidar og TDX gögnum (Pedersen o.fl., í vinnslu; Rizzoli o.fl. 2016).*

1946 and 1960 reveal an additional east-west oriented tephra field 1.5 km north of Rauðubjallar, which may support Kjartansson's (1945) interpretation that another, a third, vent was active in Trippafjöll. This vent is a fairly young looking one less than 1 km west of the 1725 vent, but since all stratigraphic relationships are buried under the 1725 lavas this suggestion needs more data before any definitive conclusion can be reached (*e.g.* geochemical analysis of the tephra and the cones and the associated lavas).

The 1389–1390 lava flow field

Fairly detailed descriptions of the location of this eruption exists. The reporting said the eruption started on Hekla ridge and subsequently a fissure opened in the woods north of Skarð (Flateyjarannáll) and the settlements in Skarð and Tjaldastaðir were buried under the lava. However, the exact locations of these place names are uncertain and have both been interpreted north and south of Selsundsfjall (Guðmundsson, 1952; 1954; Brynjólfsson, 1959; Thorarinsson, 1967). Thorarinsson (1967) assigned the location of this fissure to Rauðöldur, which is located ca. 4–5 km west of the southernmost part of Hekla ridge and is the largest preserved cinder cone in the Hekla area (1 km diameter). The argument for this is based on the description of the shape of the cinder cone itself and the tephra layers on Suðurhraun and Norðurhraun.

The 1945–1946 orthophotos capture the entire lava flow extending from Rauðöldur to Selsund called Norðurhraun (also called Selsundshraun nyrðra), which flowed up to 9 km from the vent (Figure 7B). No stratigraphic relationships have been found to contradict this interpretation, neither does the vegetation and soil data. Birch woods are currently developing on the Norðurhraun lava field suggesting several centuries of ecosystem development and the soil depth is ca. 40–50 cm, with the 1510 tephra slightly below 30 cm depth (Figure 6). Norðurhraun superposes an older lava flow with mature woodlands, that today can be seen at Oddagljúfur (Figure 7B), and it is possible that this vegetated flow could be the woods that are referred to in Flateyjarannáll.

However, Thorarinsson's interpretation does not fit with the church inventory existing from Skarð until 1397 nor does it fit the old descriptions of the location of Skarð. However, since Flateyjarannáll disagrees with church inventory and local knowledge of place names it can be argued that these historical sources should be reevaluated with respect to their validity.

1300 lava flow field

Little is known regarding the lava flow from the 1300 eruption based on historical references. The lava most likely issued from vents on Hekla ridge which was described to split in two during the initial explosive phase of the eruption, and the activity lasted nearly a year (Skálholtsannáll). It has been suggested that the lava flow called Suðurhraun (or Selsundshraun syðra), which runs along the eastern side of Selsundsfjall and around the southern end called Fálkhamar, was formed at that time (Figure 8A). Thorarinsson (1967) described this flow to be older than Hekla 1341 eruption based on tephra chronology, which is in accordance with our observations (Figure 6). Thorarinsson (1967) noted that the farm Ketilsstaðir was potentially abandoned at this time, due to lava emplacement, as reported in the Farm register (Jarðabók 1711).

Suðurhraun is superposed by Pálssteinshraun, which has been ascribed to the 1554 eruption and overlies some young prehistoric lava flows. In the 1945–1946 orthophotos the Suðurhraun lava can be traced upstream revealing that a small part of this flow got diverted by the hyaloclastite ridge Botnafjall and ran down the slopes of Hraunfossabrekkur which fits with the observations of the 1510 tephra in soil profiles on this lava flow.

The 1206 lava flow field

A fire is described in Páls saga biskups to have started on Hekla ridge December 4, 1206, but nothing is mentioned regarding the effusive activity. However, due to the 1158 lava being classified as Háahraun (Sigmarsson *et al.*, 1992) and because of historical accounts from Herbert of Clairvaux and Saxo (late 12th to early 13th century) describing that eruptions at Hekla had poured out lava, Sigmarsson *et al.* (1992) suggested Efra-Hvolshraun to be from 1206 or maybe 1222 (Figure 8B). The soil depth and vegetation support the interpretation of this being an old historical flow revealing ca. 50–60 cm of mature andic soils with the 1510 tephra at 30–40 cm depth (Figure 6). The lava is most

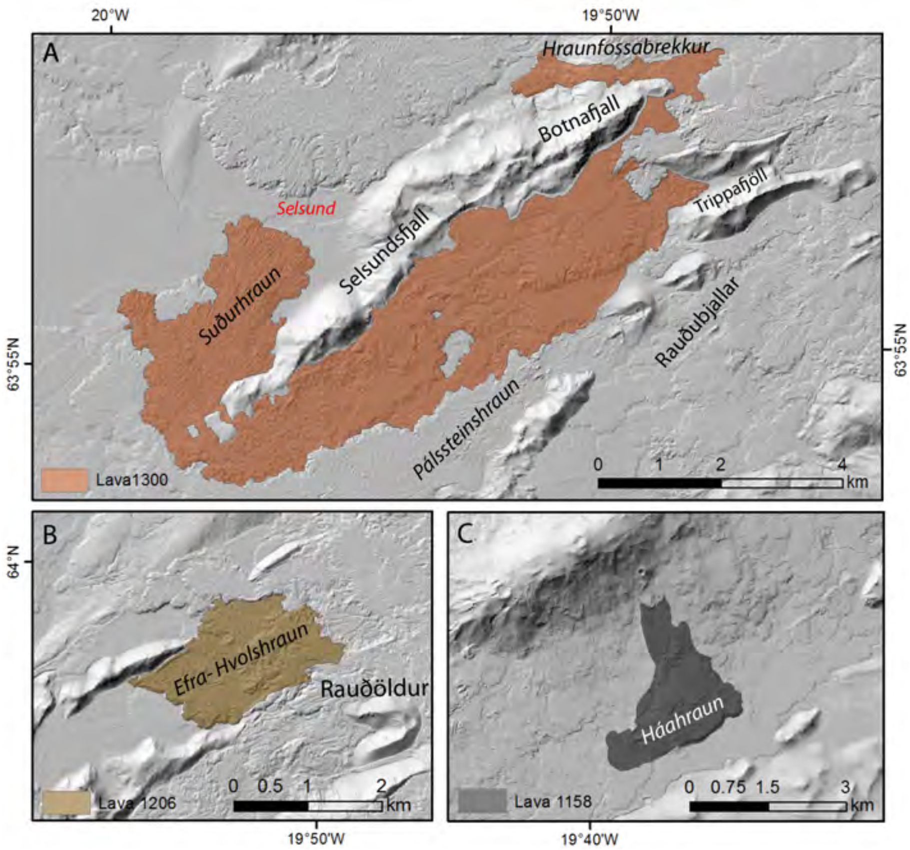


Figure 8. A. Map of the exposed 1300 lava flow field before 1947. B. Map of the exposed 1206 lava flow field before 1947. C. Map of the exposed 1158 lava flow field before 1947. Background shows hillshade from smoothed lidar DEM, with gaps filled with TDX DEM (Pedersen *et al.*, in prep., Rizzoli *et al.*, 2016). – *8. mynd. Útbreiðsla hrauna frá árinu 1300 (A), 1206 (B) og 1158 (C) samkvæmt loftmyndum sem teknar voru áður en hraunið frá 1947 rann. Hæðarlíkanið í bakgrunni er samsett úr lidar og TDX gögnum (Pedersen o.fl., í vinnslu; Rizzoli o.fl. 2016).*

likely historical since the settlement tephra layer has not been found on the flow, and no tephra layers older than the 1341 has been identified. Therefore, it cannot be ruled out that this lava flow could be from 1300 or 1222. The lava is densely covered by birch shrubs and trees similar to what is found in parts of the 1300 and 1389 lava fields.

The 1158 lava flow field

Very sparse information exists regarding this eruption and provides no information regarding lava flows. Thorarinsson (1967) suggested that the 1158 lava flow is the Efra-Hvolshraun since historical sources described lava which had been emplaced close to settled districts before the 12th century. However, Sigmarsson *et al.* (1992) showed that Háahraun has a composition identical to the 1158 tephra layer and therefore argued that Háahraun is from 1158 (Figure 8C). Háahraun is heavily affected by tephra fall and has a soil depth > 100 cm of vitric soils. The tephra covered lava is relatively densely vegetated by mosses and a biological crust stabilizing the tephra. The vegetation communities include alpine vascular plant species and reflect the difficulty for plants to inhabit a lava flow at this elevation, so close to Hekla. It is intriguing that such an old lava flow still is exposed on the sides of Hekla ridge, and suggests that this flow is very thick and thus has diverted most historical lava flows around it.

Un-identified lava flow fields

There are ca. 60 unidentified lava units which may be of historical age and another 15 which may be young prehistorical lavas. Some of the units of historical age have been grouped together based on their textural properties and spatial distribution *e.g.* if they are located along subsurface flow front, which only partly was covered with younger flows. Seven of these groups of lava units are addressed in the following section; three are located to the south of Hekla and four north and east of Hekla. The rest of the unidentified lava flows are denoted by XX and not addressed further in this article.

X1 is a distinct unit with extensive fracturing and very irregular lobes which extend to Hraunkvísl from the northern part of Vatnafjallarani south of Hekla (Figure 9). This unit was previously interpreted as 1766–1768 lavas (Thorarinsson, 1967; Montalvo, 2013), but according to our observations it is overrun by the 1725 lava and must therefore be older than 1725. The 1510 tephra is widespread in this area as a distinct tephra layer of 5–30 cm thickness (Thorarinsson, 1967), but is not identified in the soil profile above this unit and the oldest tephra layer we found is presumably the Hekla 1693 (Figure 6). Therefore, we suggest that this lava flow lobe may be from the 1510, 1597 or 1636 and could fit Jóhannesson's (1994) interpretation that the unit was from the 1510 eruption. Two kīpukas north and west of the main X1 lobe have been linked to this flow unit based on the morphological similarity and spatial closeness.

X2 is a 1 km wide and up to 6.5 km long lava flow that runs along the eastern side of Geldingafjöll and diverges into three lava tongues as it flows south and west of Geldingafjöll hyaloclastite ridge (Figure 9). Based on the western 1554 flow lobe it is tempting to assume that this fairly young looking lava flow also could be from the 1554 eruption, though the stratigraphic relationships are hidden below the 1725 lava flow which superposes these flow units. However, the X2 is clearly covered by the 1554 flow field to the southwest and the 1510 tephra layer is found directly on top of the surface so X2 has to be older than 1510 (Figure 6). When comparing the soil profile on X2 with nearby lava flows (Figure 6), including the 1300 and 1389, this flow looks younger because it has fewer tephra layers. Since we found no evidence of vegetation nor soil formation under the 1510 tephra we find it reasonable that the lava flow was <100 yr old when the 1510 tephra was deposited (Vilmundardóttir *et al.*, 2018). According to Jakobsson (1979a) X2 has basaltic composition similar to the Hekla fissure eruptions and we therefore suggest that this flow may be from the fissure eruption around 1436/1439 which Thorarinsson (1967) discarded because the annals (Bishops annals, Setbergsannáll) seem to have mixed the 1389 and 1510 eruption. There are multiple vents and vent remnants in the area around Rauðubjallar and Trippafjöll, so it seems likely that there could have been more historical fissure eruptions in this region. However, we cannot rule out that X2 also could be from the 1341 or 1300 eruption, but in that case it would require basaltic fissures to co-erupt while Hekla itself erupted, which has not been described in historical references.

X3 is a minimum 2.5 km long flow lobe, which has been heavily bisected by the 1725 lava flow. Originally, we regarded this to be a part of the early activity of the 1725 eruption, but since its lava channel is clearly crosscut by a vent, from the early phase of 1725 eruption or maybe older, this unit is older (Figure 9). Furthermore, the morphology of this unit is rougher than the smoother 1725 flow lobes.

X4 consists of three old flow lobes northeast of Hekla, with total width of more than 2.5 km (Figure 10). The 1947–1948 lava buried large portions of this flow, but it is still partly exposed. This flow seems to be of early historical age, i.e. older than the units we have mapped as 1766–1768 and 1693. The soil profiles were up to 70 cm and the lowermost part contained a reddish brown andic soil, 2–4 cm thick, with relatively high proportion of clay minerals and with properties characteristic for andosols in staple, vegetated, well drained areas (Arnalds, 2015; Arnalds and Óskarsson, 2009). On top of the reddish brown andic soil were two dark brown andic soil layers separated

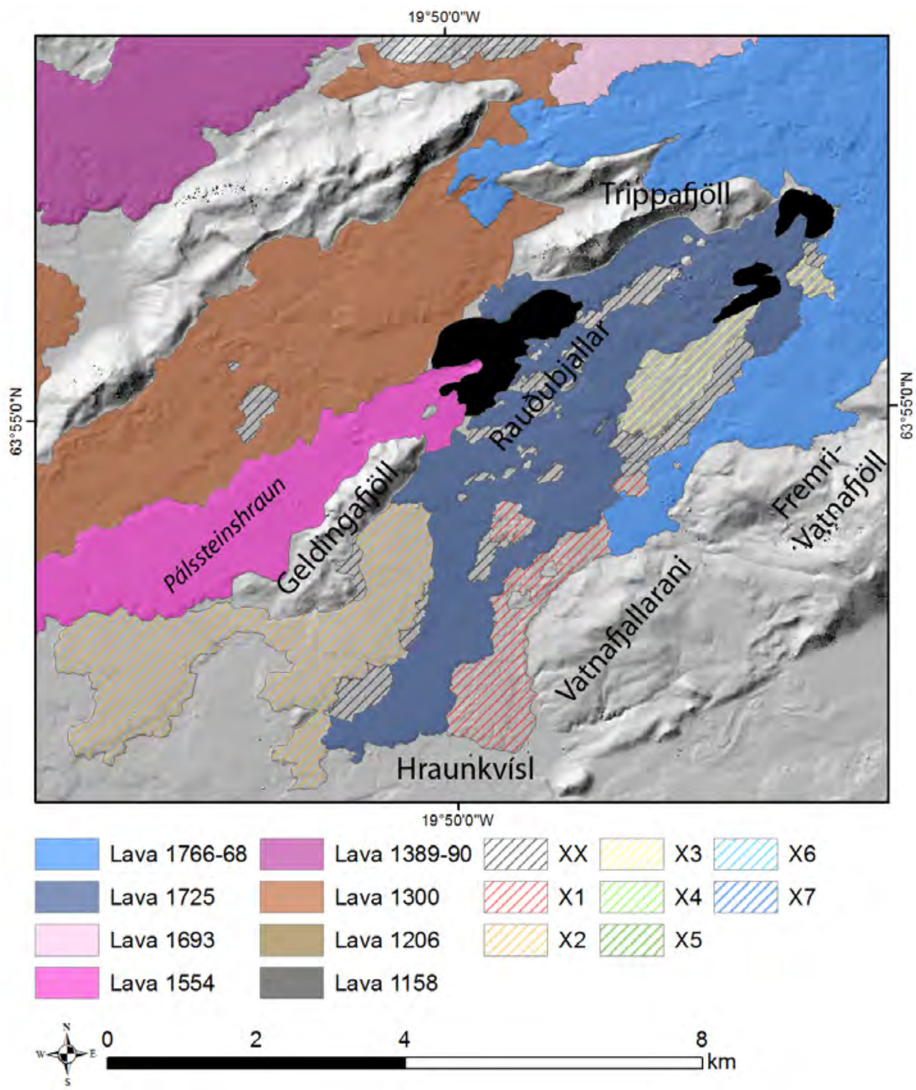


Figure 9. Map of the southern pre-1947 lava flow fields. Vents are marked in black. Background shows hillshade from smoothed 1960 DEM (Pedersen *et al.*, 2018). – *9. mynd. Kort af hraunum sunnan Heklu eins og þau litu út fyrir eldgosið árið 1947. Hæðarlíkanið í bakgrunni er gert úr loftmyndum sem teknar voru árið 1960 (Pedersen o.fl., 2018).*

by a thick bomb-rich tephra layer. We expect this unit to be of old, yet historical age, since large parts of the flow are still exposed less than 3 km from the Hekla in 1946.

X5 is an approximately 4–5 km lobe cutting into the slopes and extending north of Rauðaskál (Figure 10). This flow is heavily affected by tephra fall, but the flow front is well defined. Montalvo (2013) mapped this as a part of the 1766–1768 flows, but we interpret this flow as older, because the 1945–1946 orthophotos reveal that this unit was deeply buried by tephra before the 1947–1948 eruption unlike the 1766–1768 flow called Hringlandahraun 1–3 km west of this flow. However, we find it likely that this flow

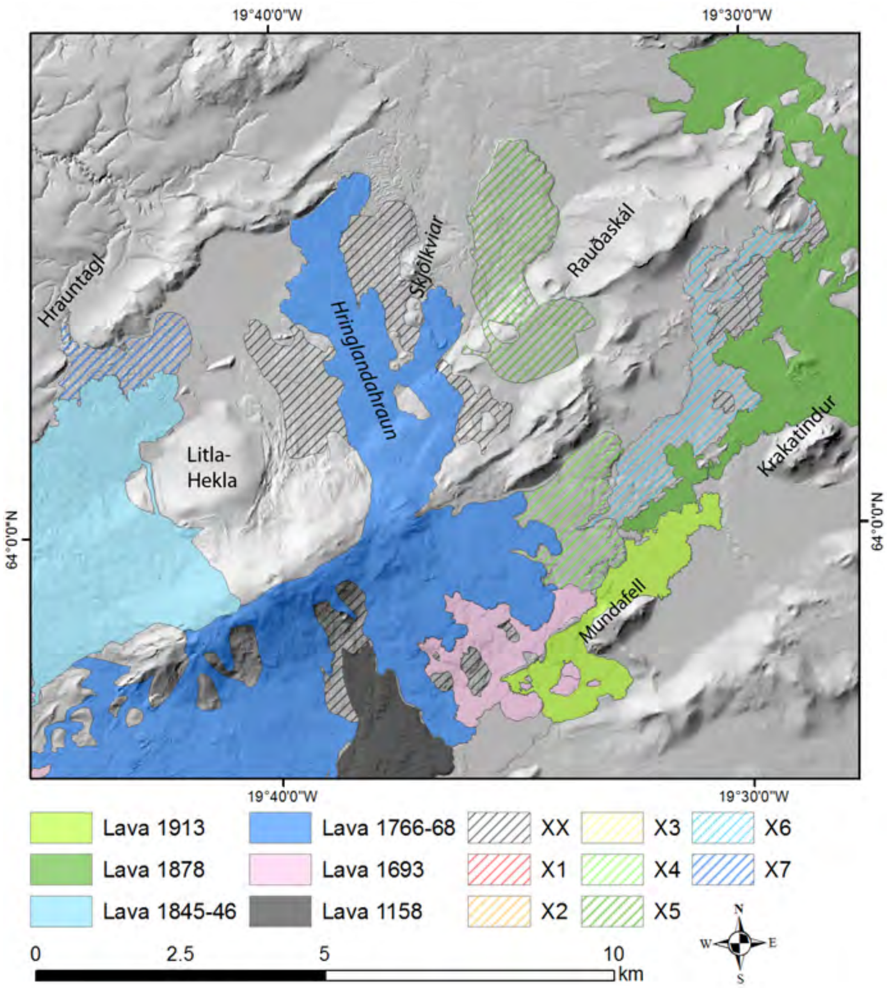


Figure 10. Map of the northern pre-1947 lava flow fields. Background shows hillshade from smoothed 1960 DEM (Pedersen *et al.*, 2018). – *10. mynd. Kort af hraunum í norðurhluta eldstöðvakerfis Heklu eins og þau litu út fyrir eldgosið árið 1947. Hæðarlíkanið í bakgrunni er gert úr loftmyndum frá 1960 (Pedersen o.fl., 2018).*

is historical, but are unable to constrain the age better than pre 1766–1768.

The X6 is a lava flow from Hekla's northeastern fissure swarm. It is covered by the 1878 lavas, whereas its fissure cuts X4 and looks fairly young, as does the lava flow itself, which despite some tephra cover reveals concentric ridges, shear zones and lava boulders.

X7 is a small lava tongue called Hrauntagl NW of Litla-Hekla (Figure 10). It is buried under the 1845–1846 and 1980–1981 lavas. The eastern part is covered by a thick deposit of tephra from the 1970–2000 eruption but the western part is vegetated. A soil profile revealed 20 cm of reworked sand, suggesting a very unstable environment, and the identification of individual tephra layers is therefore uncertain. The oldest tephra layer overlying a thin layer of soil is interpreted to be 1766, which is widespread in the area, and hence this unit could be from 1693 or older. Kaldal *et al.* (2018) suggested that this lava flow is from 1597.

DISCUSSION

The historical lava flow map highlights key features of Hekla's volcanic history, which are important from a hazard perspective. First and foremost, the spatial distributions of identified vents show fissures forming from 0–16 km from Hekla (Figure 11A-B, Table 3). Erupting vents initiating on Hekla ridge have migrated up to 5 km from the ridge during the eruptions (*e.g.* 1970 and 1389), while basaltic fissure eruptions have propagated 3–16 km from Hekla ridge during an eruption (*e.g.* 1913). Hence, there is an overlap in vent systems of 3–5 km between the basaltic fissure eruptions and eruptions that begin in Hekla ridge, which typically erupt more evolved compositions (*e.g.* basaltic andesite).

Repeated eruptions outside of Hekla are mostly confined to two areas. One area lies 4–8 km SSW of Hekla close to Trippafjöll, where the 1725 and 1554 eruption sites have been identified. In addition, there are multiple vents and remnants of vents in this area, which are likely to be from other eruptions, *e.g.* potentially the eruption that produced the X2 flow. The other area is 2–5 km NNE of Hekla close to Hringlandahraun and Rauðaskál. This is where the northern 1970 vents opened, and the craters of Rauðaskál and Skjólkvíar are located. Potentially the X5 lava flow originated from a vent in this area.

The historical lava flow fields reach up to 16 km from Hekla and produced flows with lengths up to 20 km as exemplified by the 1300 lava flow field (Figure 11C). However, within the last 250 yr lava flows have only travelled 8–9 km from Hekla (1766–1768, 1845, 1980, 1970), whereas the lava from fissure eruptions outside Hekla ridge are 2.5–9.5 km long (Table 3).

The post 1845 and 2000 lava flow maps (Figures 2 and 3) reveal how quickly Hekla resurfaces itself. The resurfacing rate can be evaluated by estimating the lava field coverage within each buffer zone delineated by distance contours from the center of Hekla ridge (Figures 11A and D). This has been done for each of the last 7 eruptions of Hekla ridge (from 2000 to 1766–1768). Within the 20th century the lava production was sufficient to bury all of Hekla out to a distance 2 km, and covered 100–50% of area between 2–4.5 km distance (Figure 11D). The flow field area during the last 250 yr could have buried all of Hekla out to a distance of 4 km from the center of Hekla ridge and covered 100–50% of area between 4–6 km distance.

The historical lava maps presented in this paper provide the most detailed mapping of Hekla to date. Previously published lava maps (Kjartansson, 1945; Thorarinsson, 1967; Jakobsson, 1979a; Montalvo, 2013), have served as an important baseline for this work. The lava flow outlines were reassessed and refined based on improved remote sensing data (in particular the historical orthophotos from 1945–1946 and 1960) and field observations (superposition, stratigraphic analysis, soil and vegetation character-

Figure 11. A. Areal extent of historical lava flow fields (1947–2000 are gray, pre-1947 are orange). Vents are marked in black and the distance from Hekla ridge is marked with red contours delineating buffer zones (in kilometres). Background shows hillshade from smoothed lidar DEM, with gaps filled with TDX DEM (Pedersen *et al.*, in prep., Rizzoli *et al.*, 2016). B. Vent distances from Hekla ridge during historical eruptions. C. Lava flow distances from Hekla ridge during historical eruptions. (D) Percentage of areal resurfacing for the last 7 eruptions at Hekla ridge within each buffer zone (marked as red contours on A). – *11. mynd. A. Útlínur hrauna frá sögulegum tíma. Hraun sem mynduðust á árunum 1947–2000 eru grá, söguleg hraun fyrir árið 1947 eru appelsínugul á litinn. Svartir flákar sýna umfang gosstöðvanna og rauðar línur fjarlægð frá miðju Heklu (í kílómetrum). Hæðarlíkanið í bakgrunni er samsett úr lidar og TDX gögnum (Pedersen o.fl., í vinnslu; Rizzoli o.fl, 2016). B. Fjarlægð milli Heklu og gosstöðva í mismunandi eldgosum Heklu frá sögulegum tíma. C. Vegalengdir hraunflæðis frá Heklu i eldgosum frá sögulegum tíma. (D) Hraunþekja frá síðustu sjö eldgosum Heklu, miðuð við fjarlægð frá Heklu (rauðar línur). Prósentuhlutfall hraunþekjunnar táknar hve hátt hlutfall yfirborðs í tiltekinni fjarlægð frá Heklu hefur verið þakið af hraunum frá síðustu sjö eldgosum eldstöðvarinnar.*

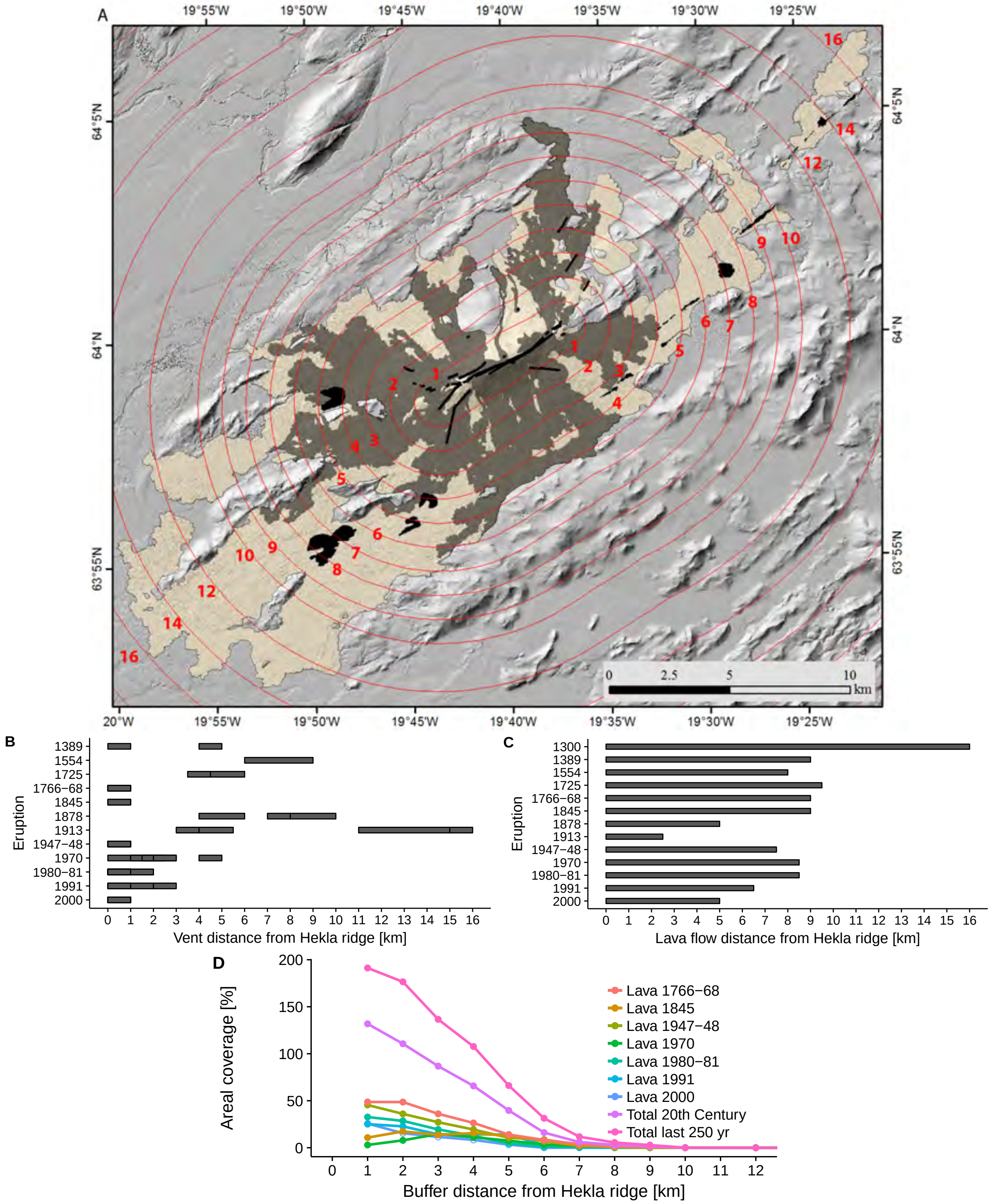

A
19°55'W
19°50'W
19°45'W
19°40'W
19°35'W
19°30'W
19°25'W
20°W
64°5'N
64°N
63°55'N
0 2.5 5 10 km
B
Eruption
1389
1554
1725
1766–68
1845
1878
1913
1947–48
1970
1980–81
1991
2000
Vent distance from Hekla ridge [km]
C
1300
Lava flow distance from Hekla ridge [km]
D
Areal coverage [%]
Buffer distance from Hekla ridge [km]
Lava 1766–68
Lava 1845
Lava 1947–48
Lava 1970
Lava 1980–81
Lava 1991
Lava 2000
Total 20th Century
Total last 250 yr

Table 3. Spatial characteristics of known historical eruptions. *Signifies that substantial part of the lava field is covered by younger lavas. #Signifies that minor parts of the flow field are likely to be covered by younger lavas. – *Tafla 3. Stærðir og rúmmál þekktra eldgosa frá Heklu. *Táknar að stór hluti hraunsins er þakinn yngri hraunum. #Táknar að minnihluti hraunsins er líklega þakinn yngri hraunum.*

Eruption	Vent distance from Hekla ridge [km]	Max flow distance from vent [km]	Area [km^2]	Average thickness [m]	Volume [km^3]	Reference
2000	0–1	5	14.59	7	0.095 ± 0.005	Pedersen *et al.*, 2018
1991	0–3	6.5	24.66	10	0.241 ± 0.019	Pedersen *et al.*, 2018
1980–81	0–2	8.5	24.56	7	0.170 ± 0.015	Pedersen *et al.*, 2018
1970	0–3; 4–5	8.5	17.13	12	0.211 ± 0.012	Pedersen *et al.*, 2018
1947–48	0–1	7.5	38.93	19	0.742 ± 0.086	Pedersen *et al.*, 2018
1913	3.5–5.5; 11–16	2.5	9.91	2	0.02	Montalvo, 2013
1878	4–6; 7–10	5	13.34	2	0.03	Montalvo, 2013
1845	0–1	9	24.75	–	–	This study
1766–1768#	0–1?	9	49.85	–	–	This study
1725#	4–6	9.5	12.17	–	–	This study
1693*	–	–	8.15	–	–	This study
1554*	6–9	8	9.00	–	–	This study
1389#	0–1; 4–5	9	12.18	–	–	This study
1300*	–	16	22.04	–	–	This study
1206*	–	–	2.75	–	–	This study
1158*	–	–	3.99	–	–	This study

istics and tephrochronology). Reviewing the sources used for previous age assignments of lava fields was very instructive. Our goal has been to make the current reasoning for age assignment more transparent, to disclose their uncertainties and to press the need for data that can further constrain the ages of the lava flow fields.

However, the number of unidentified lava units on this map reveals that future work is necessary in order to get a more comprehensive view of the historical eruptive history of Hekla. Many of these unidentified units have vegetation cover similar to older historical eruptions (> 300 yr), which is consistent with their stratigraphic position. We suggest five different routes to constrain the ages of these kīpukas:

1. Detailed tephra chronological study on the Hekla lava fields and nearby surroundings. There are very few published tephrohronological observations from historical Hekla lava flows of which Thorarinsson (1967) provided the majority. However, his observations relied on the tephrochronological understanding 50 years ago. Since then the dispersal axes of the 1158, 1206, 1222, 1341 tephras have been changed significantly (Larsen *et al.*, 2013). Furthermore, the majority of tephra layers from historical fissure eruptions have not been mapped and some of these layers may be the key to resolving the stratigraphy of unidentified kīpukas, in particular in the south-western region.

2. Analysing the geochemistry and petrology of historical lava flows provides another feasible way to correlate units from the same eruptions and potentially link lava flows to specific tephra layers like in the case of Háahraun and the 1158 eruption.

3. Review and reanalyze historical accounts from the annals and the church inventories in the light of our current understanding of eruption dynamics of the historical eruptions and compare it to recorded abandonments in the Rangárvellir area. The historical archives provide important information, which requires very detailed knowledge of individual sources in order to evaluate their reliability. Thorarinsson (1967) provided an invaluable insight, which should be followed up by a new comprehensive analysis in order to shed light on the instances where the historical sources are contradictory.

4. Paleomagnetism may provide an alternate route to correlate and potentially date some of the lava units. This technique has previously been used by Pinton *et al.* (2018) in Iceland and has been applied for lavas in Italy and Mexico (*e.g.* Arrighi *et al.*, 2006; Tanguy *et al.*, 2007; Mahgoub *et al.*, 2017).

5. Finally, radiocarbon dating of charcoal should be mentioned as a possible method, which has been used widely elsewhere. However, it is often very hard to get any exposure of the historical lava beds in the Hekla area.

We find it likely that the age constraints can be improved on X1–X3 kīpukas along with some of the other potential historical kīpukas south of Hekla by investigating the distribution of the 1597, 1554, 1510, 1389, 1341 and 1206 tephra layers. The kīpukas northeast of Hekla, such as X4-X7 may be harder to constrain due to the abundant tephra fall and lack of soil formation. However, tephra layers such as 1766–1768, 1693, 1636, 1300, 1158 and 1104 may provide key constraints on these units. Otherwise, comparisons of the petrology of the lavas with well-constrained age could also help constrain the unidentified kīpukas in the north and east of Hekla.

CONCLUSIONS

New historical lava flow maps of Hekla volcano mapped in large scale (1:2000–10.000) are provided and can be downloaded in a digital format through the EMMIRS landscape portal (http://emmirs.is/landscape-portal/). Furthermore the maps will be available through the CEDA repository and the Catalogue of Icelandic volcanoes (http://icelandicvolcanos.is/). Orthophotos from 1945–1946 and 1960 provided an opportunity to produce a pre-1947 lava flow field map. Field observations of stratigraphy, soil profiles, tephra layers, and vegetation cover and composition further constrain the ages, and enable significant improvements in the understanding of the historical eruptive history of Hekla.

Flow fields produced during 16 eruptions have been identified, of which lava flow boundaries from the 1766–1768, 1725 and 1693 have been improved significantly compared to previous mapping efforts. More than 60 unidentified lava units are suggested to be of historical age, and they reveal that future work is necessary in order to get a more comprehensive view of the historical eruptions at Hekla.

Vents from historical eruptions are identified at distances of 0–16 km from Hekla. Vents have propagated up to 5 km from Hekla ridge during eruptions. Hence, there is an overlap in vent distance of 3–5 km between the basaltic fissure eruptions and eruptions that migrate out of Hekla ridge, which typically are more evolved.

The historical lava flow fields from Hekla reach up to 16 km from Hekla ridge and have flow lengths up to 20 km as exemplified with the 1300 lava flow field. However, lava flows from Hekla in the last 250 years (1766–1768, 1845, 1980, 1970) only have travelled 8–9 km.

The resurfacing rate at Hekla has been evaluated showing that within the 20th century the produced lava is sufficient to bury all of Hekla to a distance of 2 km from the main fissure whilst the last 250 yr could have buried all of Hekla to a distance of 4 km.

Acknowledgement

The authors would first and foremost like to acknowledge the Icelandic Research fund, Grant of Excellence No. 152266-052 (Project EMMIRS) for their financial support. Special thanks to Guðrún Larsen whose guidance on tephra layers was both impressive and invaluable, Guðrún Sverrisdóttir for sharing her detailed knowledge on Hekla area, and Egill Erlendsson for analyzing our settlement tephra samples. Extended thanks to Olgeir Sigmarsson, Bergrún Arna Óladóttir and Maxwell Brown taking the time to answer various questions. Landgræðsla ríkisins are thanked for their invaluable help during field work. Farmers at Næfurholt, Galtalækur and Selsund are also thanked for interesting observations and discussions of Hekla. Carsten Kristinsson, the National Land Survey of Iceland, is thanked for providing the historical stereo photographs and the German Space Agency (DLR) is thanked for providing TanDEM-X data through the Icelandic Volcanoes Supersite project supported by the Committee on Earth Observing Satellites.

Ágrip

Hekla hefur gosið 23 sinnum svo vitað sé síðan land byggðist. Oftast hafa gosin verið blandgos og framleitt bæði gjósku og hraun. Í gosum 20. aldar var hlutfall hrauns á milli 80–100% af gosefnunum svo þau skipta verulegu máli þegar framleiðni eldstöðvarkerfisins er metin. Í þessari grein eru birtar niður-

stöður stafrænnar kortlagningar á Hekluhraunum frá sögulegum tíma eins langt aftur í tímann og unnt er. Þetta er engan veginn auðvelt viðfangsefni á svo virku eldfjalli sem Hekla er, því ný hraun hylja þau sem fyrir eru. Hraunakortin eru gerð í mælikvarða 1:2000–10000 og styðjast við uppréttaðar loftmyndir sem teknar hafa verið síðan 1945, bæði fyrir og eftir síðustu fimm eldgos. Einnig er stuðst við innbyrðis afstöðu hraunanna, landslagsform, jarðvegssnið, gjóskulög og gróðurþekju. Tekist hefur að bæta talsvert hraunakort Heklu og gert hefur verið kort af hraunum sem runnu fyrir gosið mikla 1947. Hraun frá eldstöðvarkerfi Heklu á sögulegum tíma þekja u.þ.b. 233 km^2 lands. Hraun hafa runnið allt að 16 km vegalengd frá megineldstöðinni og hraunstraumar hafa náð 20 km lengd. Á síðustu 250 árum hafa hraun þó aðeins runnið 8–9 km frá megineldstöðinni. Eldvörp á sögulegum tíma dreifast allt að 16 km út frá megineldstöðinni. Í sumum gosum hefur eldvirknin færst um allt að 5 km út frá eldstöðinni þega leið á gosið. Borin hafa verið kennsl á hraun frá 16 gosum og að auki hafa um 60 hraunflákar verið kortlagðir sem gætu verið frá gosum á sögulegum tíma. Þessi hraun eru líklega frá þekktum gosum, s.s. 1222, 1341, 1510, 1597 og 1636 en þau gætu líka verið að einhverju leyti frá gosum sem þótt hafa vafasöm, á árunum 1436–1439.

REFERENCES

Arnalds, Ó. 2015. The Soils of Iceland. *World Soils Book Series.* Springer, Dordrecht, the Netherlands, 1–183. https://doi.org/10.1007/978-94-017-9621-7

Arnalds, Ó. and H. Óskarsson 2009. Íslenskt jarðvegskort. *Náttúrufræðingurinn* 78 (3-4), 107–121.

Arrighi, S., J. C. Tanguy and M. Rosi 2006. Eruptions of the last 2200 years at Vulcano and Vulcanello (Aeolian Islands, Italy) dated by high-accuracy archeomagnetism. *Physics Earth Planet. Int.* 159, 225–233.

Bárðarson, G. 1930. Vulkan-Ausbrüche in Island I. Vulkan-Ausbrüche in der Gegend der Hekla im Jahre 1913 (in German). *Soc. Sci. Islandica*, Rit 6, Reykjavík, 1–31.

Bjarnason, I. Th., P. Cowie, M. H. Anders, L. Seeber and C. H. Scholz 1993. The 1912 Iceland earthquake rupture: Growth and development of a nascent transform system. *Bull. Seismol. Soc. Am.* 83, 416–435.

Brynjólfsson, A. 1959. Staðsetning fornbýlanna Skarðs eystra og Tjaldastaða á grundvelli nýrra rannsókna. *Náttúrufræðingurinn* 29 (3), 133–153.

Buck, W. R., P. Einarsson and B. Brandsdóttir 2006. Tectonic stress and magma chamber size as controls on dike propagation: Constraints from the 1975–1984 Krafla rifting episode. *J. Geophys. Res.* 111, B12404, 1–15. https://doi.org/10.1029/2005JB003879

Dall, J. 2003. Cross-calibration of interferometric SAR data. *IEEE Proc. Radar, Sonar and Navigation* 150(3), 177–183. https://doi.org/10.1049/ip-rsn:20030448

Dugmore, A. J., M. J. Church, K.-A. Mairs, T. H. McGovern, S. Perdikaris and O. Vesteinsson 2007. Abandoned farms, volcanic impacts, and woodland management: Revisiting Thjorsardalur, the "Pompeii of Iceland". *Arctic Anthropology* 44, 1, 1–11. https://doi.org/10.1353/arc.2011.0021

Einarsson, P. 2015. Mechanisms of earthquakes in Iceland. *Encyclopedia of Earthquake Engineering.* Beer, M., E. Patelli, I. A. Kougioumtzoglou and S.-K. Au (eds.). https://doi.org/10.1007/978-3-642-36197-5_298-1. Springer Verlag, Berlin, Heidelberg.

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

Geirsson, H., P. LaFemina, Th. Arnadottir, E. Sturkell, F. Sigmundsson, M. Travis, P. Schmidt, B. Lund, S. Hreinsdottir and R. Bennett 2012. Volcano deformation at active plate boundaries: deep magma accumulation at Hekla volcano and plate boundary deformation in south Iceland. *J. Geophys. Res.* 117, B11409, 1–18. https://doi.org/10.1029/2012JB009400

Gronvold, K., G. Larsen, P. Einarsson, S. Thorarinsson and K. Saemundsson 1983. The Hekla eruption 1980–1981. *Bull. Volcanol.* 46, 349, 349–363. https://doi.org/10.1007/BF02597770.

Gudmundsson, M. T., K. Jónsdóttir, A. Hooper, E. P. Holohan, S. A. Halldórsson, B. G. Ófeigsson, S. Cesca, K. S. Vogfjörd, F. Sigmundsson, Th. Högnadóttir, P. Einarsson, O. Sigmarsson, A. H. Jarosch, K. Jónasson, E. Magnússon, S. Hreinsdóttir, M. Bagnardi, M. Parks, V. Hjörleifsdóttir, F. Pálsson, T. R. Walter, M. P.J. Schöpfer, S. Heimann, H. I. Reynolds, S. Dumont, E. Bali, G. H. Gudfinnsson, T. Dahm, M. Roberts, M. Hensch, J. M.C. Belart, K. Spaans, S. Jakobsson, G. B. Gudmundsson, H. M. Fridriksdóttir, V. Drouin, T. Dürig, G. Adalgeirsdóttir, M. S.

Riishuus, G. B. M. Pedersen and T. van Boeckel 2016. Gradual caldera collapse at Bárdarbunga volcano, Iceland, regulated by lateral magma outflow. *Science* 353, aaf8988. https://doi.org/10.1126/science.aaf8988.

Guðmundsson, V. 1952. Eyðibýli og auðnir á Rangárvöllum. *Árbók hins íslenzka fornleifafélags* 1951–1952, 91–164.

Guðmundsson, V. 1954. Eyðibýli og auðnir á Rangárvöllum. *Árbók hins íslenska fornleifafélags* 1953, 5–79.

Gudmundsson, A., N. Oskarsson, K. Gronvold, K. Sæmundsson, O. Sigurdsson, R. Stefansson, S. Gislason, P. Einarsson, B. Brandsdottir, G. Larsen, H. Johannesson and T. Thordarson 1992. The 1991 eruption of Hekla, Iceland. *Bull. Volcanol.* 54, 238–246. https://doi.org/10.1007/BF00278391

Hreiðarsdóttir, E. Ó., G. A. Gísladóttir, K. Þórisdóttir and R. G. Gylfadóttir 2015. Abandoned settlements at the foot of Mt. Hekla: A study based on field survey in Rangárvellir. *Archaeologia Islandica* 11, 33–56.

Höskuldsson, A., N. Óskarsson, K. Vogfjörd, K. Gronvold, R. Pedersen and R. Ólafsdóttir 2007. The millennium eruption of Hekla in February 2000. *Bull. Volcanol.* 70, 169–182. https://doi.org/10.1007/s00445-007-0128-3.

Jakobsson, S. P. 1979a. Petrology of Recent basalts from the eastern volcanic zone, Iceland. *Acta Naturalia Islandica* 26, 1–103.

Jakobsson, S. P. 1979b. Outline of the petrology of Iceland. *Jökull* 29, 57–73.

Jóhannesson, H. 1994. Heklugosið 1510. Skaðvaldur í byggðum Suðurlands. Skjálftastefna 30. apríl 1994. Ágrip. *Rannsóknir á jarðfræði og jarðskjálftum Suðurlands*, 6–7.

Kaldal, I., Á. Hjartarson, K. Sæmundsson, M. Á. Sigurgeirsson and S. Víkingsson 2018. *Jarðfræðikort af Austurgosbelti - Tungnaáröræfi* 1:100.000. Íslenskar orkurannsóknir, Landsvirkjun og Umhverfis- og auðlindaráðuneytið, Reykjavík.

Kjartansson, G. 1945. Hekla. *Árbók Ferðafélags Íslands*, Reykjavík, 1–155.

Larsen, G. 1984. Recent volcanic history of Veiðivötn fissure swarm, Southern Iceland. An approach to volcanic risk assessment. *Volcanol. Geotherm. Res.* 22, 33-58. https://doi.org/10.1016/0377-0273(84)90034-9

Larsen, G., G. Sverrisdóttir, H. Jóhannesson, A. Hjartarson and P. Einarsson 2013. Hekla. In *Náttúruvá á Íslandi.* Sólnes, J., F. Sigmundsson and B. Bessason (eds.). Viðlagatrygging Íslands/ Háskólaútgafan, Reykjavík, Iceland, 189–209.

Magnússon, E. 2003. *Airborne SAR data from S-Iceland: analyses, DEM improvements and glaciological application.* Master's thesis, Department of Physics, University of Iceland, 130 pp.

Magnússon, E., J. M. C. Belart, F. Pálsson, H. Ágústsson and P. Crochet 2016. Geodetic mass balance record with rigorous uncertainty estimates deduced from aerial photographs and lidar data. Case study from Drangajökull ice cap, NW Iceland. *The Cryosphere* 10, 159–177. https://doi.org/10.5194/tc-10-159-2016

Mahgoub, A. N., H. Böhnel, C. Siebe, S. Salinas and M.-N. Guilbaud, 2017. Paleomagnetically inferred ages of a cluster of Holocene monogenetic eruptions in the Tacámbaro-Puruarán area (Michoacán, México): implications for volcanic hazards. *J. Volcanol. Geotherm. Res.* 347, 360–370. https://doi.org/10.1016/j.jvolgeores.2017.10.004

Mankasingh, U., and G. Gísladóttir 2018. Early indicators of soil formation in the Icelandic sub-arctic highlands. *Geoderma* 337, 152–163. https://doi.org/10.1016/j.geoderma.2018.09.002.

Montalvo, J. 2013. *Evaluation of lava flow volumes from Hekla volcano based on new topographic data.* Master's thesis, Faculty of Earth Sciences, University of Iceland, 48 pp.

Ofeigsson, B. G., A. Hooper, F. Sigmundsson, E. Sturkell and R. Grapenthin 2011. Deep magma storage at Hekla Volcano, Iceland, revealed by InSAR time series analysis. *J. Geophys. Res.* 116, B05401, 1–15. https://doi.org/10.1029/2010JB007576

Pedersen, G. B. M., J. M. C. Belart, E. Magnusson, O. K. Vilmundardóttir, F. Kizel, F. S. Sigurmundsson, G. Gísladóttir and J. A. Benediktsson 2018. Hekla volcano, Iceland, in the 20th century: Lava volumes, magma supply and effusion rates. *Geophys. Res. Lett.* 45, 1805–1813, doi:https://doi.org/10.1002/2017GL076887

Pedersen, G. B. M., O. K. Vilmundardóttir, F. Kizel, J. M. C. Belart, N. Falco, F. S. Sigurmundsson, R. Rustowicz, G. Gísladóttir and J. A. Benediktsson in prep. *Open benchmark repository of the Hekla volcano.*

Pinton, A., G. Giordano, F. Speranza and T. Thordarson 2018. Paleomagnetism of Holocene lava flows from the Reykjanes Peninsula and the Tungnaá lava sequence (Iceland): implications for flow correlation and ages. *Bull. Volcanol.* 80, 10. https://doi.org/10.1007/s00445-017-1187-8

Rizzoli, P., M. Martone, C. Gonzalez, C. Wecklich, D. Borla Tridon, B. Bräutigam, M. Bachmann, D. Schulze, T. Fritz, M. Huber, B. Wessel, G. Krieger, M. Zink and A. Moreira 2016. Generation and performance assessment of the global TanDEM-X digital elevation model. *ISPRS J. Photogramm. Remote Sens.* 132, 119–139, ISSN 0924-2716. https://doi.org/10.1016/j.isprsjprs.2017.08.008

Saemundsson, K. 1978. Fissure swarms and central volcanoes of the neovolcanic zones of Iceland. *Geol. J. Spec. Iss.* 10, 415–432.

Schythe, J. C. 1847. *Hekla og dens sidste Udbrud.* Bianco Lunos bogtrykkeri, Köbenhavn, 1–155.

Sigmarsson, O., M. Condomines and S. Fourcade 1992. A detailed Th, Sr and O isotope study of Hekla: Differentiation process in an Icelandic volcano. *Contrib. Mineral. Petrol.* 112, 20–34. https://doi.org/10.1007/BF00310953

Sigmundsson, F., S. Hreinsdóttir, A. Hooper, Th. Árnadóttir, R. Pedersen, M. J. Roberts, N. Óskarsson, A. Auriac, J. Decriem, P. Einarsson, H. Geirsson, M. Hensch, B. G. Ófeigsson, E. Sturkell, H. Sveinbjörnsson and K. L. Feigl 2010. Intrusion triggering of the 2010 Eyjafjallajökull explosive eruption. *Nature* 468, 426–430. https://doi.org/10.1038/nature09558

Sigmundsson, F., A. Hooper, S. Hreinsdóttir, K.S. Vogfjörd, B. G. Ófeigsson, E. R. Heimisson, S. Dumont, M. Parks, K. Spaans, G. B. Guðmundsson, V. Drouin, T. Árnadóttir, K. Jónsdóttir, M. T. Gudmundsson, T. Högnadóttir, H. M. Fridriksdóttir, M. Hensch, P. Einarsson, E. Magnússon, S. Samsonov, B. Brandsdóttir, R. S. White, T. Ágústsdóttir, T. Greenfield, R. G. Green, Á. R. Hjartardóttir, R. Pedersen, R. A. Bennett, H. Geirsson, P. C. La Femina, H. Björnsson, F. Pálsson, E. Sturkell, C. J. Been, M. Möllhoff, A. K. Braiden and E. P. S. Eibl 2015. Segmented lateral dyke growth in a rifting event at Bárðarbunga volcanic system, Iceland. *Nature* 517, 191–195, https://doi.org/10.1038/nature14111.

Soosalu, H. and P. Einarsson 2004. Seismic contraints on magma chambers at Hekla and Torfajökull volcanoes, Iceland. *Bull. Volcanol.* 66, 276–286. https://doi.org/10.1007/s00445-003-0310-1

Soosalu, H. and P. Einarsson 2005. Seismic characteristics of the Hekla volcano and its surroundings, Iceland. *Jökull* 55, 87–106.

Sturkell, E., K. Ágústsson, A. T. Linde, S. I. Sacks, P. Einarsson, F. Sigmundsson, H. Geirsson, R. Pedersen, P. C. LaFemina and H. Ólafsson 2013. New insights into volcanic activity from strain and other deformation data for the Hekla 2000 eruption. *J. Volcanol. Geotherm. Res.* 256, 78–86. https://doi.org/10.1016/j.jvolgeores.2013.02.001

Sverrisdóttir, G. 2007. Hybrid magma generation preceding Plinian silicic eruptions at Hekla, Iceland: Evidence from mineralogy and chemistry of two zoned deposits. *Geol. Mag.* 144, 643–659. https://doi.org/10.1017/S0016756807003470

Tanguy, J. C., M. Condomines, M. Le Goff, V. Chillemi, S. L. Delfa and G. Patané 2007. Mount Etna eruptions of the last 2,750 years: revised chronology and location through archeomagnetic and ^{226}Ra-^{230}Th dating. *Bull. Volcanol.* 70, 55–83. https://doi.org/10.1007/s00445-007-0121-x

Thorarinsson, S. 1950. The eruption of Mt. Hekla 1947–1948. *Bull. Volcanol.* 10, 157–168. https://doi.org/10.1007/BF02596085

Thórarinsson, S. 1967. *The eruption of Hekla 1947–1948 I: The eruptions of Hekla in historical times. A tephrochronological study.* Soc. Sci. Islandica, Reykjavík, 1–171.

Thórarinsson, S. 1970. *Hekla.* 54 pp. Reykjavík, Almenna Bókafélagið.

Thórarinsson, S. 1976. *The eruption of Hekla 1947–1948 IV: Course of events.* Soc. Sci. Islandica, Reykjavik, 1–44.

Thórarinsson, S. and G. E. Sigvaldason 1972. The Hekla eruption of 1970. *Bull. Volcanol.* 36, 269–288. https://doi.org/10.1007/BF02596870

Thordarson, T. and G. Larsen 2007. Volcanism in Iceland in historical time: Volcano types, eruption styles and eruptive history. *J. Geodynamics* 43, 118–152. https://doi.org/10.1016/j.jog.2006.09.005

Thoroddsen, Þ. 1925. *Die Geschichte der Isländischen Vulkane* (In German). D. Kgl. Danske Vidensk. Selsk. Skrifter, Naturvidensk. og Mathem. Afd., 8. Række, IX, 458 pp., Copenhagen.

Vilmundardóttir, O. K., F. S. Sigurmundsson, G. B. M. Pedersen, J. M.-C. Belart, F. Kizel, N. Falco, J. A. Benediktsson and G. Gísladóttir 2018. Of mosses and men: Plant succession, soil development and soil carbon accretion in the sub-Arctic volcanic landscape of Hekla, Iceland. *Progress in Physical Geography.* https://doi.org/10.1177/0309133318798754