

The Katla volcano S-Iceland: Holocene tephra stratigraphy and eruption frequency

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Abstract — *The Katla volcano of the Eastern Volcanic Zone (EVZ) is characterised by subglacial explosive eruptions of Fe-Ti basalts. The Holocene eruption history and magma evolution at Katla volcano is assessed based on the stratigraphy and major-element composition of tephra layers in a composite soil section east of the volcano. A total of 208 tephra layers were found, 18 layers are of historical age and 190 are prehistoric, deposited during the last ~8400 years. Of the 208 layers, 126 were analyzed for major-element composition. Of those 126 tephra layers, 102 are typical Katla Fe-Ti basalts, another 7 are Fe-Ti basalt layers containing rare grains of silicic composition, and 2 layers are basaltic icelandites with high Fe-Ti content. Ten silicic Katla (SILK) tephra layers were also identified in the composite section. An age model for the section was constructed using soil accumulation rate (SAR) between tephra layers previously dated by the ¹⁴C method. According to the tephrochronology on the east side of the volcano, the prehistoric eruption frequency is higher than that of historical time by a factor of 2. In view of the knowledge that prehistoric Katla tephra layers were also dispersed to the south, west and north of the volcano, the true prehistoric eruption frequency is likely to be as high as 4 events/100 years. Moreover, if prevailing wind directions have not changed much during the Holocene, over 300 explosive basalt eruptions are likely to have occurred at the Katla volcano in the last 8400 years. The highest eruption frequency of basalt is observed between 2.5 to 4.5 ka and between 7.0 to 8.5 ka. Both these periods correspond to main peaks in eruption frequency of the silicic SILK layers. Finally, abrupt shifts in magma compositions divide the ~8400 years record into eight intervals of 500-1700 year duration, designated with either a constant composition, irregular or systematic variations of major-element composition with time.*

INTRODUCTION

The majority of Holocene and Quaternary tephra in North Europe originate in Iceland despite the dominance of basaltic volcanism. Many of the most active volcanoes are capped by or covered by glaciers and, consequently, subglacial eruptions driven by explosive water-magma interactions are common in Iceland. Such eruptions are the characteristic style of activity at the three most active basalt-dominated cen-

tral volcanoes in Iceland; the Grímsvötn, Bárðarbunga and Katla volcanoes of the Eastern Volcanic Zone (e.g. Thorarinsson, 1974, 1975; Larsen; 2000, Larsen *et al.*, 1998; Hafliðason *et al.*, 2000). Phreatomagmatic eruptions at these volcanoes and on their associated fissure swarms have produced some of the most widespread basaltic tephra layers of the Holocene era, which include historical eruptions of the Katla volcano 1755 AD and 1625 AD (e.g. Thorarinsson,

1981), Veiðivötn 1477 AD and Vatnaöldur ~870 AD (Larsen, 1984) and the prehistoric 10,300 year old Saksunarvatn eruption (Mangerud *et al.*, 1986; Jóhannesdóttir *et al.*, 2005). Another major contributor to formation of Holocene tephra layers in Iceland is the Hekla volcano in S-Iceland, which is also located in the Eastern Volcanic Zone and is characterized by intermediate to silicic volcanism (e.g. Thorarinnsson, 1967, 1981; Larsen and Thorarinnsson, 1977; Dugmore *et al.*, 1995a). All of the abovementioned volcanoes are located in the Eastern Volcanic Zone (EVZ), (Figure 1). In the following, “Katla volcano” (or Katla) refers to the ice-covered central volcano, and “Katla volcanic system” (or Katla system) refers to both the central volcano and the associated fissure swarm.

Icelandic soils contain a record of explosive volcanism in the form of tephra layers extending back 8–9000 years (7–8000 ¹⁴C years BP, e.g. Larsen 2000; Hafliðason *et al.*, 2000). In lake sediments the record can reach as far back as 10–12,000 years (9–10,500 ¹⁴C years BP, e.g. Björck *et al.*, 1992; Jóhannesdóttir *et al.*, 2005). It is a custom to divide the tephra record into two groups; the historical part, covering the period since the Viking settlement (870 AD to present), and the prehistoric part, which refers to all Holocene tephra layers pre-dating the Viking settlement. The Holocene tephra record is a valuable source of information on the postglacial eruption history in Iceland and is a very reliable record for constructing the longer-term eruption history at a given volcano. It also provides the means for assessing the nature of eruptive activity and magma evolution over specific time periods.

The aim of this study is to evaluate the history and eruption frequency of the Katla volcanic system during the Holocene. This was accomplished by detailed logging and sampling of closely spaced soil profiles that contain a record of explosive volcanism at Katla volcano over the last 8.4 ka. The Holocene tephra stratigraphy of the region is presented and we use pre-existing ¹⁴C-dates of tephra layers (Table 1) in conjunction with the calculated soil accumulation rate (SAR) to establish a comprehensive chronology for the tephra layers preserved in the soils to the east

of the volcano. Major-element composition is the key criterion used to identify the source volcano for individual tephra layers. It is shown that eruption frequency and compositional variations are greater in the prehistoric era compared to that in historical time.

KATLA VOLCANIC SYSTEM: GEOLOGIC SETTING AND ERUPTION HISTORY

The Katla volcanic system is situated in the southern sector of the Eastern Volcanic Zone (EVZ) in South-Iceland and takes its name from the notorious subglacial Katla fissure. The 80-km-long system is made up of an ice-capped central volcano and an associated SW-NE trending fissure swarm (Jakobsson 1979; Figure 1). The central volcano (1450 m), is the second largest of its kind in Iceland and features a 110 km² ice-filled summit caldera that is up to 700 m deep (Björnsson *et al.*, 2000). The Katla fissure, which is the inferred source vent for all historical eruptions at the volcano since the 12th century, is situated in the southern part of the caldera. The fissure swarm is demarcated by SW-NE and E-W trending volcanic fissures of Holocene and historical age and represents the ice-free part of the system (Figure 1). Furthermore, the available data indicates that the system has been characterized by Fe-Ti basalt volcanism throughout its history and felsic rocks of intermediate and silicic compositions represent a minor component in the erupted products (e.g. Jakobsson, 1979; Larsen, 1979; Jóhannesson and Sæmundsson, 1998; Lacasse *et al.*, 1995; Hildebrand *et al.*, 1998; Larsen *et al.*, 2001; Thordarson *et al.*, 2001).

Katla volcanic system is the second most active system in Iceland during historical time, with 21 recorded eruptions since 870 AD. The established chronology reveals 1–3 eruptions per century, with an average repose time of 48 years (range, 13–95 years) between events (Larsen, 2000). Twenty of the historical eruptions were explosive subglacial basalt eruptions that took place on fissures within or along the periphery of the caldera. These eruptions have produced widespread tephra layers with volume ranging from 0.02 to 1.5 km³ (Thorarinnsson, 1975; Larsen, 2000).

Holocene tephra stratigraphy and eruption frequency of Katla, S-Iceland

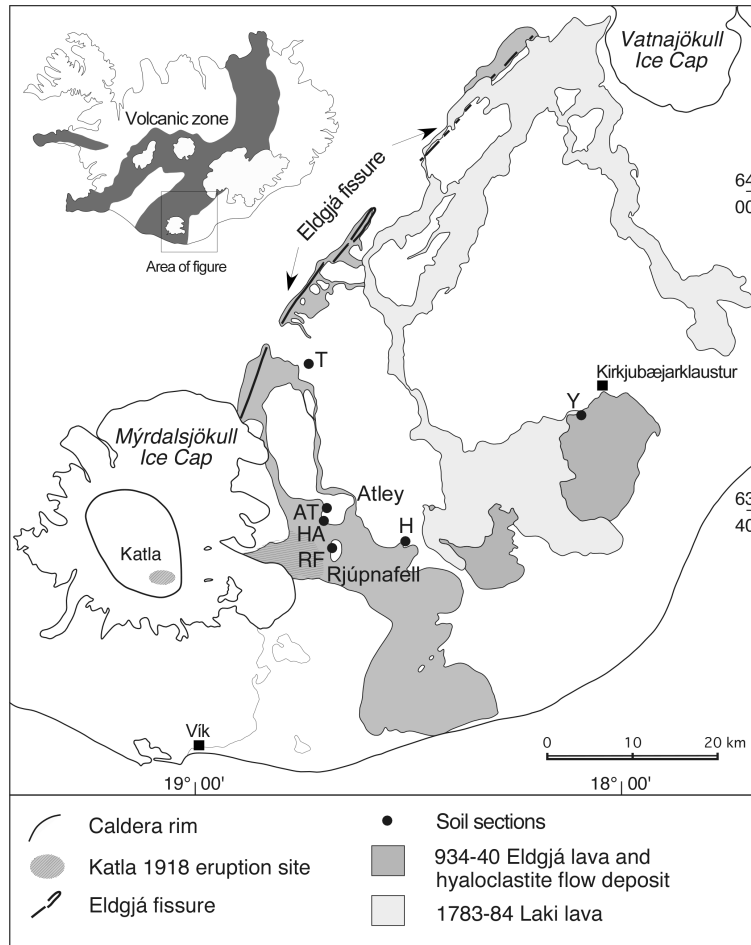


Figure 1. A map of the study area showing the location of the measured soil profiles. The prehistoric tephra stratigraphy was documented in profiles at Atley (AT and HA) and Rjúpnafell (RF), whereas the historical tephra stratigraphy was obtained from profiles at Hrífunes (H), Ytri-Dalbær (Y) and Tjaldgilsháls (T). – *Kort af rannsóknarsvæðinu og nágrenni. Jarðvegssnið með forsögulegum gjóskulögum voru mæld og sýnum safnað á tveim stöðum í Atley (AT og HA) og í Rjúpnafelli (RF). Sýni af gjóskulögum frá sögulegum tíma eru úr jarðvegssniðum á Tjaldgilshálsi (T), Ytri Dalbæ (Y) og Hrífunesi (H) (Guðrún Larsen 1981).*

The only historical eruption in the Katla system outside of the central volcano was the 934–940 AD Eldgjá Fires, which is the largest known flood-lava eruption on Earth during the historical period. The eruption took place on a discontinuous 75 km-long SW-NE trending volcanic fissure that produced 18.2 km³ of lava and 1.4 km³ (DRE) of tephra (Larsen, 2000; Thordarson *et al.*, 2001). In the context of this outline

of historical activity on the Katla system, it is worth noting that 87 years have passed since the last visible eruption (i.e. 1918). Increased precursor activity within the volcano in recent years suggests that an eruption may be imminent.

Although much less is known about the prehistoric eruption history of the Katla system, the style and nature of the activity during the Holocene ap-

Table 1. a) Key marker tephra layers in the study area. Also shown are published ¹⁴C-ages, calibrated years, and source volcanic system for each tephra layer (Larsen *et al.*, 2001; Dugmore *et al.*, 1995b; Grönvold *et al.*, 1995). b) Estimated ¹⁴C age of key tephra layers and Hólmsár Fires from their relative position compared to dated tephra layers (Larsen *et al.*, 2001), calibrated after Stuiver *et al.*, (1998) assuming a standard deviation of 100 years. An eruption age based on the SAR-method (see discussion in text) is also given for those tephra layers that have not been dated by the radiocarbon method. – a) *Tímasett lykilgjóskulög á rannsóknasvæðinu, aldur þeirra og uppruni (Guðrún Larsen og fl., 2001; Andrew Dugmore og fl., 1995; Karl Grönvold og fl., 1995). Taflan sýnir geislakolsaldur og leiðréttan aldur samkvæmt trjáhringjatali (Stuiver og fl., 1998). Í næstsíðasta dálki er aldur miðaður við árið 2005 (ekki 1950). b) Lykillög af áætluðum aldri miðað við tímasett gjóskulög og áætlaður aldur Hólmsárelda (Guðrún Larsen og fl., 2001). Taflan sýnir geislakolsaldur (gert er ráð fyrir ±100 ára staðalfrávik) og leiðréttan aldur fjögurra lykillaga á sama hátt og í 1a), aldur í árum fæst með að bæta 2005 árum við tölur í fjórða dálki. Reiknaður aldur, byggður á jarðvegsþykknun (SAR) milli tímasettra lykillaga, er hins vegar 90–195 árum hærri, eins og sýnt er í fimmta dálki.*

| Tephra layer | Log number | Publ. ¹⁴ C age ¹ | Calibr./calend. year ² | Cal. age bf 2005 AD | Volcanic system |
|--------------|------------|--|-----------------------------------|---------------------|-----------------|
| Settlement | AT-2 | | ~870 AD | 1135 years | Veidivötn |
| SILK-UN | AT-49 | 2660±50 BP | 850±70 BC | ~2855 years | Katla (SILK) |
| SILK-MN | AT-65 | 2975±12 BP | 1230±30 BC | ~3235 years | Katla (SILK) |
| SILK-LN | AT-70 | 3139±40 BP | 1440±75 BC | ~3445 years | Katla (SILK) |
| HS | AT-80 | 3515±55 BP | 1855±125 BC | ~3860 years | Hekla |
| H4 | HA-1 | 3826±12 BP | 2255±55 BC | ~4260 years | Hekla |
| Katla | RF-5 | 6400±80 BP | 5360±130 BC | ~7365 years | Katla |
| A13 | RF-44 | 7505±42 BP | 6380±55 BC | ~8385 years | Torfajökull? |

¹Age values are given relative to the calendar year 1950.

²Calibrated after Stuiver *et al.*, (1998).

| Tephra layer | Log number | Estim. ¹⁴ C age ¹ | Estim. calibr. year ² | SAR age bf 2005 AD ³ | Volcanic system |
|--------------|------------|---|----------------------------------|---------------------------------|-----------------|
| SILK-N2 | HA-11 | ~4200 BP | ~2790 BC | ~4960 years | Katla (SILK) |
| SILK-N1 | HA-27 | ~4900 BP | ~3730 BC | ~5830 years | Katla (SILK) |
| SILK-A1 | HA-30 | ~5000 BP | ~3810 BC | ~6010 years | Katla (SILK) |
| A6 | RF-1 | | | ~7130 years | Torfajökull |
| Hólmsár Fire | RF-14? | ~6800 BP | ~5680 BC | ~7560 years | Katla |

¹Larsen *et al.*, (2001).

²Estimated ¹⁴C age calibrated by the method of Stuiver *et al.*, (1998)

³Calculated age with the SAR method (see text for further details)

pears to be similar to that observed in historical times. The number of Holocene subglacial explosive eruptions at the Katla volcano was previously estimated to have exceeded 180 eruptions, of which > 170 are basaltic, and 12 are felsic (Larsen, 2000). In contrast, the ice-free part of the system, or the fissure swarm outside the central volcano, has had a much lower

eruption frequency, or only 8–12 effusive basalt eruptions during the Holocene. Nonetheless, the activity on the fissure swarm includes the two largest events in the Katla system; the Hólmsá Fires ~7700 years ago (≥5 km³) in addition to the above mentioned Eldgjá Fires (Larsen, 2000).

A principal difference between the activity in historical and prehistoric times is that in the latter period the Katla volcano produced dacitic (SILK) tephra along with the typical basaltic activity. These SILK layers were produced over a period of ~6000 years, extending from ~7600 to ~1600 years ago and corresponding to ~6600 to ~1680 ¹⁴C years BP (Larsen *et al.*, 2001).

METHODS

Field methods and criteria

In order to obtain a representative composite tephra section, selection of suitable soil profiles is critical. Firstly, such profiles have to be located at an appropriate distance from the source volcano. Close to a volcano the tephra is often deposited on barren ground, increasing the likelihood of erosion and reworking of the primary fall. This decreases the preservation potential of individual layers and may also result in significant contamination between adjacent tephra layers. On the other hand, a soil section too far from the source volcano will not include tephra fall from low-intensity eruptions due to their limited dispersal. Secondly, the topography has to be favourable. Tephra layers are best preserved in topographic lows which commonly act as sediment traps ensuring rapid burial of the tephra. Thirdly, the sections should contain tephra layers that show minimal post-depositional reworking and disturbance, i.e. contain the primary facies of the tephra fall.

The macroscopic characteristics that are used to distinguish individual tephra layers are a function of several factors. The colour of the tephra is a direct function of chemical composition, changing from black to white with increasing silica. Properties such as grain size and size distribution, sorting and clast shapes are symptomatic of the nature of the explosive activity that produced the layer. The type and content of crystals and lithics are also diagnostic features in some tephra layers (Table 2a, 2b). Felsic tephra layers are readily identified in Icelandic soils by their light colour and are therefore ideal key marker horizons for correlation between outcrops. The soils of the study area include over 20 felsic tephra layers formed by ex-

plosive eruptions at the Katla, Hekla, Torfajökull, and Öræfajökull volcanoes.

Table 2a: Criteria used during field measurements. a) Grain size classification. – *Einkenni notuð við greiningu gjóskulaga á vettvangi. a) Kornastærðir.*

| Grain size (mm) | Nomenclature |
|-----------------|------------------|
| >64 | Blocks and bombs |
| 32–64 | Coarse lapilli |
| 16–32 | Medium lapilli |
| 2–16 | Fine lapilli |
| 1–2 | Coarse ash |
| 0,064–1 | Medium ash |
| <0,064 | Fine ash |

The principal historical marker tephra layers found in the study area east of Katla volcano (Figure 1) originate from Hekla (H), Veiðivötn (V), Öræfajökull (Ö) and Eldgjá (E). The historical part of the tephra stratigraphy includes 7 key marker layers. From the youngest to the oldest, these are: H-1845, a brown andesite tephra consisting of very coarse ash; H-1597, an andesite layer composed of bluish-black fine ash; V-1477, a distinct basaltic tephra layer made up of greyish-green to greyish-brown fine ash; H-1389, a brown andesite layer comprised of coarse ash; Ö-1362, a yellow-white (rhyolite) very-fine to fine ash that is present as a sub-centimetre-thick discontinuous layer; H-1206 is olive-grey fine ash of andesitic/dacitic composition; and finally the basaltic tephra of E-934, a black to brown bedded layer of lapilli and ash (Thordarson *et al.*, 1998; Larsen, 2000). The Vatnaöldur tephra, the basaltic component of the Settlement Layer, formed in a phreatomagmatic fissure eruption in the Veiðivötn volcanic system around 870 AD (Larsen, 1984; Grönvold *et al.*, 1995; Zielinski *et al.*, 1997), is a prominent marker layer that marks the transition from historical to prehistoric times. It is readily distinguished in soil profiles of the area studied by its greenish-grey to greenish-black colour and its relatively high proportion of plagioclase crystal fragments.

In all, seven prehistoric tephra layers found in the study area have been dated by the radiocarbon method, six felsic and one basaltic (RF4), and five ad-

ditional tephra layers have been assigned an approximate radiocarbon age (Table 1a, 1b; Larsen *et al.*, 2001). A total of four silicic Hekla layers have been identified in the prehistoric part of the studied section: HM, HN, HS and H4. They are all characterised by light-coloured lower parts and bluish-black upper parts (Figure 2). The last two tephra layers have been dated, having ages of ~ 3860 and ~ 4260 years, respectively (^{14}C -age of 3515 ± 55 and 3826 ± 12 years BP, Table 1a; Larsen *et al.*, 2001; Dugmore *et al.*, 1995b). The HM and HN tephra layers have not been dated but their stratigraphic position indicates an age of ~ 3000 years. The soil thickness between them and the SAR derived in this study indicates that these two layers were formed by eruptions separated by ~ 50 years.



Figure 2. An example of a marker tephra layer: H4 (3826 ± 12 years BP; Dugmore *et al.*, 1995b) from the Hekla volcano, S-Iceland. – *Dæmi um leiðarlag, Heklugjóskulagið H4 (3826 ± 12 geislakolsára, Andrew Dugmore og fl. 1995b) í jarðvegssniði í Atley.*

Two of the felsic marker layers, labelled A6 and A13 by Larsen *et al.*, (2001), are distinguished by white pumice grains in a matrix of olive-grey ash. The latter has an age of ~ 8380 years (^{14}C age of 7505 ± 42 years BP, Larsen *et al.*, 2001), whereas the former has an estimated eruption age of ~ 7100 years (calculated from SAR).

Other layers that are readily recognised include the dacitic SILK layers from the Katla volcano. These layers are characterised by their olive-green colour and needle-like pumice grains that resemble chips

of wood, making these layers unique among the Holocene felsic tephra layers in Iceland. Ten SILK layers have been identified in the study area and three of those (SILK-UN, -MN, -LN) have been dated, having ages of ~ 2855 , ~ 3235 and ~ 3445 years, respectively, (^{14}C age of 2660 ± 50 , 2975 ± 12 and 3139 ± 40 BP, Table 1a; Larsen *et al.*, 2001).

Basaltic tephra layers from the Katla volcano are readily distinguished from other basaltic tephra layers by their brownish-black to coal-black colour and components. They consist of poorly- to highly-vesicular ash- to lapilli-size glass grains (Table 2a) characterised by curvi-planar fracture surfaces. Clasts with fluidal surfaces (i.e. achneliths as defined by Walker and Croasdale, 1972) are present in most tephra layers, but in minor amounts. The glass grains contain 1-5 modal% phenocrysts and groundmass crystals of plagioclase, olivine, clinopyroxene and rare magnetite. Crystalline mafic and felsic wall-rock lithics, as well as hyaloclastite, and crystal fragments of plagioclase and olivine, are present in very trace amounts ($< 1\%$).

Construction of the composite soil section

The composite tephra profile measured and sampled in this study contains the prehistoric part of the tephra succession as preserved in soil profiles east of the Katla volcano (Figures 1 and 3). The historical part of the succession, with at least 18 tephra layers from various sources, was previously sampled and analysed by Larsen (1981, 2000). Twenty-one historical tephra layers produced by the Katla volcanic system are known from soil sections around the volcano (~ 870 AD to 1918 AD). Ten historical Katla layers and the Eldgjá tephra layer have been identified east of the Katla volcano (Larsen, 1981, 2000). For this study, nine historical Katla layers were analysed from three separate soil sections: at Hrífunes, about 8 km south-east of Atley; at Tjaldgilsháls, about 20 km northwest of Atley; and at Ytri-Dalbær, about 30 km east-north-east of Atley (Figure 1).

The prehistoric tephra section is a composite one, stitched together from three separate sections measured at closely-spaced locations. The three locations are Atley (AT and HA) and Rjúpnafell (RF) (Figures 3a-3d). This composite section has an accumu-

Table 2b: Criteria used during field measurements. b) Key parameters used for describing tephra layers in a soil profile. – *Einkenni notuð við greiningu gjóskulaga á vettvangi. b) Önnur útlitseinkenni (þykkt gjóskulags, snertifletir gjósku og jarðvegs, litur gjósku, kornastærð, byggingareinkenni gjóskulags, bergbrot, annað).*

| Parameters | Description |
|-------------------------|---|
| Thickness | Three to five thickness measurements were done on each layer to obtain an average value and information on minimum and maximum thickness in any one section. Tephra thickness values are a function of eruption intensity and/or distance from the main dispersal axis. |
| Contacts | Pristine sub-aerial tephra fall deposits have sharp and non-erosional contacts. Deviations may suggest post-depositional reworking. |
| Colour | Colour of tephra layers reflects their composition. Basaltic tephra layers are typically black, brownish-black, or greyish black, whereas tephra layers of intermediate compositions are brown to greyish brown. Felsic layers are typically light coloured, with colours changing from olive-grey to light grey to yellowish-white to white in accordance with increasing SiO ₂ contents. |
| Grain size | Estimates of mean grain size and sorting for each layer, classification of grain types and measurements of five largest grains were used to obtain qualitative information on the eruption type and intensity. |
| Depositional structures | Internal bedding (stratification), bed-forms, size grading and fabric provided information on modes of transport and deposition (i.e. the part representing the primary fall versus that produced by local reworking of deposits). In case of primary tephra fall deposits internal stratification may reflect changes in eruption style or continuity of the activity, whereas size grading may reflect changes in eruption intensity. |
| Rock components | The relative abundance of pyroclasts and other accessory components, such as wall-rock lithics and crystal fragments, was documented and can be useful indicator of eruption type and style. |
| Other | Observations that provide further information about the impact on the local environment (i.e. presence of tree trunks/molds or material of archaeological significance). |

lated thickness of ~980 cm and provides a continuous record spanning ~7300 years from ~1100–8400 years ago (Figures 4a, 4b). The uppermost part of the prehistoric tephra succession is preserved in a continuous profile at Atley, which for sake of convenience was divided into 4 sections (Figures 3a-3b).

The ~520 cm-thick soil profile contains 99 tephra layers. The topmost layer measured and sampled was the one immediately above the Settlement Layer and the last one measured was the Hekla layer H4 (Table 1a and Figures 4a, 4b). The subsequent time period is well preserved in an outcrop about 1 km farther south (HA) (Figure 3c), where a ~280 cm-thick soil profile contains 49 tephra layers between the chronostratigraphic markers H4 and A6 (Table 1). The remaining part of the prehistoric tephra stratigraphy is preserved

in a soil profile at Rjúpnafell (RF), ~4 km to the south of the Atley location. There, a ~180 cm-thick soil profile contains 43 layers between the marker layer A6 and A13 (Table 1). Many of these oldest layers are partly indurated (Figure 3d). In total, we identified 190 tephra layers in the prehistoric soil profiles and 18 layers in the historical part, or 208 tephra layers in total. Of those, 183 layers were sampled and 126 were analysed for major-element composition.

Chemical analyses

Major-element composition can often be used to determine the source volcano for a given tephra layer because several volcanic systems in Iceland are characterised by magmas of distinct composition (Jakobs-son, 1979).

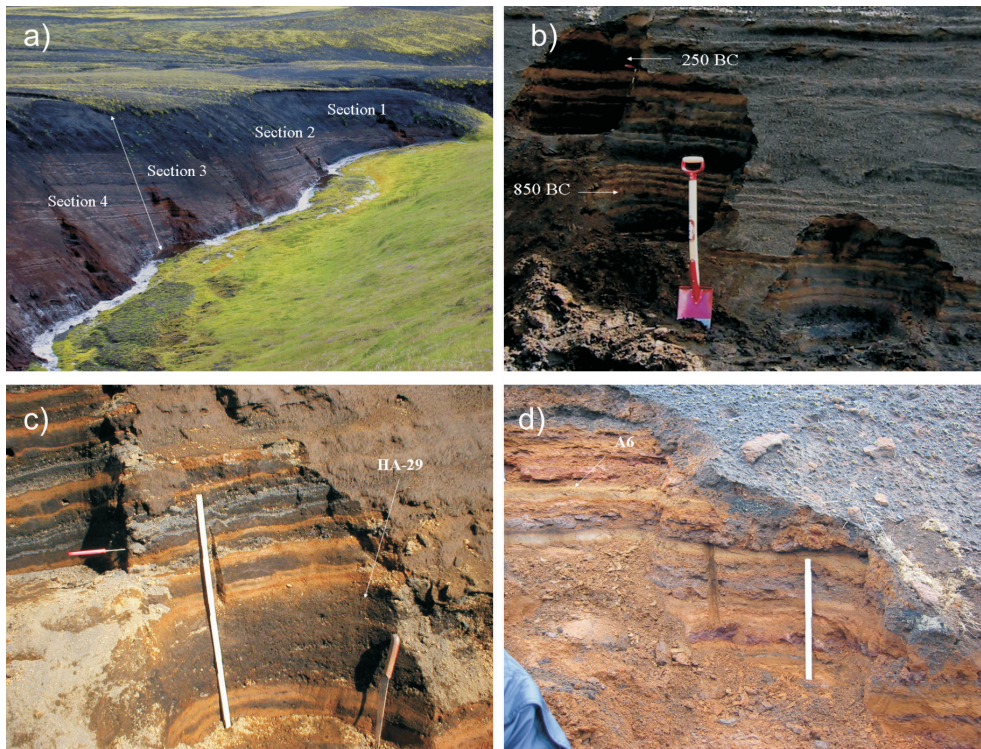


Figure 3. Photographs showing the soil sections measured during this study. a) The four subsections of the larger Atley outcrop (AT). The total thickness of the soil profile (arrowed) is approximately 5 m. b) Close-up at the tephra succession in subsection 2 in the Atley outcrop. Shovel is 1 m. c) Central part of the profile at the other Atley outcrop (HA) showing a 22–26 cm thick tephra layer from Katla volcano, ~5900 years old. Scale is 80 cm. d) Upper-most part of the Rjúpnafell profile (RF) showing partly cemented tephra layers in the oldest soils encountered in this study. The thin yellow layer near the top of the photograph is the key tephra marker layer A6 from Torfajökull volcano (~7130 years). – *Ljósmyndir af jarðvegssniðum með forsögulegum gjóskulögum. a) Snið AT í Atley, mælt í fjórum hlutum. Þykkt jarðvegs og gjósku (hvít ör) er um 5 metrar. b) Nærmynd af hluta 2. Skóflan er um 1 m á lengd. c) Snið HA í Atley, miðhluti. Neðarlega á myndinni er 22–26 cm þykkt gjóskulag frá Kötlu, ~5900 ára gamalt. Mælikvarðinn er 80 cm langur. d) Efsti hluti sniðs í Rjúpnafelli sem sýnir hálfhörðnuð gjóskulög í elsta jarðveginum sem rannsóknin náði til. Þunna gulleita lagið sem örin bendir á er leidarlagið A6, ~7130 ára gamalt, ættað frá Torfajökli.*

Microprobe analyses were obtained on a Cameca SX 100 at the Laboratoire Magmas et Volcans, Clermont-Ferrand. The instrument was calibrated on natural and synthetic mineral standards and raw data were corrected by an improved ZAF procedure. The elements Na, Mg, Al, Ca and Si were measured using 15 kV accelerating voltage, 8 nA beam current, 10 μm beam diameter and counting time was 10 s on the peak and background. The elements Ti, P and Fe

were measured under the same conditions but over a longer counting time: 30 s for Ti and 40 s for P and Fe. The elements K, Mn, S and Cl were measured using a beam current of 50 nA during 50 s (S), 100 s (K and Cl) and 150 s (Mn), with same accelerating voltage and beam diameter as for previous elements. Total analysis time per sample was 6 min and 20 s. An external glass standard, ALV981R23 (Metrich and Clocchiatti, 1989), was analysed several times during each

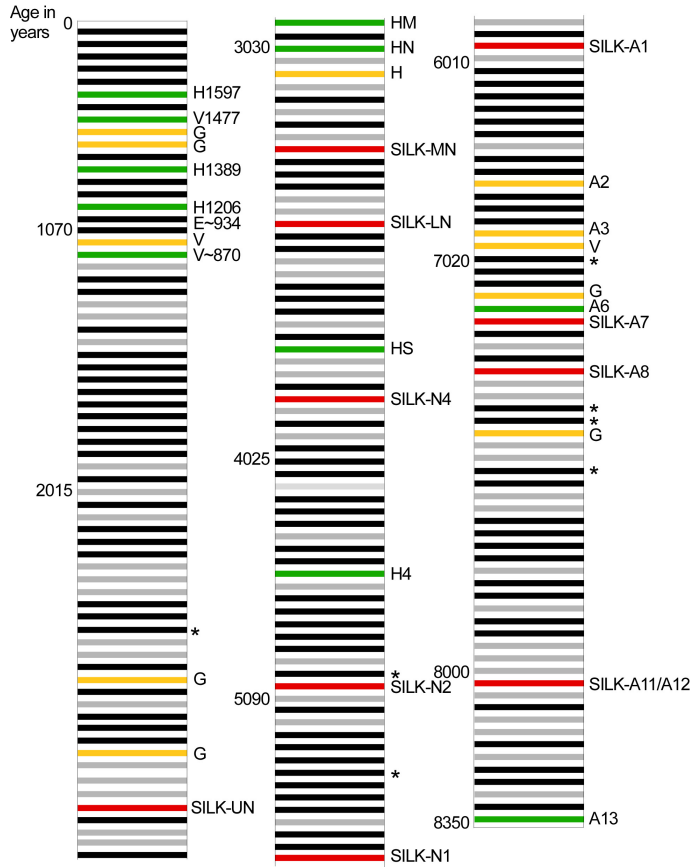


Figure 4a. A composite tephra section showing the historical part, adapted from Larsen *et al.*, (2001) and the prehistoric part measured in this study. For clarity, the same thickness has been assigned to each tephra layer and the soil between them. Eight tephra layers occurring sporadically are not shown. The numbers on the left are ages (before 2005 AD) of tephra layers calculated from the SAR (see discussion in text); only the age of the first layer in a new millennium is indicated. Note that the age scale is not linear. Basaltic Katla tephra layers are shown in black (origin confirmed by chemical analyses) and in grey (identification based on field characteristics). The SILK layers, marker tephra layers and known tephra layers from other volcanic systems than Katla are

shown in red, green and yellow colours, respectively. Note that the silicic layers A2 and A3 are most likely SILK-layers but their origin has not yet been confirmed by chemical analyses. The stars on the right side of the column represent tephra layers containing glass of two compositions, a typical Katla basalt composition and a dacite (SILK) composition or rhyolite composition. Abbreviations are H: Hekla, V: Veiðivötn, G: Grímsvötn. – a) Samsett jarðvegs- og gjóskulagasnið. Forsögulegi hlutinn var mældur sumarið 2003, sögulegi hlutinn er að mestu samkvæmt Guðrúnu Larsen o.fl. (2001). Öll gjóskulög og jarðvegsþykkir eru sýnd sem línur af sömu þykkt (8 örþunnum og slitróttum gjóskulögum er þó sleppt). Tölur vinstra megin á sniðasúlu eru aldur í árum (miðað við 2005), reiknaður út frá upphleðsluhraða jarðvegs (SAR), og sýna aldur fyrsta gjóskulags á hverju árþúsundi. Athugið að tímakvarðinn er ekki línulegur. Basísk Kötlu-gjóskulög, þar sem uppruni er staðfestur með efnagreiningu, eru svört. Basísk gjóskulög með útlits-einkenni Kötlu-gjósku (ekki efnagreind) eru grá. Sú Kötlu-gjóskulög (SILK) eru rauð, leiðarlög eru græn og gjóskulög frá öðrum eldstöðvakerfum eru gul. Gjóskulög A2 og A3 eru líklega sú Kötlu-lög en hafa ekki verið efnagreind. Stjörnur hægra megin á sniðasúlu eru við gjóskulög með tvenns konar glerkornum, meginhlutinn er dæmigert Kötlu-basalt, en innanum eru korn með dasít (SILK) eða rýólítsamsetningu. Skammstafanir á nöfnum eldstöðvakerfa eru H: Hekla; V: Veiðivötn; G: Grímsvötn.

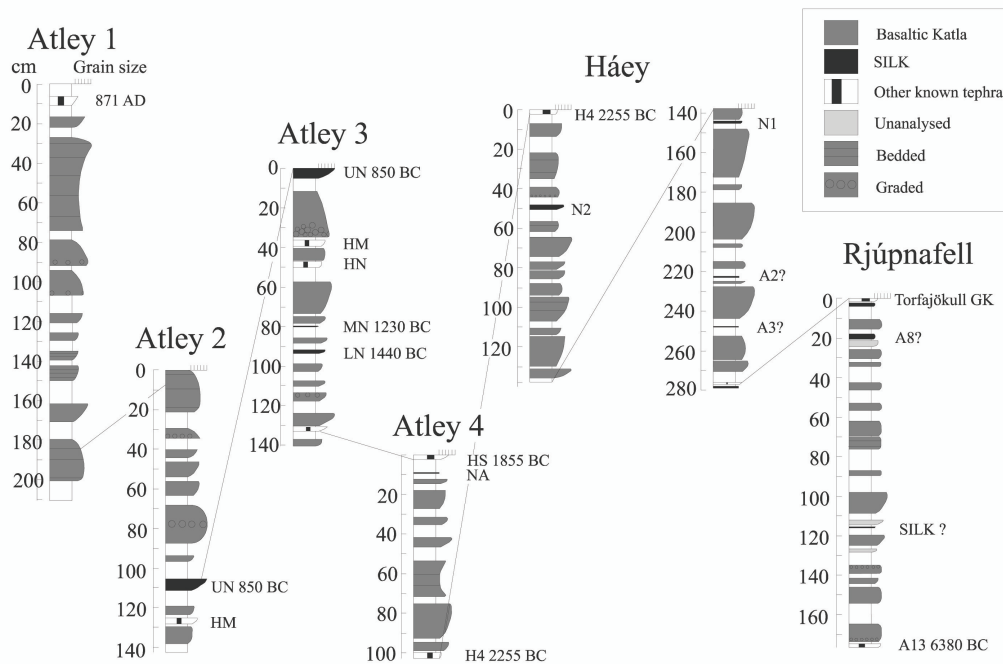


Figure 4b. Simplified soil logs showing the thickest tephra layers, characteristic grain sizes and the connections between subsections and outcrops. Grain size is indicated by tick marks (<0.2, 1, 2, 10, 20, >20 mm) at the top of the logs. – b) *Einfaldað snið sem sýnir þykkustu gjóskulöggin, einkennandi kornastærð og tengingar milli sniða. Kornastærð (<0.2, 1, 2, 10, 20, >20 mm) er sýnd með höfum efst á hverri sniðasúlu.*

microprobe session and all results are relative to that standard. At least five different glass fragments were analysed and the mean value used to characterise each tephra layer for further discussion (Óladóttir, 2004).

Dating of tephra layers using soil accumulation rate

The age of the seven prehistoric marker layers in the region has been determined by the ¹⁴C-method, and age of the Settlement layer has been determined in the Greenland ice cores (Table 1a). These tephra layers cover the period from ~870 AD to ~6380 BC whereas the time between successive dated layers ranges from 210 to 3100 years (Table 3). The mean soil accumulation rate (SAR) is obtained for time periods between two successively dated tephra layers. The procedure is straightforward, because the

SAR for the period between two dated layers is simply the total soil thickness divided by age difference of the tephra layers. The approximate age of individual tephra layers can then be calculated by assuming constant SAR between the dated layers.

RESULTS AND DISCUSSION

The SAR age model

The results of the SAR calculations are presented in Table 3. On the whole, the SAR varies from 0.027 cm/year to 0.081 cm/year in the composite section, with a mean value of 0.054 cm/year. In the AT outcrop, Atley, the first 2700 years of prehistoric time show a rather steady SAR value, ranging from 0.034–0.047 cm/year. Then the rate jumps to 0.081 cm/year before dropping to its lowest observed value, 0.027

Table 3: Mean SAR (soil accumulation rate) values calculated between tephra layers dated by ^{14}C -method. Layers UN, MN and LN are SILK layers, HS and H4 are Hekla layers (Larsen *et al.*, 2001), RF4 is a basaltic Katla layer and the A13 layer is of probable Torfajökull origin. – *Reiknaður upphleðsluhraði jarðvegs (SAR) milli lykilmjósulaga sem hafa verið tímasett með geislakoli. Tímabilin milli þeirra eru mismunandi. Gert er ráð fyrir að upphleðsluhraðinn sé jafn á hverju tímabili og önnur gjóskulög fá aldur samkvæmt því. Lykillög merkt UN, MN og LN eru súr Kötlulög, HS og H4 eru Heklulög, RF4 er basískt Kötlulag og A13 er e.t.v. áttað frá Torfajökli.*

| Dated tephra layers | Section | Period length (years) | Mean SAR (cm/year) |
|-------------------------|---------------|-----------------------|--------------------|
| Eldgjá-Settlement Layer | Atley | 64 | 0.091 |
| Settlement Layer-UN | Atley | 1720 | 0.047 |
| UN-MN | Atley | 380 | 0.039 |
| MN-LN | Atley | 210 | 0.034 |
| LN-HS | Atley | 415 | 0.041 |
| HS-H4 | Atley | 400 | 0.081 |
| H4-RF4 | Atley-Hillock | 3100 | 0.027 |
| RF4-A13 | Rjúpnafell | 1020 | 0.071 |

cm/year. In the HA outcrop, Atley, the calculated SAR is unusually low, 0.027 cm/year. This most likely reflects special conditions for soil accumulation at the site rather than an absolute change in the regional SAR, especially since the average SAR calculated for the Rjúpnafell site, representing the lowest part of the composite section, is 0.071 cm/year (Table 3).

The age of an individual tephra layer as calculated from the SAR should be taken as an approximate value. First of all, the ^{14}C age measurements involve considerable uncertainties, up to 130 years (at the 95% confidence level) when combined with the uncertainties inherent in the calibration procedure of Stuiver *et al.*, (1998). Moreover, the age is obtained from charcoal or other organic material (i.e. peat or tree trunks) found in or immediately below the tephra layers. Therefore, the age of the organic material can be slightly higher than the age of the tephra deposit itself (e.g. Thordarson *et al.*, 1998; Sveinbjarnardóttir, 2003).

Another source of error in these calculations is the assumption that the SAR is constant within individual periods. However, it is well known that SARs are a function of many variables, including climate, to-

pography, drainage and vegetation (e.g. Thorarinsson, 1961). This type of error is likely to be enhanced in the longer time intervals such as the one between the marker layers H4 and RF4 (Table 3). However, section locations are not a factor in the age calculations of the tephra layers because each section begins and ends with a ^{14}C dated tephra layer and the SAR for all but one time interval (H4-RF4) is calculated between dated layers of the same outcrops. Taking all these uncertainties into account, the accuracy of the ages reported here is estimated as ± 250 years.

In order to check the accuracy of the SAR calculations, an estimated age of three Katla SILK layers using a different approach than in this study (Larsen *et al.*, 2001 and Table 1b) was compared to the calculated age derived from the SAR. The difference between the estimated and calculated ages ranges from 90 to 195 years, which is lower than the estimated 250 year uncertainty. Having constructed an age model for the soil section, time-series of the tephra stratigraphy can be established. The time-series is used to calculate the Holocene frequency of explosive basalt eruptions within the Katla volcanic system and to address the compositional variability of its basalts, during the last 8400 years.

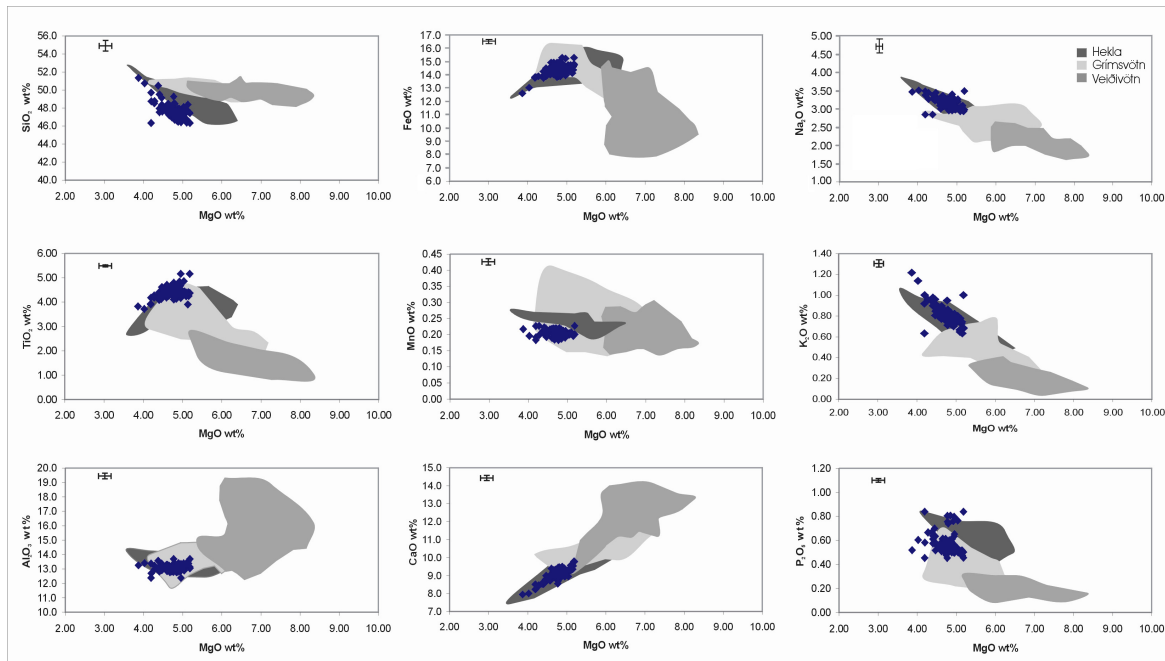


Figure 5. Major-elements plotted against MgO. The compositional fields of basalt from Hekla (shaded dark grey), Grímsvötn (light grey) and Veidivötn (medium grey) volcanic systems are shown for comparison. Data is from Jakobsson (1979), Steinþórsson (1977), Vilmundardóttir (1977), Óskarsson *et al.*, (1982), Grönvold and Jóhannesson (1984), Steinþórsson *et al.*, (1985), Sigmarsson *et al.*, (1992) and Thordarson *et al.*, (1996, 2001, 2003). Katla data points from this study are shown as diamonds and the error bars are indicated when the bar is larger than size of the data points. – *Graf sem sýnir aðalefni forsögulegra og sögulegra Kötlugjósakulaga (bláir tíglar) sem fall af magnesíumoxíði. Til samanburðar er sýnd efnasamsetning basalts frá Hekluakerfi (dökkgrátt svæði), Grímsvatnakerfi (ljósgrátt) og Veidivatnakerfi (milligrátt), samkvæmt efnagreiningum Sveins Jakobssonar (1979), Sigurðar Steinþórssonar (1977), Elsu Vilmundardóttur (1977), Nielsar Óskarssonar og fl. (1982), Karls Grönvolds og Hauks Jóhannessonar (1984), Sigurðar Steinþórssonar og fl. (1985), Olgeirs Sigmarssonar og fl. (1992) og Þorvaldar Þórðarssonar og fl. (1996, 2001, 2003).*

Major-element composition

Several geochemical studies have been conducted on Katla lava and tephra over the last four decades (Robson and Spector, 1962; Sigvaldason and Óskarsson, 1976; Jakobsson, 1979; Einarsson *et al.*, 1980; Larsen *et al.*, 2001; Lacasse *et al.*, 1995; Thordarson *et al.*, 2001, 2003). These studies present both whole-rock and glass analyses using different methods (i.e. wet chemistry, XRF and electron microprobe) in a range of laboratories, yielding major-element composition of rather homogeneous and evolved basalts rich in Fe and Ti. In Figures 5 and 6 are displayed the pub-

lished compositional variability of basalts from the Eastern Volcanic Zone together with the results of this study. The comparison of our results with the published Katla data confirms that 111 out of 126 analysed layers originated from the Katla volcanic system.

In this study, SiO₂ in mafic Katla magma ranges from 46.3 to 51.3 wt% and TiO₂ is notably high in Katla magmas, ranging from 3.71 to 5.16 wt%. Concentrations of FeO, MgO, K₂O and P₂O₅ fall in the range 2.6–15.3, 3.87–5.19, 0.63–1.22 and 0.45–0.84 wt%, respectively. Also shown on Fig-

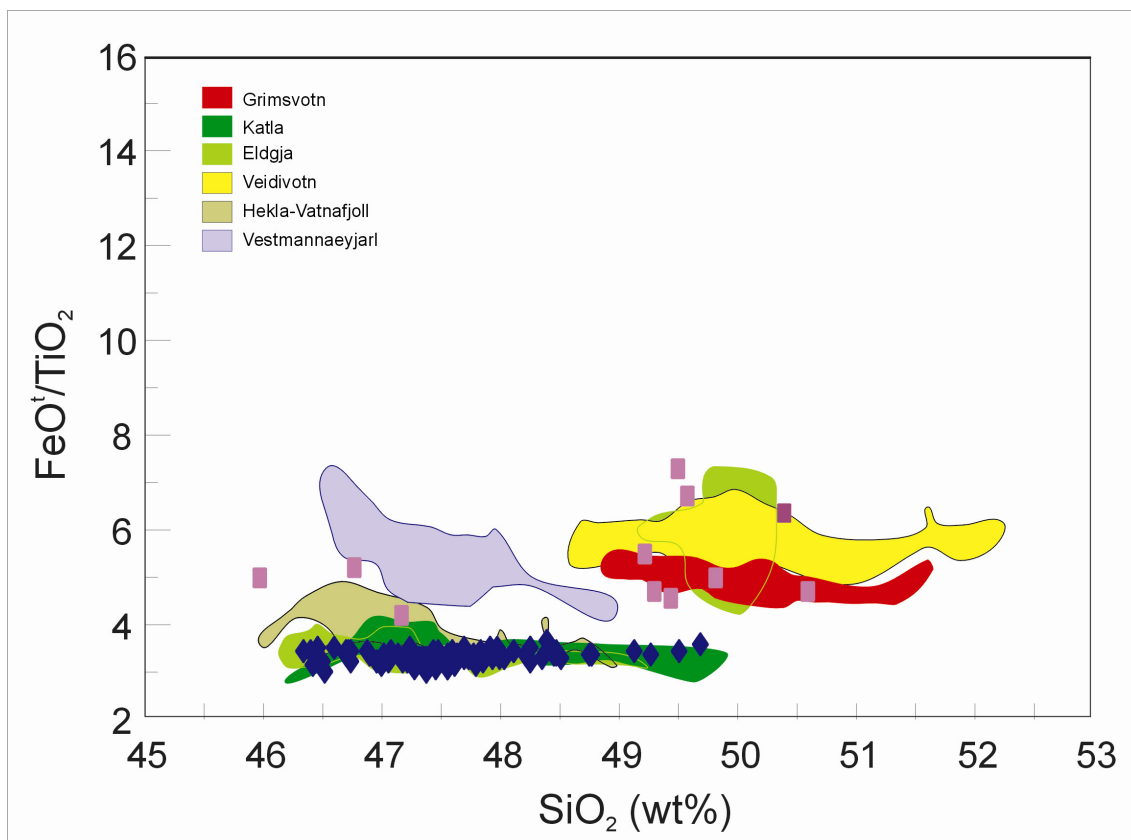


Figure 6. Basalt compositional fields for five indicated volcanic systems of the EVZ. Data from Jakobsson (1979), Steinþórsson (1977), Vilmundardóttir (1977), Óskarsson *et al.*, (1982), Grönvold and Jóhannesson (1984), Steinþórsson *et al.*, (1985), Sigmarsson *et al.*, (1992) and Thordarson *et al.*, (1996, 2001, 2003). The data of this study is plotted as diamonds (Katla tephra) and as squares (other volcanic systems). – *Graf sem sýnir hlutfall járn- og títanoxíða á móti kísiloxíði fyrir fimm eldstöðvakerfi á Eystra gosbeltinu samkvæmt efnagreiningum Sveins Jakobssonar (1979), Sigurðar Steinþórssonar (1977), Elsu Vilmundardóttur (1977), Níelsar Óskarssonar og fl. (1982), Karls Grönvolds og Hauks Jóhannessonar (1984), Sigurðar Steinþórssonar og fl. (1985), Olgeirs Sigmarssonar og fl. (1992), og Þorvaldar Þórðarsonar og fl. (1996, 2001, 2003). Bláir tíglar sýna að efnagreiningum á forsögulegum og sögulegum Kötlugjóskulögum í þessu verkefni ber vel saman við áður birt gögn. Ferningar sýna efnasamsetningu gjóskulaga frá öðrum eldstöðvakerfum.*

Figure 5 are the compositional fields of basalts from the Hekla/Vatnafjöll, Veidivötn and Grímsvötn volcanic systems. The Katla volcanic system products are readily distinguished from that of the Grímsvötn and Veidivötn systems on element to element plots, but such plots do not discriminate between the Fe-Ti

basalts from the Katla and Hekla/Vatnafjöll systems. However, the products of these two systems are better distinguished by their FeO/TiO₂ value (Figure 6).

The discrimination plots indicate that out of the 108 prehistoric tephra layers that were analysed, 101 originated from the Katla volcanic system. The data

also shows that 99 layers have a Fe-Ti basalt composition typical for the Katla system and seven of those layers contain sporadic grains of silicic glass. Two layers are basaltic icelandites of probable Katla origin because of their high Fe-Ti content. Other dark-coloured prehistoric tephra layers in the composite profile belong to the Grímsvötn, Veidivötn and Hekla volcanic systems (Figure 5). The prehistoric part of the composite section also contains 16 felsic layers, of which ten are SILK layers. Only two of these layers were analysed in this study (i.e. SILK-N4 and -A7) because most of them have been analysed previously by Larsen *et al.*, (2001). The remaining six felsic layers are the known marker tephra layers from the Hekla and, most likely, the Torfajökull volcanic systems.

The Katla tephra time-series reveals distinct periodic patterns in major-element composition of the basaltic tephra layers, illustrated by SiO₂ concentrations versus time (Figure 7). Three compositional patterns are identified: (a) periods where incompatible elements increase steadily with time, (b) periods with no discernable change in the major element compositions (stable conditions), and (c) periods where changes in magma composition appear to be random with respect to time (Óladóttir, 2004). Each of these patterns are thought to reflect distinct conditions for magma supply and evolution within the plumbing system beneath the Katla volcano. The exact nature of these compositional patterns and the implication they may have for the plumbing system of the volcano is beyond the scope of this paper and will be discussed elsewhere (Óladóttir *et al.*, in preparation).

However, on the basis of these temporal variations in composition, we divide the Holocene activity into eight periods, here labelled I-VIII (Figure 7). Six of the periods are relatively short, or between 510-980 years long. Two are fairly long, each spanning about 1700 years (Figure 7 and Table 4). A cyclic behaviour is observed where a constant value (period VIII) is followed by an irregular one (VII) which is then replaced by a gradual change (VI). This cycle repeats itself through periods V-II and the last period (historical time) demonstrates the beginning of the third cycle.

Eruption frequency of basalts

The proportion of Katla layers in the soil profile as identified in the field is similar to that obtained using chemical composition as the discriminator. On the basis of field identification, using criteria such as colour, grain size and clast morphology, 172 out of 208 tephra layers, or 83% of all measured layers, were assigned to the Katla volcanic system. Of these 172, we measured the chemical composition of 111 layers (representing 88% of the 126 layers analysed). In all cases, the assigned Katla origin was confirmed by the obtained chemical composition. Therefore we are confident in our field identification and use the number of Katla layers identified during field measurements in our calculations of the Holocene eruption frequency.

The true eruption frequency at a given volcano can only be obtained if all its eruptions are known. This is most easily achieved for time periods where reliable eyewitness or written records exist. For periods where such records are not available, such as the Holocene, the accuracy of the calculated eruption frequency depends on the quality of an acquired data set or, in the case of this study, the completeness of the tephra stratigraphy. In this context it is important to recognize that tephra dispersal is primarily controlled by the eruption intensity and wind direction and to some degree the eruption duration, because the dispersal of tephra in sustained events is more strongly affected by changes in eruption intensity and wind direction. Consequently, a complete record of explosive eruptions within a volcanic system such as Katla requires detailed measurements of the tephra stratigraphy in soil profiles at proximal and medial locations circumscribing all possible vent regions. This is, however, only possible in regions where the soil has been conserved or at least where different soil sections are not too far apart.

This study is confined to tephra layers deposited east of the Katla volcano. Comparison of the number of tephra layers found between marker tephra layers in soil sections east and west of the volcano shows a certain similarity. The similarity between eruption frequency patterns to the east and west of the volcano is sufficiently close to derive that of the volcano itself from the eastern soil sections. During historical time,

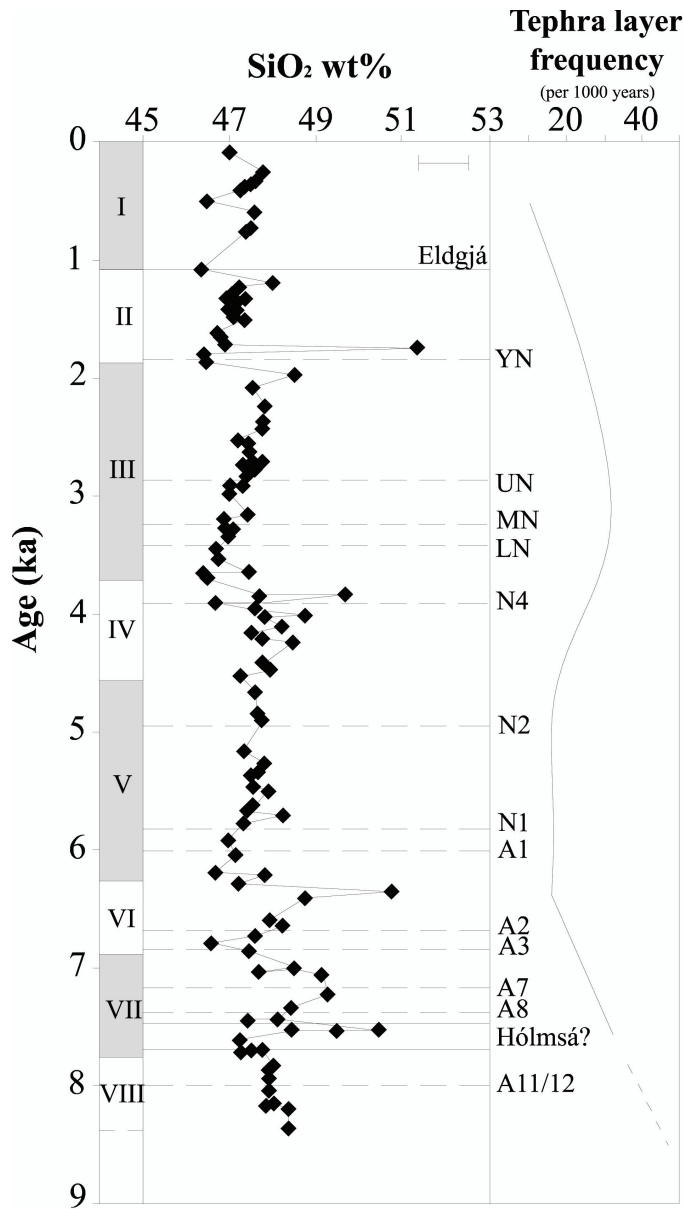


Figure 7. SiO₂ content of Katla tephra plotted against age in kiloyears (ka). The age curve is constructed using 2005 AD as a reference year and is based on calculated SAR values and ¹⁴C ages for dated tephra layers. The column on the left shows eight periods (numbered I-VIII) identified on the basis of compositional patterns. Age of the SILK layers is indicated by broken lines and the solid lines indicate the timing of the Eldgjá and Hólmsá Fires. Tephra layer frequency vs. age is shown by the curve on the right side. The frequency is calculated for every 1000 years and regardless of the period boundaries. The VIII period only includes 300 years and the broken curve denotes normalised values to 1000 years. The true eruption frequency is likely to be close to double the values indicated by the curve (see text for further discussion). – Graf sem sýnir breytingar á styrk kísiloxíðs í Kötlujósukulögum með tíma. Aldurslíkanið byggir á upphleðsluhraða jarðvegs (SAR) milli tímasettra gjóskulaga (sjá töflu 1a). Aldur er hér miðaður við árið 2005. Súlan til vinstri sýnir 8 tímaseið (I-VIII) sem skilgreind hafa verið á grundvelli efnasamsetningar gjóskulaganna sem ýmist hefur verið stöðug (VIII), sveiflast óreglulega (VII) eða breyst kerfisbundið með tíma (VI). Tímaseiðin næst á eftir (V-III) sýna samskonar hegðun. Á núverandi tímaseiði (sögulegum tíma) eru óreglulegar sveiflur í efnasamsetningunni. Brotnar línur sýna hvenær súr Kötluög mynduðust og heildregnar línur sýna hvenær stærstu eldarnir á Kötlukerfinu urðu. Elsta tímaseiðið (VIII) er aðeins um 300 ár og brotna kúrfan er framreiknuð miðað við 1000 ár. Fjöldi gjóskulaga/1000 ár er sýndur til hægri á myndinni. Raunveruleg gostíðni á Kötlukerfinu er að líkindum tvöfalt hærri (sjá útdrátt).

Table 4: Periods of compositional patterns (I–VIII in column 1). Column 2 lists the tephra layers limiting each period; column 3 shows the length of each period, column 4 shows the calculated tephra layer frequency; and the average time between formation of successive tephra layers is given in column 5. Approximately half of historical Katla eruptions are recorded as tephra layers in the study area. Consequently, the true eruption frequency is most likely double that of the tephra layer frequency and the true mean repose time is close to the half of the value listed for the average time between successive tephra layers (see text for further discussion). – *Tímaskeið sem afmarkast af snöggum breytingum á aðalefnasamsetningu Kötlukviku (I–VIII í fyrsta dálki). Í öðrum dálki eru yngstu og elstu gjóskulög á hverju tímaskeiði, í þriðja dálki er lengd hvers tímaskeiðs, í fjórða dálki er fjöldi gjóskulaga sem féllu á rannsóknasvæðinu á hverjum 100 árum, og í fimmta dálki er meðaltímalengd milli gjóskulaga reiknuð. Um helmingur þeirra gjóskulaga sem féllu á sögulegum tíma finnst á rannsóknasvæðinu. Samkvæmt því má ætla að raunveruleg tíðni Kötlugosa á forsögulegum tíma geti verið tvöfalt hærri en gildin í fjórða dálki og að meðalgoshléin geti verið helmingi styttri en sýnt er í fimmta dálki.*

| Time period | Bounding layers | Length (years) | Tephra layer frequency (per 100 years) | Average interval (years) |
|-------------|-----------------|----------------|--|--------------------------|
| I | 1918AD–Eldgjá | 980 | 1.00 | 98 |
| II | Eldgjá–AT19 | 800 | 2.15 | 47 |
| III | AT21–AT77 | 1700 | 2.80 | 35 |
| IV | AT79–HA4 | 630 | 3.15 | 32 |
| V | HA5–HA34 | 1750 | 1.35 | 73 |
| VI | HA35–HA43 | 510 | 1.55 | 64 |
| VII | HA46–RF20 | 700 | 2.60 | 39 |
| VIII | RF21–RF43 | 650 | 3.15 | 32 |

there are 20 known eruptions from the Katla volcano and at least 10 of those tephra layers are present in the area east of the volcano. About half of the eruptions are therefore preserved in soil profiles east of the volcano, so the number of tephra layers there can be doubled to estimate the total number of eruptions from Katla. An implicit assumption here is that the weather pattern (wind directions, strength etc.) has remained similar during the last 8400 years.

The overall tephra layer frequency in the composite soil profile measured for this work (Figure 4a and b), is 2.6 tephra layers per 100 years in prehistoric times (190 eruptions in 7300 years). Considering only tephra layers from the Katla system, the prehistoric frequency is 2.2 layers per 100 years. A minimum value of 1.4 layers per 100 years is obtained if we only consider layers that have their Katla origin confirmed by microprobe. The value 2.2 layers per 100 years is a factor of 2 higher than the frequency obtained for the historical period (~1 event per 100 years for

historical tephra layers in the eastern sector; Larsen, 2000). Accepting our argument as presented above, that the eastern sector only preserves one half of the tephra layers produced by explosive Katla eruptions, the long-term average eruption frequency in prehistoric times could be as high as 4 events per 100 years. This frequency corresponds to a total of ~300 explosive basaltic Katla eruptions over 7300 years (i.e. the period 1100 to ~8400 years ago). This estimate can be verified (or disproved) by a systematic study of the Holocene tephra stratigraphy around Katla volcano, focusing on measuring soil profiles in the region to the west and south of Mýrdalsjökull.

Temporal changes in the Holocene eruption frequency

The Holocene eruption frequency is evaluated using periodicities of 200, 400, 500, 700 and 1000 years and the data are plotted on Figure 8. The results show that the frequency distribution is characterized by two

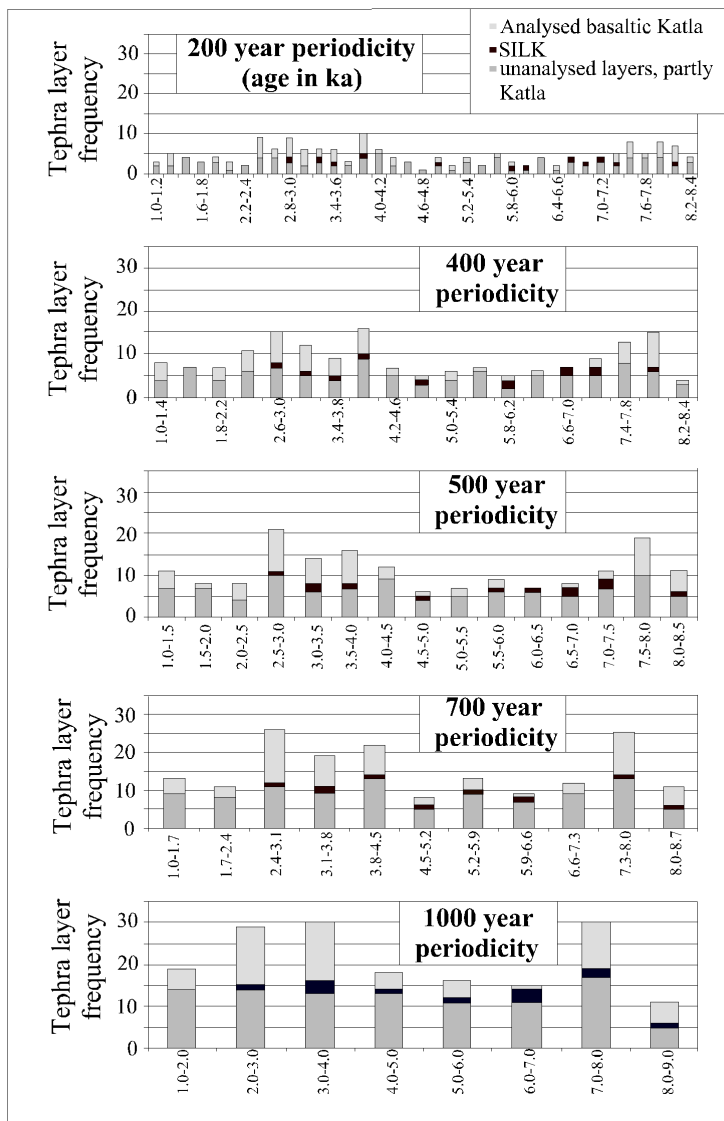


Figure 8. The Holocene tephra layer frequency calculated for five different running cycles (i.e. periods of 200, 400, 500, 700 and 1000 years). Regardless of the cycle length, the resulting frequency curve is always characterized by two peaks, although the younger peak is broader and possibly double. – *Fjöldi gjóskulaga á tímaeiningu (reiknaður fyrir 200, 400, 500, 700 og 1000 ára tímabil) í samsetta jarðvegssniðinu. Tveir til þrjár toppar koma fram óháð því hvaða tímaeining er valin.*

(or possibly three) peaks, regardless of the periodicity used. This is exemplified here by the 500 year periodicity, which reveals a significant increase in the basalt eruption frequency during the periods 2.5–4.5 ka and 7.0–8.5 ka (Figures 8 and 9). A similar trend is observed in a soil section west of the volcano (Larsen, unpubl. results). The eruptions that produced the dacitic SILK layers have a repose time of 100-1000

years (Larsen *et al.*, 2001) and at first glance they appear to be fairly evenly distributed through time. However, a closer examination indicates two peaks in the frequency distribution for the SILK layers, one at ca. 7.1–7.4 ka and another at 3–4 ka (6200–6600 ¹⁴C yr BP and 2700–3600 ¹⁴C yr BP; Larsen *et al.*, 2001). These peaks correspond to those of the frequency distribution for the basalt eruptions. Although the SILK

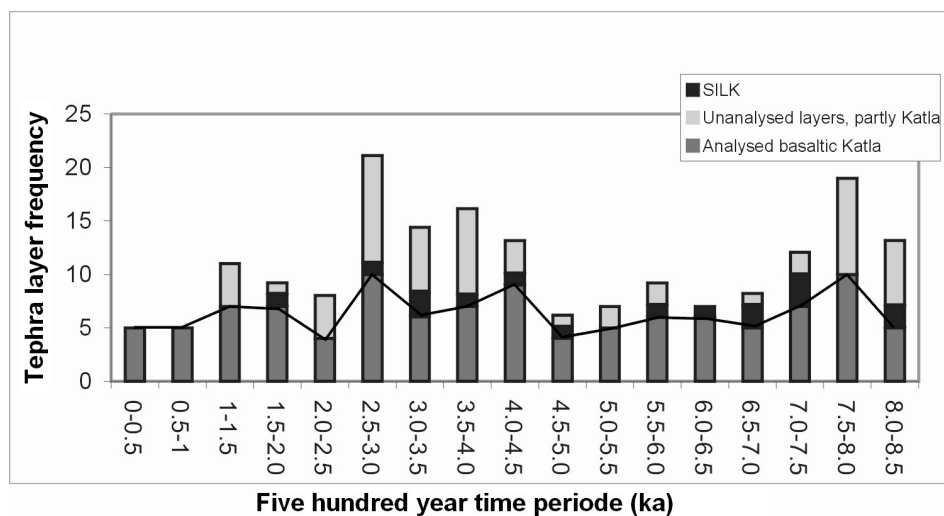


Figure 9. Number of Katla tephra layers per five hundred years of the composite soil profile, covering ~8500 years (0–1 ka is historical time). The SILK layers (YN, N3, A9, A12) that were not present in the composite soil profile are included. Solid line only includes basaltic Katla tephra layers that have been analysed for major element composition. The mean value is 1.4 events per 100 years. Using the total number (= 172) of Katla tephra layers based on field identification, the mean value is 2.2 layers per 100 years in prehistoric times and the true mean frequency is likely to be close to 4 events per century. In historical time the tephra layer frequency on the east side of the volcano is ~1 event per 100 years, whereas the true eruption frequency is ~2 event per 100 years (e.g. Larsen, 2000; see text for further details). – *Fjöldi Kötlugjóskulaga á hverjum 500 árum í samsetta jarðvegssniðinu (0–1 ka er sögulegur tími). Öll þekkt súr Kötlulög eru höfð með í talningunni þótt sum þeirra fyndust ekki í samsetta sniðinu (YN, N3, A9, A12 bætast við) til að kanna tengls síru gjóskulaganna við toppa í góstiðinni. Heildregna línán sýnir fjölda efnagreindra gjóskulaga. Meðaltalið er 1.4 gos/100 ár. Ef gjóskulög greind sem Kötlulög á útlitseinkennum eru tekin með (samtsals 172) er meðaltalið 2.2. gos/100 ár á forsögulegum tíma. Í ljósi þess að helmingur Kötlulaga frá sögulegum tíma finnst austan við Kötlueldstöðina (þ.e. 10 af 20 Kötlulögum, sbr. Guðrún Larsen 2000) er líklegt að góstiðnin á forsögulegum tíma hafi verið nálægt 4 Kötlugosum á öld.*

layers are produced during periods characterized by both high and low basalt eruption frequency, there is an obvious correlation between the increase in dacite eruption frequency and basalt eruption frequency.

Periods I-VIII and eruption frequency

Significant variations are also observed between the periods defined by the compositional patterns (Table 4). The lowest frequency of explosive basalt eruptions is found in period I (historical time), whereas the highest frequency is in period IV. The latter corresponds to the younger frequency peak in volcanic activity at the Katla system (Figures 7 and 9). The av-

erage time interval between the formation of basaltic tephra layers is shortest in periods IV and VIII, 32 years in both instances, but longest in periods I (98 years) and V (73 years). Note that the time intervals quoted here are two times longer than the true repose time between eruptions, assuming again that the tephra sequence east of Katla volcano represent only half of the total number of its eruptions. The average repose times as calculated from the composite soil sections for each period (Table 4) can be compared between different time periods since the risk of missing out tephra layers is expected to be the same throughout the time studied. Consequently, the aver-

age repose time for explosive basalt eruptions at Katla volcano in Holocene times is on the order of 25 years, emphasising that in recent times the volcano has been relatively quiet. The historical eruption frequency is a factor of two lower than that observed for prehistoric times.

Implications for future activity of Katla volcano

The calculated SAR ages for the prehistoric Katla layers in our composite soil profile indicate that the time interval between the deposition of successive tephra layers has been as short as 2 years and as long as 164 years. This suggests that the true repose time between prehistoric explosive Katla eruptions is highly variable and spans two orders of magnitude (< 1 year to > 80 years). This is interesting in the context of the time that has passed since the last visible eruption from the Katla fissure (i.e. AD 1918), which currently stands at 87 years and is second in the record to the 95 years between the Katla eruptions in AD 1262 and AD 1357. This observation suggests that activity at Katla volcano is declining. This notion, however, does not eliminate the possibility of imminent eruption, but rather suggests that in view of longer time-scales the volcano is either calming down or changing behaviour.

The periodic intensification in prehistoric eruption frequency over specific time intervals most likely reflects an increase in the flux of basaltic magma into the upper regimes of the Katla plumbing system. The net result is an increase in heat flux from depth that may enhance the production of felsic magma at shallower levels via partial melting of the surrounding crust. This can explain the observed correlation in the timing of the eruption frequency peaks for basalt and dacite eruptions. Consequently, the lower eruption frequency in historical time does not support the occurrence of an imminent felsic eruption, unless the behaviour of the volcano is changing.

This study has focused on the frequency of explosive eruptions at the Katla system and changes therein during the Holocene. Although eruption frequency and its variations are likely to be directly correlated with magma productivity, the exact relationship between these two variables is still poorly constrained. Magma productivity at the Katla system, defined as

the volume of erupted material per unit time, has not yet been assessed quantitatively but is relevant for future research. However, the proposed hypothesis for production of felsic magma can be assessed from major- and trace-element composition of the individual tephra layers and their isotope ratios, thus permitting further discussion of the magma plumbing system beneath the Katla system and its behaviour during the last millennia.

CONCLUSIONS

The Holocene eruption history of the Katla volcanic system is recorded by tephra layers in soil profiles in the surrounding regions. A composite soil section east of Mýrdalsjökull containing 208 tephra layers and spanning 8400 years was measured and sampled for this study. Eighteen of the tephra layers were formed during historical time (i.e. the last 11 centuries), whereas 190 layers are prehistoric and represent 7300 years of volcanic history. About 88% of these tephra layers, or 182 in total, are based on field identification assigned to explosive eruptions within the Katla volcanic system. This tally includes 172 basaltic and 10 felsic layers. A Katla origin of 111 basaltic layers was confirmed by major element analyses.

All of the tephra layers have been dated using a SAR (soil accumulation rate) age model, established by measuring the average SAR between seven ^{14}C -dated marker layers. In turn, this data was used to evaluate the long-term frequency of explosive eruptions within the Katla system over the last 8400 years. The mean eruption frequency during prehistoric times was on the order of 4 eruptions per century, compared to ~ 2 eruptions per century in historical time. Eruption frequency appears to have peaked at 6–7 eruptions per century in the periods 7.0–8.5 ka and 2.5–4.5 ka. The total number of explosive basalt eruptions at the Katla volcanic system over the last 8400 years is estimated to be a minimum of 300.

Chemical analyses show that the magma composition produced by the Katla volcano throughout the Holocene is mostly evolved Fe-Ti basalts, showing small-scale but systematic compositional variation

with time. These compositional variations have enabled us to divide the 8400 year-long record into eight periods, each lasting 500-1700 years. The data also show that during prehistoric time the Katla volcano produced greater volumes of differentiated magmas (i.e. basaltic icelandite, dacite and rhyolite) than it has during the last 11 centuries.

The frequency of basaltic eruptions and their magma composition are unaffected by the occurrence of felsic eruptions. However, the frequency of felsic eruptions is highest at times when the basalt activity is at its peak, suggesting a causal relationship.

Acknowledgements

This paper is based on a Master-study at the Laboratoire Magmas et Volcans (LMV), CNRS-Université Blaise Pascal in Clermont-Ferrand, financed by the French government through a student's grant (Bourse d'étude no. 20035296). Michelle Veschambre and Jean-Luc Devidal are genuinely thanked for their great help with electron microprobe analyses. Support for this work was provided by the French-Icelandic collaboration programme "Jules Verne"; and the Icelandic Centre for Research, Rannís, which respectively funded travel cost and microprobe analyses. We are grateful to Magnús T. Guðmundsson and Sigurður Steinþórsson for their constructive review of the manuscript.

ÁGRIP

Eldvirknin í Kötlueldstöðinni á Eystra gosbeltinu (1. mynd) einkennist af basískum þeytigosum á sprungum sem opnast undir jökli. Gosefnin eru gjóska með háu járn- og títanmagni. Gjóskulagaskipan í samsettu jarðvegssniði austan eldstöðvarinnar og efnasamsetning Kötlugjóskunnar varpa ljósi á gossögu og þróun kviku á Nútíma. Alls fundust 208 gjóskulög frá 8400 ára tímabili í þessu samsetta jarðvegssniði, 18 þeirra frá sögulegum tíma og 190 frá forsögulegum tíma (2.–4. mynd; 1. og 3. tafla). Aðalefni voru greind í rúmum helmingi þeirra, eða 126 gjóskulögum af 208. Af þessum 126 gjóskulögum eru 109 úr basaltgjósku með háu járn- og títanmagni dæmigerðu fyrir Kötlueldstöðina (5. og 6. mynd), en í 7 þessara gjóskulaga eru að auki stöku korn af súru gleri. Tvö gjóskulög

teljast vera basaltískt andesít en járn og títan er álíka hátt og í basaltinu. Í samsetta jarðvegssniðinu fundust einnig 10 súr Kötluög (SILK-lög) frá forsögulegum tíma (mynd 4a).

Helmingur Kötlugosa á sögulegum tíma (síðustu 11 öldum), eða 10 af 20 Kötlugosum, skildu eftir gjóskulag austan Kötlueldstöðvarinnar. Fjöldi basískra Kötluaga í samsetta jarðvegssniðinu bendir til að gostíðni á forsögulegum tíma hafi verið hærri en á sögulegum tíma. Ef ríkjandi vindáttir voru þær sömu á forsögulegum tíma gæti gostíðnin þá hafa verið tvöfalt hærri, þ.e. 4 Kötlugos að meðaltali á hverjum hundrað árum í stað tveggja eins og verið hefur á sögulegum tíma. Þá er jafnframt líklegt að basísk Kötlugos síðustu 8400 árin séu yfir 300 talsins. Hæst var gostíðnin á tveim tímabilum fyrir u.þ.b. 2500–4500 árum og u.þ.b. 7000–8400 árum (7. og 8. mynd), og það gildir bæði um basísku og súru Kötlugosin.

Efnasamsetningu Kötlugjóskulaganna ber vel saman við efnagreiningar á gosefnum frá Kötlukerfinu sem áður hafa verið birtar (6. mynd). Snöggar breytingar á aðalefnasamsetningu basískrar Kötlukviku afmarka 8 mislög tímaseið í þróun kvikunnar (7. mynd og 4. tafla) þar sem efnasamsetningin er ýmist stöðug, sveiflast óreglulega eða breytist kerfisbundið með tíma. Breytileikinn er innan þeirra marka sem áður voru þekkt en tengsl tímabáttar og efnasamsetningar munu varpa frekara ljósi á þróun Kötlukvikunnar síðustu 8400 ár.

Aldurslíkan fyrir forsögulega hluta jarðvegssniðsins tekur mið af upphleðsluhraða jarðvegs milli gjóskulaga sem tímasett hafa verið með geislakolsgreiningu (1. og 3. tafla). Lengsti tími milli þess að Kötlugjóskulög féllu á þessu svæði er 164 ár og skemmsti tími er 2 ár. Sé gert ráð fyrir að jarðvegssniðið geymi helming gjóskulaganna má ætla að lengsta goshlé hafi verið um 80 ár og það skemmsta um 1 ár. Lengsta goshlé á sögulegum tíma er 95 ár, að frátöldu > 200 ára goshléi eftir Eldgjárgos á 10. öld. Gostíðnin síðustu aldirnar er sú lægsta í gossögu Kötlu á síðustu 8400 árum (9. mynd) og vekur upp spurningar um hvort virkni eldstöðvarinnar sé að dvína. Það útilokar þó ekki gos á næstu árum eða áratugum.

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