Flow of lava into fissures in the rift zones of Iceland

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Abstract — *In several eruptions of the Krafla volcanic system during the magmatic rifting episode of 1975-1984 it was observed that lava flowed from the surface into preexisting, open fissures of the Krafla fissure swarm. In one instance, during 18 hours of the eruption in July 1980, almost all the erupted lava disappeared into one fissure at a distance of 2 km from the eruptive one. The receiving fissure consequently widened and propagated northwards along the rift. Apparently, dikes were formed that were fed from the surface and propagated horizontally and downwards. In some instances the lava from these dikes reappeared at the surface and was erupted for the second time. The down-flowing lava was not always fully degassed and continued releasing gas as it was filling the receiving fissure. In such cases spattering was observed from the down-flowing lava. In other instances lava accumulated in low spots above fissures that subsequently widened and drained the accumulated lava from below, leaving a "bathtub ring" of solid crust around it. Since these observations at Krafla, several similar cases have been identified in other parts of the rift zones of Iceland, including both the Northern Volcanic Zone and the Reykjanes Peninsula Oblique Rift. Based on petrological data, it is inferred that two prehistoric lavas erupted near the Krafla caldera may have flowed along fissures of the Krafla fissure swarm and erupted for the second time in the Kelduhverfi district, 30 km down–rift. Furthermore, such processes have occurred during the currently ongoing activity on the Reykjanes Peninsula. They may significantly affect the predicted flow paths in lava flow simulations and the design of preventive measures such as lava flow barriers. Although this process has only been documented in Iceland and Hawaii, it is likely to occur in other subaerial magmatic rift zones worldwide.*

Key words: Dikes fed from the surface, secondary rifting, secondary eruptions, rift zone eruptions

INTRODUCTION

Dikes are generally defined as fractures injected with material of different origin than the host rock. The dike fill may be of sedimentary or magmatic origin. Sedimentary (or clastic) dikes may be fed from the original surface layer (e.g., van der Meer *et al.*, 2008), but it has conventionally been assumed that magmatic dikes are fed from a magma source at depth, either by upward or lateral propagation from the source (e.g., Sigmundsson *et al.*, 2015, 2018; Einarsson and Brandsdóttir, 1980; Rubin and Pollard, 1988). Down-

ward propagation has not been considered an important process in the formation of magmatic dikes. The direct observation of the lava flow of the Krafla eruption of July 1980 in Iceland disappearing into an open fissure within the rift zone (Figure 1) came as a shock, even though such an occurrence should have been an obvious and anticipated event. The receiving fissure was subsequently widened and large-scale rifting propagated along the rift as more lava entered the fissure. Similar events were observed during following eruptions of the Krafla Fires 1975–1984 (Einarsson, 1991a,b), in particular the eruptions of January-
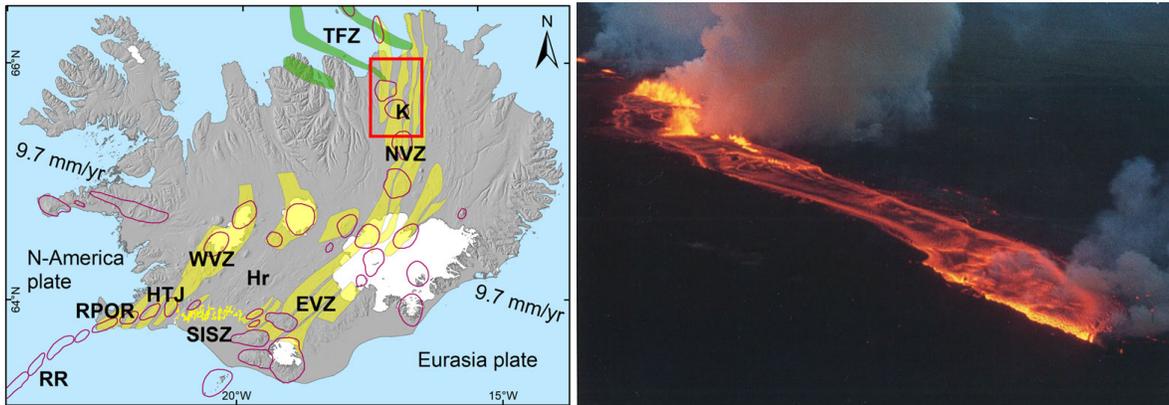
Figure 1: Left. A location map of Iceland, showing the plate boundaries and the main volcanic systems. The outlines of central volcanic complexes are shown in red. The Krafla central volcano is marked with **K**, the Hengill Triple Junction with **HTJ**, the Reykjanes Peninsula Oblique Rift with **RPOR**. **NVZ** is the Northern Volcanic Zone, **SISZ** is the South Iceland Seismic Zone, the transform connecting the Eastern Volcanic Zone (**EVZ**) to the **RPOR**. **Hr** is the Hreppar Microplate. **TFZ** is the Tjörnes Fracture Zone, the transform connecting the **NVZ** to the Kolbeinsey Ridge offshore. The red rectangle shows the area of the map in Figure 2. The tilt of the text line for the spreading rate indicates the spreading direction. Right: Aerial photograph taken during the first few hours of the lava eruption in the Krafla fissure swarm on July 10, 1980. The erupting fissure system is seen in the left, upper corner of the photograph. The lava flows along the Krafla fissure swarm for about 2 km and then disappears into a fissure at one of the boundary faults of the graben structure. Photo: Axel Björnsson. (From Einarsson 1991b). – *T.v. Kort af Íslandi sem sýnir staðsetningu þeirra staða sem við sögu koma. Sýnd eru flekaskil og eldstöðvarkerfi. Útlínur megineldstöðva eru rauðar. Megineldstöð Kröflu er merkt með* **K***, Hengilsþrískilin með* **HTJ***, skáreksbeltið á Reykjanesskaga með* **RPOR***.* **NVZ** *er Norðurgosbeltið,* **SISZ** *skjálftabelti Suðurlands,* **EVZ** *Austurgosbeltið,* **Hr** *Hreppaflekinn,* **TFZ** *Tjörnesbrotabeltið sem tengir Norðurgosbeltið við flekaskilin á Kolbeinseyjarhrygg. Rauði ramminn sýnir svæðið sem jarðfræðikortið á 2. mynd nær yfir. Hallinn á textanum sem gefur rekhraðann sýnir rekstefnu meginflekanna. T.h. Mynd tekin úr flugvél skömmu eftir að hraungos hófst við Éthóla í Gjástykki 10. júlí 1980. Frá gossprungunum í efra vinstra horni myndarinnar rennur hraunið um það bil tvo kílómetra norður eftir sprungusveimnum og hverfur niður í misgengissprungu í breiðum fossi á móts við Hrútafjöll. Myndina tók Axel Björnsson.*

February 1981 and September 1984. The importance of subsurface lava flow fed from the surface has since then been recognized in geological mapping of the rift zones of Northern Iceland (Sæmundsson *et al.*, 2012) and SW-Iceland (Sæmundsson *et al.*, 2010), and study of the tectonics of the Hengill Triple Junction (Steigerwald *et al.*, 2018). Other cases of similar observations were summarized by Orr *et al.* (2024), all of them from Kilauea volcano in Hawaii. It is, however, likely that processes associated with surface fed lava flows in fissures play an important role in the structure of volcanically active rift zones in other parts of the world. In Icelandic the word "gjávella" has been coined for this phenomenon (Sæmundsson *et al.*, 2012).

In this paper we attempt to give an overview of known cases of lava flowing into fissures in Iceland. Most of these cases have so far not been properly documented in the scientific literature. The stimulation for this documentation comes from the series of volcano-tectonic events that has been ongoing at the plate boundary in SW-Iceland since 2019. The events include earthquake swarms, inflation events, dike injections and, so far, twelve eruptions of basaltic lava (e.g., Sigmundsson *et al.*, 2022, 2024; Pedersen *et al.*, 2022; Hjartardóttir *et al.*, 2023; Parks *et al.*, 2023, 2025; Halldórsson *et al.*, 2022; Matthews *et al.*, 2024). Several intense lava flow events have taken place within heavily fissured areas and accurate forecasts of lava flow paths are of primary importance in

this relatively densely populated area of Iceland. Flow of lava along surface fissures has to be taken into account when preventive measures and barriers are designed.

THE KRAFLA RIFTING EPISODE

Several of the cases we document here of lava flowing into fissures are from the Krafla fissure swarm, and the series of eruptions there during the rifting episode of 1975–1984 (Björnsson *et al.*, 1977; Einarsson, 1991b; Sæmundsson, 1991; Buck *et al.*, 2006; Hjartardóttir *et al.*, 2012; Einarsson and Brandsdóttir, 2021). The Krafla volcanic system, consisting of the Krafla central volcano and its associated fissure swarms, is located at the divergent plate boundary between North-America and and Eurasia Plates (Figures 1 and 2). The fissure swarms of the divergent plate boundaries generally have the structure of a broad graben, 5–10 km wide. Open fissures are common within the grabens, but also along the trace of the boundary faults. This can be understood from fracture mechanics, as the dip angle of normal faults increases towards the surface, from 60–70° at depth to 90° at the surface. This leads to a component of opening at the surface.

The Krafla section of the plate boundary became active in 1974–1975 with increased seismic activity of the Krafla central volcano, followed by a dike intrusion propagating laterally along the fissure swarm for over 80 km. A small eruption on December 20, 1975, in the center of the caldera abruptly stopped when the dike propagated out of the caldera. The caldera subsequently deflated by 2 m, a process that lasted about three months. This initial phase of the activity was followed by 9 years of inflation of the caldera, punctuated by deflation events of various sizes, when magmatic dikes were injected laterally into the fissure swarms to the north and south of the caldera. Extensive rifting was observed on the fissure swarm during these events. A maximum of 8–9 m of extension were estimated for the central part of the fissure swarm, diminishing towards the ends (Tryggvason, 1984). A total of about 20 deflation events were identified, nine of which were accompanied by eruptions. The first four eruptions were small and short-lived, but an eruption in July 1980 marked a new chapter in the course

of events. Most of the mobilized magma reached the surface about 5 km north of the caldera. Subsequent eruptions were also quite intense with lava issuing from 2–9 km long fissures extending from the center of the caldera into the northern fissure swarm. The lavas from these eruptions flowed across heavily fissured terrain and inevitably flowed into the fissures on many occasions (Einarsson, 1991b).

The eruption of July 10–18, 1980

The eruption was preceded by four months of relatively rapid inflation of the caldera. The inflation turned into slow deflation at 8 h on July 10 and an hour later spasmodic tremor set in, a rapid succession of small earthquakes that propagated out of the caldera into the northern fissure swarm (Einarsson, 1991b). The seismic activity increased with time and around noon several low-frequency events indicated opening of surface fractures. An eruption began at 12:53 on a four-km long, en-echelon system of eruptive fissures within the northern fissure swarm. The lava flowed northwards along the graben in the center of the fissure swarm in broad lava river (Figure 1) for about 2 km, but then it disappeared into a wide fissure in a 170 m wide lava fall. This went on for about 18 hours, i.e. almost all the erupted material during that time was returned back to the crust. The eruption slowly waned, the eruptive fissure segments became inactive one after another until the eruption faded out on July 18.

When visited on July 14, there was still some flow of lava into the fissure and there were indications that the lava had flowed along the fissure (Figure 3). By that time a substantial lava flow field had also accumulated on the graben floor.

On a visit to the northern lava front on July 16, it was verified that the receiving fissure had widened by at least two meters where it continued beyond the lava front (Figure 4 left). The fissure was steaming for several hundred meters indicating interaction of the melt with the ground water (Figure 4 right).

The eruption of January 30 – February 4, 1981

Following the inflation periods after an eruption in October 1980 and a small dike injection in December 1980, deflation of the caldera set in on January
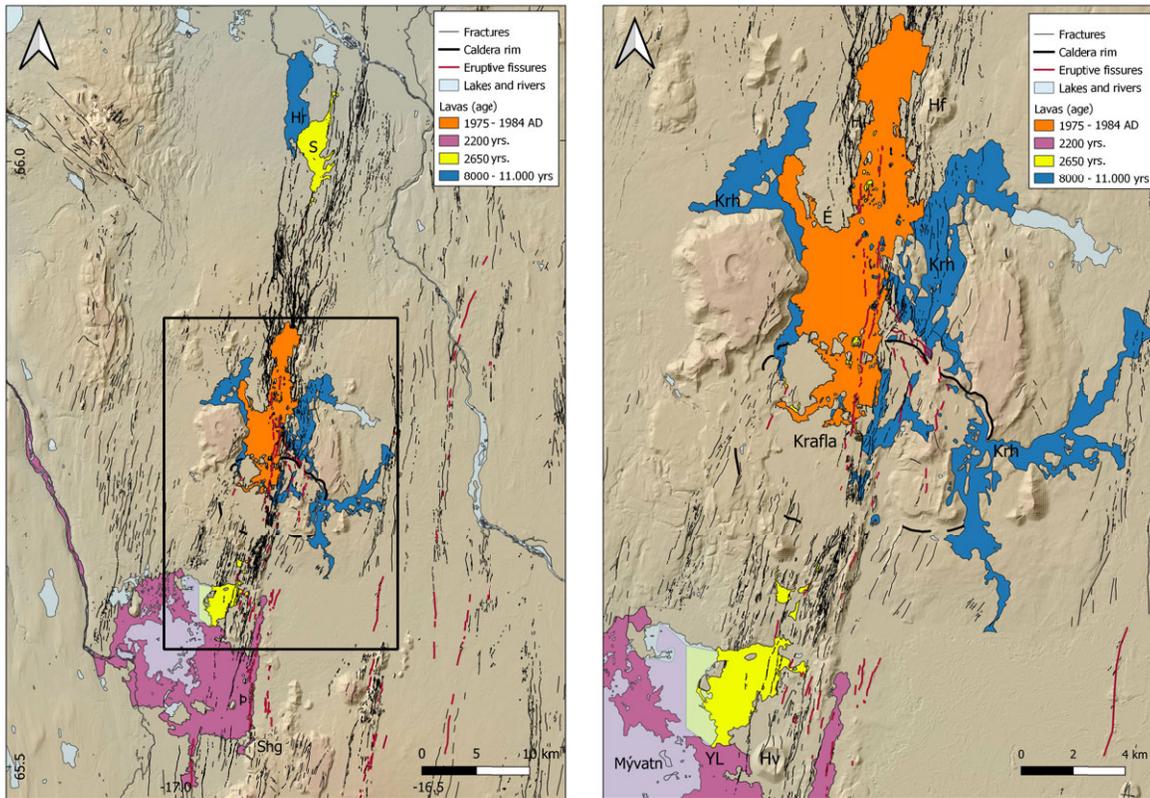
Figure 2. Left: The Krafla volcanic system on the plate boundary in Northern Iceland. The geological formations are from the map of Sæmundsson *et al.* (2012), the fractures and faults from Hjartardóttir *et al.* (2012, 2016). The remnants of the Krafla caldera fault are shown, as well as the 1975–1984 lavas, also the Skinnstakkahraun and Hraungarðahraun secondary eruption products (**S** and **Hr**), Þrengslaborgir crater row (**Þ**), and Seljahjallagil (**Shg**). Right: A map of the Krafla Central Volcano showing the caldera faults and the lavas of the Kröfluháls (**Krh**, blue) and Hverfjall (**Hv**) Fires (yellow), as well as the rifting episode of 1975–1984 (orange). Also shown are Éthólar (**É**), Hrútafjöll (**Hf**), Hituhólar (**Hi**), Hverfjall (**Hv**) and the younger Laxár lava (**YL**). – *T.v. Kort af eldstöðvarkerfi Kröflu. Jarðmyndanir eru samkvæmt jarðfræðikorti Kristjáns Sæmundssonar o. fl. (2012), sprungur og misgengi samkvæmt kortlagningu Ástu Rutar Hjartardóttur o. fl. (2012, 2016). Einnig eru sýnd öskjumisgengi Kröflueldstöðvarinnar, hraun frá umbrotahrinunni 1975–1984, Skinnstakkahraun og Hraungarðahraun í Kelduhverfi (**S** og **Hr**), gígaröð Þrengslaborga (**Þ**) og Seljahjallagil (**Shg**). T.h. Kort af megineldstöð Kröflu. Sýnd eru öskjumisgengin og hraun frá Kröfluháls- (**Krh**), Hverfjalls- (**Hv**) og Kröflueldum 1975–1984 (blá, gul, appelsínugul). Einnig eru merktir Éthólar (**É**), Hrútafjöll (**Hf**), Hituhólar (**Hi**) og Laxárhraun yngra (**YL**).*

30, 1981 at 7 h. Spasmodic tremor began about half an hour later. The seismicity pointed to a dike injection into the northern fissure swarm, but propagating slowly (Einarsson, 1991b). The first low-frequency earthquake was detected at 13:13. An eruption broke out at 14:10 at Éthólar in the northern fissure swarm (Figure 2), on a 2 km long fissure, seven hours after

the beginning of the deflation was detected. The lava flowed mainly to the north, into the lowest part of the fissure swarm, where it accumulated. Widespread evidence of lava flowing into fissures can be found in this area, also for widening of these fissures consequently (Figure 5). Examples can also be found in this area for re-eruption of the lava, i.e. lava oozing out of a

Figure 3. Lava was still trickling into the fissure (left) and flowing along it (right) at the margin of the lava flow on July 14, 1980. Photos:/*Myndir* PE. – *T.v. Hraun rann enn niður í sprunguna við hraunröndina og eftir henni (t.h.) 14. júlí, 1980.*

Figure 4. Left: Large-scale widening of the receiving fissure and collapse of the fissure walls at the northern front of the lava, observed on July 16. View towards the north. Right: Steaming fissure on July 16 at the northern front of the lava. Fresh lava flow in the background and faint outline of the remaining erupting crater on the horizon to the left, seen through the eruption haze. View towards the south. Photos: PE. – *T.v. Miklar sprunguhreyfingar urðu við norðurjaðar hraunsins frá gosinu í júlí 1980. Sprungan sem tók við hrauninu í byrjun gossins víkkaði og úr gjárveggjunum hrundi. Myndin er tekin 16. júlí og er horft til norðurs. T.h. Mikil gufa steig upp frá sprungunni á kílómeters-löngum kafla við norðurjaðar hraunsins, 16. júlí. Í fjarska má greina svart, nýtt hraun og gosstrókinn frá gígnum sem lengst gaus. Myndin er tekin í suðurátt. Myndir PE.*

Figure 5. Left: Flow of lava into a fissure near Hituhólar (Figure 2) at the western edge of the new lava field erupted in January-February 1981. Right: Fresh, degassed lava was extruded out of a fissure in several places at the west edge of the new lava field in January-February 1981 near Hituhólar. Recent movements are obvious along the fissure. Photos by PE taken in 2010. – *T.v. Hraun rann í sprungu við Hituhóla (sjá 2. mynd) við vesturjaðar hraunbreiðunnar sem varð til í gosinu í janúar-febrúar 1981. T.h. Ferskt, afgasað hraun kom upp úr sprungum á nokkrum stöðum vestan við hraunflákann úr gosinu í janúar-febrúar 1981. Sprungurnar bera merki um nýlegar hreyfingar. Myndirnar tók PE 2010.*

fissure that has received lava in a different location. This lava appears to have been degassed and no eruptive craters or cones were formed. There were also indications that fissures covered by the main flow field were receiving lava, but this was difficult to verify for obvious reasons.

The eruption of September, 1984

The last eruption of the Krafla episode began on September 4, 1984, after a long period of intermittent inflation of the magma chamber within the caldera, following the previous eruption of November 1981. Precursory signals were first detected at 20:25 h when tiltmeters showed the beginning of slow deflation in the caldera. The speed increased and 15 minutes later the seismographs showed spasmodic tremor and small earthquakes (Einarsson, 2018) with increasing magnitude. A prominent low-frequency earthquake was recorded at 23:40 h, and 9 minutes later the sky was lit up by an eruption. Within an hour an 8.5 km long fissure was erupting, extending from the center of the caldera into the northern fissure swarm. The lava flow rate was very high for several hours, with continuous glowing lava field surrounding the whole erupting fissure. The fissure became discontinuous on the second day as individual segments became inactive. On the third day all eruptive activity within the caldera had stopped. On September 7 eruptive activity was limited to two craters, steaming crater at the caldera rim and a crater at the northern end of the fissure erupting lava. Then a remarkable and unusual change occurred. Instead of tapering out as previous eruptions had done, the eruption began increasing, as seen in both the fountain height and the intensity of the eruption tremor recorded on local seismographs. The lava flowed mainly to the north, along the fissure swarm. The eruption came to a rather sudden end on September 18.

The eruption offered several opportunities to observe lava flow into fissures. The most dramatic cases were observed during the eruption at the eastern edge of the lava flow, south of Hrútafjöll hyaloclastite ridge (Figure 2). The lava during the first night of the eruption was flowing along the scarp of one of the boundary faults of the graben. The fissure along the trace of the fault was filled with lava, then it widened and subsequently received considerable volume of lava, as witnessed by a lava channel leading into the fissure (Figure 6). The down-flowing lava apparently was not

totally degassed as it descended into the fissure, because the flow was associated with spattering. Spatter and minor amounts of scoria were deposited on the banks of the fissure. This process may also have been affected by the presence of ground water. A patch of degassed lava was extruded out of a splay fissure about 400 m from the main one (Figure 7).

Kerlingarhóll

Two patches of prehistoric lava are found in the Kelduhverfi area on top of the large, ∼10 ka old Stóravíti lava flow (**Hr** and **S** in Figure 2). An ash-layer from the Hverfjall eruption south of Krafla (Figure 2) is found immediately beneath one of them, Skinnstakkahraun, **ssh** in the map of Sæmundsson *et al.* (2012), which indicates age between 2600 and 3000 a (Sæmundsson, 1991 p. 71 and 74). The area of the lava field is about 13 km². The unusual looking source of the lava is described by Elíasson (1979), Opheim and Gudmundsson (1989), and Sæmundsson (1991). The lava originates in a row of low hills, Kerlingarhóll, without spatter or cinder cones. A modest depression, sometimes with a system of lava caves is found at the summit of the hills (Figure 8). Very

limited evidence is found of degassing during the extrusion of the lava. Based on the contemporaneous eruptive activity at Hverfjall and Éthólar, Sæmundsson (1991) suggested that the Skinnstakkahraun lava was fed by flow of lava in the fissures of the Krafla fissure swarm from an eruption site at Éthólar, about 5 km north of the caldera rim, during the Hverfjall fires. The elevation difference between the extrusion sites at Kerlingarhóll and the primary eruption site at Éthólar is about 200 m and the horizontal distance is 10–15 km.

Another flow with similar features emerges from beneath the Skinnstakkahraun field, Hraungarðahraun, **hgh** in the map of Sæmundsson *et al.* (2012). It is suggested that this flow also originated in eruptive activity within the Krafla central volcano 8000–11 000 years ago (Sæmundsson *et al.*, 2012). The distance between the primary and secondary eruption sites is of the order of 30 km.

To further test these ideas, we analysed whole rock composition of these two lavas in Kelduhverfi following the methodology described in Rooyakkers *et al.* (2024). Samples were collected from both lava units in Kelduhverfi.

Figure 6. Left: Lava flowed into the open fissure at the boundary fault of the Krafla fissure swarm south of Hrútafjöll (Figure 2) on September 4, 1984. Right: The lava left a mark on the fissure walls before the fissure widened and the level sank. Photos taken by PE in 2010. – *T.v. Hraun flæddi niður í sprungur við eystra jaðarmisgengi Kröflusprungusveimsins skammt sunnan Hrútafjalla 4. september 1984. T.h. Hraunið sem flæddi niður í sprunguna sunnan Hrútafjalla skildi eftir sig storknaða skán efst í sprungunni áður en sprungan gleikkaði og yfirborð hraunsins seig í henni. Myndir PE 2010.*

Figure 7. Some of the secondary lava flows at the edge of the main lava field were quite extensive, see person in the background. This patch of lava was extruded east of the main lava field near Hrútafjöll during the 1984 eruption. Photo: PE 2010. – *Sumar gjávellurnar við Hrútafjöll frá gosinu 1984 eru nokkuð umfangsmiklar. Mynd PE 2010.*

Figure 8. Left: The Kerlingarhóll hills, the sources of the secondary lava flow, Skinnstakkahraun, in Kelduhverfi, (**S** in Figure 2). Right: The summit areas of the Skinnstakkahraun lava sources have a series of caves and tunnels but no spatter or other evidence of degassing. – *T.v. Kerlingarhóll sunnan Kelduhverfis, upptakastaður Skinnstakkahrauns (**S** á 2. mynd), sem líklega er gjávella frá Kröflu. T.h. Upptakastaður gjávellunnar Skinnstakkahrauns einkennist af hellakerfi. Ekki sést þar hraungjall eða aðrar vísbendingar um afgösun.*

The whole rock data (Table 1) reveal a clear compositional difference between the two lavas (Figure 9). The Kerlingarhóll / Skinnstakkahraun is similar to the relatively homogeneous and evolved lavas (MgO< 7wt.%) that have characterised almost all late postglacial (i.e., <7 ka) Krafla eruptions (Nicholson, 1990; Rooyakkers *et al.*, 2024). Notably, the Kerlingarhóll / Skinnstakkahraun is compositionally identical to other lavas that erupted during the Hverfjall Fires, supporting a link between the two. In con-
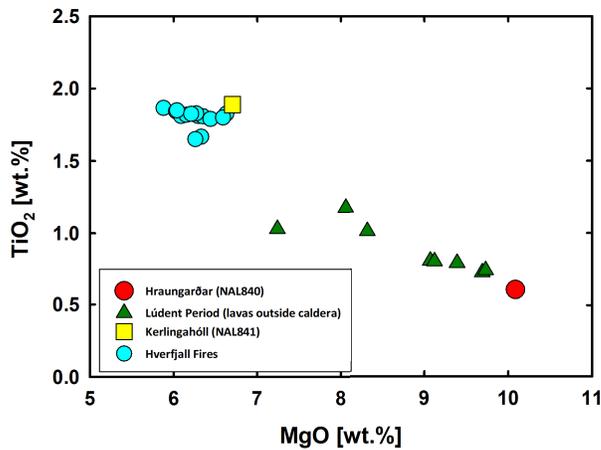
Figure 9. A plot of MgO and TiO_2 contents of Skinn-stakkahraun (NAL-841) and Hraungarðahraun (NAL-840) along with comparative data from both the Hverfjall Fires and a series of early-post glacial flows from the Lúdent period that erupted near, but outside the Krafla caldera (Krh in Figure 2b), (Nicholson, 1990), see Figure 2. - *Graf sem sýnir MgO og TiO₂ styrk sýna úr Skinnstakkahrauni og Hraungarðahrauni ásamt gögnum frá Hverfjallseldum og hraunum frá fyrri hluta Nútíma sem eiga upptök nálægt, en utan Kröfluöskjunnar, gjarnan kennd við Kröfluháls (sjá 2. mynd).*

Table 1. Whole rock major element concentrations. Total sum before normalization is in the last column; other data is displayed as wt.% normalized to 100%. n=x refers to separate portions of powders that are processed.black – *Styrkur aðalefna í bergsýnum. Summa heildar er gefin í aftasta dálk en önnur gögn gefin sem þyngdarprósenta af 100%. n=x er fjöldi tvítaka sama sýnis sem efnagreind voru.*

Sample	SiO₂ wt. %	Al₂O₃ wt. %	FeO wt. %	MnO wt. %	MgO wt. %	CaO wt. %	Na₂O wt. %	K₂O wt. %	TiO₂ wt. %	P₂O₅ wt. %	Sum %
NAL 840 (n=2)	49.21	15.91	9.09	0.16	10.09	13.22	1.63	0.056	0.61	0.042	99.92
NAL 841 (n=2)	49.76	13.82	14.14	0.23	6.70	10.57	2.37	0.313	1.89	0.189	100.05

trast, Hraungarðahraun is among the most primitive lavas ever associated with Krafla. It is compositionally similar, but slightly more primitive (higher MgO and lower TiO_2), to the early-post glacial flows from the Lúdent period that erupted outside the Krafla caldera, sometimes called the Kröfluháls lavas (Krh in Figure 2b). In summary, the whole rock composition of these two lavas in Kelduhverfi supports earlier ideas of their origin.

OTHER CASES OF LAVA FLOWS INTO FISSURES IN ICELAND

Seljahjallagil

A rather dramatic example of lava flowing into a fracture is found in the large Younger Laxá Lava, a flow of 220 km² in area and estimated volume of 2–3 km³. This lava forms the surface in most of the Mývatn area, south of Krafla volcano (Figure 2). It flowed down the Aðaldalur valley to the shore in Skjálfandi bay about 2000 years ago (Þórarinsson, 1966). This lava issued from the Þrengslaborgir eruptive fissure system (**Þ** in Figure 2). The southernmost crater of the Þrengslaborgir crater row is located in Seljahjallagil gorge (**Shg** in Figure 2). There the crater cone sits on top of a much older lava flow from the Ketildyngja lava shield, the Older Laxá Lava, that flowed down the gorge. The size of the cone suggests that the crater was active for considerable time, possibly several days, and yet the lava flow issued from it is insignificant. A well formed, about 200 m long lava channel connects the crater with a sink down the gully (Figures 10 and 11). The sink is located on a fault that cuts across the gully and is a part of the fissure system of Þrengslaborgir. Apparently, this sink received most of the lava issued from this southernmost crater of the Þrengslaborgir crater row. The sink has a diameter of about 30 m and almost circular, vertical walls.
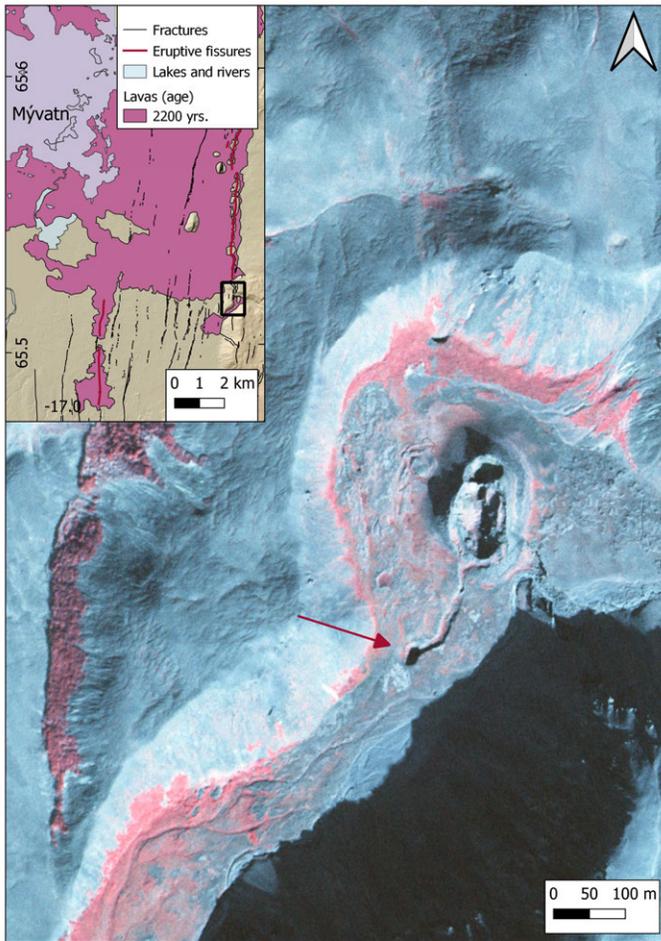
Figure 10. Aerial infrared photograph of the Seljahjallagil gorge (**Shg** in Figure 2), showing the southernmost crater of the Þrengslaborgir crater row (**Þ** in Figure 2), the source of the Younger Laxá lava. The lava flow channel from the crater to the sink, SW of the crater is clearly visible. – *Innrauð loftmynd af Seljahjallagili (***Shg** *á 2. mynd) og syðsta gíg-opi Þrengslaborga (***Þ** *á 2. mynd), gossprungunnar sem myndaði Laxárhraunið yngra fyrir um 2000 árum. Hrauntröð er greinileg frá gígnum til suðvesturs en hún hverfur við svelg um 200 m frá gígnum. Þar hefur hraunið runnið niður í sprungu.*
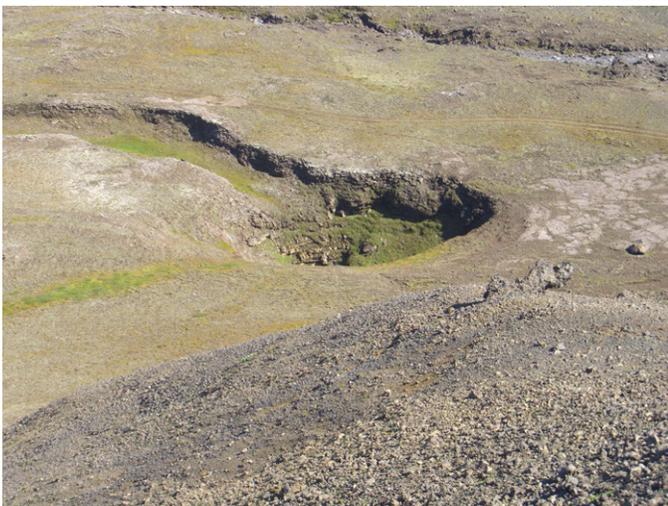

Figure 11. The lava sink in Seljahjallagil. The lava flowed a short distance from a crater just outside the frame of the picture and into the pit crater located on a N-S fault cutting the gully. – *Hraunsvelgurinn í Seljahjallagili. Hraunið frá syðsta gíg Þrengslaborga rann um hrauntröð og niður í svelginn sem liggur á N-S sprungu sem sker gilið.*

Ongoing series of volcano-tectonic events on the Reykjanes Peninsula Oblique Rift

The volcano-tectonic episode on the Reykjanes Peninsula plate boundary that began in 2019 has, at the time of writing, included twelve basaltic lava eruptions (Parks *et al.*, 2025; Matthews *et al.*, 2024). Nine of these eruptions occurred within the Svartsengi volcanic system, that also contains a swarm of rift structures with open fissures. All these eruptions have been fissure eruptions with a vigorous beginning phase lasting 1–2 days. Five of the eruptions then went into a low-output phase with few active craters that lingered on for 2–7 weeks. At least two cases have been found where lava is suspected to have entered open fissures with serious consequences:

1. An eruption began on January 14 at 07:57, 2024 on the Sundhnúkur eruptive fissure, two km NE of the town of Grindavík. The eruptive fissure attained a length of one kilometer in a few tens of minutes and then reached a stable configuration. Around noon lava began oozing out of a fissure just a few tens of meters outside the town, less than a km from the southern tip of the eruptive fissure. The small and microcrystalline lava flow destroyed three houses in Grindavík (Matthews *et al.*, 2024). It is still debated whether this small patch of lava originated from the lava flow farther up-rift or directly from the underlying dike.

2. The eruption that began on May 29 at 12:46, 2024 on the Sundhnúkur fissure, about 5 km NE of Grindavík, reached a maximum length of 3.5 km in about two hours. As the eruptive activity began to wane at the southern tip of the fissure, it was observed that lava flowing along the fissure began to flow into the southernmost section of the fissure. This went on for a few minutes, but then a column of brown ash was observed to emanate from this part. Apparently, the down-flowing lava hit the groundwater, producing an explosive phase. The explosive activity continued for a few tens of minutes.

In both cases described above the receiving fissure is a direct continuation of the eruptive fissure.

Hengill

Steigerwald *et al.*, (2020) report an interesting case of apparent secondary rifting associated with a drained pond of lava in the ∼2000 years old Nesjahraun lava in the Hengill fissure swarm near the Hengill Triple Junction, SW-Iceland (Figure 1). The pond occupied a topographic depression and is surrounded by a „bathtub ring" of solid lava. Flow structures in the lava indicate that the draining took place below the surface through a fault. No surface outflow is visible. A smooth lava was issued from the same fault, downslope from the pond, apparently followed by significant slip on it.

Stóri Hamradalur

A potential case for underground drainage of a lava pond through a fissure is described on the geological map of SW-Iceland by Sæmundsson *et al.* (2010). The site is within the Krísuvík fissure swarm on the Reykjanes Peninsula Oblique Rift (Figure 1), within the plate boundary section that has been activated since 2019 (e.g., Geirsson *et al.*, 2021). A part of a graben structure, Stóri Hamradalur, bounded on the east side by a normal fault and on the western side by a mountain slope, was partially filled by lava during the latest eruptive activity of the Krísuvík volcanic system in the twelfth century, as demonstrated by a thin lava veneer on the mountain slope marking the level of the lava about 17 m above the present valley floor. The draining of the lava pond must have taken place below the visible surface, most likely by the opening of the normal fault bounding the east side of the graben. Whether the lava re-emerged somewhere down-rift remains unknown.

DISCUSSION

The flow of lava into open surface fractures appears to be a common occurrence in Icelandic rift zones. This is not surprising. Open fissures are one of the characteristics of active rift zones, and so are eruptions of lava. Furthermore, the consequence of the process should be equally foreseeable. An open fracture, tens or hundreds of meters deep, with stress-free walls is likely to widen and propagate, both downward and horizontally, when it is filled with high-density fluid such as magma. If the fracture is a part of a densely spaced swarm of fissures the widening may be taken up by contraction of nearby, parallel fissures.

It may therefore not always lead to a true widening across the rift zone (Orr *et al.*, 2024). The experience from the 1980 July Krafla eruption shows that the rate of down-flow can be high and persistent. Almost all the lava produced in the eruption during the first 18 hours flowed into an open fissure. The resulting dike, fed from above, apparently attained a horizontal length of at least 4 km and interacted with the groundwater a good part of the distance. The receiving fissure widened by 1–2 m. Our petrological and structural study of two prehistoric lavas in the northern part of the Krafla fissure swarm suggests that surface fed dikes may propagate much farther, of the order of 15–30 km.

In principle, the physical processes active during magma injection from the surface are not significantly different from a dike injection at depth. The pressure gradient driving the dike may be generated by the tectonic stress like in the case of the Grindavík dike of November 2023 (Sigmundsson *et al.*, 2024) or the surface elevation gradient as was demonstrated with the Bárðarbunga dike of 2014 (Sigmundsson *et al.*, 2015; Heimisson *et al.*, 2015). In addition to the direct effect of the injection from above on the stress field driving the dike there may be secondary triggering effects on fault slip, such as increasing pore pressure due to magma or even heated groundwater.

In structural studies of lava successions in Iceland and elsewhere it has been customary to interpret dikes as feeder dikes if they can be linked to a horizontal deposit, lava or other eruptive products (e.g., Corti *et al.*, 2025; Sigurgeirsson, 1995). In some cases it may be the opposite, i.e., that the dike is fed from the lava flow above it in the succession. Two examples of this are implied in the study of the Hengill area by Sæmundsson (1967, p. 35 and 41). In structural modeling of crustal formation at a divergent plate boundary, like the work of Pálmason (1986), e.g., the partitioning of dikes versus lavas in the crust as a function of depth is a derived outcome. The assumption is that the dikes are intruded from depth and therefore the frequency of dikes must increase with depth. These models have to be modified allowing for the possibility that a fraction of the dikes may be fed laterally from a magma chamber or even from above, from surface lavas.

It is necessary to take fissures into account when simulating lava flows for hazard studies. During lava eruptions in populated areas it may be realistic to divert lava flows and protect important infrastructure such as highways, power and communication lines, pipelines, harbours and power stations. Erecting diversion barriers may be useful, as demonstrated during the 1973 Heimaey eruption (Jónsson, 1993; Williams, 1997) when the harbour was saved by a combination of barriers and water cooling of the lava front. The Heimaey eruption occurred in the intraplate, flank zone of South Iceland (Sæmundsson, 1979; Einarsson, 2008), where open fissures are rare. The situation is very different in the currently active oblique rift of the Reykjanes Peninsula where twelve eruptions have occurred since 2021 in close vicinity of population centers (Pedersen *et al.*, 2022; Sigmundsson *et al.*, 2022, 2024; Parks *et al.*, 2023, 2025), partly within a densely fractured fissure swarm. An extensive barrier system has been built, mainly to protect the town of Grindavík, the power station of Svartsengi, the geothermal spa of the Blue Lagoon, and related infrastructure such as power lines and pipelines (e.g., Sigtryggsdóttir *et al.*, 2025). The success of the operation may be severely compromised if the lava flows into a fissure upstream of the barrier and out of the same fissure downstream of the barrier. Furthermore, secondary rifting may occur ahead of the flowing lava (Figure 4), and disrupt the protective barrier.

Re-introduction of flowing lavas into fissure and possible re-eruption, has important consequences for using the chemical composition of such erupted material for reconstructing magma transport processes. For example, re-erupted lavas are likely to suffer extensive loss of volatiles which facilitates rapid growth of microcrystalline assemblages due to degassing-induced crystallization (e.g., Applegarth *et al.*, 2013). The phase relationships of such materials, both groundmass glass and microphenocrystal content and compositions, strongly controlled by low-pressure (near-atmospheric) processes, are unlikely to return any meaningful constraints on crustal magma transport. Care must be taken when applying melt-based barometers to scoria samples characterized by high microcrystalline contents (e.g., Caracciolo *et al.*, 2023).

SUMMARY OF CONCLUSIONS

⋆ Magmatic dikes may be fed from above.

⋆ A magma-filled fissure may propagate both laterally and downward, and may induce secondary rifting.

⋆ Lava that has entered a fissure from a lava-flow may find its way to the surface and erupt for the second time. Secondary eruptions may occur at distances of tens of kilometers from the primary eruption. Such secondary eruption sites are sometimes characterized by the absence of crater formations, cinder or spatter. Presence of cinder and spatter is not necessarily proof of primary eruption, however. Spatter and cinder may be produced by lava flowing into fissures and interacting with ground water.

⋆ The change of dike density with depth in a lava succession must be interpreted with caution, taking into account that some of the dikes may be fed from above or laterally. A dike physically connected to a lava flow in a lava succession may not be a feeder dike. It may in fact be fed from the lava.

⋆ Lava may flow long distances in fissures, irrespective of surface topography. Fissures must be taken into account in lava flow simulations and design of preventive barriers.

⋆ The possibility of residence time at the surface must be considered when the pre-eruptive history of an erupted lava sample is regenerated and interpreted.

Acknowledgements

ÁGRIP

Í nokkrum af gosunum í Kröflueldum 1975-1984 varð fólk vitni að því að hraun rann niður í opnar gjár. Fyrsti atburðurinn af þessu tagi sem tekið var eftir varð í gosinu í Gjástykki í júlí 1980. Þá rann hraunstraumur frá gosstöðvunum við Éthóla um tveggja kílómetra leið norður eftir Gjástykki og hvarf þar í breiðum fossi niður í eitt af jaðarmisgengjum sigdalsins vestan Hrútafjalla (1. mynd). Þetta stóð í 18 klukkustundir. Stór hluti hraunsins sem upp kom í gosinu rann þarna niður í jarðskorpuna aftur. Sprungan sem tók við hrauninu gliðnaði mikið og náði gliðnunin talsvert norður eftir Gjástykkinu. Þarna varð til berggangur sem fékk efni sitt ofan frá og breiddist út bæði lárétt og niður á við. Svipuð atburðarás sást í síðari eldgosum í Gjástykki, sérstaklega í janúar-febrúar 1981 og september 1984. Þá sást einnig hvar hraun, sem runnið hafði niður í gjá kom upp úr henni aftur og gaus þannig í annað sinn. Stungið hefur verið upp á nýyrðinu „gjávella" fyrir slík hraun (Sæmundsson og fl. 2010). Stundum náði hraunið ekki að losna við allt gasið áður en það rann niður í gjá. Myndaðist þá haugur af gjalli umhverfis staðinn þar sem hraunið streymdi niður í gjána. Hugsanlega kom grunnvatn hér einnig við sögu. Einnig mátti sjá hvar uppistaða hálfstorknaðs hrauns tæmdist þegar gjá, hulin undir hraunbreiðunni, gliðnaði og tæmdi fljótandi hluta hraunsins neðan frá. Eftir því sem best er vitað eru þessar athuganir frá Kröfluumbrotunum þær fyrstu sinnar tegundar í heiminum. Svipaðar athuganir hafa síðan verið gerðar á Hawaii, í sambandi við gos í Kilauea 2014. Reynslan frá Kröflu hefur verð notuð nokkrum sinnum við túlkun á jarðlögum í gosbeltum Íslands. Tvö hraun í Kelduhverfi stinga í stúf við umhverfi sitt og bera bergfræðileg einkenni Kröflueldstöðvarinnar. Færð eru rök fyrir því að hið yngra, Skinnstakkahraun, sé upprunnið í svokölluðum Hverfjallseldum fyrir u.þ.b. 2600 árum, hafi runnið niður í gjár skammt norðan Kröflu og komið upp aftur í Kerlingarhól eftir meira en 15 km ferðalag eftir sprungusveim Kröflukerfisins. Eldra hraunið, Hraungarðahraun, ber einkenni Kröfluhrauna frá Kröfluhálsi sem talin eru 8–11 þúsund ára gömul. Fjarlægð milli gosstöðvanna og uppkomustaðar Hraungarðahrauns er um 30 km. Borin hafa verið kennsl á að minnsta kosti þrjá staði til viðbótar þar sem hraun hafa runnið í sprungur. Í Seljahjallagili í Mývatnssveit rann hraun frá syðsta gíg Þrengslaborga ofan í nærliggjandi sprungu í svelg. Á Hellisheiði, austan við Stórameitil, má sjá hvar hraunuppistaða hefur tæmst við rennsli niður í sprungu. Á Reykjanesskaga er að finna ummerki um svipaða atburðarás í Stóra-Hamradal.

Nauðsynlegt er að hafa hraunrennsli í og eftir sprungum í huga þegar hönnuð eru varnarvirki til að verja innviði gegn hraunrennsli. Vísbendingar eru um að gosvirkni innan varnargarða við Grindavík í gosunum í janúar og maí 2024 sé þannig til komin.

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Author contributions

PE wrote the first draft of the text and contributed the photographs. KS is an authority on the geology of the rift zones of Iceland and contributed some of the cases documented. ÁRH led the field work of 2010 to the Krafla fissure swarm and drafted the maps. KG collected the samples for petrological analysis, that were supervised by SAH. All the authors participated in the final version of the manuscript.