Hazards from lava–river interactions during the 1783–1784 Laki fissure eruption

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ABSTRACT

Interactions between lava flows and surface water are not always considered in hazard assessments, despite abundant historical and geological evidence that they can create significant secondary hazards (e.g. floods, steam explosions). We combine contemporary accounts of the 1783–1784 Laki fissure eruption in southern Iceland with morphological analysis of the geological deposits to reconstruct the lava–water interactions their impact on residents. We find that lava disrupted the local river systems, impounded water that flooded farms and impeded travel, and drove steam explosions that created at least 2979 rootless cones on the lava flow.

Using aerial photographs and satellite-derived digital terrain models, we mapped and measured 12 of the 15 rootless cone groups on the Laki lava field. We have identified one new rootless cone group and provide data that suggest another cone group previously attributed to the 939–940 AD Eldgjá eruption was created by the Laki eruption. We then use contemporary accounts to estimate formation dates and environments for each cone group, which formed in wetland/lake areas, on riverbeds and near areas of impounded water. Furthermore, comparison with previous field studies shows that assessments using remote sensing can be used to identify and map meter-scale and larger features on a lava flow, although remote mapping lacks the detail of field observations.

Our findings highlight the different ways in which lava can interact with surface water, threatening people, property, water supplies, and infrastructure. For these reasons, anticipation of such interactions is important in lava flow hazard assessment in regions with abundant surface water; we further demonstrate that remote sensing can be an effective tool for identifying lava–water interactions in past lava flows.

INTRODUCTION

Interactions between lava flows and surface water or ice are common and are responsible for a wide range of deposits and hazards (e.g. Fagents and Thordarson, 2007). While most of these interactions occur in coastal settings, there is also abundant geological evidence for lava flows interacting with and disrupting river systems (e.g. Fenton et al., 2004; Crow et al., 2008; O'Connor and Burns, 2009; Ely et al., 2012; Deligne, 2012). However, most studies of lava–river interactions focus on river and landscape evolution, and they are rarely considered for lava flow hazard assessments (Deligne et al., 2016).

The 1783–1784 Laki fissure eruption in southern Iceland presents an excellent case study of the interactions between a large lava flow and the surrounding hydrology. The eruption occurred in a particularly wet part of Iceland and disrupted two major river systems, as recorded by contemporary observers of the eruption, especially the Rev. Jón Steingrímsson (1728–1791; Björnsson, 1783; Steingrímsson 1783a and b; Steingrímsson et al., 1783; Jónsson, 1784; Pálsson, 1784; Stephensen, 1785; Einarsson et al., 1984; Kunz, 1998; Fell, 2002). These accounts have allowed volcanologists to reconstruct the evolution of the eruption in great detail, from the dates when each individual fissure opened and the progression of the lava flow to the immediate and long-term effects on the local communities (e.g. Thordarson and Self, 1993; Thordarson, 2003; Thordarson et al., 2003). However, less attention has been paid to the parts of these eyewitness accounts related to the interaction of lava flows with surface water.

Because so much is known about the Laki eruption, both from analysis of historical accounts (e.g. Kunz, 1998; Thordarson et al., 2003) and from recent detailed field studies (Thordarson and Self, 1993; Thordarson et al., 1996; Thordarson et al., 1998; Bruno et al., 2004; Guilbaud et al., 2005; Hamilton et al., 2010a; b), it also presents an opportunity to test the use of remote sensing as a tool for broad-scale assessments of lava flows and morphological evidence for their interaction with water. Remote sensing through satellite-derived data, particularly with the advent of high-resolution digital terrain models such as the 2 m/pixel ArcticDEM, offers an efficient method for assessing entire lava fields. It allows volcanologists, geomorphologists and hazard assessors to take a whole-flow view and can help identify features that may not be obvious on the ground. It also opens areas that may be otherwise inaccessible and can strip away the masking effects of vegetation. Remote sensing, however, has its limitations: spatial resolution is often poor compared to ground-based techniques, and field studies are vital for ground-truthing interpretations. Here we examine the Laki lava flow field using both satellite images and the high-resolution ArcticDEM, and compare the results with the findings of previous field-based studies. Our aim is to show the capabilities and limitations of remote sensing for hazard mapping. Toward this end, we also use contemporary accounts of the Laki eruption to constrain the spatial locations of the observed interactions between the lava flow and the local hydrologic system. We highlight not only the range of hazards caused by lava–water interactions during the eruption, but also their effect on the local population. We also review and assess the deposits of explosive lava–water interactions (rootless cones) across the Laki lava field, and compare the data that can be obtained through remote sensing with previous ground-based studies. Finally, we take a broad view and discuss the hazards posed by lava–water interactions in future eruptions, the implications for hazard assessments and planning scenarios, and how remote sensing can be best used in these situations to help emergency planners.

BACKGROUND

Lava–Water Interactions

The abundance of both water and effusive volcanism on Earth means that subaerial lava flows and water come into contact in a wide range of environments: coastal, lacustrine, fluvial, wetland and ice. In this paper, we use 'lava–water interactions' (LWI) as an umbrella term to describe the wide range of outcomes when these two fluids meet: from relatively passive interactions such as lava flows entering water bodies or damming rivers, to steam explosions caused by lava trapping pockets of water or, more commonly, water-laden sediment. Here, we briefly describe the main deposits from LWI and the environments in which they form.

Ocean Entries

Lava deltas form where a lava flow enters a large body of water, e.g. sea, ocean or lake, where it quenches and fragments, building up steeply dipping foreset beds of glassy, clastic rubble (hyaloclastite). When subaerial lava later advances over these deposits, it creates new land (e.g. Skilling, 2002; Umino et al., 2006). Lava deltas are often unstable, however, and prone to subsidence or collapse under their own weight (Kauahikaua et al., 1993). When deltas collapse, lava tubes feeding the flow front may be severed, exposing the hot interior lava directly to water, which can cause explosive tephra blasts, lava fountaining and bubble bursts driven by steam (Mattox and Mangan, 1997).

Some lava flows remain coherent as they enter water, producing the subaqueous lava flows that are common at ocean ridges, seamounts and in coastal waters and lakes. Subaqueous lava flows display a range of surface morphologies, including rubbly, lobate and pillowed, or channelized forms (e.g., Moore et al., 1973; Moore, 1975; Tribble, 1991; Gregg and Smith, 2003). Where trapped steam passively degasses through thick inflated flows or ponded lava, it solidifies the surrounding lava, leaving behind hollow pillars (Gregg and Chadwick, 1996). These are most common in submarine settings but have also been recorded in subaerial lava flows in Iceland (Gregg and Christle 2013; Boreham et al., 2018).

Lava–River Interactions

Lava–river interactions are widely recognized as modifying river drainages and affecting landscape evolution. Notable and well-studied examples in the USA include the Columbia River and its tributaries (e.g. O'Connor et al., 2009; Ely et al., 2012; Deligne et al., 2017; Jensen and Donnelly-

Nolan, 2017; and references therein), and the Colorado River in the Grand Canyon (e.g. Crow et al., 2008; Fenton et al., 2004; 2006).

Where a lava flow enters a canyon, gorge or valley, the style of lava–water interaction varies depending on the geometry of the interaction. Where lava meets a river on low-relief topography, the river can divert around the lava flow rather than be dammed by it. For example, when the 2014 Holuhraun lava flow from Bárðarbunga entered the channel of the Jökulsá á Fjöllum river, lava–river interactions were limited to passive steaming with only a few steam explosions (Pedersen et al., 2017). Here, lava displaced the water from the riverbed but the coarse, gravelly sediments were permeable enough to allow the water to escape passively from the lava.

Where a lava flow enters and blocks a steep river canyon, the river cannot go around the flow and is therefore dammed. On the upstream side, the dam comprises dipping foreset beds of pillow lavas and hyaloclastite debris where the lava interacted with river water, covered by a topset bed of coherent, subaerially emplaced lava that generally exhibits columnar jointing (e.g. Crow et al., 2008; Ely et al., 2012) These features are sometimes repeated in vertical cross section, indicating persistent lava–water interaction with rising water levels behind the dam (Crow et al., 2008). The downstream side of the dam is characterized by gently sloping subaerial lava flows, which may run for great distances along the dried-up riverbed (Crow et al., 2008)

Lava dams impound water, creating upstream lakes and wetlands that may persist for tens of thousands of years. For example, the West Crater lava dam on the Owyhee River created an upstream lake at least 29 km long that persisted for ~24 ka (Orem, 2010). The Lava Butte flow dammed the Deschutes River in Oregon creating Lake Benham, which persisted from ~7 ka to ~1.95 ka, extending >22 km upstream and covering ~48 km^2 (Deligne et al., 2017). Damming of the McKenzie River in Oregon by the Clear Lake South lava ~3 ka created Clear Lake, which is still present today (Deligne, 2012).

Lava dams may vary substantially in permeability, from impermeable dams that create large, long-lived upstream lakes to more permeable dams where water exploits cracks, lava tubes and pore space in tephra and cinder deposits inside or underneath the dam (Crow et al., 2008). Springs at the base of the downstream side of lava dams are common, even where impounded water is still present (e.g. Clear Lake; Deligne, 2012). Similar springs at the base of Benham Falls and Dillon Falls, Oregon show that the lava dam that created Lake Benham was also leaky (Deligne et al., 2017). Failure of lava dames have been variously interpreted from downstream deposits as the consequence of sudden, catastrophic outburst flooding (Fenton et al., 2006) or gradual overtopping and erosion (Crow et al., 2008).

Lava dam formation and failure has been studied by geomorphologists to understand the evolution of drainage systems, with little attention paid to the potential hazards of dam formation or failure. Impounded water upstream of a lava dam has been recognized as hazard (Scott et al., 1999), but disruption to water supplies downstream is not considered in volcanic hazard assessments, despite the risk to agriculture, industry, hydroelectric power generation and drinking water (Deligne, 2012; Deligne et al., 2016).

Cooling Effect of Water on Lava

Where the Holuhraun lava entered the Jökulsá á Fjöllum river, the cooling effect of the river water slowed the advance of the lava front by an order of magnitude, causing the lava to over-thicken at the flow front and eventually causing the main lava channel to overflow in several places (Pedersen et al., 2017). Similar overthickening is found where the Clear Lake East lava flow entered Clear Lake, creating a 25-m-thick flow-front that stops abruptly on a steep slope (Deligne, 2012).

Water cooling has been used to deliberately quench active lava flow fronts for the purpose of stalling and diverting lava flows, most notably during the 1973 eruption of Eldfell on Heimaey, Vestmannaeyjar, Iceland (Williams and Moore, 1983; Williams, 1997; Morgan, 2000). From February to July 1973, approx. 56 km^3 of seawater was sprayed onto the lava front to try to save an important harbor, which housed Iceland’s largest fishing fleet (Williams and Moore, 1983). Similar methods have since been attempted to divert lava flows from Mauna Loa and Kīlauea on Big Island, Hawai’i, but were unsuccessful (Williams, 1997).

Rootless Cones

Rootless cones, also known as pseudocraters, are roughly circular mounds of scoria, ash and/or welded spatter, typically with a single central crater though sometimes with multiple craters (e.g. Thorarinsson, 1953; Fagents and Thordarson, 2007; Hamilton et al., 2010a; Noguchi et al., 2016; Figure 1). They’re known as ‘rootless cones’ because they are fed by lava from the interior of an active lava flow and are not connected to a magma source at depth, so have no geological ‘roots’. Instead, they are formed by steam explosions that can occur when a basaltic lava flow interact with surface water and saturated sediments, e.g. a lake, river, wetland, and around the edge of snow packs (e.g. Edwards et al., 2012).

Rootless cones are not particularly common in the geologic record, although they are found on lava flows across the world, from the Columbia River Flood Basalts to the Galapagos Islands and Hawai’i (Jurado-Chichay et al., 1996; Mattox and Mangan, 1997; Reynolds et al., 2015), and have been used to infer the presence of lava and near-surface water or ice on Mars (e.g. Fagents et al., 2002; Jaeger et al., 2010; Keszthelyi et al., 2010; Hamilton et al., 2011). Additionally, as they are easily buried by later lava flows or eroded by water (e.g. floods or wave action in coastal or lake settings), their formation may be more common than the geologic record implies. Rootless cones are particularly common in Iceland, forming on at least 8 different lava flows over the last 8500 years, due to the frequency of basaltic effusive eruptions and the wet environment (Fagents and Thordarson, 2007).

Rootless cones typically comprise inversely graded layers of scoria interbedded with layers of ash and excavated sediments, which surround a central conduit of welded ash and debris (Thorarinsson, 1953; Fagents and Thordarson, 2007). The upper cone layers also contain larger (centimeter to decimeter) sizes scoria capped with a layer of spatter (Thordarson and Höskuldsson, 2002; Fagents and Thordarson, 2007; Figure 1C).

Cone morphology depends on the dynamics of the lava–water interaction during formation (Greeley and Fagents, 2001; Fagents et al., 2002; Fagents and Thordarson, 2007; Stevenson et al., 2012; Hamilton et al., 2017; Fitch et al., 2017; Boreham et al., 2018). Repeated high-intensity explosions at a single site build large, layered edifices (≤450 m basal diameter; Fagents and Thordarson, 2007; Hamilton et al., 2017). Some of these have multiple craters or contain smaller inner cones built by discrete explosive episodes (Noguchi et al., 2016). At the other end of the spectrum, Hamilton et al. (2010b) mapped cones as small as 2 m basal diameter in their detailed study of a cone group on the Laki lava flow, and the Younger Laxá Lava created a field of thousands of small hornitos where it flowed over wetlands (≤5 m diameter; Boreham et al., 2018).

Early models of rootless cone formation suggested that steam explosions initiated in pockets of water trapped underneath a lava flow (Thorarinsson, 1953). Fagents et al. (2002) refined this model, suggesting that conduction from lava heats water or ice in the underlying sediment, generates steams and initiates a rootless eruption when the pore pressure exceeds the confining pressure of the overlying flow. Lava that fills the excavated crater leads to further heat transfer, steam generation and explosions. Fagents and Thordarson (2007) later suggested that the presence of excavated sediment in rootless cones indicates pre-explosion mixing between molten lava and underling sediments. In addition, the presence of very fine ash (<62 μm) in rootless cones has been taken as evidence for molten fuel–coolant interactions as the driving mechanism for rootless eruptions (Fagents and Thordarson, 2007). In this model, fluid lava mingles with saturated underling sediments, increasing the contact surface area between the two materials and trapping decimeter-sized pockets of wet sediment. Rapid heat transfer from lava to the trapped water generates water vapor at explosive pressures, leading to fragmentation of the lava. This leads to a cycle of increasing contact surface area, heat transfer rates, fragmentation, and steam generation, which drives a steam explosion (Fagents and Thordarson, 2007; Hamilton et al, 2010a and b; Fitch et al., 2017; Hamilton et al., 2017).

The role of sediment in this process is important, as water is both less dense and less viscous than lava, so free-flowing water and lava do not readily mingle. Liquified sediment slurries are much closer in density and viscosity to lava, which may allow them to mingle with lava and promote explosive LWI (White, 1996). The low permeability of fine lacustrine sediments will also contribute to rootless eruptions by preventing steam escape and increasing the build-up of pore pressure as the sediment is heated. The effect of sediment porosity and permeability on magma–water interaction and mingling has been well documented in the formation of peperites (e.g. Skilling et al., 2002).

The morphology and spatial distribution of the cones is affected by the mode of lava supply, with lava tubes, sheets and channels producing distinct patterns (Hamilton et al., 2010a). For example, concentrated lava supplies (tubes and channels) may increase the local stress in the basal crust of the lava flow, causing cracks that allow direct contact between lava and waterlogged sediments. This mechanism of triggering rootless eruptions builds cones (or half-cones) that follow the path of the lava tube or channel. In contrast, rootless cones formed on sheet lobes tend to cluster into groups that may exhibit regular spacing (Bruno et al., 2004). This ‘self-organization’ can be explained by competition between neighboring cones for water supplies trapped in the underlying sediment (Hamilton et al., 2010b).

On the scale of entire lava flows, the size and type of rootless cone formed is determined by a combination of local lava flux and water availability (controlled by the type of underlying sediment; Boreham et al., 2018). These controls are illustrated by significant differences in crater radius and cone type within the >6000 rootless cones created by the Younger Laxá Lava in NE Iceland as it flowed through the large, shallow Lake Mývatn and interacted with rivers and wetlands in the broad glacial valley of Aðaldalur (Thorarinsson, 1951, 1953; Boreham et al., 2018). Sustained lava supplies and abundant water from Mývatn and its saturated sediments created large (>120 m crater diameter) multi-cratered edifices through sustained pulses of explosive activity. In distal flow reaches, where the water was limited to distributed lakes and wetlands, the cones are smaller and predominantly single–cratered (<68 m crater diameter in the center, <20 m along the margins). Where water supplies were even more limited, deposits are dominated by hornitos and small spatter cones.

1783–1784 Laki Fissure Eruption

The Laki fissure eruption took place in the Síða highlands, ~50 km inland from Iceland’s south coast. The fissure lies in Iceland’s Eastern Volcanic Zone, an embryonic rift system on the spreading center between the North American and European tectonic plates (Thordarson and Höskuldsson, 2008). It is part of the Grímsvötn Volcanic System, which stretches ~70 km from Laki in the southwest to the Grímsvötn caldera under the Vatnajökull icecap in the northeast (Figure 2A; e.g. Sigmarsson et al., 1991; Thordarson and Larsen, 2007). The eruption was named after Mt Laki, a pre-existing mountain that is cut by the fissure (Thordarson et al., 2003). It is also referred to as the Skaftár Fires, because the lava occupied the gorge of the river Skaftá. The crater row is known as Lakagígar.

Numerous parallel fissures of Plio-Pleistocene and Holocene age record the long history of volcano-tectonic activity in the region (Thordarson and Larsen, 2007). One of these parallel fissures is from the 939–940 CE Eldgjá eruption fed by Katla volcano, which erupted 19.7 km^3 of lava and 1.3 km^2 of tephra, and partly underlies the Laki lava field (Figure 2A; Moreland et al., 2019). The Eldgjá lava created an extensive group of >4000 rootless cones covering approx. 50 km^2 in the Landbrot district (Figure 2A; Thorarinsson, 1953), some of which have been buried by the Laki lava (Guilbaud et al., 2005).

The Laki fissure eruption lasted from June 1783 to February 1784 (Thordarson and Self, 1993). Over that period, 14.7 km^3 (dense rock equivalent) of lava and tephra was erupted, along with 122 Tg of SO_2 (Thordarson et al., 1996). The resulting cooling contributed to crop failure across Europe and North America (Schmidt et al., 2011 and 2012) and has been linked to excess mortality across Europe (e.g. Grattan et al., 2003; Witham and Oppenheimer, 2004). Locally, famine killed >20% of Iceland's inhabitants (Thordarson et al., 2003). Previous studies (Thordarson and Self, 1993; Thordarson, 2003; Thordarson et al., 2003) have established a detailed chronology of the eruption from physical volcanological evidence and analysis of contemporary reports, which we briefly summarize here.

The eruption started on 8^{th} June 1783 after 3 weeks of felt seismic unrest, with the opening of the first of ten fissure segments (Thordarson and Self, 1993; Thordarson et al., 2003). Over the following 8 months, the fissure propagated from south-west to north-east. Throughout June and July, fissure segments 1-5 opened on the south-west side of Mt Laki. Lava was channeled through the Úlfarsdalur and Varmárdalur valleys into the deep and narrow Skaftá gorge and towards the districts of Álftaver, Landbrot, Meðalland, Síða and Skaftártunga, collectively known as the Fire Districts (Figure 2).

On 29^{th} of July 1783, fissure segment 6 opened on the north-east side of Mt Laki (Thordarson and Self, 1993). Topographically constrained by the highlands and Mt Laki, subsequent lava flows were channeled into the Hverfisfljót gorge or north towards the upper reaches of the Skaftá river (Figure 2). The lava that flowed south through the Hverfisfljót gorge spread across Fljótshverfi and the eastern edge of the Landbrot district (Figure 2A). Fissure segments 7–10 continued in a northeast trend towards Grímsvötn, sending more lava flows down the Hverfisfljót gorge. Eruptive activity at the fissure ceased in Feb 1784, although earthquakes and eruption columns from Grímsvötn were recorded in April 1874 and May 1785 (Thordarson and Self, 1993; Thordarson et al., 2003).

Thordarson and Self (1993) used tephrostratigraphy alongside accounts of seismicity and ash fall to determine opening dates for each of the fissure segments. At two of the fissure segments (4 and 6), rising magma interacted with groundwater and constructed phreatomagmatic tuff cones (Thordarson et al., 2003).

The progression of the lava front has been established through analysis of contemporary accounts, first by Thordarson and Self (1993), and then in more detail by Thordarson et al. (2003; Figure S1). A morphological analysis of the Laki lava field was conducted by Guilbaud et al., (2005), using field observations and high-resolution aerial photographs. They concluded that most of the flow was emplaced as inflating pāhoehoe sheets but identified areas where the top crust was disturbed and broken into plates that rafted on the lava and piled up down-flow, creating rubbly surface textures. Guilbaud et al. (2005) also noted the widespread presence of hummocky regions around the flow margins and determined these to be outbreaks from the front of the advancing lava flow that failed to coalesce into a single coherent sheet flow.

Individual rootless cones were first mapped by Thordarson et al. (1998), focusing on the rootless cones near Mt Leiðólfsfell (group 6 in this study; Figure 2C; Figure 3). They found that these cones formed when the lava interacted with the waterlogged bed of the Hellisá river and dated them to the 17th of June based on tephra stratigraphy and contemporary accounts. Bruno et al. (2004) mapped the large group of cones near fissure segment 1 from aerial photographs (group 1 in this study; Figure 1D; Figure 3). Hamilton et al. (2010a, 2010b) mapped the same group in much more detail using a Differential Global Position System (DGPS) survey. This study also established that the group 1 cones formed during the opening days of the eruption, fueled by lava from fissure segment 1. From tephra stratigraphy and the high-resolution digital terrain model (DTM) from their DGPS study, they concluded that the group was formed in six discrete phases as lava was directed around existing topographical features, with each phase lasting a few days.

In summary, despite the detailed analysis of the lava flow and reconstruction of its emplacement from contemporary records, and the recognition that the lava flow dammed several rivers (Thordarson et al., 2003), previous studies include very little on the wider effects of LWI and the resulting hazards. Additionally, although rootless cones have long been recognized on the Laki lava field, and previous studies have identified 13 different cone groups (groups 1–3, 5, 6, 9–15 in this study; Thorarinsson, 1968; Thordarson and Self, 1993; Thordarson et al., 2003; Bruno et al., 2004; Guilbaud et al., 2005), there has been no comprehensive review of these cone groups and their relationship to the lava flow and water sources, and only two of these groups have been mapped in detail (groups 1 and 6).

Hydrological Setting of the 1783–1784 Laki Fissure Eruption

We give a brief description of the present-day hydrology and environment around the Laki fissure and the Fire Districts to put the contemporary accounts (Appendix 1) and results of this paper into context (Figures 2B, S2). Most important are the two major rivers that flow through the region: the Skaftá and the Hverfisfljót. Prior to the eruption, both the Skaftá and Hverfisfljót river gorges were deeper: up to 74 m and 28 m respectively (Thordarson and Self, 1993). Both rivers were displaced from their pre-eruption paths as the gorges filled with lava, as was the Hellisá river near Mt Leiðólfsfell (Thordarson et al., 1998).

The Skaftá river drains ~3640 km^2 and has an average discharge of 115 m^3/s, measured at the Skaftárdalur farmstead (http://www.katlageopark.com/geosites/skafta/), though discharge is higher at the height of summer. The river now flows along the northern and western boundaries of the Laki lava field. Its source is meltwater from the Skaftárjökull glacier, an outlet of the Vatnajökull icecap. It is also fed by tributaries carrying precipitation and spring-water off the highlands. It flows southwest from the icecap as a braided river, parallel to the Laki fissure. The river comes together as it enters Úlfarsdalur, then turns south as it passes into the Skaftá gorge. Along the gorge, the Skaftá river is joined by the Hellisá river and other small tributaries. Where the gorge opens out into the lowlands, the river splits into three branches. The most westerly branch flows south around the western margin of the Laki lava field and merges with the Tungufljót and Hólmsá rivers to become the Kúðafljót. The central, and smallest, branch is called Árkvíslar and flows south-east into the center of the Laki lava field, where it dries up as the water permeates into cracks in the lava flow. It follows the approximate course of the pre-eruption river Melkvísl, which is referred to in contemporary accounts but was buried by lava. The third branch runs east-northeast towards Kirkjubæjarklaustur between the scarp of the Síða highlands and the edge of the lava field. It is fed by several tributaries, including the Holtsá and Fjaðará rivers, before turning south-east and draining into the North Atlantic Ocean.

The Hverfisfljót is fed by meltwater from the Síðujökull glacier (part of the Vatnajökull icecap), and discharge varies significantly with season: 50–150 m^3/s in summer, dropping to 5–30 m^3 in winter (https://www.nat.is/hverfisfljot-river/). The Laki lava filled in the Hverfisfljót gorge proper, displacing the river to the east. In the highlands, the river now flows along the eastern edge of the Laki lava field for ~10 km before diverting around a mountain. South of the mountain, it follows the eastern margin of the Laki lava for a further 14 km. As it emerges onto the plains, the Hverfisfljót follows the northeast margin of the Laki lava and merges with other rivers, including the Núpsvötn and Brunná, before flowing south-southeast into the North Atlantic Ocean. However, prior to the eruption the river spread from Hvoll in the east to Orustahóll in the west, ~8.4 km (https://www.nat.is/hverfisfljot-river/; Figure 2C).

Prior to the Laki eruption, the site of the Laki fissures, the Varmárdalur valley, was enclosed at the southern end by the 40–50–m–high Galti-Hrossatungur ridge (Figure 2A; Hamilton et al., 2010a). The valley was described as one of the 'boggiest dells' in the highlands (Thordarson et al., 2003; A2 in Appendix 1) and would have drained through a narrow valley north of the Hrossatungur mountain, which is now filled with Laki lava. By contrast, the lowland Fire Districts had been rich agricultural land, used for livestock grazing and cultivating crops such as hay (on silt or loam soils) and lyme grass (on sandy soils; see A3–A11 in Appendix 1). The substrates in the Fire Districts today fall into five major categories: bare or moss-covered lava, aeolian sands covering lavas, fluvio-glacial sands (sandur plains, primarily on the coast), silt loams and peats (Figure S2; Nygard, 1959), with the latter hosting most of the farming areas. Although the Laki lava now covers part of the land, it is likely that the exposed sediments are similar today to those at the time of the eruption.

METHODS

Analysis of Contemporary Sources

Contemporary accounts of the eruptive activity and its impacts on the local and national population are a valuable source of data for understanding how the eruption progressed, and how the lava interacted with the landscape. The most detailed accounts, which are the source of most of our data, were written by Rev. Jón Steingrímsson (1728–1791), pastor to the affected Síða district during the eruption and based at Prestbakki (Figure 2C). He chronicled events in the Fire Districts throughout the eruption, including observations of ash clouds at the fissure, ash fall throughout the districts, the progress of the lava flows, the behavior of the local rivers, and the effect of the eruption on the residents and their livestock (Steingrímsson 1783a, b; Steingrímsson and Ólafsson, 1783; Kunz, 1998). Other contemporary accounts were collected into a single volume alongside modern research (Einarsson et al., 1984), including statements from the local people and accounts from local prefects (Stephensen, 1785), pastors from neighboring parishes (Björnsson, 1783) and a medical student at a local hospital (Pálsson, 1784). This collection is published in Icelandic, but Thordarson et al. (2003) published English translations of selected passages in their study of contemporary accounts of the Laki fissure eruption. Where these passages refer to the lava flow and its interaction with lakes, rivers or other water, we have used Thordarson et al.'s (2003) translations to corroborate Kunz's (1998) translation of Steingrímsson's accounts.

We reviewed these accounts and collated passages that describe interactions between the lava and water, flooding, and explosive LWI. We also noted descriptions of the pre-eruptive environment (land use, locations of lakes etc.) and weather conditions (e.g. heavy rain or snow) that might affect the rivers or lava flow. These passages allowed us to construct a timeline of the lava–river interactions and fit it alongside the existing eruption chronology from Thordarson et al. (2003), including dates of lava surges, fissure migration and lava production rate. These passages are presented in tables in Appendix 1, grouped by theme, and cross-referenced throughout the Results and Discussion. They are organized chronologically, with the passage of interest (in English), the date, and the source text. Each passage has a unique reference number given by a combination of the table number and row number, e.g. A1 refers to row 1 in Table A. From the timeline of events, we attribute likely formation dates to previously undated rootless cone groups.

We mapped the locations of these events (e.g. floods, destroyed farms, other LWI) using the Quantum Geographic Information System (QGIS) software package. It is impossible to accurately map the extent of each area covered by water, so we estimate the flooding extents using named locations and qualitative descriptions in the primary sources. Where sources do describe the extent of floods, we have estimated the flooded area in QGIS by measuring the area from the edge of the lava flow to the flooded locations, following topographic features. We also combined mapped descriptions of land use with a regional soil map (Nygard, 1959) to understand the type of substrate that the lava flowed over (Figure S2).

In their analysis of contemporary accounts of the Laki fissure eruption, Thordarson et al. (2003) established that the directions quoted differ from the true directions. This is because contemporary writers used a prominent scarp running from the end of the Skaftá gorge to Kirkjubæjarklaustur (an old sea-cliff) as the basis for local navigation. They assumed that the scarp ran East-West, but it actually runs 15^{o}–25^{o} anti-clockwise of E–W, hence the error in the quoted directions. We accounted for this in our analysis of the texts and, where possible, used existing place names and a modern high-resolution map of Iceland (http://map.is).

Rootless Cone Identification, Digitization and Statistical Modelling

We mapped the location of individual cones in all cone groups previously identified in the Laki lava field. In addition, we have identified two new groups of rootless cones that appear related to the Laki eruption and have expanded the extent of one of the already-identified cone group. Where the resolution of our data allowed, we have also measured the crater area of individual cones.

We used a combination of aerial photographs and high resolution (2 m/pixel) DTMs available through the ArcticDEM project. These DTMs are derived from images gathered by instruments on-board the WorldView 1, 2 and 3 satellites, and provided in tiles, (data available online at https://livingatlas2.arcgis.com/arcticdemexplorer/) that we stitched together to cover the full extent of the Laki lava field. Aerial photographs came from Google Earth and Loftmyndir ehf. (available through http://map.is). The Loftmyndir ehf. images have a spatial resolution of 0.15–1 m/pixel (Loftmyndir, 2014; Noguchi et al., 2016). The resolution of images in Google Earth varies across the Laki lava field. The best resolved areas are those covered by WorldView 2 images, including the Skaftá river gorge, eastern part of the Fire Districts, and Hverfisfljót river gorge, and have a maximum resolution of 0.5 m/pixel (image references and capture dates in Supplementary Table 1). The remaining area, which includes most of the fissure and highlands, is covered by CNES/Airbus images, for which Google Earth does not provide a metadata, but are considerably lower resolution. The contrast between the two sets of images can be seen in Figure S3, which covers the boundary between the WorldView and CNES/Airbus images. In these lower resolution areas we relied heavily on the ArcticDEM and reference to the Loftmyndir ehf. images. We digitized the cones in QGIS using the images and DTMs as a base map, according to the method of Boreham et al. (2018), which is based on extensive comparison between field observations, aerial photographs and DTMs of rootless cone groups on the Younger Laxá Lava in northern Iceland. We digitized cones as a single point at the center, or inferred center for incomplete cones, of the crater, and used ellipsoids to approximate the craters. We calculated the radius of a circle of equal area as a measure for cone side, using the built-in field calculator in QGIS. We then gave each cone a unique identified (e.g. *Lk2_1* for cone 1 in group 2). We attempted to classify each cone group as either 'river/flood' or 'wetlands/lake', according to our best guess of their formation environment, including the cone location on the lava flow, the local topography and hydrology, and contemporary descriptions (TABLE 1). We recognize that these classifications are far from perfect, as the topography and hydrology were significantly altered by the Laki eruption and we lack sediment samples from each location to confirm the pre-eruptive conditions.

We exported the digitized cone data as a comma separated variable file for analysis. We used a simple linear model to test the relation between crater radius and formation environment, using the statistical software package *R*. We also compared the distribution of Laki cone sizes to rootless cones on the Younger Laxá Lava in northeast Iceland (data from Boreham et al., 2018). The scripts, raw, and processed data files are all available in Supplementary Material.

We recognize that the number of rootless cones identified is a minimum estimate, as some are too small to identify from aerial images or the ArcticDEM, and some may have been eroded or covered by later lava. To assess the limits of our method, we then compared our results with those of Hamilton et al. (2010a; 2010b), who provide detailed maps of the Hnúta and Hrossatungur rootless cones (group 1 in this study).

Not Rootless Cones

There are 8 areas of the Laki lava field where previous studies had indicated rootless cone or possible rootless cone groups, but where were could not find any evidence of rootless cones (Figure S4A). However, we did find features that resembled inflation or collapse pits, based on the presence of cracks around the perimeter of the pits and into the surface of the surrounding lava (Figure S4B). We also found features that looked like rootless cones but are covered by later stages of the lava flow (Figure S4C). We have not included any of these areas in our count of rootless cone groups on the Laki lava field. Some of these areas may have been misidentified as rootless cones in previous studies; some may have rootless cone groups that we missed or are all too small to resolve from aerial photographs or the ArcticDEM.

Electron Probe Analysis of Rootless Cone Tephra

There is one group of rootless cones on the Laki lava field that was previously attributed to the Eldgjá lava flow (Group 8 on Fig. 2; Guilbaud et al., 2005). However, the prominence of the cones above the Laki lava in an area where contemporary accounts show that there was a large body of impounded water led us to question this attribution. We analyzed tephra samples from two rootless cones in this group (collected by AR in summer 2018; see TABLE 2 for sample co-ordinates) and measured the major element composition of the matrix glass using a Cameca SX100 electron microprobe at the University of Bristol with a 20 keV beam, current of 10nA and spot size of 10μm. We checked the beam calibration against the Kakanui hornblende (Carpenter and Vicenzi, 2012) and Columbia River basaltic glass secondary standards before and after analysis of our samples. We analyzed seven points per sample and calculated their mean. We also analyzed samples of fissure-proximal Laki lava and scoria from a rootless cone in the Landbrotshólar group, created by the Eldgjá eruption. The full set of collected data, standard deviations on the measurements, detection limits, and calibration against secondary standards can be found in Supplementary Materials.

The Katla (Eldgjá) and Grímsvötn (Laki) volcanic systems can be distinguished by the FeO/TiO_2 ratio (Larsen 1981; Óladóttir et al., 2008). We compared our data to published compositions of matrix glass in tephra and lava samples from the Eldgjá and Laki eruptions, and the Grímsvötn and Kalta volcanic systems (Thordarson et al., 1996; Thordarson et al., 2001; Guilbaud et al., 2007; Óladóttir et al., 2008) to determine the parent lava flow for the rootless cone group of uncertain origin. As a note, one reviewer suggested that the Hálsagígar/Botnar lava flow could also be the parent lava. We were unable to find any published glass chemistry data for this lava flow, so have uses the whole rock composition to give a first-order comparison to our data (Jakobsson, 1979).

RESULTS

Contemporary accounts of the eruption describe the interactions between the Laki lava and local rivers, and the resulting impacts, which we summarize in chronological order and cross-references to the relevant passages in contemporary accounts (see Appendix 1: letters and numbers are keyed to the appendix tables, so C1 is table C, passage 1). We then describe the different rootless cone groups across the Laki lava field.

Lava–Water Interactions in the Contemporary Accounts

As lava entered the Skaftá river gorge, it quickly dammed the river, as evidenced by the reduced flow at the southern end of the gorge on the 9th of June; the river had almost completely dried up by the 10th, fed only by inputs from local tributaries (see passages B1–B5 in Appendix 1; Thordarson et al., 2003). Large steam clouds were seen above the gorge on the 11th (B6). The first surge of lava exited the Skaftá gorge into the Síða district on the 12th of June (Thordarson and Self, 1993; Thordarson et al., 2003). Steingrímsson described what appear to be rootless eruptions as the lava advanced, noting that *"when the molten lava ran into wet-lands or streams of water, the explosions were as loud as if many cannon had fired"* (C1). This first surge followed the course of the river and covered an area of the older Eldgjá lava field that had been used for forestry and grazing (A6, B8–B10). The continued supply of lava gradually filled the Skaftá gorge, damming its tributaries and impounding water. On the 18th of June, another surge of lava dammed the Búlandsá river (Figures 4, 5), causing the water level to rise and flood the nearby farm (B11).

As the lava spread into the lowland districts it split into three branches, channeled by the (now mostly dry) rivers in the area, before spreading laterally to cover the land in between (B13). The middle branch followed the course of the (now buried) Melkvísl river, destroying several properties in its path, including farmland and pastures, and displaced the river water, causing flooding (B12, B13, B15, B16, B18, B19, B28, B29; Figure 4). The most westerly branch of the lava entered the Kúðafljót river and followed it south (B22). As the flow spread, it dammed the river near Hrífunes. Since the Kúðafljót's two main tributaries (the Tungufljót and Hólmsá rivers) were still flowing, this created a temporary lava-dammed lake that flooded nearby farms (B23). Based on descriptions of the flood extent (from Hrífunes in the south to the ford at Hemruvað in the north), we estimate the area inundated with water covered at least 10.9 km^2 (Figures 4, 6). The third lava branch followed the Skaftá river east along the edge of the Síða scarp and dammed two tributaries, the Holtsá and Fjaðará rivers, flooding several farms and pastures (B17, B24–B27; Figure 4). Between the 2nd and 20th of July, the impounded rivers rose and eventually *"came flooding down upon the heaped-up lava, and violently quenched it"* (B30, B31). Throughout this period, the Fire Districts experienced frequent heavy rain and occasional snow (Table D), which exacerbated the flooding (D7).

As the fissure propagated northeast, lava was channeled towards the Hverfisfljót gorge, rather than towards the Skaftá river. On the 31st of July, the water in the Hverfisfljót river became hot and steamy (B32). The river level began to drop on the 1st of August and by the 4th of August it had completely dried up. The first lava exited the gorge on the 7th of August (B33–B35). This lava dammed tributaries to the Hverfisfljót river, causing flooding and hindering travel across the region (B36–B38; Figure 4).

By the 21st of September, the Skaftá and Hverfisfljót rivers were both flowing (B41), although the Hverfisfljót river dried up again on the 29th (B42). Lava continued to flow down the Hverfisfljót gorge throughout autumn and winter 1783. The fissure eruption continued until February of 1784.

Rootless Cones

We have identified two new groups of rootless cones on the Laki lava field, in addition to those identified by previous studies (Figure 3). Mapping the location of all the individual cones visible in remote sensing datasets, we count 2979 cones spread across at least 15 groups, ranging from fissure-proximal to ~47 km from the fissure. Based on their locations and the published lava flow chronology, we determined the likely timing of each group's formation, although there is still considerable uncertainty in many of these dates (TABLE 1). We now briefly describe each cone group.

Lava from the opening phase of the eruption at fissure segment 1 flowed south and formed a large group of rootless cones where it encountered a wetland or shallow lake, ~2.5 km south of the fissure (group 1; Figure S3; Hamilton et al., 2010a). These cones were formed in six distinct phases, starting on the 8th of June and continuing until at least the 15th (Hamilton et al., 2010a). Here, we mapped 910 cones, whereas Hamilton et al. (2010a) identified ~930 cones with 2216 explosion sites using a DGPS study where they walked the boundaries of each geological feature (lava flow margins, kipuka, cones, craters rims and floors, explosion sites). This comparison shows that remote sensing does a good job of identifying individual cones but lacks the resolution for individual crater mapping at this location.

On the northern side of fissure segment 1, the lava entered Úlfarsdalur and dammed the Skaftá river. Just upstream of where the lava first enters the gorge is a group of small rootless cones (group 2; Figure S3). The current Skaftá river flows along the western edge of this (group 2). Additionally, numerous 10–30-m-diameter mounds are located in the course of the current river; these may be the eroded remains of more cones. The timing of the formation of this group is ambiguous. When lava first entered the gorge, it would have encountered the saturated sediments of the Skaftá riverbed and may have formed these rootless cones. However, the lava in this part of the gorge is >70 m thick (Thordarson and Self, 1993) and any deposits from the early stages of the eruption could well be buried. If the cones formed later in the eruption, then the source of water (or water-saturated sediments) is unclear. One possibility is that the cones formed early in the eruption on top of a stable crust, which was then uplifted as the underlying lava flow inflated.

East of group 1 is a similar but smaller group of cones (group 3; Figure S3) that may have formed in a similar environment. The group itself sits on the northern side of the Galti-Hrossatungur ridge, a 40-50 m high antiform that separated Varmárdalur from the next valley and was buried by the Laki lava (Hamilton et al., 2010a).

There are three groups of cones in the valley between the Galti-Hrossatungur ridge and Mt Leiðólfsfell (groups 4-6). Group 4 (Figures S3) has not been identified in previous studies and comprises a cluster of small cones near the eastern edge of the flow, next to a small lava-dammed pond. This pond probably formed during or after the eruption, when lava flow blocked a small river carrying precipitation and seasonal meltwater off the nearby mountains. In contrast, the cones in group 5 (Figure S5) are spread across the breadth of the valley and the group is cut by subsequent lava channels. The valley-filling spread of this group suggests that it may have formed in a wetland environment. Group 6 lies across the mouth of the valley where the Hellisá river joins the Skaftá gorge, near Mt Leiðólfsfell (Figure S6). The group 6 cones were mapped by Thordarson et al. (1998), who linked them to a contemporary account of explosions where the lava dammed the Hellisá river on the 17th of June 1783 (see C2 and C3 in Appendix 1). Later surges of lava have partially covered this group, but cones are still visible on both sides of a central lava channel. The time between fissure segment 3 opening and the creation of the Leiðólfsfell cones (4 days), indicates that the lava advanced by 5-6 km per day (Thordarson et al., 1998), allowing us to estimate the first possible formation dates of the groups 3–6 (TABLE 1).

Group 7 is a cluster of small rootless cones, isolated in the middle of the lava flow at the north end of Varmárdalur (Figure S6). The resolution of the Google Earth images in this part of the valley is too low to accurately map these cones and they are too small to resolve through the ArcticDEM, though they are clearly visible in Loftmyndir ehf. images. An anonymous reviewer has suggested that these cones pre-date the Laki eruption and sit on a kipuka in the lava flow. However, previous studies linked them to the Laki eruption (Thordarson and Self, 1993; Thordarson et al. 2003; Guilbaud et al., 2005) and we have no evidence that contradicts these studies.

Group 8 lies on the lowland plain near the farm Ytri-Ásar (Figures 6, S6). Guilbaud et al. (2005) originally identified these cones as belonging to the earlier Eldgjá lava flow, which underlies the Laki lava field throughout the region. Major-element analysis of groundmass glass in tephra samples from two of these cones, however, show that they are tholeiitic basalt and do not match the composition of the Eldgjá eruption (TABLE 2, Figure 7). The composition is very similar to that of samples from lava selvages and other rootless cones on the Laki lava field (comparison data from Thordarson et al., 1996 and Guilbaud et al., 2007). We also tested the reviewer hypothesis that they may have been formed by the c. 6000 BP Hálsargígar eruption, also a tholeiitic basalt. Whole-rock data (Jakobsson, 1979) show that the Hálsargígar lava is 2.25 wt.% lower in SiO_2 and has a higher FeO/TiO_2 ratio than the reported Laki whole-rock composition. For these reasons, we suggest that neither the Eldgjá nor Hálsagígar eruptions are a good geochemical match for the Ásar (group 8) rootless cones, and that they were probably formed by the Laki eruption. Steingrímsson described an extensive lava-dammed lake near the Ásar cones (B23) as the lava dammed the nearby rivers. It is possible these cones formed in waterlogged sediments on the edge of this temporary lake, but there may have been another pre-existing body of water in the area. Another group of rootless cones lies approx. 2 km south of the Ásar group, which have also been attributed to the Eldgjá eruption (Guilbaud et al., 2005). Since we did not analyze samples from these cones, we cannot comment on their provenance.

The remainder of the Laki rootless cone groups lie in the highlands near the fissure, and there are no descriptions of their formation. We can, however, infer their order of formation from the eruption sequence. The opening of fissure segment 6 on the north side of Mt Laki on 29th July created a phreatomagmatic tuff ring and clusters of rootless cones on the south side of the fissure segment (groups 9 and 10; Figure S7; Thordarson and Self, 1993). Lava from fissure segment 6 also flowed north toward the upper reaches of the Skaftá river, creating rootless cones ~2 km from the fissure segment (group 11). Lava from fissure segment 7, which opened on the 23rd of August, created four separate groups of rootless cones, probably in late August or early September (groups 12–15; Figures S7, S8). The cones closest to the fissure segment (group 12) form a cluster of large single-cratered and multi-cratered cones, probably in a wetland or shallow lake area. The remaining three groups formed where the lava flow approaches the current braided channel of the Skaftá river. The more northern and middle groups (13, 15) have been eroded by subsequent flooding, but the southern group (14) is intact and contains numerous small, closely spaced scoriaceous cones. We have also extended the boundaries of group 13 compared to Bruno et al. (2004), who first identified cones in this area. These cones groups probably formed either on the waterlogged sediments of the Skaftá riverbed or surrounding wetlands.

By the time the lava reached this area, the Skaftá river had been dammed downstream for almost two months, meaning that water would have backed up in the river channel. While we do not know the extent or depth of the impounded water, we can make an approximation using the discharge of the Skaftá river and the valley dimensions. Thordarson and Self (1993) estimated that the lava in this part of the flow is ~15 m thick. By measuring the area of the Skaftá river channel behind the lava dam and multiplying by this depth, we can estimate the total volume of water needed to flood the river channel back to the location of the rootless cone groups (Figure 8). Measurements from the lava dam to rootless cone groups 14 (minimum extent) and 13 (maximum extent) give areas of 20 km^2 (0.303 km^3 to 15 m depth) and 42 km^2 (0.633 km^3 to 15 m depth) respectively. The current average discharge of the Skaftá river is 115 m^3/s. This includes contributions from the Hellisá river and other tributaries, so is likely to be higher than the discharge in the upper reaches of the river. However, Steingrímsson records that the pre-eruption river levels were unusually high and that there was heavy rain throughout, which would have increased the river discharge. For the purposes of this estimation, and without a way to quantify either effect, we will assume that these two factors cancel each other out and use the quoted current average discharge. Based on these assumptions, it would take ~30 days for water to back up to group 14, and ~64 days to reach group 13. Given that the Skaftá river was dammed on the 9th of June, and that both rootless cone groups formed in late August, it is plausible that these areas were flooded when the rootless cones formed.

Cone Sizes

We were able to map and measure cone sizes in 12 of the 15 identified rootless cone groups. The cones in groups 4, 7 and 10 were too small to see in the ArcticDEM, the Google Earth image resolution in these areas is poor, and the Loftmyndir ehf. were not sufficient for mapping these groups. Cones in the other groups have cone sizes (crater radius) across the lava field, from 0.5–89.8 m. However, most of the cones measured (88.2 %) have a crater radius <10 m, and 56.9 % are <4 m radius (TABLE 3). This distribution is similar to that found at the Younger Laxá Lava in northeast Iceland (83.3 % < 10 m; 44.4 % < 4 m), excluding the large expanse of hornitos on the latter flow, which have a different formation mechanism (Figure 9; Boreham et al., 2018). Spacing between cones correlates with crater radius ($r = 0.51$, $p < 0.005$), as observed on the Younger Laxá Lava. We found no statistically significant relation between cone size and estimated formation environment (adjusted $r^2 = 0.007$, $p < 0.005$).

As noted above, the resolution of our data is insufficient to map individual explosion craters. For example, Hamilton et al (2010a) identified a total of 2038 eruption craters, the smallest of which had a crater radius of 0.4 m; the smallest crater we could identify is >0.5 m radius. Our ability to identify cones from satellite images and DTMs is based on the visible contrast between the crater and the cone walls, which depends on the image processing, the angle and strength of the sun in photographs, and the height and slope difference between cone and crater. For smaller features, this contrast is lower, making it hard to pick out individual cones and craters. Similarly, overlapping craters in a single cone can be very hard to distinguish unless their crater rims are meters apart and cast distinct shadows. Our success in identifying cones, however, is demonstrated by the comparison between ~930 cones reported by Hamilton et al., (2010a; 680 in the northern half of the group, and 250 in the southern half) without our count of 910 for the same region.

DISCUSSION

The Laki eruption highlights the hazards posed by lava–water interactions (LWI), particularly lava–river interactions, which are not often included in lava flow models and hazard assessments (Deligne, 2012; Deligne et al., 2016). Not only does it demonstrate the wide range of hazards, but it also allows reconstructions based on eyewitness accounts and knowledge of the eruption progression from field studies. This makes Laki a good case study to test the use of remote sensing for whole lava field assessments, particularly to determine the circumstances in which different hazards arise and how they develop. In this section, we discuss the major hazards of LWI as illustrated by both the Laki eruption and other examples, the value of remote sensing tools in assessing past LWI deposits, and the hazard implications for similar future eruptions.

Lava–River Interactions and Flooding

The Laki lava dammed or affected the course of at least 10 rivers across the Fire Districts: the Skaftá, Hellisá, Búlandsá, Holtsá, Fjaðará. Tungufljót, Hólmsá, Kúðafljót, Hverfisfljót and Brunná (Figure 4), and possibly many more small tributaries in the highlands. The Skaftá river dammed quickly in Úlfarsdalur due to the combination of high lava effusion rate and the deep, narrow geometry of the gorge. Impounded water above the lava dam would have been further constrained by the Fögrufjöll ridge to the northwest and the Laki lava to the southeast (Figure 8). Along the length of the Skaftá gorge, the lava flow blocked smaller tributaries, causing water to back up in steep-sided valleys. There is evidence of passive LWI in Skælingar in the highlands, where the Laki lava dammed two tributaries of the Skaftá river (Figure 2C; Gregg and Christle, 2013). In other areas, there are accounts of impounded water flooding farms. In some cases, valley-confined water bodies overtopped the dams. In contrast, where the lava dammed the larger Tungufljót, Hólmsá and Kúðafljót rivers on the plains, the impounded lake covered a large area (10.9 km^2). However, it was only temporary as the rivers diverted around the lava and across soil banks near Hrífunes. From this we can see that steep topography favors dams and impounded water, while in areas of lower relief, rivers are diverted, and water impoundment is less likely.

More generally, during the Laki eruption, lava-induced flooding was short-lived: ~3 weeks passed between lava damming the Holtsá and Fjaðará rivers (2nd July and 13th July; B12, B13) and impounded water overtopping the dam (20th July; B17, B18), though contemporary accounts do not record how long the dam persisted and upstream flooding lasted. Upstream impoundment of the larger Skaftá river lasted at least a few months (from the 9th of June until ~21st of September 1783; B1, B41). Blockage of the Hverfisfljót river was episodic, linked to activity at the fissure. The first blockage lasted from the 3rd of August until ~21st of September (fissure segments 6–8); the river then dried up again when fissure segment 9 opened on the 29th of September, indicating the formation of a fresh dam (B42). The fact that no lava-dammed lakes from the Laki eruption persist today, even in areas of steep topography, is probably a consequence of both the leakiness of the dams and the permeability of underlying bedrock. The Laki lava primarily lies on top of older lava flows, including the 939–940 AD Eldgjá lava, which contain cracks and vesicles that give the lavas a high permeability. Leakage of water through both dams and young lava flows is seen, for example, at Benham Falls, Sahalie Falls and Koosah Falls in Oregon, USA (Deligne et al., 2017). In contrast, the long-lived lava-dammed lakes in the Grand Canyon, AZ, USA and on the Owyhee River, OR, USA formed on low permeability sedimentary rocks, meaning that water had to either erode the dam or incise a new path around it (Crow et al., 2008; Ely et al., 2012). This slower process created upstream lakes that persisted for up to tens of thousands of years (e.g. Orem, 2010).

Steingrímsson also describes the impact of outburst flooding from lava dams on the eastern margin of the lava flow near Kirkjubæjarklaustur. Most famous is what later became known as the ‘Fire Sermon’, which Steingrímsson thought would be the last sermon in his church as it was threatened by the encroaching lava. When he and the congregation “*went out to see how the fire had advanced, it turned out that it had not come a foot nearer than before. During the time which had elapsed, it had collected and piled up in the same place, layer upon layer […]. The rivers Holtsá and Fjaðará poured over the dams which the new lava had made them, and with great torrents and splashing smothered the fire*” (Kunz, 1998; B30, B31). Although it is possible that the flow was reaching its natural end (Thordarson and Self, 1993), Steingrímsson’s account makes an interesting case for the role of water in at least slowing, if not stopping, the flow advance. For example, the Clear Lake East lava flow stalled and thickened as it entered Clear Lake, Oregon, USA (Deligne, 2012). Similarly, a preserved inflation front at the distal end of the Younger Laxá Lava in northeast Iceland is flanked by rootless cones, suggesting that the inflation occurred when the lava stalled as it interacted with water. There is a similar preserved inflation front near rootless cone group 8 on the Laki lava field (Figure 6). Thus, although individual lava lobes can stall for a variety of reasons (e.g. a reduction in effusion rate or redirection of lava supply to another flow lobe; e.g. Dietterich and Cashman, 2014), cooling by water is an effective way to stall lava advance, as most famously demonstrated during the 1973 Heimaey eruption in Iceland (e.g. Williams and Moore, 1983).

The Laki eruption shows that even temporary flooding and disruption of river flows can cause significant problems. Impounded or displaced water from dammed rivers devastated at least 9 farms that had escaped direct damage from the lava flow (B11, B16, B17, B21, B23, B25, B27, B28, B29, B37, B39). Moreover, contact with the lava made the water boil and steam (B11), and adversely affected the water quality. Additionally, the extent of flooding was exacerbated by the unusually high river levels before the eruption (A1) and heavy rainfall throughout (D1–D14), a common occurrence in southern Iceland. As well as damaging property and farmland, flooding temporarily cut off access to some farms, and turned previously passable areas into quicksand, making travel across the region difficult and hindering attempts to get aid to isolated dwellings (B36, B38). While current roads and other infrastructure are more robust than they were in the 1780s, in large part because of responses to frequent jökulhlaups (glacial outburst floods), flooding from future eruptions has the potential to wash out roads and bridges, delaying evacuations or the delivery of aid to affected areas. These events demonstrate how the risk to property and infrastructure extends beyond the edge of the lava flow and how areas away from the path of the flow can still be adversely affected.

More generally, lava–river interactions are problematic for downstream communities that rely on rivers for industry, irrigation and other daily water requirements. Indeed, contemporary accounts describe how pollution of the rivers by the eruption cause livestock to sicken and stop producing milk (Kunz, 1998). This forced locals to drink water instead of milk, which also made them sick (B32, B33). Where lava–river interaction is widespread, disruption to water supplies has the potential to impact communities hundreds of kilometers from the vent, and to affect industry, agriculture and hydroelectricity generation in addition to drinking water (Deligne, 2012).

Finally, large fissure eruptions in Iceland are often associated with accompanying activity or unrest in nearby subglacial volcanic systems, e.g. Eldgjá (940 CE) with Katla Volcanic System, Laki with Grímsvötn, and Holuhraun (2014) with Bárðarbunga caldera (Thordarson et al., 2001; Thordarson and Self, 1993; Pedersen et al., 2017). Ash clouds from Grímsvötn were witnessed throughout, and for over a year after, the Laki fissure eruption, with accompanying jökulhlaups recorded in April 1784 and November 1785 (Thordarson and Self, 1993). Jökulhlaups accompanying eruptive activity represent additional hazards to travel and infrastructure.

Explosive Lava-Water Interactions

The widespread rootless cone groups across the Laki lava field show that explosive LWI occurred throughout the Laki eruption. Steingrímsson described the explosions caused as the first surge of lava poured down the Skaftá gorge across the wet sediments of the riverbed (D1). Morphologic evidence for explosive LWI includes rootless cone groups that are found both in wetland/shallow lake environments (e.g. group 1) and on saturated riverbeds (e.g. group 6). There are also cone groups close to where the lava entered areas of impounded water. This mirrors events during the Younger Laxá Lava eruption in north-east Iceland, which created rootless cones around the shore of a large lake, then in numerous groups across three river valleys where lava met wetlands and dammed rivers (Boreham et al., 2018).

While we do not know for certain what the pre-eruption conditions were, cones in group 8 and groups 13–15 all formed on relatively flat topography upstream of earlier lava dams, where contemporary accounts described impounded water or where we expect water to have accumulated. This would have created large areas of saturated sediment, capable of driving rootless eruptions when covered by lava from later stages of the eruption.

However, rootless cones did not form at all lava–river interaction sites during the Laki eruption. Notably, there are no rootless cones near Kirkjubæjarklaustur where the lava dammed the Holtsá or Fjaðará rivers, nor where the lava dammed tributaries in the Skaftá and Hverfisfljót gorges. In these cases, all of the lava was confined to the downstream side of the dam, so the dams acted as a barrier between the saturated riverbed sediments and the hot, fluid interior of the lava flow, and thus prevented rootless eruptions. Where water built up and overtopped the lava dams, e.g. near Kirkjubæjarklaustur, the lava flow was rapidly quenched, again preventing rootless eruptions (B17, B18).

Similarly, there are no rootless cones on the southern flow margin in the Meðalland and Landbrot districts, despite accounts of flooding and the presence of >4000 cones created by the 939–940 CE Eldgjá lava when it covered glacial outwash plains in this region. The ArcticDEM shows that the Eldgjá lava field is 5–10 m thick at the margins in this area, similar to the Laki lava field. Therefore, the most likely explanation for the lack of rootless cones is a change in the available water. Contemporary accounts show that at the time of the Laki eruption farms in this area grew lyme grass (A9, D8), which prefers porous, sandy soils. Indeed, modern soil maps show that adjacent areas (not covered by Laki lava) are aeolian sand deposits lying on top of the Eldgjá lava. It seems likely that these highly permeable sediments, as well as the inherent permeability of the Eldgjá lava, would have enabled sufficient steam escape to prevent rootless eruptions. Importantly, these sediments provide a stark contrast to the low-permeability, peaty sediments underlying the Laki rootless cone groups in the highlands.

These examples demonstrate how the hydrology, constraining topography and lava flow behavior combine to determine whether explosive LWI occurs. In all cases, the physical properties of the underlying sediments probably control the nature of LWI, with fine-grained, low permeability sediments most conducive to rootless eruptions. As witnessed rootless eruptions are rare, we rely heavily on evidence from past lava flows to recognize the range of environments where they can form and help identify potentially hazardous areas for future eruptions.

Despite their abundance, rootless cones were probably less of a hazard for the local population than other LWI during the Laki eruption. Most Laki cones are in the highlands near the fissure, and there are no explicit accounts of rootless eruptions causing injury or damage. However, presence of a cone group (8) in the Fire Districts, ~47 km from the fissure, is a reminder that they can happen anywhere along a lava flow given the right conditions, i.e. saturated, low permeability sediments.

Tephra from rootless eruptions can be thrown >100 m from the explosion site (Hamilton et al., 2017), and debris from similar littoral rootless eruptions in Hawai'i created jets of steam and lava >60 m high that injured several onlookers (Mattox, 1994). It is unlikely that many people will be this close to an active lava flow, although a group of tourists, film crew and volcanologists were injured by a rootless eruption on Mt Etna in 2016 (Andronico et al., 2018). Their unpredictability makes them a potential hazard for volcanologists and emergency workers during an eruption. Indeed, ballistics are most likely to cause fatalities for field researchers and are of key concern when assessing risk for field work (Brown et al., 2017; Deligne et al., 2018).

Remote Sensing for Lava Flow Assessments

Assessing morphologic evidence for lava–water interaction during the Laki eruption using aerial photographs and satellite-derived DTMs allowed us to quickly and cheaply analyze the whole 600 km^2 lava field. All the data are freely available for research purposes and were analyzed through open-source software. We were able to cover a much larger area that would be feasible in a field campaign during the same timeframe, and to map 2979 rootless cones and measure 2831 cones in 12 of the 15 identified groups. For comparison, Hamilton et al.'s (2010a) DGPS study of rootless cone group 1 (2.77 km^2) took place over five successive field seasons.

The whole-field view provided by aerial photographs and DTMs can also reveal large-scale features that are hard to spot on the ground. For example, the ArcticDEM shows the full extent of the group 13 cones, only some of which were previously identified by Bruno et al. (2004) and Guilbaud et al. (2005). The ArcticDEM, in particular, allowed us to identify a number of eroded cones that are not apparent in satellite images because of their low relief and the low contrast between the cone sides and craters. Similarly, preserved inflation fronts can be mapped in profile using DTMs, as illustrated by the front near cone group 8 (Figure 6). GIS software allows measurement of slope and other derived data that can aid feature identification and provide the basis for further geospatial and statistical analyses.

In remote sensing, the size of discernible features depends on the spatial resolution of the data, so there is bias towards identifying larger features. For example, we were able to map and measure 97.8% of the rootless cones in group 1 identified by Hamilton et al., (2010a) but were unable to see multiple explosion sites within individual cones. Another illustrative example is the field of ~3800 hornitos (<5 m diameter) on the Younger Laxá Lava in northeast Iceland (Boreham et al., 2018). Here we used high resolution (9 cm/pixel) DTMs derived from an unmanned aerial vehicle (UAV) survey to map the detailed (sub-meter) morphology of the hornitos and underlying lava flow, and remove some of the masking effect of vegetation, but individual UAV surveys were limited to a few hundred square meters. However, aerial photographs and the ArcticDEM allowed us to map and accurately count individual hornitos across the whole lava field. Thus, while we appreciate the importance of field studies, we note that increasing use of UAVs and DTMs created using Structure-from-Motion is bridging the gap between field-based and remote-sensing-based surveys, allowing high-resolution surveying of several square km in days rather than months.

An additional advantage of remote sensing is access to all parts of the flow, even the most remote. For example, we suspect that the group 4 rootless cones had been missed by previous studies because they are small (<10 m basal diameter) and lie >2 km from the nearest track. This makes remote sensing an invaluable tool for difficult-to-access field areas, and it is the only option available for planetary volcanologists. In contrast, only field studies allow reconstruction of tephrostratigraphy and observations of fine-scale lava flow morphology have been key in reconstructing the events of the Laki fissure eruption and evolution of the lava flow (e.g. Thordarson and Self, 1993; Guilbaud et al., 2005; Hamilton et al., 2010a). For example, our test of the origin of the group 8 rootless cones in this study required analysis of tephra samples from the cones and candidate parent lava flows. Similarly, determining the exact mechanism of rootless cone formation in different groups would require sediment samples from different locations.

Suggestions for Future Hazard Assessments

LWI hazards are generally overlooked in volcanic risk assessments. Ignoring LWI makes sense in volcanic environments that lack (near-)surface water, which is common in frequently active regions such as Hawai'i. However, there are many volcanically active regions with considerable surface water where LWI is a significant potential hazard. Of particular concern are regions with distributed vents, as are common in volcanic fields and rift zones, in proximity to large river systems. For example, the Oregon Cascades in northwest USA, have a long history of basaltic volcanism near large rivers that are close to or upstream of population centers (O'Connor et al., 2009; Deligne, 2012; Deligne et al., 2016; Deligne et al., 2017). Similarly, Iceland has frequent rift-related basaltic eruptions, and receives abundant precipitation that, along with the many glaciers, feeds numerous active river systems. Indeed, the abundance of rootless cones across Iceland is testament to the frequency of LWI during Icelandic eruptions. Other vulnerable areas include the East African Rift System, which has numerous lakes and probable rootless cone deposits have been identified in Laki Kivu (Ross et al., 2014). Similarly, both the Jingbo and Wudalianchi volcanic fields in China have produced basaltic lava flows within the last 3 ka that created lava-dammed lakes, which are now popular tourist attractions (Gao et al., 2013a; Global Volcanism Program, http://volcano.si.edu/). A lava flow that encroached into one of these lakes created thousands of hornitos as steam escaped through the lava (Gao et al., 2013b), like those on the Younger Laxá Lava in NE Iceland (Boreham et al., 2018).

In addition to recognizing past deposits of LWI, such as rootless cones, DTMs are useful for assessing at-risk areas. For a given vent location, DTMs are key to identifying likely lava paths (e.g. Dietterich et al., 2017) and areas where lava flows may be channeled, increasing the distance lava travels (e.g. Dietterich and Cashman, 2014), as happened for both the Laki eruption (Thordarson and Self, 1993; Guilbaud et al., 2007) and the Younger Laxá Lava (Boreham et al., 2018). Topographic analysis can also be used to identify where lava is likely to interact with rivers, and whether rivers will be impounded or diverted around a lava flow. Some lava flow models, such as LavaSIM, can model water-cooling of a lava flow and assess whether the path of a given lava flow is likely to be affected by water-cooling (Fujita et al., 2008).

Identifying the likely path of a lava flow and where it will interact with surface water can be used for LWI risk assessments. Communities likely to be impacted by impounded water can be identified using flood models. In addition, assessments of infrastructure networks (e.g. water, power, fuel, telecommunications) in areas with high LWI hazard could highlight key vulnerabilities, identify roads and bridges susceptible to eruption-induced flooding, and identify communities that could be cut off from vital services, similar to the DEVORA project for Auckland Volcanic Field (Hayes et al., 2018). Maps of possible flooding can also be combined with sediment maps to highlight areas where rootless eruptions are more likely, i.e. low permeability sediments close to lakes or impounded water.

Depending on the spatial and remote sensing data available (DTMs, aerial photographs, hydrologic maps, soil maps, infrastructure maps), simple hazard assessments can be made in a matter of hours. Therefore, this approach could be used during an eruption to predict LWI as a lava flow develops. Lava flow models (e.g. DOWNFLOW; Favalli et al., 2005) are already used to predict lava flow paths during active eruptions, alongside overflights and UAV surveys to monitor flow development (Dietterich et al., 2019). These flights can also be used to visually inspect the expected flow path and identify areas of standing water or waterlogged ground where LWI could occur. Where overflights are not possible, a visual check of satellite images can be used instead. Lava flow modelling would provide timescales for lava reaching these regions and, depending on the model, may incorporate water-cooling to update lava flow paths (e.g. LavaSIM; Fujita et al., 2008). Where lava is expected to enter or block a river, flood models can be used to predict the likely extent and impact of any upstream flooding on homes or infrastructure. In the event of flooding or predicted flooding, soil maps could help identify whether rootless eruptions are likely. For example, during the 2018 Holuhraun eruption, rootless eruptions were assessed to be a low risk because of the high permeability of the Jökulsá á Fjöllum river sediments.

CONCLUDING REMARKS

The Laki fissure eruption demonstrates what can happen when lava flows and rivers interact and can be used to guide volcanic risk and hazard assessments. While lava–river interaction deposits have been studied elsewhere, the addition of eyewitness accounts of these interactions makes Laki unique and provides valuable information about the range of different LWI hazards and the circumstances under which they occur. The lava flows dammed at least 10 rivers, impounding water, flooding farms, hindering travel across the region, and polluting water supplies. LWI created at least 2979 rootless cones across 15 distinct groups. Some of these groups formed near impounded water, suggesting that the lava–river interactions created the conditions necessary for rootless eruptions. The eyewitness accounts at Laki are particularly important because short-term hazards such as floods and water pollution may not leave geological deposits that indicate the scale of damage caused. Combining these accounts with study of the geological deposits improves our understanding of these hazards and the deposits they leave behind, helps us look for evidence of LWI at past unobserved lava flows, and recognize the potential risks for future similar eruptions.

Our study shows that remote sensing can provide flow-field-wide evidence of LWI and improve our understanding of potential future hazards. The combination of aerial photographs and satellite-derived DTMs enables efficient analysis of lava flow morphologies and rootless cones over large and difficult-to-access lava flows, and provides a reliable tool for mapping rootless cones and large-scale lava flow morphologies. This kind of analysis allows comparison between multiple sites and can strip away the masking effects of vegetation. Although remote sensing cannot replace the detail and nuance obtained from field studies, it can help direct fieldwork by identifying features of interest and allows quantitative assessment of flow-field morphology. In cases where field sites are truly inaccessible, such as planetary lava flows, comparison with similar features that have been studied in the field provides a useful reality check.

This study also raises further questions about lava–river interactions and their associated hazards. To our knowledge, Laki is the only eruption where there are eyewitness accounts of lava–

river interaction, from rapid damming of a river by a high-flux lava flow in a narrow gorge, to rivers diverting around or being displaced by lava on a broad plain. These accounts also suggest that the impounded water affected the emplacement of the lava flow. To accurately assess future hazard, we need to know more about the tipping points in the battle between lava and rivers. For example, what balance of lava flux and river discharge is required for a river to divert, stall or stop a lava flow? How does the confining topography affect the formation of lava dams for varying lava flux and river discharge? How do the local conditions affect the longevity of lava dams and impounded lakes, and can we predict when they might fail?

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SUPPLEMENTARY MATERIALS

Supplementary materials to this paper are available open access in the University of Bristol Data Repository (https://data.bris.ac.uk/data/dataset/ch1ck57uyjms2m9c7pb7svuke). This includes full glass chemistry data and probe calibration data, rootless cone location, area, and nearest neighbor data, the *R* script used for data processing, supplementary methods, supplementary figures and full color versions of the figures in this paper. Further supplementary materials are available through the GSAB data repository, including supplementary figures (identical to those in UoB data repository), the Appendix, and supplementary table S1.

REFERENCES CITED

Andronico, D., Cappelli, L., Ciancitto, F., Cioni, R., Cristaldi, A., and Corsaro, R.A., 2018, The 16 March 2017 phreatomagmatic explosion at Mt Etna, Italy; Cities on Volcanoes 10, Naples, Italy.

Björnsson, E., 1783, Relation eins prests sem ár 1783 ferðaðist um sumarið á Suðurland frá Múlasýslu yfir Skaftafells bæði áfram og heimleiðis (Relation by one pastor, who travelled in the summer 1783 in Southern Iceland from Múlashire through Skaftafellshire back and forth) *in* Einarsson, T., Gudbergsson, G.M., Gunnlaugsson, G.Á., Rafnsson, S., and Thorarinsson, S., eds., Skaftáreldar 1783–1784, Ritgerðir og Heimildir: Reykjavík, Mal og Menning, 1984, p. 295–297.

Boreham, F., Cashman, K., Rust, A., and Höskuldsson, Á., 2018, Linking lava flow morphology, water availability and rootless cone formation on the Younger Laxá Lava, NE Iceland: Journal of Volcanology and Geothermal Research, v. 364, p. 1–19, doi:10.1016/j.jvolgeores.2018.08.019.

Brown, S., Jenkins, S.F., Sparks, R.S.J., Odbert, H., and Auker, M.R, 2017, Volcanic fatalities database: analysis of volcanic threat with distance and victim classification; Journal of Applied Volcanology, v. 6, doi:10.1186/s13617-017-0067-4.

Bruno, B.C., Fagents, S.A., Thordarson, Th., Baloga, S.M, and Pilger, E., 2004, Clustering within rootless cone groups on Iceland and Mars: Effect of non-random processes, Journal of Geophysical Research, v., 109.

Carpenter, P.K., and Vicenzi, E.P., 20120, Mineral reference standards and quantitative electro-probe microanalysis, Microscopy and Microanalysis, v. 18, p. 1734–1735

Crow, R., Karlstrom, K.E., McIntosh, W., Peters, L., and Dunbar, N., 2008, History of Quaternary volcanism and lava dams in western Grand Canyon based on lidar analysis, ^{40}Ar/^{39}Ar dating, and field studies: Implications for flow stratigraphy, timing of volcanic events, and lava dams, Geosphere, v. 4, p. 183–206, doi: 10.1130/GES00133.1.

Deligne, N.I., 2012, After the flow: landscape response to the emplacement of Holocene lava flows, Central Oregon Cascades, USA [PhD thesis]: University of Oregon, 217 p.

Deligne, N.I., Conrey, R.M., Cashman, K.V., Champion, D.E., and Amidon, W.H., 2016, Holocene volcanism of the upper McKenzie River catchment, central Oregon Cascades, USA: GSA Bulletin, v. 218 p. 1618–1635, doi:10.1130/B31405.1.

Deligne, N.I., Mckay, D., Conrey, R., Grant, G.E., Johnson, E.R., O'Connor, J, and Sweeney, K., 2017, A Field-trip guide to mafic volcanism of the Cascade Range in central Oregon – A volcanic, tectonic, hydrologic, and geomorphic journey: U.S. Geological Survey Scientific Investigations Report 2017–5022–H, 94 p., https://doi.org/sir20175022H.

Deligne, N.I., Jolly, G.E., Taig, T., and Webb, T.H., 2018, Evaluating life-safety risk for fieldwork on active volcanoes: the volcano life risk estimator (VoLREst), a volcano observatory's decision-support tool; Journal of Applied Volcanology, v.7, doi:10.1186/s13617-018-0076-y.

Dietterich, H.R., and Cashman, K.V., 2014, Channel networks within lava flows: Formation, evolution, and implications for flow behavior, Journal of Geophysical Research: Earth Surface, v. 119, p., 1704–1724.

Dietterich, H.R., Lev, E., Chen, J., Richardson, J.A., Cashman, K.V., 2017, Benchmarking computational fluid dynamics models of lava flow simulation for hazard assessment, forecasting, and risk management, Journal of Applied Volcanology, v. 6

Dietterich, H.R., Patrick, M.R., Diefenback, A.K., Parcheta, C., Lev, E., and Folks, N.L., 2018, Lava flow hazard modeling and the assessment of effusion rates and topographic change with UAS and lidar during the 2018 Kilauea lower East Rift Zone eruption AGU Fall Meeting Abstracts.

Edwards, B., Magnússon, E., Thordarson, T., Guðmundsson, M., Höskuldsson, A., Oddson, B., and Haklar, J., 2012, Interactions between lava and snow/ice during the 2010 Fimmvörðuháls eruption, south-central Iceland: Journal of Geophysical Research, v. 117, B04302, doi:10.1029/2011JB008985.

Einarsson, T., Guðbergsson, G.M., Gunnlaugsson, G.Á., Rafnsson, S., and Thórarinsson, S., editors, 1984, Skaftáreldar 1783–1784, Ritgerðir og Heimildir: Reykjavík, Mal og Menning.

Ely, L.L., Brossy, C.C., House, P.K., Safran, E.B., O'Connor, J.E., Champion, D.E., Fenton, C.R., Bondre, N., Orem, C.A., Grant, G.E., Henry, C.D., and Turrin, B.D., 2012, Owyhee River intracanyon lava flows: Does the river give a dam?: GSA Bulletin, v. 124, p. 1667–1687, doi:10.1130/B30574.1.

Fagents, S., Lanagan, P., and Greeley, R., 2002, Rootless cones on Mars: a consequence of lava-ground ice interaction, *in* Smellie, J.L., and Chapman, M.G., eds., Volcano-Ice Interaction on Earth and Mars: London, Geological Society [London] Special Publication 202 p. 295–317.

Fagents, S., and Thordarson, T., 2007, Rootless volcanic cones in Iceland and on Mars, *in* Chapman, M.G., editor, The Geology of Mars: Evidence from Earth-Based Analogs: Cambridge, Cambridge University Press, p. 151–177.

Favalli, M., Pareschi, M.T., Neri, A., and Isola, I., 2005, Forecasting lava flow paths by a stochastic approach, Geophysical Research Letters, v. 32.

Fell, M., 2002, A very present help in trouble: the autobiography of the fire-priest by Rev. Jón Steingrímsson: New York, P. Lang.

Fenton, C.R., Poreda, R.J., Nash, B.P., Webb, R.H., and Cerling, T.E., 2004, Geochemical discrimination of the five Pleistocene lava-dam outburst-flood deposits, western Grand Canyon, Arizona, The Journal of Geology, v. 112, p. 91–110.

Fenton, C.R., Webb, R.H., and Cerling, T.E., 2006, Peak discharge of a Pleistocene lava-dam outburst flood in Grand Canyon, Arizona, USA, Quaternary Research, v. 26, p. 324–335.

Fitch, E.P., Fagents, S.A., Thordarson, T., and Hamilton, C.W., 2017, Fragmentation mechanisms associated with explosive lava–water interactions in a lacustrine environment: Bulletin of Volcanology, v. 79, p. 12.

Fujita, E., Hidaka, M., and Goto, A., 2009, Simulations of measures to control lava flows, Bulletin of Volcanology, v. 71, p. 401–408.

Gao, W., Li, J., Mao, X., and Li, H., 2013a, Geologic and Geomorphological Value of the Monogenetic Volcanoes in Wudalianchi National Park, NE China, Geoheritage, v. 5, p. 73–85.

Gao, W., Li, J., Mao, X., and Zhang, T., 2013b, Discussion on genetic mechanism of hornitos in Wudalianchi volcanic province, Acta Petrologica Sinica, v. 26, p. 309–317.

Grattan, J., Durand, M., and Taylor, S., 2003, Illness and elevated human mortality in Europe coincidence with the Laki Fissure eruption *in* Oppenheimer, C., Pyle, D.M., and Barclay, J., eds., Volcanic Degassing: Geological Society [London] Special Publications 213, p. 401–414.

Greeley, R., and Fagents, S.A., 2001, Icelandic pseudocraters as analogs to some volcanic cones on Mars: Journal of Geophysical Research, v. 106, p. 20,527–20,546.

Gregg, T.K.P., and Chadwick, W.W. Jr., 1996, Submarine lava-flow inflation: A model for the formation of lava pillars, Geology, v.24, p. 981–984.

Gregg, T.K.P., and Smith, D.K., 2003, Volcanic investigations of the Puna Ridge, Hawai'i: relations of lava flow morphologies and underlying slopes, Journal of Volcanology and Geothermal Research, v. 126, p. 63–77.

Gregg, T.K.P, and Christle, K.W., 2013, Non-explosive lava–water interaction in Skaelingar, Iceland and the formation of subaerial lava pillars, Journal of Volcanology and Geothermal Research, v. 246, p. 36–48.

Guilbaud, M-N., Thordarson, Th., and Blake, S., 2005, Morphology, surface structures, and emplacement of lavas produced by Laki, A.D. 1783-1784, *in* Manga, M., and Ventura, G., eds., Kinematics and dynamics of lava flows: Geological Society of America Special Paper 396, p. 81–102, doi:10.1130/2005.2396(7).

Guilbaud, M-N., Blake, S., Thordarson, T., and Self, F., 2007, Role of Syn-eruptive Cooling and Degassing on Textures of Lavas from the AD 1783-1784 Laki Eruption, South Iceland: Journal of Petrology v. 48, p. 1265–1294.

Hamilton, C.W., Thordarson, Th., and Fagents, S.A., 2010a, Explosive lava-water interactions I: architecture and emplacement chronology of volcanic rootless cone groups in the 1783-1784 Laki lava flow, Iceland: Bulletin of Volcanology, v. 72, p. 449–467.

Hamilton, C.W., Fagents, S.A., and Thordarson, Th., 2010b, Explosive lava–water interactions II: self-organization processes among volcanic rootless eruption sites in the 1783-1784 Laki lava flow, Iceland: Bulletin of Volcanology, v. 72, p. 469–485.

Hamilton, C.W., Fagents, S.A., and Thordarson, Th., 2011, Lava-ground ice interaction in Elysium Planitia, Mars: Geomorphological and geospatial analysis of the Tartarus Colles cone groups: Journal of Geophysical Research, v. 116, E03004.

Hamilton C.W., Fitch E.P., Fagents S.A., and Thordarson Th., 2017, Rootless tephra stratigraphy and emplacement processes, Bulletin of Volcanology, v. 79.

Hayes, J.L., Tsang, S.W., Fitzgerald, R.G., Blake, D.M., Deligne, N.I., Doherty, A., Hopkins, J.L., Hurst, A.W., Le Corvec, N., Leonard, G.S., Lindsay, J.M., Miller, C.A., Németh, K., Smid, E., White, J.D.L., and Wilson, T.M., 2018, The DEVORA scenarios: multi-hazard eruption scenarios for the Aukland Volcanic Field, GNS Science Report 2018/29, 138 p., doi: 10.21420/G20652.

Jakobsson, S.P., 1979, Petrology of recent basalts of the Eastern Volcanic Zone, Iceland, Acta Naturalia Islandica, 26.

Jaeger, W.L., Keszthelyi, L.P., Skinner, J.A., Milazzo, M.P., McEwen, A.S., Titus, T.N., Rosiek, M.R., Galuszka, D.M., Howington-Kraus, E., Kirk, R.L., and HiRISE Team, 2010, Emplacement of the youngest flood lava on Mars: A short, turbulent story: Icarus, v. 2015, p. 230–243.

Jensen, R.A., and Donnelly-Nolan, J.M., 2017, Field-trip guide to the geologic highlights of Newberry Volcano, Oregon, U.S. Geological Survey Scientific Investigations Report 2017–5022–J2

Jónsson, J., 1784, A letter from Síra Jón Jónsson of Mýrar regarding the flight from Hólmasel during the Laki eruption of 1783 *in* Fell, M., translator., 2002, A very present help in trouble: the autobiography of the fire-priest by Rev. Jón Steingrímsson: New York, P. Lang.

Jurado-Chichay, Z., Rowland, S., and Walker, G.P.L., 1996, The formation of circular littoral cones from tube-fed pāhoehoe: Mauna Loa, Hawai'i: Bulletin of Volcanology, v. 57, p. 471-482, doi:10.1007/BF00304433.

Kauahikaua, J., Denlinger, R., Foster, J., and Keszthelyi, L., 1993, Lava delta instability: Is it mass-wasting or is it triggered by lava flowing through tubes?, Eos, Transactions of the American Geophysical Union, v. 74, p. 616.

Keszthelyi, L.P., Jaeger, W.L., Dundas, C.M., Martínez-Alonso, S., McEwen, A.S., and Milazzo, M.P., 2010, Hydrovolcanic features on Mars: Preliminary observations from the first Mars year of HiRISE imaging: Icarus, v. 205, p. 211–229.

Kunz K, translator, 1998, Fires of the Earth: The Laki Eruption 1783-1784 by the Rev. Jón Steingrímsson: Reykjavík, University of Iceland Press.

Mattox, T.N., 1993, Where Lava Meets the Sea: Kilauea Volcano, Hawai'i, Earthquakes and Volcanoes, v. 24, p. 160–177.

Mattox, T.N., and Mangan, M.T., 1997, Littoral hydrovolcanic explosions: a case study of lava-seawater interaction at Kīlauea Volcano: Journal of Volcanology and Geothermal Research, v. 75, p. 1-17, doi:10.1016/S0377-0273(96)00048-0.

Moore, J.G., Phillips, R.L., Peterson, D.W., and Swanson, D.A., 1973, Flow of Lava into the Sea, 1969-1971, Kīlauea Volcano, Hawaii, Geological Society of America Bulletin, v. 84, p. 537–546.

Moore, J.G., 1975, Mechanism of Formation of Pillow Lava, American Scientist, v. 63, p. 269–277.

Moreland, W.M., Thordarson, Th., Houghton, B.F., and Larsen, G., 2019, Driving mechanisms of subaerial ad subglacial explosive episodes during the 10th century Eldgjá fissure eruption, southern Iceland, Volcanica, v. 2, p. 129–150, doi:10.20909/vol.02.02.129150.

Morgan, A.V., 2000, The Eldfell Eruption, Heimaey, Iceland: A 25-Year Retrospective: Geoscience Canada, v. 27(1).

Noguchi, R., Höskuldsson, Á., and Kurita, K., 2016, Detailed topographical, distributional, and material analyses of rootless cones in Mývatn, Iceland, Journal of Volcanology and Geothermal Research, v. 318, p. 89-102.

Nygard, I., 1959, Jardvegskort af Islandi (soil map of Iceland): University Research Institute, Reykjavík, scale 1:750 000, 1 sheet.

O'Connor, J.E., and Burns, S.F., 2009, Cataclysms and Controversy – Aspects of the geomorphology of the Columbia River Gorge, Geological Society of America, Field Guide 15, p. 237–251.

Óladóttir, B.A., Sigmarsson, O., Larsen, G., and Thordarson, Th., 2008, Katla volcano, Iceland: magma composition, dynamics and eruption frequency as recorded by Holocene tephra layers, Bulletin of Volcanology, v. 70, p. 475–493.

Orem, C.A., 2010, Lacustrine sediment record of multiple Quaternary lava dams on the Owyhee River, Southeastern Oregon [MSc thesis]: Central Washington University, 137 p.

Pálsson, S., 1784, Historia ignis in oriente Islandiæ erumpentis Anno 1783, qvoad innotuit in tractu Skagafjördensi, complectitur in se et effectus varios (The story of the earth fire which broke out in Eastern Iceland in the year 1783, as long as it was observed in Skagafjörður; concerning the progress of the eruption and its various effects), *in* Einarsson, T., Gudbergsson, G.M., Gunnlaugsson, G.Á., Rafnsson, S., and Thorarinsson, S., eds., 1984, Skaftáreldar 1783–1784, Ritgerðir og Heimildir: Reykjavík, Mal og Menning, p. 419–422.

Pedersen, G.B.M., Höskuldsson, Á., Dürig, T., Thordarson, T., Jónsdóttir, I., Riishuss, M.S., Óskarsson, B.V., Dumont, S., Magnusson, E., Gudmundsson, M.T., Sigmundsson, F., Drouin, V.J.P.B., Gallagher, C., Askew, R., Gudnason, J., Moreland, W.M., Nikkola, P., Reynolds, H.I., Schmith, J., and the IES eruption team, 2017, Lava field evolution and emplacement dynamics of the 2014–2015 basaltic fissure eruption at Holuhraun, Iceland: Journal of Volcanology and Geothermal Research, v. 340, p. 155–169, doi:10.1016/j.volgeores.2017.02.027.

Reynolds, P., Brown, R.J., Thordarson, Th., Llewellin, E.W., and Fielding, K., 2015, Rootless cone eruption processes informed by dissected tephra deposits and conduits, Bulletin of Volcanology, v. 77, p. 72.

Ross, K.A., Smets, B., De Batist, M., Hilbe, M., Schmid, M., and Anselmetti, F.S., 2014, Lake-level rise in the late Pleistocene and active subaquatic volcanism since the Holocene in Laki Kivu, East African Rift, Geomorphology, v. 221, p. 274–285.

Schmidt, A., Ostro, B., Carslaw, K.S., Wilson, M., Thordarson, Th., Mann, G.W., and Simmons, A.J., 2011, Excess mortality in Europe following a future Laki-style Icelandic eruption: Proceedings of the National Academy of Sciences, v. 108, no. 38, p. 15715.

Schmidt, A., Thordarson, Th., Oman, L., Robock, A., and Self, S., 2012, Climactic impact of the long-lasting 1783 Laki eruption: Inapplicability of mass-independent sulfur isotopic composition measurement: Journal of Geophysical Research, v. 117, doi:10.1029/2012JD018414.

Scott, W.E., Iverson, R.M., Schilling, S.P., and Fisher, B.J., 1999, Volcano hazards in the Three Sisters Region, Oregon: U.S. Geological Survey Open-File Report 99-437.

Skilling, I.P., 2002, Basaltic pāhoehoe lava–fed deltas: large-scale characteristics, clast generation, emplacement processes and environmental discrimination, *in* Smellie, J.L. and Chapman, M.G. (eds), Volcano–Ice Interaction on Earth and Mars, Geological Society, London, Special Publications, v. 202, p. 91–113.

Skilling, I.P., White, J.D.L., and McPhie, J., 2002, Peperite: a review of magma–sediment mingling, Journal of Volcanology and Geothermal Research, v. 114, p. 1–17.

Sigmarsson O., Condomines, M., Grönvold, K., and Thordarson, Th., 1991, Extreme magma homogeneity in the 1783–84 Lakagigar Eruption: Origin of a large volume of evolved basalt in Iceland, Geophysical Research Letters, v. 18, no. 12, p. 2229–2232

Steingrímsson, J., 1783a, Lítið ágrip um nýja eldsuppkomu í vestariparti Skaftafellssýslu og þess verkanir sem framkommar eru (A short compendium of the recent volcanic outburst in western part of Skaftafellshire) *in* Einarsson, T., Gudbergsson, G.M., Gunnlaugsson, G.Á., Rafnsson, S., and Thorarinsson, S., eds., 1984, Skaftáreldar 1783–1784, Ritgerðir og Heimildir: Reykjavík, Mal og Menning, p. 272–274.

Steingrímsson, J., 1783b, Póstur úr bréfi prófasts síra Jóns Steingrímssonar (Abstract from a letter to Rev. Bjarni Jónsson) *in* Safn til Sögu Íslands IV, Copenhagen 1907–1915, p. 69–71.

Steingrímsson, J., Ólafsson, S., 1783, Einfold og sönn frásaga um jarðeldshlaupið í Skaftafellssýslu árið 1783 (A simple but true narrative of the eruption in Skaftafellshire in the year 1783) *in* Safn til Sögu Íslands IV, Copenhagen 1907–1915, p. 58-69.

Stephensen, O., 1785, Abstract from prefect Stephensen's letter to Erichsen, the deputy of the treasury, dated 15 August 1783 *in* Einarsson, T., Gudbergsson, G.M., Gunnlaugsson, G.Á., Rafnsson, S., and Thorarinsson, S., eds., 1984, Skaftáreldar 1783–1784, Ritgerðir og Heimildir: Reykjavík, Mal og Menning, p. 279.

Stevenson, J.A., Mitchell, N.C., Mochrie, F., Cassidy, M., and Pinkerton, H., 2012, Lava penetrating water: the different behaviours of pāhoehoe and 'a'ā at the Nesjahraun, Þingvellir, Iceland: Bulletin of Volcanology, v. 74, p 33–46.

Thordarson, Th., and Self, S., 1993, The Laki (Skaftár Fires) and Grímsvötn eruptions in 1783-1785: Bulletin of Volcanology, v. 55, p. 233–263.

Thordarson, Th., Self, S., Óskarsson, N., and Hulsebosch, T., 1996, Sulfur, chlorine, and fluorine degassing and atmospheric loading by the 1783–1784 AD Laki (Skaftár Fires) eruption in Iceland: Bulletin of Volcanology, v. 58, p. 205–255.

Thordarson, Th., Miller, D.J., and Larsen, G., 1998, New data on the age and origin of the Leiðólfsfell Cone Group in south Iceland: Jökull, v. 46.

Thordarson, Th., Miller, D.J., Larsen, G., Self, S., and Sigurdsson, H., 2001, New estimates of sulfur degassing and atmospheric mass-loading by the 934 AD Eldgjá eruption: Journal of Volcanology and Geothermal Research, v. 108, p. 33–54.

Thordarson, Th., 2003, The 1783–1785 A.D. Laki-Grímsvötn eruptions I: A critical look at the contemporary chronicles: Jökull, v. 53, p. 1–-10.

Thordarson, Th., Larsen, G., Steinþórsson, S., and Self, S., 2003, The 1783-1785 A.D. Laki-Grímsvötn eruptions II: Appraisal based on contemporary accounts: Jökull, v. 53, p. 11–48.

Thordarson, Th., and Larsen, G., 2007, Volcanism in Iceland in historical time: Volcano types, eruption styles and eruptive history, Journal of Geodynamics, v. 43, p. 118-152.

Thordarson, Th., and Höskuldsson, Á., 2008, Postglacial volcanism in Iceland, Jökull, v. 58.

Thorarinsson, S., 1951, Laxárgljúfur and Laxárhraun: A Tephrochronological Study, Geografiska Annaler, v. 33, p. 1–89.

Thorarinsson, S., 1953, The Crater Groups in Iceland, Bulletin of Volcanology, v. 14, p. 3-44.

Thorarinsson, S., 1968, The Lakagigar eruption of 1783 and the Lakagigar crater row, Natturufraedhingurinn, v. 37, p. 27-57.

Tribble, G.W., 1991, Underwater observations of active lava flows from Kīlauea volcano, Hawaii, Geology, v. 19, p. 633–636

Umino, S., Nonaka, M., and Kauahikaua, J., 2006, Emplacement of subaerial pahoehoe lava sheet flows into water: 1990 Kupaianaha flow of Kilauea volcano at Kaimu Bay, Hawai'i, Bulletin of Volcanology, v. 69, p. 125–139

White, J.D.L., 1996, Impure coolants and interaction dynamics of phreatomagmatic eruptions, Journal of Volcanology and Geothermal Research, v. 74, p. 155–170.

Williams, R.S., and Moore, J.G., 1983, Man against volcano: the eruption on Heimaey, Vestmannaeyjar, Iceland, US Department of the Interior, Geological Survey.

Williams, R.S., 1997, Lava-cooling operations during the 1973 eruption of Eldfell volcano, Heimaey, Vestmannaeyjar, Iceland: U.S. Geological Survey Open-File Report 97-724.

Witham, C.S., and Oppenheimer, C., 2004, Mortality in England during the 1783–4 Laki Craters eruption: Bulletin of Volcanology, v. 67, p. 15-26.

FIGURES

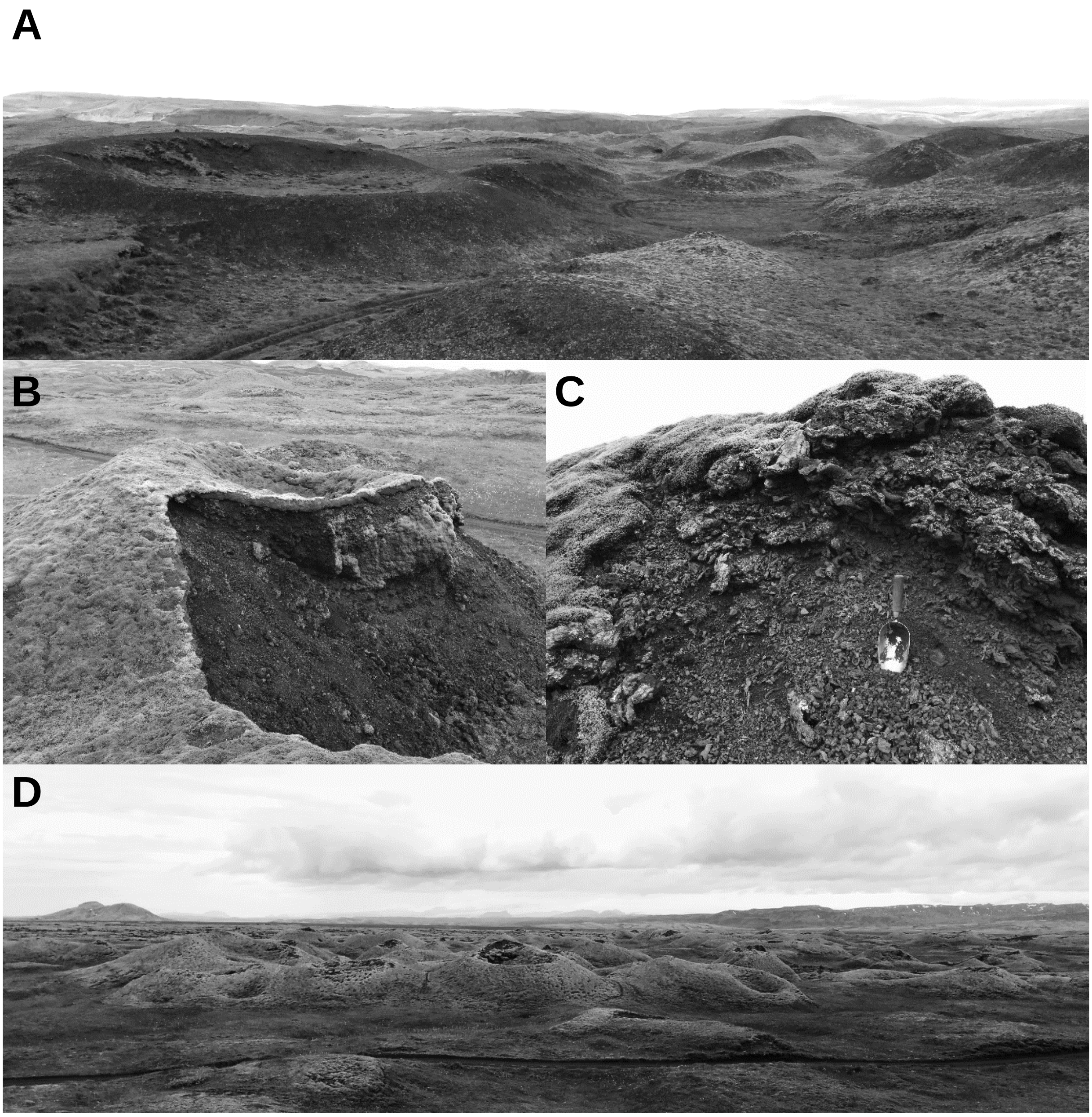

Figure 1. Photographs of rootless cones. (A) Rootless cones from the Landbrots group created by the 934-940 AD Eldgjá eruption. (B) View of a partially excavated rootless cone on the Laki lava field (from group 1 in this study), showing the central crater and layer of moss-covered spatter on the cone flanks. (C) Close-up of the same rootless cone, showing the layers of ash and lapilli-sized scoria topped with welded spatter, with trowel for scale. (D) Wider view of the rootless cones in group 1 of this study.

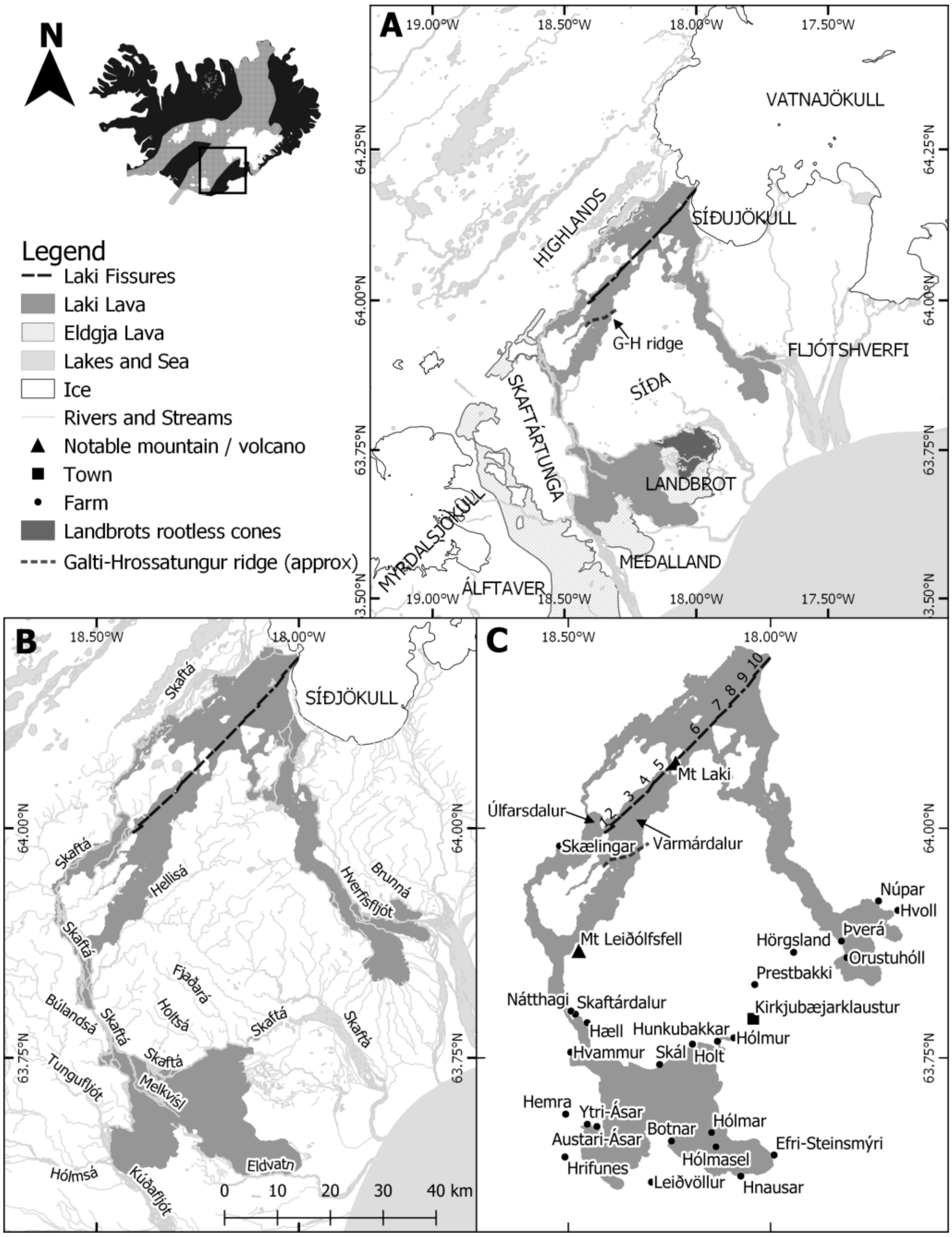

Figure 2. Overview of the Laki region showing the extent of the 1783-1784 lava flow (grey) and major landmarks. (A) Laki lava field in relation to the different regions affected by the eruption, the underlying Eldgjá lava field (hatched light grey, based on Thordarson et al., 2001), and the Katla and Grímsvötn volcanic centers (black triangles). (B) Hydrological map of the region surrounding the Laki lava field, noting the key rivers that interacted with the lava. (C) Key locations across the Laki region. Farms are marked by small black circles, and the local town of Kirkjubæjarklaustur is shown with a black square. Key mountains are marked by black triangles. The individual vents of the Laki fissure are shown by the black line and numbered in the order in which they opened. **Inset**: Iceland and its volcanic zones. Box shows the region covered by main figure. Map data ©OpenStreetMap contributors and available from https://www.openstreetmap.org.

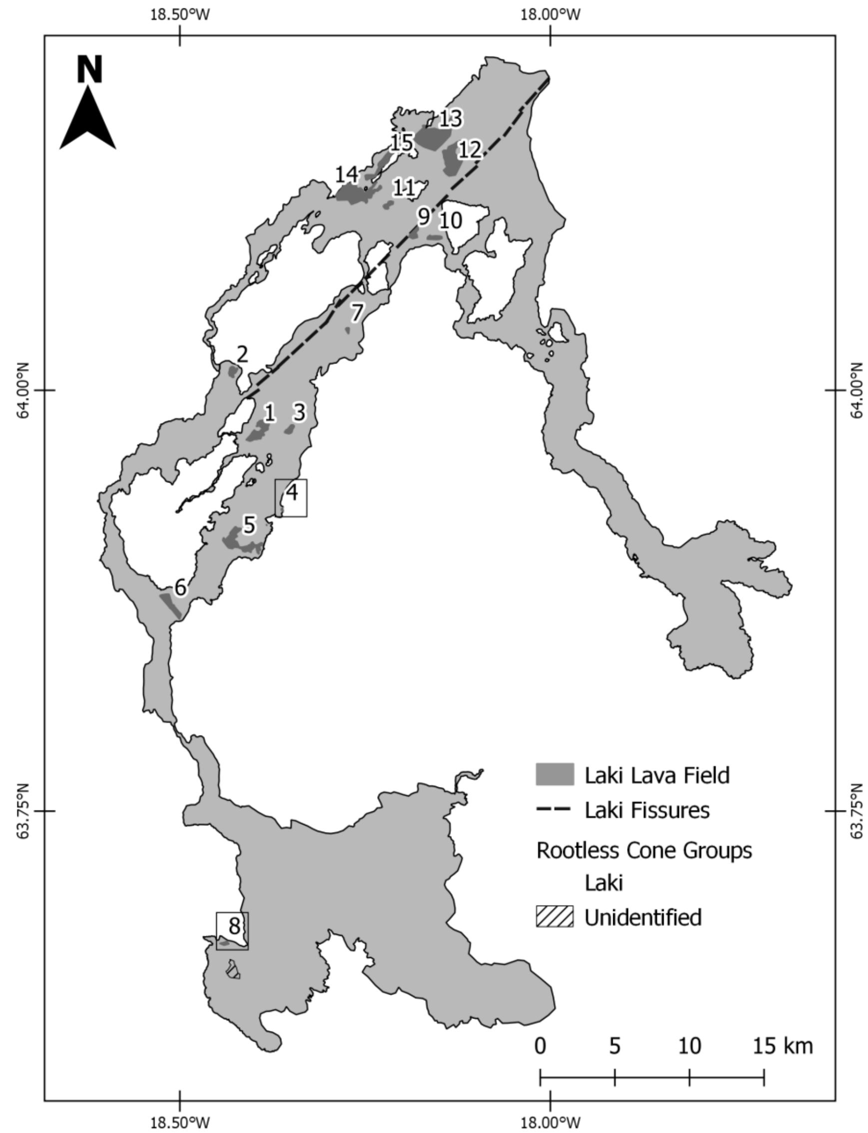

Figure 3. Overview of the Laki lava field showing the eruption fissure (dashed black line) and rootless cone groups (dark grey areas). Rootless cone groups that are new to this study are surrounded by a black box.

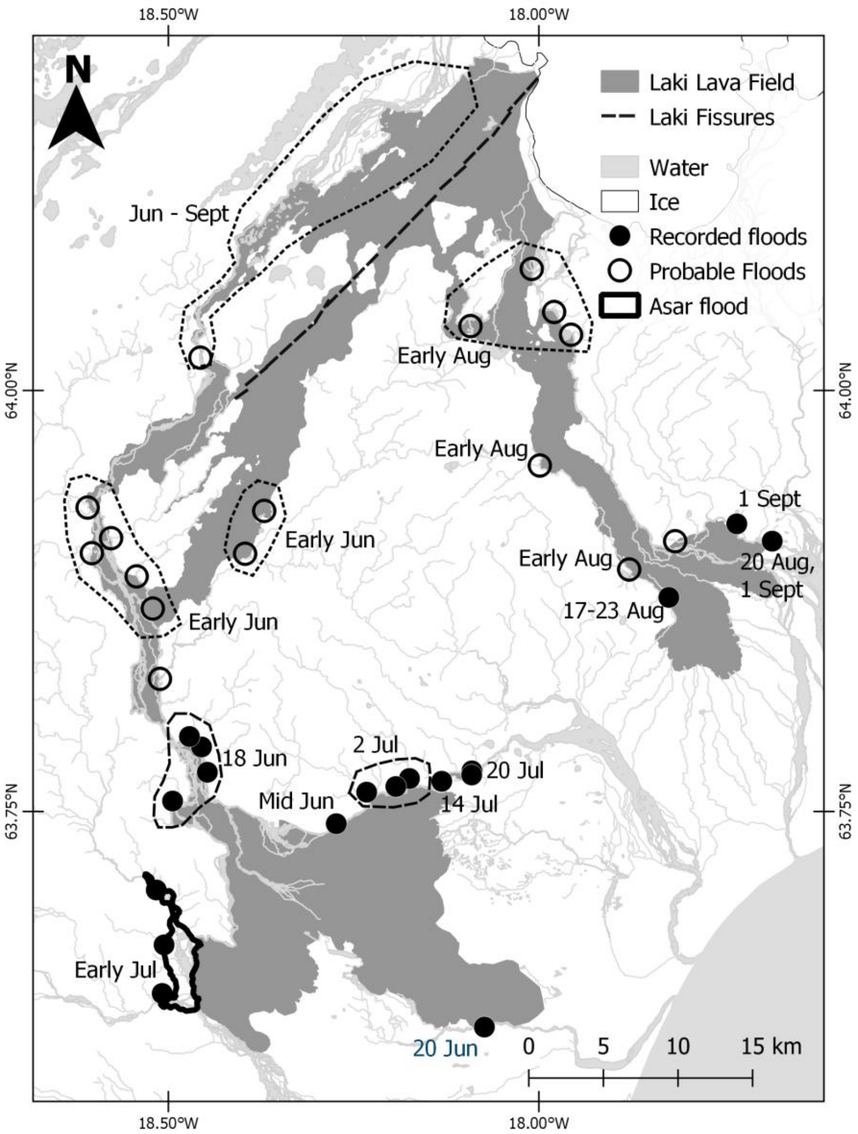

Figure 4. Floods caused by the Laki eruption. Flooded locations named in eyewitness accounts are shown as solid dark circles. Likely flooding locations where there were not eyewitness accounts are shown by light circles. The estimated extent of a temporary lava-dammed lake is shaded. Dates, or probable dates, are given for each event. Locations that flooded on the same date are grouped by dashed lines.

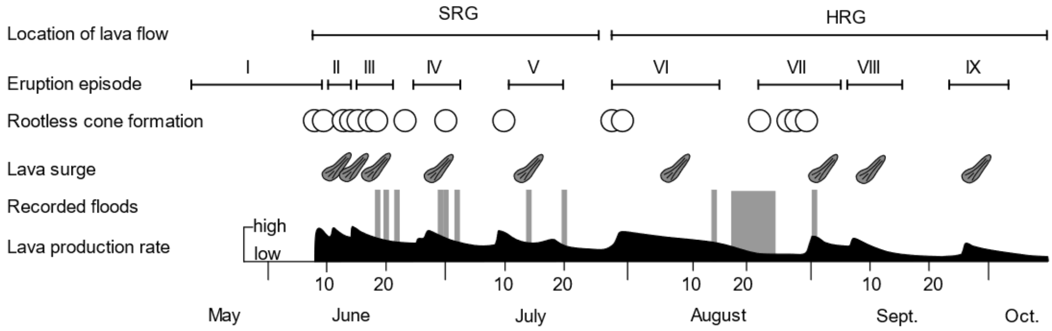

Figure 5. Timeline of the Laki eruption from May–October 1783, showing the active vent, formation of rootless cones, lava surges, recorded floods, lava production rate, and whether the lava was flowing down the Skaftá river gorge (SRG) or Hverfisfljót river gorge (HRG). Modified from Thordarson et al. (2003).

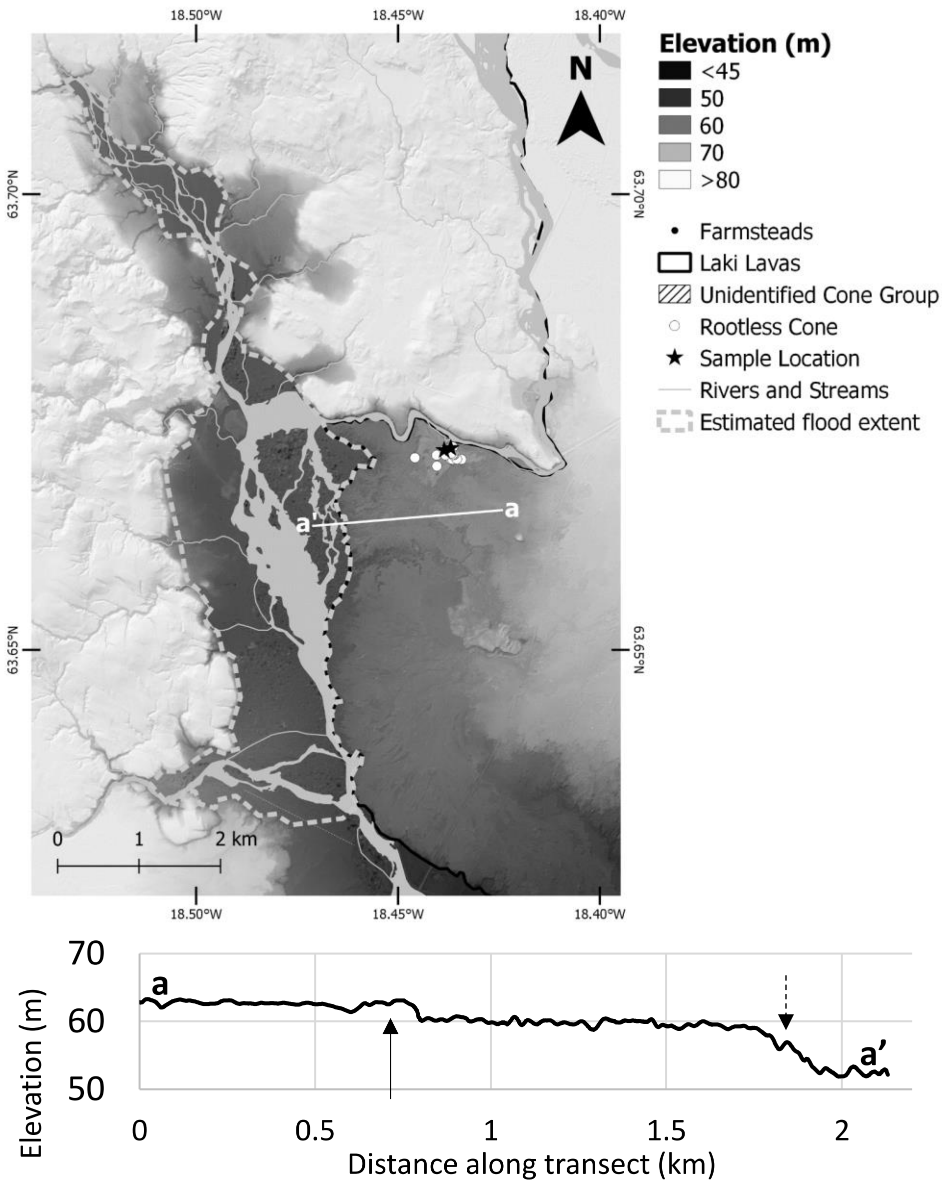

Figure 6. View of the western edge of the lava flow where it met the Kúðafljót river. The estimated extent of the temporary lava-dammed lake created is indicated by a dashed black line. Rootless cones on the Laki lava flow are shown as white circles. Black stars indicate sample locations. Profile a–a' shows the elevation of the lava flow surface, highlighting a preserved inflation front (marked by a black arrow), the downstream hummocky margin, and the edge of the lava flow (black arrow, dashed line). The morphology and elevation of the lava surface is from the ArcticDEM (created by the Polar Geospatial Center from DigitalGlobe, Inc. imagery.)

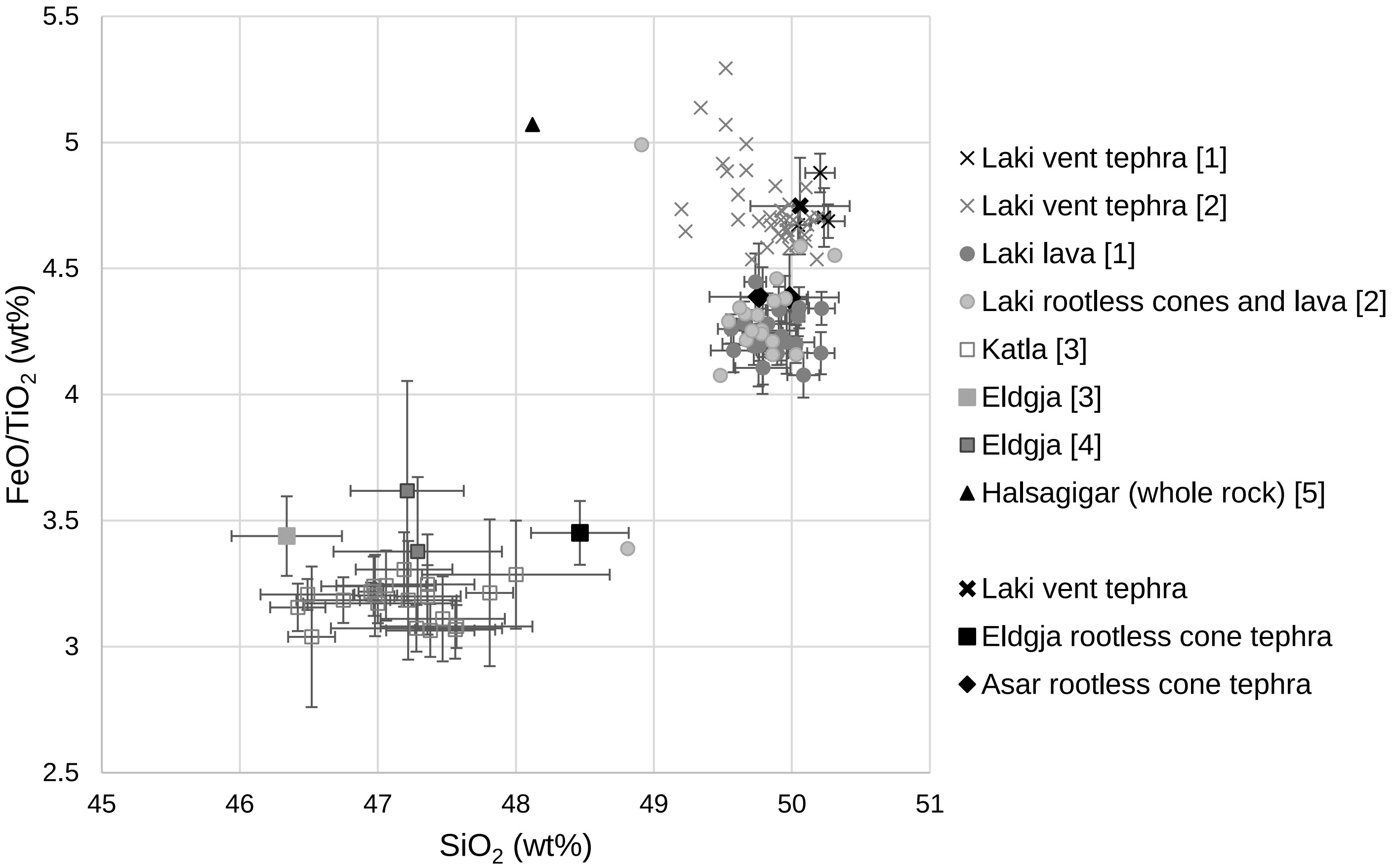

Figure 7. Plot of SiO_2 against FeO/TiO_2 of matrix glass from the rootless cones in group 8 (black diamonds), vent-proximal Laki lava (black cross) and rootless cones in Landbrotshólar, created by the 940 CE Eldgjá eruption (black square). These are overlaid on previously published compositions from the Laki eruption, Katla volcanic system and Hálsagígar eruption: [1] Guilbaud et al., 2007; [2] Thordarson et al., 1996; [3] Óladóttir et al., 2008; [4] Thordarson et al., 2001; [5] Jakobsson, 1979.

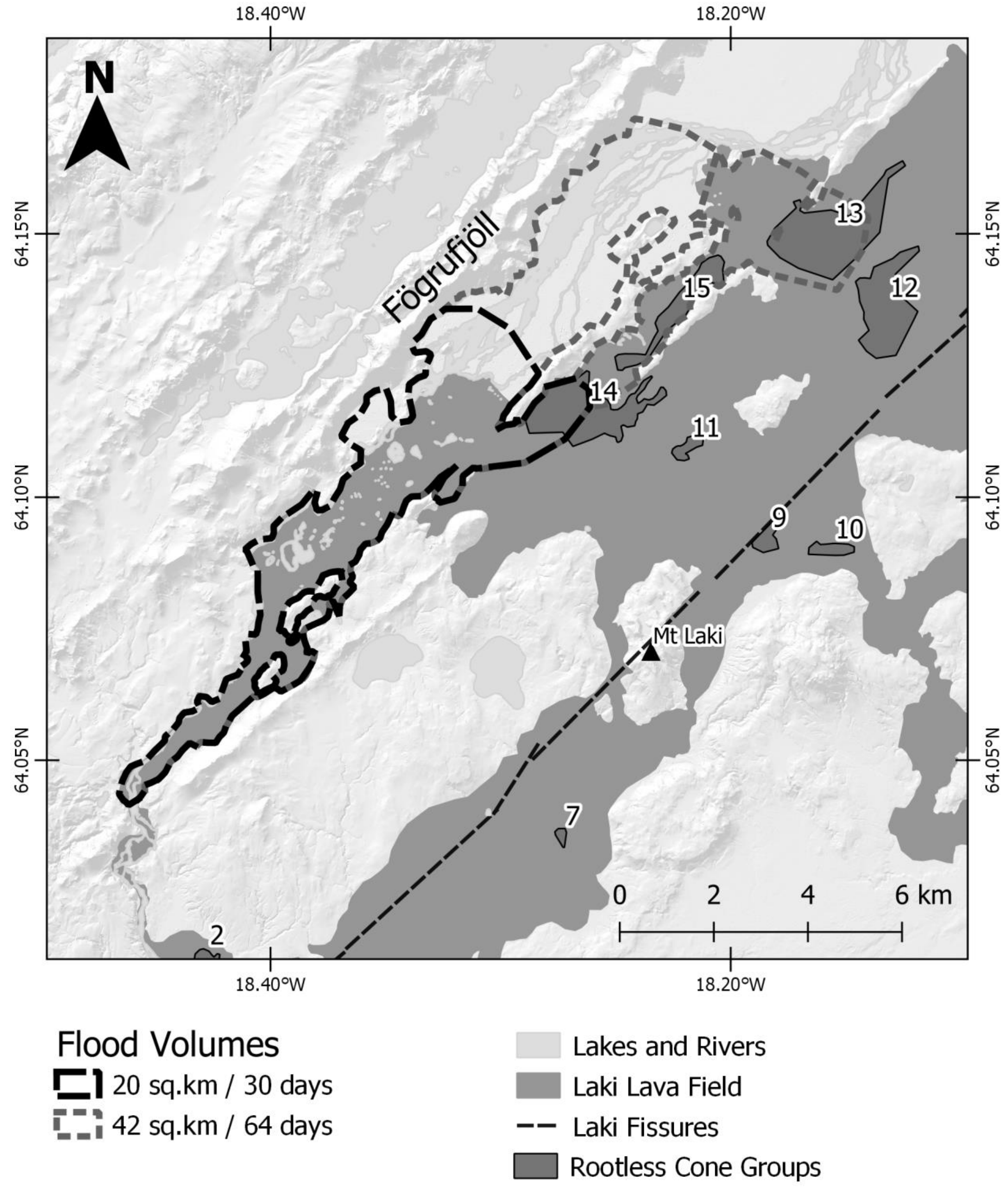

Figure 8. Approximate extents of possible impounded water in the upper reaches of the Skaftá river 30 and 64 days after the river was dammed. Flood extents are shown as speckled areas. Rootless cone groups are shaded in dark grey.

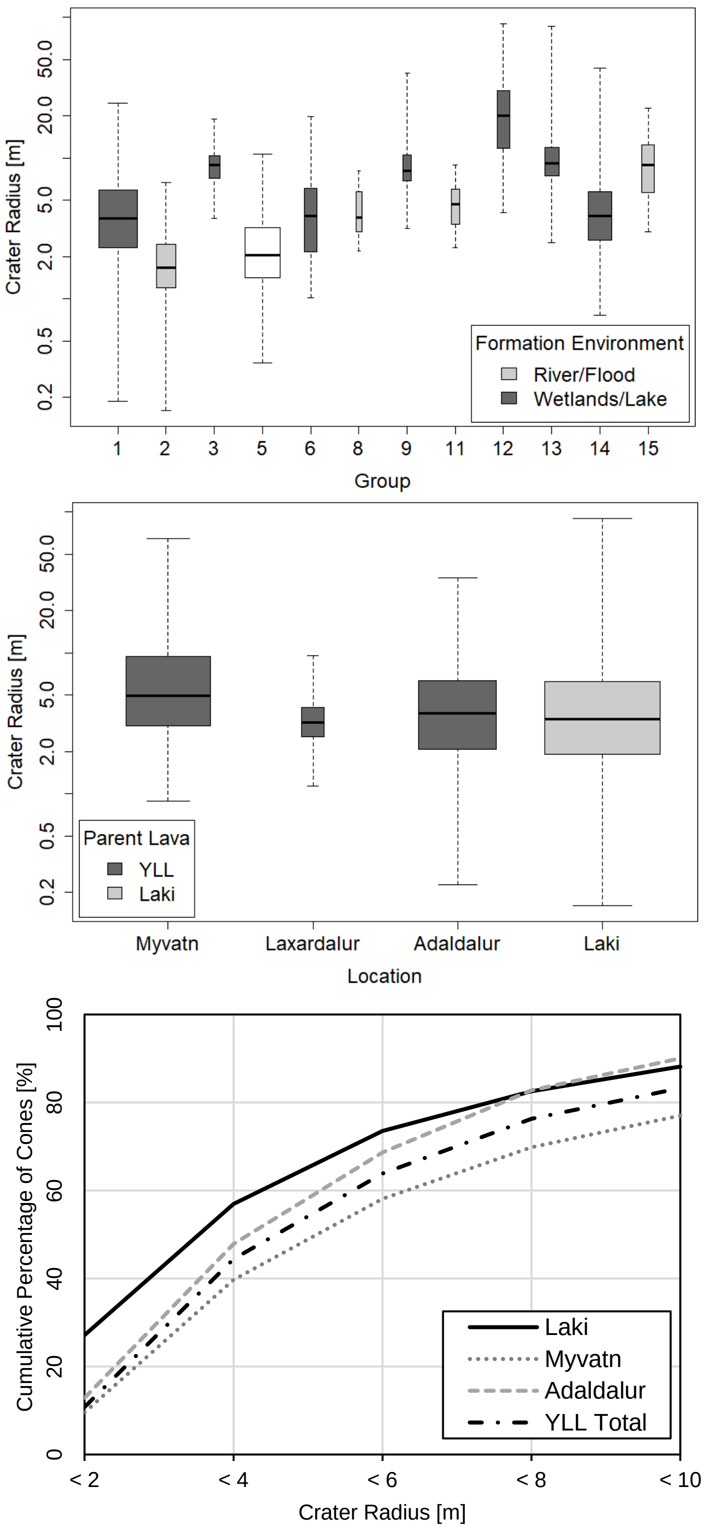

Figure 9. Top: Distribution of Laki rootless cone size (crater radius) by group number, colored by formation environment. Middle: Comparison between the total cone size distribution at Laki and on the Younger Laxá Lava, with cones colored by parent lava flow. Bottom: Comparison of the cumulative percentage of small cones (<10 m crater radius) on the Laki and Younger Laxá Lava.

TABLES

TABLE 1. LIKELY FORMATION DATES OF THE LAKI ROOTLESS CONE GROUPS, THE ENVIRONMENTS THEY FORMED IN AND THE DATING EVIDENCE

Group	Date	Location and probable formation environment	First identified in…	Date based on…
1	8th–15th June	Wetland or shallow lake near fissure segment 1	Thorarinsson (1968) (CHECK)	Hamilton et al., 2010a
2	9th–10th June	Skaftá riverbed in Úlfarsdalur	Thorarinsson (1968) (CHECK)	Drying up of the Skaftá
3	13th–14th June	Wetland or shallow lake east of group 1	Thordarson and Self (1993)	Opening of FS3 + lava travel time
4	14th–15th June	Eastern margin of lava flow near Grenbotnar	This study	Opening of FS3 + lava travel time
5	15th–16th June	Spread across width of lava flow north of Eyrarhólmur, likely formed in wetlands given broad extent of group?	Thordarson and Self (1993)	Opening of FS3 + lava travel time
6	17th June	Old Hellisá riverbed where it joins the Skaftá river gorge	Thordarson and Self (1993)	Thordarson et al., 1998
7	23rd June	Wetland or lake near fissure segment 4	Thordarson and Self (1993)	Opening of FS4
8	~30th June	Near Ytri-Ásar farm, possibly from impounded water from the Tungufljót and Hólmsá rivers	This study – attributed to Eldgjá eruption by Guilbaud et al. (2005)	Steingrímsson's account (D8, D9)
9	29th July	Wetland or lake (?) near FS7	Thordarson et al. (2003)	Opening of FS6
10	29th July	Wetland or lake (?) east of FS7	Guilbaud et al. (2005)	Opening of FS6
11	20th–30th July	Wetland or small lake (?) north of FS6	Thordarson et al. (2003)	Opening of FS7 + lava travel time
12	23rd August	Wetland (?) near the upper reaches of the Skaftá river bed	Thordarson et al. (2003)	Opening of FS7 + lava travel time
13	Late August	Upper reaches of the Skaftá river bed	Guilbaud et al. (2005) – area extended by this study	Opening of FS7 + lava travel time
14	Late August	Upper reaches of the Skaftá river bed	Thordarson et al. (2003)	Opening of FS7 + lava travel time
15	Late August	Upper reaches of the Skaftá river bed	Thordarson et al. (2003)	Opening of FS7 + lava travel time

TABLE 2. MAJOR ELEMENT COMPOSITION OF MATRIX GLASS IN TEPHRA SAMPLES FROM LAKI AND ELDGJÁ LAVA FLOWS AND ROOTLESS CONES

Sample	Rootless cone tephra near Ásar farm		Rootless cone tephra from Landbrots (Eldgjá)	Tephra from Laki fissure segment 3
Location	(-18.4369, 63.6722)		(-17.9803, 63.7614)	(-18.3046, 64.0357)
SiO_2^+	49.76 (0.36)	49.98 (0.36)	48.46 (0.35)	50.06 (0.36)
TiO_2	3.70 (0.07)	3.71 (0.07)	5.03 (0.08)	3.29 (0.07)
Al_2O_3	11.63 (0.20)	11.70 (0.20)	11.40 (0.19)	12.54 (0.20)
FeO	16.22 (0.47)	16.27 (0.32)	17.36 (0.35)	15.64 (0.31)
MnO	0.30 (0.08)	0.27 (0.08)	0.23 (0.08)	0.26 (0.08)
MgO	4.69 (0.16)	4.68 (0.16)	4.16 (0.15)	5.12 (0.17)
CaO	9.44 (0.21)	9.41 (0.21)	7.22 (0.17)	9.74 (0.22)
Na_2O	2.74 (0.18)	2.80 (0.19)	2.48 (0.18)	2.15 (0.16)
K_2O	0.55 (0.05)	0.56 (0.05)	1.52 (0.08)	0.46 (0.05)
P_2O_5	0.42 (0.03)	0.42 (0.03)	0.81 (0.04)	0.36 (0.03)
Total	99.46	99.79	98.67	99.56
FeO/TiO_2	4.39 (0.21)	4.39 (0.17)	3.45 (0.13)	4.74 (0.19)

Major element composition is given as the mean weight percentage of seven points per sample. Standard deviation for each element is given in parentheses.
Co-ordinates given in decimal degrees (WGS84)

TABLE 3. DISTRIBUTION OF ROOTLESS CONE TYPE AND SIZE ACROSS THE LAKI LAVA FIELD

Group	Distance from vent [km]	No. of cones	Crater Radius [m]						
			Min	Q1	Median	Mean	Q3	Max	Std Dev
1	2.6	910	0.5#	2.3	3.7	4.9	5.9	24.6	3.8
2	3.8	282	0.6#	1.2	1.7	1.9	2.4	6.7	1.1
3	3.9	70	3.7	7.2	9.0	9.0	10.3	18.8	2.8
4+	8.9	51	*Not measured*						
5	11.7	776	0.5#	1.4	2.0	2.6	3.2	10.6	1.6
6	17.8	98	1.0	2.2	3.9	4.4	6.1	19.8	2.8
7+	1.6	34	*Not measured*						
8	47.1	20	2.2	3.0	3.8	4.5	5.7	8.1	1.7
9	0.1	44	3.2	6.9	8.2	10.4	10.5	40.3	7.1
10+	1.5	?	*Not measured*						
11	2.5	44	2.3	3.4	4.7	4.9	5.9	8.9	1.8
12	1.7	88	4.1	44.7	19.8	23.3	30.1	89.8	16.5
13	3.7	120	2.5	7.5	9.2	11.6	12.0	85.7	9.7
14	7.8	342	0.8	2.7	3.9	5.5	5.7	43.6	5.3
15	11.3	100	3.0	5.7	9.0	9.7	12.3	22.5	4.7
All	n/a	2979	0.5#	1.9	3.4	5.3	6.2	89.8	6.3

#Minimum crater radius in these groups is limited by the resolution of available aerial photographs. Cones with smaller craters were identified but not measured.

+Crater radii of rootless cones in these groups were not measured because they are too small to be discerned with the available aerial photographs.

APPENDIX – SELECTED PASSAGES FROM CONTEMPORARY SOURCES

This appendix includes selected passages from contemporary accounts of the 1783–1784 Laki fissure eruption, describing the area before the eruption (A), the lava flow progress, lava–river interactions and flooding (B), explosive lava–water interactions (C) and weather during the eruption (D). Full references to the sources are on the final page

TABLE A – CONDITIONS BEFORE THE ERUPTION

Ref	Source	Date	Details	Passage
A1	7	Spring 1783	High river levels before eruption	*The water level was unusually high in the Skaftá River and the water dirty and ill-smelling*
A2	6	June 1783	Description of area around Laki fissures	*The lava from comes from one of the boggiest dells here in the Síða highlands, to the north of us*
A3	3	1778-1783	Description of the Fire Districts before the eruption	*In this district there was a great abundance of livestock and sheep – so much so that some of the farmers hardly knew how much they owned*
A4	1	Pre-1783		*For a number of years preceding this volcanic fire and scourge of the land, this country had experienced high fertility and great bounty*
A6	1	15th June	Laki lava destroys the older Eldgjá lava	*In addition the surge of this fire laid waste and covered all the older lava between the Síða and Skaftártunga areas, which was covered with extensive dwarf birch and willow shrub and one of the most serviceable stretches of grazing land*
A7	1	15th June		*A second surge headed south towards the Meðalland area where there were already two large fields of older lava, Botnahraun and Steinsmýrarhraun.*
A8	1	15th June	Laki lava destroys the older Eldgjá lava	*In the path of the stream was a stretch of old lava, under and through which the flood of fire was eating its way […]. The outermost layer, or crust, of the older lava that remained behind could be swept off like dross.*

TABLE A – CONDITIONS BEFORE THE ERUPTION

Ref	Source	Date	Details	Passage
A9	1	19th June	Description of hydrology in Meðalland before the lava flow	*In a great shower of sparks the fire now set its course southeast towards the Meðalland area, following primarily the course of the stream Melkvísl, which previously had flower from the river Skaftá into a spring-fed river. Near its source, the river was called the Botnar stream, for the farm on that name which stood to the west of it a short distance from its source. This stream flower eastward above Meðalland, To the south, under the edge of the former lava, the farm Hólmar stood on an islet of land, with the church at Hólmasel on a leve bank south of it. The farm Efri-Steins'yri lay to the north, where the river turned to the southeast toward the sea and away from the lava, with the former farmsite there to the east-southeast somewhat farther away and the farm Syðri-Steinsmýri on the other side of the stream. A stream called Feðgakvísl, which megan in Meðalland to the east and south of Hólmasel, flowed eastwards to join the Steinmýri stream to the south of Steinsmýri. The farm Efri-Fljótar stood on the north side of this stream and Syðri-Fljótar on the bacnk to the south of it.*
A10	1	19th – 24th June	Lava destroys rich farmlands in Meðalland	*The great flood of fire which poured forth that same day […] laid waste and destroyed Hólmar, a farm worth 12 hundreds, both of the Fljótar farms, worth 24 hundreds, Hólmasel, 12 hundreds, Botnar, 12 hundreds and forced so much water towards the farm Hnausar that it was uninhabitable for four years afterwards. It came very close to destroying both the Steinsmýri farms […]. The fire did destroy much of their meadows and lyme grass lands.*
A11	1	30th June	Lava destroys pastures at Austari-Ásar and Ytri-Ásar	*This flood of fire then spread itself out over the land of the farms of Austari-Ásar and Ytir-Ásar, approaching the high land upon which these farms stand. There it laid waste and covered with lava hay meadows, pastures and lyme grass lands belonging to the farms*

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TABLE B – LAVA RIVER–INTERACTIONS AND FLOODING

Ref	Source	Date	Details	Passage
B1	1	9th June	Lava begins to dam the Skaftá	*The flow of the river Skaftá, a stream so great that at the ferry site here horses had to swim some seventy fathoms to cross it, and which ran eastward along the Síða area, now began to decrease substantially*
B2	1	10th June	Skaftá river dries up	*By now the river Skaftá had dried up entirely, except for the water emptying into it from local streams*
B3	5			*It became apparent that the Skaftá was beginning to decline and was the same day dry in front of the monastery, except for small streams that flowed from the mountains*
B4	7			*To everybody's surprise the Skaftá River dried up and disappeared on this day*
B5	5			*…it was noticed that the Skaftá River had dwindled considerably apart from the tributaries, which flowed into it from the mountains bordering the Síða district*
B6	2	11th June	Cloud of steam seen over the Skaftá gorge	*We noticed that the great Skaftá River had dried up… North of us further up the gorge we saw a high smoke or steam cloud […] the whole gorge was filled with lava and its sides were glowing like iron. The rocks, both the glowing and unburned ones collided in the air causing loud cracking sounds"*
B7	2	12th June	Progress of the lava slowed down by a fishing lake	*But the threat of fire which now occurred did not in hurry inevitably fall here on the people and animals in most countries. Due to God's wise counsel, one apparent obstacle stood in the way and altered and reduced the progression of the fire, a single whirlpool in one of the fishing lakes*
B8	1		Lava exits the Skaftá gorge into the Fire Districts	*Now the flood of lava spilled out of the canyon of the River Skaftá and poured forth with frightening speed, crashing, roaring and thundering*

TABLE B – LAVA RIVER–INTERACTIONS AND FLOODING

Ref	Source	Date	Details	Passage
B9	1	12th June	Lava preferentially follows the course of the Skaftá	*At first this fiery flood followed the course of the river, and then spread over the banks and out over the older lava fields*
B10	2			*[the lava] first processed to follow the main path of the river*
B11	1	18th June	Lava dams tributaries and causes flooding in Skaftá gorge	*On both sides the water of rivers and streams, whose paths were blocked, collected to the west and below Hæll and the farm Hvammur, which was soon devastated by floodwaters. Both these waters, and any others which the fire did not dry up or set alight and were dammed up here and there along the edges of the fire, were turned into a boiling lake of or hot springs. From these pools, and the flood of fire itself, rose thick steam and vapours, which were especially foul smelling.*
B12	1	19th June	Lava occupies course of the Melkvísl river	*The great flood of fire which poured forth that same day (on the 19th) quickly filled up the course of the river and during the course of these same five days laid waste and destroyed Hólmar*
B13	5			*…the flow split up, one branch advanced eastward along the mountain [Skálarheiði], but another due south along the channel of the river Melkvísl*
B14	9	20th June	Lava flows along the plain of the Hellisá river	*…an exploratory party went as far north into the highlands as possible to investigate the status here. Those who knew the highlands recognised that the fires emerged from three small lava streams in the northern part of the pasture (almost a [day's journey on horse] to the west from the glaciers), located on a flat fluvial plain north of the Hellisá river. The valley [Varmárdalur] where the inhabitants of Síða picked roots was east of the lava streams. Activity increased with loud cracking, ejecta, ashy cloud, yes a storm emerging from the earth. The lava streams grew steadily and covered more ground as they moved away from the source until they merged into one main stream, which flowed like molten copper, first into the above mentioned valley, and when it was filled, the lava threw itself westwards off the mountains above the southwestern part of the Síða district, into the Skaftá River gorge.*

TABLE B – LAVA RIVER–INTERACTIONS AND FLOODING

Ref	Source	Date	Details	Passage
B15	5		Lava crossed the Melkvísl and Steinsmýrarfljót rivers	*This Saturday when the lava passed over the Melkvísl rapids, it ran very rapidly across the Steinsmýrarfljót River and onto the Stekkjatún grass fields north of the farm Hólmasel*
B16	1		Lava causes flooding at Hnausar	*[the lava] forced so much water towards the farm Hnausar [on the southern edge of the lava flow] that it was uninhabitable for years afterwards.*
B17	1	22nd June	Lava flow rips up turf and floods farm of Skál	*There came a fiery surge up near the mountain Skálarfjall and the slopes and bluffs east of the farm Skál, which stood amongst them in a fair and sheltered valley facing south. A brook flowed down the valley on each side of the farm and the church stood in front of the row of farm buildings. This surge pressed so close against the lower, front extremes of the ridges, that the sod was uprooted and twisted like a ribbon. […] This dammed up the streams and the situation was made worse by unceasing rain. The inhabitants of the farm deserted the house and fled higher up the slopes behind it, sleeping in outbuildings and tents. They took anything that was of value with them […] so that they should not meet the same fate as Hólmasel. Because of the downpour, however, they kept their cows in the cowshed, which proved to be of little help because the waters rose more quickly than they had expected and flooded church, house and cowshed alike. […] The water which flooded the farm bubbled and boiled in the heat.*

TABLE B – LAVA RIVER–INTERACTIONS AND FLOODING

Ref	Source	Date	Details	Passage
B18	1		Lava crosses river near Hólmskirkja and destroys the church	*The newly constructed church Hólmskirkja […] was destroyed by fire. All the ornaments in the church, its books and burial implements burned as well, as did the beautiful bell from Þykkvabæjarklaustur weighing 240 pounds, which had been loaned to the church with the bishop's consent until an appropriate bell had been obtained. This had been done and an order had been given for the bell to be returned to Þykkvabæjarklaustur, but it had not yet been carried out, with the result that the church ornaments and other possessions, which might easily have been removed, burned there and were destroyed. Some people have placed the blame with the minister there who, upon having removed his own belongings and those of others from the church, locked it and left the key in another building before he left on Friday. […] The fact that, compared to the others, he was so slow to waken to the danger and remove his property was probably due to a delusion – he had expected the fire to come to a halt and be extinguished in the river which ran above the farm. Both he and others were mistaken here, as it was only natural that the greater force should subdue the lesser, as proved to be true here. But in this case it went even farther: as the fire poured and tumbled into the water it was turned into fuel and began itself to combust as if it were the purest of oils, and to this I myself and others are living witnesses.*
B19	1	22nd June	Lava crosses river at Botnar and farmer loses flock	*Another noteworthy example: the farmer who lived at Botnar, […] was preparing to leave the farm he collected together on an island in the river a great number of his sheep, which he intended to have herded away. The fire, however, spread over the river and the island more quickly than he expected, so that after only a brief time there was neither hide nor hair of them to be seen.*
B20	1	24th June	Lava observed coming from the Hellisá river channel	*…men from Skaftártunga went to explore what was happening to the north of the settlement; they saw that the lava had emerged from the channel of the Hellisá River, here in the pasture.* [Note that the lava must have been flowing through this area a week previously, based on the accounts of rootless cone formation at Leiðólfsfell (Thordarson et al., 1998)]

TABLE B – LAVA RIVER–INTERACTIONS AND FLOODING

Ref	Source	Date	Details	Passage
B21	1	29th June	Lava and floodwaters inundate Hvammur again	*The same fiery lava entered the farm Hvammur […] so much water had flooded the farm site that it was never again located in the same place*
B22	1	30th June	Lava flow splits into three branches to follow the rivers	*The flood of fire streaming from the canyon now split into three separate branches: one flowest west into the stream Landá, which had left the river Skaftá at Skaftártunga and emptied into the river Kúðafljót between Hraun and Leiðvöllur. The other two branches went east, the more southerly of them headed towards the Landbrot region and the bore northerly east along the settlements of the Síða mountains.*
B23	1	30th June and following days	Lava dams Tungufljót, Hólmsá and Kúðafljot rivers	*The most westerly of the streams of fire, which followed the course of the Landá, now laid waste to the farm of Botnar. […] This flood of fire then spread itself out over the land of the farms of Austari-Ásar and Ytri-Ásar, approaching the high land upon which these farms stand. There it laid waste and covered with lava hay meadows, pastures and lyme grass lands belonging to the farms, especially Austari-Ásar. This flood of fire continued on to the river Kúðafljót, filling up much of its course, and then flowing a good way along it until it stopped down distance about Leiðvöllur. In doing so, it dammed up the Tungufljót and the river Hólmsá at Hrífunes. The whole area, up to the gravelling knolls of the gorge Fauskalækjargljúfur, was turned into a fjord, covering the meadows of Flöguengjar as far as the ford Hemruvað*
B24	1	1st July	North branch of lava follows the Skaftá	*The most northern branch ran into the old course of the river Skaftá, where much of the first surge was now cooling and hardening, and then out of the channel again in several directions.*
B25	1	2nd July	North branch of lava flow dams the Holtsá and Fjaðará rivers	*The liquid fire poured forth over the land so that everything became mixed together. It dammed up the river Holtsá, so that the valley filled with water, after which it crossed the river bed to burn down the Holt farmstead and continued east along the slopes and dammed up the river Fjaðará, which is now called Fjaðará. This flooded the meadows Heiðarengjar, at the foot of the slopes, with water and sand.*

TABLE B – LAVA RIVER–INTERACTIONS AND FLOODING

Ref	Source	Date	Details	Passage
B26	5	13th July		*…the lava swelled up and flowed east towards Dælur and Fjaðará River, blocked the river in its gorge, then followed its channel advancing beyond the promontory.*
B27	1	14th July	Lava causes flooding at Hunkubakkar	*Although the fire did not burn down Hunkubakkar, which stood on the bank north of the river, the water which subsequently streamed north from the lava so eroded the home field there that most of it will be given up and the buildings moved to a less-threatened site*
B28	1		Floods damage Hólmur farm	*The farm Hólmur in the Landbrot region […] suffered considerably where the streams which formerly ran to both sides of the farm were dammed up, along with other waters higher up. As a result the farm can now only be reached from one direction, and not at all when the rivers are high*
B29	1			*To the north of the river, across from Hólmur, was a croft belonging to Kirkjubæjarklaustur called Laxárness. It was only occasionally inhabited and was so flooded by water that it will never be inhabited again*
B30	1	20th July	Fire Sermon	*I was filled with sorrow at the thought that this might well be the last service to be held in the church, as the terror which now threatened and approached ever nearer appeared likely to destroy it as it had the other two. […] After the service concluded and men went out to see how the fire had advanced, it turned out that it had come not a foot nearer than before. During the time which have elapsed, it had collected and piled up in the same place, layer upon layer, in a downward sloping channel some 70 fathoms wide and 20 deep, and will rest there in plain sight until the end of the world, unless transformed once again. The rivers Holtsá and Fjaðará poured over the dams which the new lava had made them, and with great torrents and splashing smothered the fire, which was churning and rumbling in the channel, then poured forwards and off the front of the aforementioned pile, streaming and splashing. There was so much water that horses should not cross the river at all by the cloister all that day.*

TABLE B – LAVA RIVER–INTERACTIONS AND FLOODING

Ref	Source	Date	Details	Passage
B31	3			*The molten lava now began to flow down the [Skaftá] riverbed; and it seemed inevitable that it would destroy the church. It was in full course down the slope of the riverbed, heading for the monastic farm and the church. […] We called fervently and earnestly upon God, who so ordained it that the lava did not advance a single foot beyond where it had been before the service. Instead, it piled itself up in a heap, layer upon layer. In addition, all the local lakes and rivers came flooding down upon the heaped-up lava, and violently quenched it.*
B32	1	31st July	Lava begins to interaction with Hverfisfljót river	*The cloud of smoke and steam moved along the gorge of the river Hverfisfljót, which was almost as wide and deep as that of the river Skaftá, and contained almost as much water. In some of the channels the water seethed with the heat*
B33	1	1st August	Flow starts to drop in the Hverfisfljót	*The same shrieking continued on the 1st, 2nd and 3rd of August, accompanied by quaking, thundering and lightning, with a flow of fire behind the mountains which dried up the river Hverfisfljót*
B34	2	3rd August	Hverfisfljót dries up	*…people noticed that the water in the Hverfisfljót River was getting warmer. The temperature increased steadily until it finally dried up.*
B35	1	7th August	Lava exits Hverfisfljót gorge	*On August 7th the first visible stream of fire poured from the Hverfisfljót gorge. On the 8th and 9th, it continued to follow the course of the river*
B36	1	14th August	Flooding observed along eastern edge of lava flow from Hverfisfljót gorge	*I went up to Hörgsland, eastward up on the hearth, to see whether there was a possibility of crossing over in front of the point where the lava flow had advanced. There I saw a huge flood of water churning seaward to the east of the lava which was simply impossible to cross.*
B37	1	17th–23rd August	Flood waters begin to subside but continue to damage farmland	*The waters previously mentioned now began to subside, as the farmer at Þverá clearly noticed, and he began preparations to leave for good when the fire and water began to damage his home field and hay meadow.*

TABLE B – LAVA RIVER–INTERACTIONS AND FLOODING

Ref	Source	Date	Details	Passage
B38	1	20th August	Floods make travel difficult in the area	*I decided to make an attempt to journey eastwards… When I reached the river Brunná at Hvoll I first sank into quicksand and then had to swim the horse from one bank to the other… [We] returned by the common route which was further inland, thinking the water would be shallower there than at Hvoll, which proved to be the case. But so much glacial silt and floodwater had collected on those alluvial flats that it took the boy and I from six o'clock one evening until around nine the next morning to cross there… After that no one crossed there.*
B39	1	1st September	2nd surge of lava exits Hverfisfljót gorge and damns the river Brunná	*[The lava] dammed up the river Brunná just above and across from Núpar, then followed its course along the older lava as far as Hvoll, where it stopped short of destroying the route used by travellers. […] The river Brunná later found a new course following the old lava, much of which it eroded and thus damaged the lamb-pen field near Núpar.*
B40	1	7th September	All of the local mountain rivers dry up	*There was such a mass of fire beyond the mountains that it dried up and combusted all the lakes and streams which had previously coursed the gravel flats*
B41	1	21st September	Skaftá and Hverfisfljót flow again	*From that day on no one suffered ant severe damage from any flooding. Both the rivers Skaftá and Hverfisfljót and all the streams of the mountains about the settlements have now found themselves a path once more and have not yet caused any great damage*
B42	1	29th September	Hverfisfljót dries up again as fissure 9 opens	*They were followed by the same outbursts of great fire beyond the mountains which dried up a great portion of the rivers and streams which had made their way through the lava*
B43	1	Throughout July, August and September	Lava flow keeps rivers dry	*All that month along with August and September the lava flow continued to flow out of the Skaftá River gorge, but in late September the flow dwindled and stopped. At this time, sheep and other goods were taken over the lava flow west of Skaftárdalur because the lava that was still flowing further up in the pasture kept the rivers to the north of the Skaftárdalur farm dry.*

TABLE B – LAVA RIVER–INTERACTIONS AND FLOODING

Ref	Source	Date	Details	Passage
B44	3	Throughout eruption	Eruption contaminated water supply, causing sickness	*The flesh of the livestock that we ate was thoroughly contaminated, and so was the water that we had to drink. My physical strength now began for the first time to be undermined, since I had to drink so much of the water and was constantly harassed with problems during that entire period*
B45	3			*We became so used to drinking water that it tasted to us like sweet whey. But it was polluted and brought in its train more disorders than I care to mention.*

TABLE C – EXPLOSIVE LAVA-WATER INTERACTIONS

Ref	Source	Date	Details	Passage
C1	1	12th June	Rootless eruptions on the bed of the Skaftá	*When the molten lava ran into wet-lands or streams of water, the explosions were as loud as if many cannon had fired*
C2	1	17th June	Formation of the Leiðólfsfell rootless cones (6) (Thordarson et al., 1998)	*The flames of fire then rose so high that from the afore-mentioned canyon Úlfardalsgjá to the northwest, from which a steady rushing and boiling sound could be heard […] The volcanic fires reached over the Geirland heath, where the Geirland property had a shieling*
C3	1			*The fire column was seen from Prestbakki farm above the Geirlandsheiði moor.*

TABLE C – EXPLOSIVE LAVA-WATER INTERACTIONS

Ref	Source	Date	Details	Passage
C4	5	18th July	Rootless eruptions from lava flow in Skaftá gorge	*…more had come on around the Skaftá River gorge and nearby areas, was clearly visible on the ground as later observations revealed; it was ripped apart and had been thrown around and had undergone amazing transformation. There were found here and there fire-blobs, which had fallen down from the air and burned the grass around them as they chilled and lithified. Some of these blobs were half buried in the ground and shaped like a cow-dung. Others were shaped like twisted bundles and had pierced into the ground and broken up on impact. These fire-blobs appeared to weigh around ten pounds or more.* [Note: attributed by Thordarson et al. (2003) to rootless eruptions within the Skaftá gorge. No known surviving rootless cones associated with this description]
C5	1		Spatter from rootless eruptions	*Near the farm Skaftárdalur on the eastern side of the Skaftá River gorge lava bombs, which had fallen out of the air, could still be seen, some were elongated and twisted together like cow-dung. Some were still in one piece; others had broken up on impact.*

TABLE D – WEATHER CONDITIONS DURING THE ERUPTION

Ref	Source	Date	Details	Passage
D1	4	8th June	Eruption cloud brings heavy rain	*The heavy rain which fell from the eruption from the fire and smoke columns that rose from the fissure […] contained salty and sulphur smelling water which caused smarting in the eyes and on the skin*
D2	6			*For the next three days the ash-fall was accompanied by heavy rainfall*
D3	1	9th June	Eruption cloud brings heavy rain	*That night heavy rainfall came down from it*

TABLE D – WEATHER CONDITIONS DURING THE ERUPTION

Ref	Source	Date	Details	Passage
D4	5			*…torrential rain from the plume that now continuously rose higher and higher by the day. The rain was loaded with before mentioned sandy ash and hairs, light blue in colour and smelled like a mixture of nitrate and sulphur.*
D5	1		Snowfall	*Snowfall and snowdrift in the easterly wind, that was derived from the plume*
D6	5	14th June	Heavy rainfall	*…in the early evening a heavy rainfall occurred from the plume*
D7	1	Mid-June	Floods exacerbated by rain	*[The lava] has risen so high there that it is almost on a level with the ridges. This dammed up the streams and the situation was made worse by unceasing rain. […] the waters rose more quickly than they had expected and flooded church, house and cowshed alike. […] The water which flooded the farm bubbled and boiled in the heat.*
D8	5	21st June	Snowfall, rain, and foggy weather	*… large amount of ash fell here in the Síða district, followed by sleet and snowfall so that the mountains became white*
D9	8			*…followed by rainy and foggy weather. The face of the earth became white.*
D10	1			*…wind from the east with rain [in Síða district] …*
D11	1	27th June	Torrential rain	*…wind was from the west and bringing with it a torrential rainfall.*
D12	1	11th-12th July	Heavy rain	*Heavy rain and wind so the volcanic ash was washed down in the ground or was blown off such that the ground was visible again*
D13	5	22nd July	Heavy rain	*…occasional heavy rainfall, and during this time columns of fire and smoke with intermittent thunder and rumbling were observed in the pasture.*
D14	1	1st-7th September	Heavy rain	*Rain and acrid rain, fog and mist, thunder and lightning occurred frequently that week.*

SOURCES

1) Steingrímsson, J (1784; trans. Kunz K, 1998) *Fires of the Earth: The Laki Eruption 1783-1784*, Reykjavík, University of Iceland Press
2) Pálsson S (1784; translation from Thordarson et al., 2003) *Historia ignis in oriente Islandiæ erumpentis Anno 1783, qvoad innotuit in tractu Skagafjördensi, complectitur in se et effectus varios (The story of the earth fire which broke out in Eastern Iceland in the year 1783, as long as it was observed in Skagafjörður; concerning the progress of the eruption and its various effects)*, in Einarsson T, Gudbergsson GM, Gunnlaugsson GÁ, Rafnsson S, Thorarinsson S (eds.) *Skaftáreldar 1783–1784, Ritgerðir og Heimildir*, Mal og Menning, Reykjavík 1984, 419-422
3) Steingrímsson J (trans. Fell M; 2002) *A Very Present Help in Trouble – The Autobiography of the Fire Priest*, New York, P. Lang
4) Steingrímsson J (1783a; trans. Thordarson et al., 2003) *Lítið ágrip um nýja eldsuppkomu í vestariparti Skaftafellssýslu og þess verkanir sem framkommar eru (A short compendium of the recent volcanic outburst in western part of Skaftafellshire)* in Einarsson T, Gudbergsson GM, Gunnlaugsson GÁ, Rafnsson S, Thorarinsson S (eds.) *Skaftáreldar 1783–1784, Ritgerðir og Heimildir*, Mal og Menning, Reykjavík 1984, 272–274
5) Steingrímsson J and Ólafsson S (1783; trans. Thordarson et al., 2003) *Einfold og sönn frásaga um jarðeldshlaupið í Skaftafellssýslu árið 1783 (A simple but true narrative of the eruption in Skaftafellshire in the year 1783)* in *Safn til Sögu Íslands IV*, Copenhagen 1907–1915, 58-69
6) Steingrímsson J (1783b; trans. Thordarson et al., 2003) *Póstur úr bréfi prófasts síra Jóns Steingrímssonar (Abstract from a letter to Rev. Bjarni Jónsson)* in *Safn til Sögu Íslands IV*, Copenhagen 1907–1915, 69–71
7) Stephensen O (1785; trans. Thordarson et al., 2003) *Abstract from prefect Stephensen's letter to Erichsen, the deputy of the treasury, dated 15 August 1783* in Einarsson T, Gudbergsson GM, Gunnlaugsson GÁ, Rafnsson S, Thorarinsson S (eds.) *Skaftáreldar 1783–1784, Ritgerðir og Heimildir*, Mal og Menning, Reykjavík 1984, 279
8) Pétursson M (1784; trans. Thordarson et al., 2003) Höskuldsstaðarannáll 1730–1784, *Annálar 1400–1800, (Annales Islandici)* IV. Hið Íslenska Bókmenntafélag, Reykjavík 1940–1948, 463–603

9) Björnsson E (1783; trans. Thordarson et al., 2003) *Relation eins prests sem ár 1783 ferðaðist um sumarið á Suðurland frá Múlasýslu yfir Skaftafells bæði áfram og heimleiðis (Relation by one pastor, who travelled in the summer 1783 in Southern Iceland from Múlashire through Skaftafellshire back and forth)* in Einarsson T, Gudbergsson GM, Gunnlaugsson GÁ, Rafnsson S, Thorarinsson S (eds.) *Skaftáreldar 1783–1784, Ritgerðir og Heimildir*, Mal og Menning, Reykjavík 1984, 295–297