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RESEARCH ARTICLE

Tectonic framework and fault structures in the Fagradalsfjall segment of the Reykjanes Peninsula Oblique Rift, Iceland

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Abstract

The two volcanic eruptions of 2021 and 2022 at Fagradalsfjall in SW Iceland occurred within the Reykjanes Peninsula Oblique Rift, a segment of the complex boundary in Iceland between the North America and Eurasia Plates. Two of the plate boundary segments are highly oblique to the overall plate velocity vector, i.e., the Reykjanes Peninsula and the Grímsey oblique rifts. They contain both volcanic systems and seismogenic strike-slip faults. Oblique spreading leads to extensive volcanism and large earthquakes, a combination that is otherwise uncommon in Iceland. The fissure swarms of individual volcanic systems contain normal faults and fissures, arranged en echelon along the plate boundary. The fissure swarms fade out as they extend into the plates on either side. These volcano-tectonic rift structures on the Reykjanes Peninsula are overprinted by sets of parallel, N-S striking transcurrent faults that generate the largest earthquakes in the zones, up to M 6.5. Their surface expressions are en echelon fracture arrays and push-up structures. The distance between them varies from 0.3 to 5 km. They are most prominent in the areas between the overlapping fissure swarms, and together they form a bookshelf-type fault system taking up the shear component of plate movements across the oblique rift zones. The Fagradalsfjall volcanic system is located between the fissure swarms of the Svartsengi and Krísuvík fissure swarms. It lacks its own fissure swarm, which is otherwise one of the characteristics of Icelandic volcanic systems. We present maps of surface fracturing structures of the area and interpret them as the result of strike-slip displacement on underlying N-S faults. About 20 faults are implied along a 8-km-long section of the plate boundary. In addition to these bookshelf-type faults, several areas have been identified where earthquakes appear to line up along ENE-WSW-striking, fault-like structures. These structures have so far only been seen at the surface in one place despite a thorough search. Taken together, the N-S and the ENE-WSW faults form a conjugate set of faults. The implied tectonic stress field has a horizontal maximum principal stress with a N45°E orientation, and a minimum principal stress with a N135°E orientation, perpendicular to the fissure swarms on the peninsula and the dike intrusion that preceded the Fagradalsfjall eruption in 2021. It is postulated that bookshelf faulting is one of the characteristics of unstable or immature plate boundaries.

Keywords Mid-Atlantic plate boundary · Oblique rift · Transtensional boundary · Fagradalsfjall volcanic system · Bookshelf faulting · Strike-slip structures

Introduction

The Reykjanes Peninsula in SW Iceland is produced by volcanism along a section of the mid-Atlantic plate boundary which is highly oblique with respect to the spreading direction. It forms a transition between the Reykjanes Ridge offshore to the west and the Hengill Triple Junction in the east, where it meets the Western Volcanic Zone and the transform zone of South Iceland (Fig. 1) (Einarsson 2008; 1991a). The overall trend of the volcanic zone is about 70°, whereas the relative spreading direction of the North American and Eurasian Plates at this location is 105° as derived from the

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Low intensity basalt eruptions: the 2021 Geldingadalir and 2022 Meradalir eruptions of the Fagradalsfjall Fires, SW Iceland.

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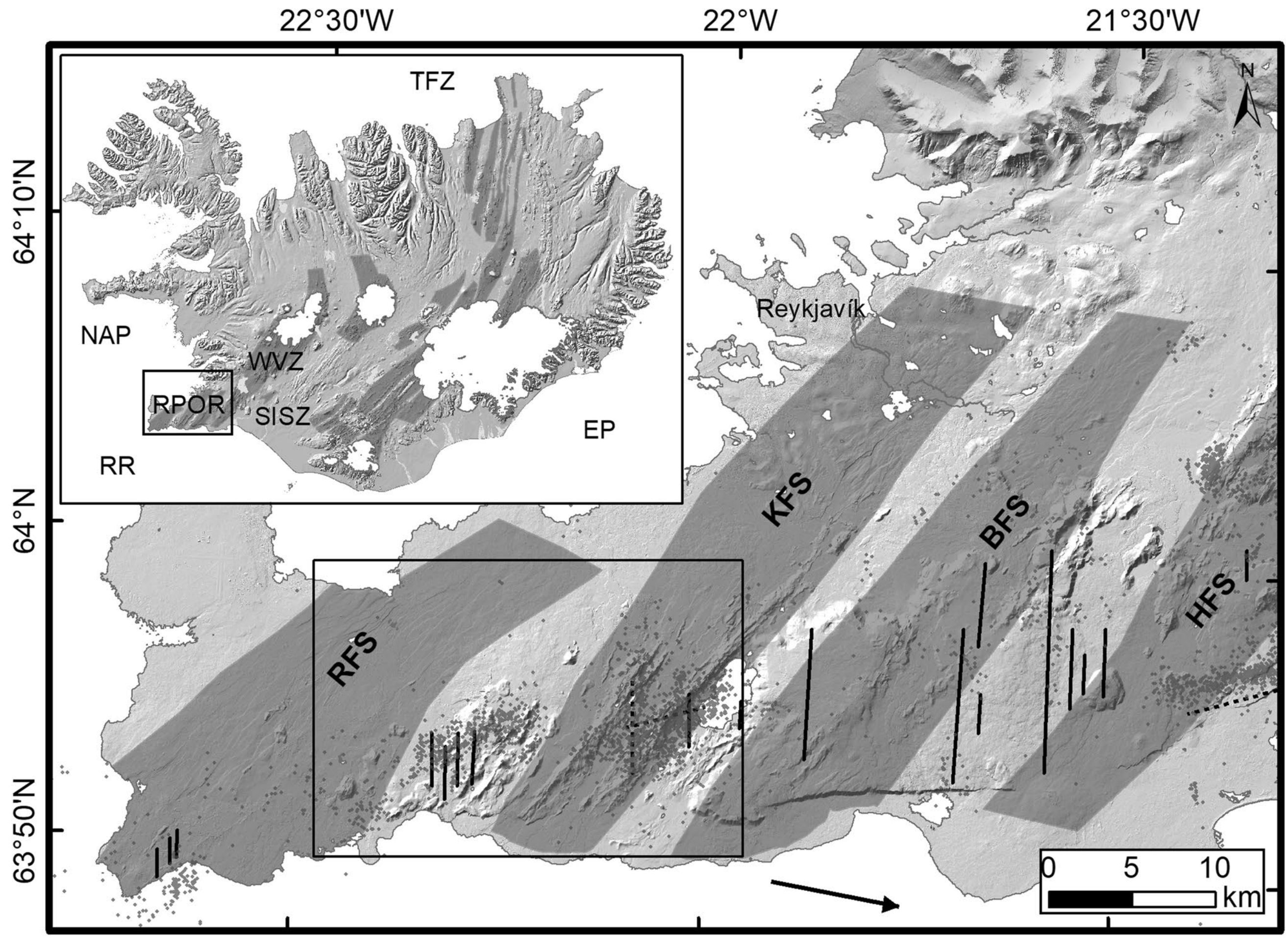

Fig. 1 Structure of the Reykjanes Peninsula Oblique Rift (RPOR). Fissure swarms are shaded; mapped strike-slip faults are shown with thick lines. Arrow shows the direction of relative plate motion across the boundary between the North America Plate (NAP) and the Eurasia Plate (EP). The main fissure swarms of Reykjanes (RFS), Krísuvík (KFS), Brennisteinsfjöll (BFS), and Hengill (HFS) are marked. The main transform boundaries of Iceland are shown in the inset map: the South Iceland Seismic Zone (SISZ) and the Tjörnes Fracture Zone (TFZ). The Western Volcanic Zone (WVZ) meets the RPOR and SISZ in a triple junction. The rectangle shows the map area of Fig. 2. Modified from Einarsson et al. (2018)

NUVEL model (DeMets et al. 2010) of plate movements. Eruptive fissures, open fissures, and normal faults are the most pronounced structural features along the plate boundary. They are arranged into swarms, four of which have been identified on the peninsula. Each swarm passes through an area of high volcanic productivity and geothermal activity. Together these structural features define a volcanic system (Jakobsson 1979; Sæmundsson 1978), the on-land equivalent of a ridge segment or an axial volcanic ridge (AVR) on the Reykjanes Ridge (Searle et al. 1998). The fissure swarms have a trend of about 30–40° and are thus arranged en echelon with respect to the plate boundary (Fig. 1).

The Reykjanes Peninsula is unique among the active branches of the plate boundary in Iceland and for that matter in the whole mid-Atlantic ridge. It is a zone of both high volcanic productivity and seismic activity. Earthquakes larger than magnitude 6 occur in the area and are apparently associated with strike-slip faulting. The peninsula thus possesses characteristics of both a spreading ridge and a transform zone (Einarsson 1979, 2008). The presently active seismic zone is considerably narrower than the faulted zone. It is 2–5 km wide and cuts obliquely across the fissure swarms (Fig. 1). The depth of hypocenters is mostly 1–5 km in the western part of the peninsula but seems to increase toward the east. Depths of 8–9 km have been found in the middle part (Klein et al. 1973, 1977). Fault plane solutions are generally of normal faulting and strike-slip type, often in close proximity to each other. The T-axes are consistently in the NW-quadrant and nearly horizontal. The plates are thus shown to be separated by a zone of distributed deformation, not a simple fault.

It has been of some concern that most of the recognised structures at the surface are of extensional character in spite of the highly oblique geometry of the plate boundary. The partitioning of the plate motion vector into extension and transcurrent motion has been enigmatic. Faults striking N-S have been known in the plate boundary region since the eighties (Sigurðsson 1985; Johannesson 1989), but the sense of displacement along them was unknown for a decade. Fracture arrays mapped in student projects revealed en echelon pattern indicating right-lateral strike-slip (Erlendsson and Einarsson 1996; Einarsson and Eyjólfsson 1998). In this paper, we present detailed mapping of faults within the Fagradalsfjall volcanic segment and identify about 20 parallel faults similar to those found along the full length of the Reykjanes Peninsula (Clifton and Kattenhorn 2006; Einarsson et al. 2018). The transform component of the plate velocity vector is thus shown to be accomodated by a series of parallel, transverse, N-S faults, and the rotation of the blocks between them. The transform motion here thus occurs in very much the same way as the transform motion along the South Iceland Seismic Zone farther east along the plate boundary (Einarsson et al. 1981; Sigmundsson et al. 1995).

The Reykjanes Peninsula Oblique Rift

This segment of the plate boundary connects the other segments of the Icelandic plate boundary to the Reykjanes Ridge offshore. The boundary as traced by the belt of seismicity (Klein et al. 1973, 1977; Björnsson et al. 2018) has a trend of 70°E and is therefore highly oblique to the spreading vector. Accordingly, both magmatic and seismic activities are high. Several volcanic systems have been defined along the plate boundary. The southern fissure swarm of the Hengill system extends into the area, and farther west Brennisteinsfjöll, Krísuvík, and Reykjanes have been defined (Fig. 1). Sometimes, the last two are split in two parts and the extra branches are named Trölladyngja and Svartsengi, respectively. The fissure swarms trend NE and are therefore arranged en echelon along the boundary.

Magmatism along this boundary is highly episodic on a time scale of a thousand years. During magmatic times, the plate boundary deformation is most likely focused on the fissure swarms, dike intrusions, and eruptive fissures. The last magmatic episodes were in the period 900–1240 AD (Sæmundsson and Sigurgeirsson 2013; Sæmundsson et al. 2020). During non-magmatic times, the plate boundary deformation is taken up by a series of strike-slip faults (Hreinsdóttir et al. 2001). During the last decades, most of the larger earthquakes along this segment have occurred on N-S striking strike-slip faults and the sense of faulting has been right-lateral (Einarsson 2008; Árnadóttir et al. 2004; Keiding et al. 2008, 2009). Occasional activation of the conjugate set of faults has been seen (Hjaltadóttir and Vogfjörð 2006; Hjaltadóttir 2009; Parameswaran et al. 2020), i.e., left-lateral faults with ENE strike. The N-S faults are visible at the surface in several places on the Peninsula (Erlendsson and Einarsson 1996; Clifton and Kattenhorn 2006; Einarsson et al. 2018), but the ENE-WSW set of faults is mainly seen in the distribution of hypocenters. A study of focal mechanisms of earthquakes during 1997–2006 confirms prevalence of oblique strike-slip faulting (Keiding et al. 2009) with ESE-trending least compressive horizontal stress. Keiding et al. (2008, 2009) compared the state of stress along the Reykjanes Peninsula plate boundary as reflected by earthquake focal mechanisms to the strain across the boundary as determined by GPS geodetic methods (Sturkell et al. 1994; Hreinsdóttir et al. 2001; Vadon and Sigmundsson 1997). The direction of the least compressive horizontal stress was found to coincide almost perfectly with the direction of the greatest extensional strain rate, confirming that the stresses driving the seismicity are controlled by the plate motion.

A new situation appears to be developing on the Reykjanes Peninsula since December 2019, with repeated earthquake swarms along the western part of the Reykjanes Peninsula plate boundary, and including intrusions of magma, and possibly supercritical gas, at shallow crustal levels (Geirsson et al. 2021; Flóvenz et al. 2022) in three or more different places. A dike intrusion that began on February 24, 2021, triggered a sequence of earthquakes along the boundary until it reached the surface on March 19 and fed an eruption (Sigmundsson et al. 2022). The eruptive activity came to a halt on September 18, 2021 (Pedersen et al. 2022). A second dike was injected below Fagradalsfjall in late December 2021, also triggering earthquakes along the plate boundary for a week but did not reach the surface. A third dike that began propagating on July 30, 2022, reached the surface four days later and fed an eruption that lasted 18 days. Considering the previous episodic behavior of volcanism in this rift segment, further magmatic activity is anticipated in coming decades or centuries.

Previous mapping work

Even though the first studies of earthquake focal mechanisms on the Peninsula (Klein et al. 1973; Einarsson 1979) revealed primarily strike-slip faulting, surface faults with that sense of motion were not identified until later. The careful geological mapping of Jónsson (1978) showed mostly the prominent normal faults and fissures striking NE-SW, arranged into four fissure swarms. Faults with more northerly strike were identified by Sigurðsson (1985, 1986) and Sigurðsson et al. (1978), but the sense of motion was not determined at that time. Detailed mapping of one of these N-S lineaments in 1996, subsequently termed the Hvalhnúkur Fault, revealed structures like en echelon fracture arrays and push-ups typical for strike-slip faults in the South Iceland Seismic Zone, a transform branch of the plate boundary (Erlendsson and Einarsson 1996; Einarsson 2010).

The sense of slip was shown to be right-lateral, consistent with the earthquake focal mechanisms. Fault structures along the Reykjanes Peninsula plate boundary were in the following years the subject of student exercises, as reported in one BS-thesis (Eyjólfsson 1998) and several presentations at meetings of the Geoscience Society of Iceland (e.g., Einarsson and Eyjólfsson 1998; Einarsson et al. 2006, 2015, 2018, 2019; Engström et al. 2000; Hjartardóttir et al. 2019). A pattern emerged from these studies, showing many parallel, N-S striking strike-slip faults arranged side-by side along the plate boundary. This fault pattern is superimposed on the more prominent pattern of fissure swarms with NE-SW orientation, as shown in publications by Hreinsdóttir et al. (2001), Clifton and Kattenhorn (2006), and Jenness and Clifton (2009). The surface structure of the six easternmost N-S faults of the Reykjanes Peninsula plate boundary were documented and described by Einarsson et al. (2018). These faults are considered the sources of the most serious seismic hazard in the capital area of Reykjavík (Fig. 1). The pattern of N-S faults continues at the triple junction with the Western Volcanic Zone and the South Iceland Seismic Zone, as documented by Steigerwald et al. (2018).

Methods

The mapping reported here was done by combining thorough study of aerial photographs and field mapping. Recent digital elevation models (DEM) were also very helpful in identifying faults. The surface formations in the study area are primarily of two kinds: Holocene lava flows and Pleistocene subglacial volcanic constructs. The mapping is essentially two-dimensional, since no cross sections are available, due to the youth of the crust at this constructive plate boundary.

The degree of difficulty in identifying the relevant structures is highly variable in the area. Some of the lavas have a smooth surface where fault structures are easily seen and distinguished from ordinary lava structures due to flow and cooling. In other lava flows the surface may be extremely rough and fractured, and fault structures are almost not identifiable. The lava flows from the last eruptive episode that ended in 1240 AD have covered many of the active faults and have not been fractured much since their formation. The fault structures in the Pleistocene formations have been largely obliterated, both due to longer exposure to erosional forces and the lower resistance of the hyaloclastites formed by subglacial volcanism.

Field mapping of the faults reported in this paper was done with differential GPS receivers, i.e., receivers that use the signal from the global positioning system satellites and a signal from a reference station to locate the antenna. A reference station at the tip of Reykjanes is conveniently located for this project and a location accuracy better than 0.4 m can be achieved (Erlendsson and Einarsson 1996). The receiver is carried along the features to be mapped and the data recorded in a data logger. The data are then plotted on a map in the lab using the GIS or other comparable software.

The most prominent fracture arrays

The fractures and faults of the Fagradalsfjall segment of the plate boundary are quite different from those of the adjacent segments, Reykjanes and Svartsengi immediately to the west and Krísuvík to the east, where the prominent fissure swarms dominate the structural grain. Our study area is defined between the fissure swarms, limited on the west side by the outermost structures of the Reykjanes-Svartsengi fissure swarm, the Sundhnúkar eruptive fissure (Fig. 2), and on the east side by the Méltunnuklif Fault, the westernmost normal fault of the Krísuvík fissure swarm. Within this study area, the long NE-SW striking normal faults and graben structures are missing. Instead, individual fractures are short, of the order of tens to hundreds of meters, and almost always arranged in left-stepping, en echelon arrays with a N-S trend, indicating right-lateral strike-slip on underlying faults. Tips of adjacent fractures are frequently connected by push-ups, compressional structures that typically accompany surface fractures above strike-slip faults (e.g. Einarsson 2010). Field examples of these structures are shown in Fig. 3. A ground fracture and its left-stepping push-up in the background are shown in Fig. 3a. A typical push-up of crushed lava is shown in Fig. 3b. A depression above a fracture and a row of push-ups on the top plateau of Fagradalsfjall are shown in Fig. 3c. A row of sinkholes in the vegetation above a fracture on the bottom of the Meradalir valley, now covered by the lava of 2021, is shown in Fig.3d.

The structural characteristics of the arrays are variable and are affected by the surface formations where they are exposed. We group the fracture arrays according to their geological locations and give them numbers for future reference, numbered from west to east. Guidance regarding geological formations and age is provided by the maps of Jónsson (1978), Sæmundsson (1995a), and Sæmundsson et al. (2016).

The Dalahraun fracture arrays

Most of the area west of the Fagradalsfjall massif is covered by the Dalahraun lava flow (H-27 of Jónsson 1978). The lava is considered to be older than 3000 years but younger than 8000 years (Saemundsson et al. 2016). Its source is mostly covered by younger flows but is a part of the neighboring Svartsengi volcanic system. The ~ 2000-year-old Sundhnúkar lava field covers the area to the west of the Dalahraun lava and has relatively few visible fractures. The

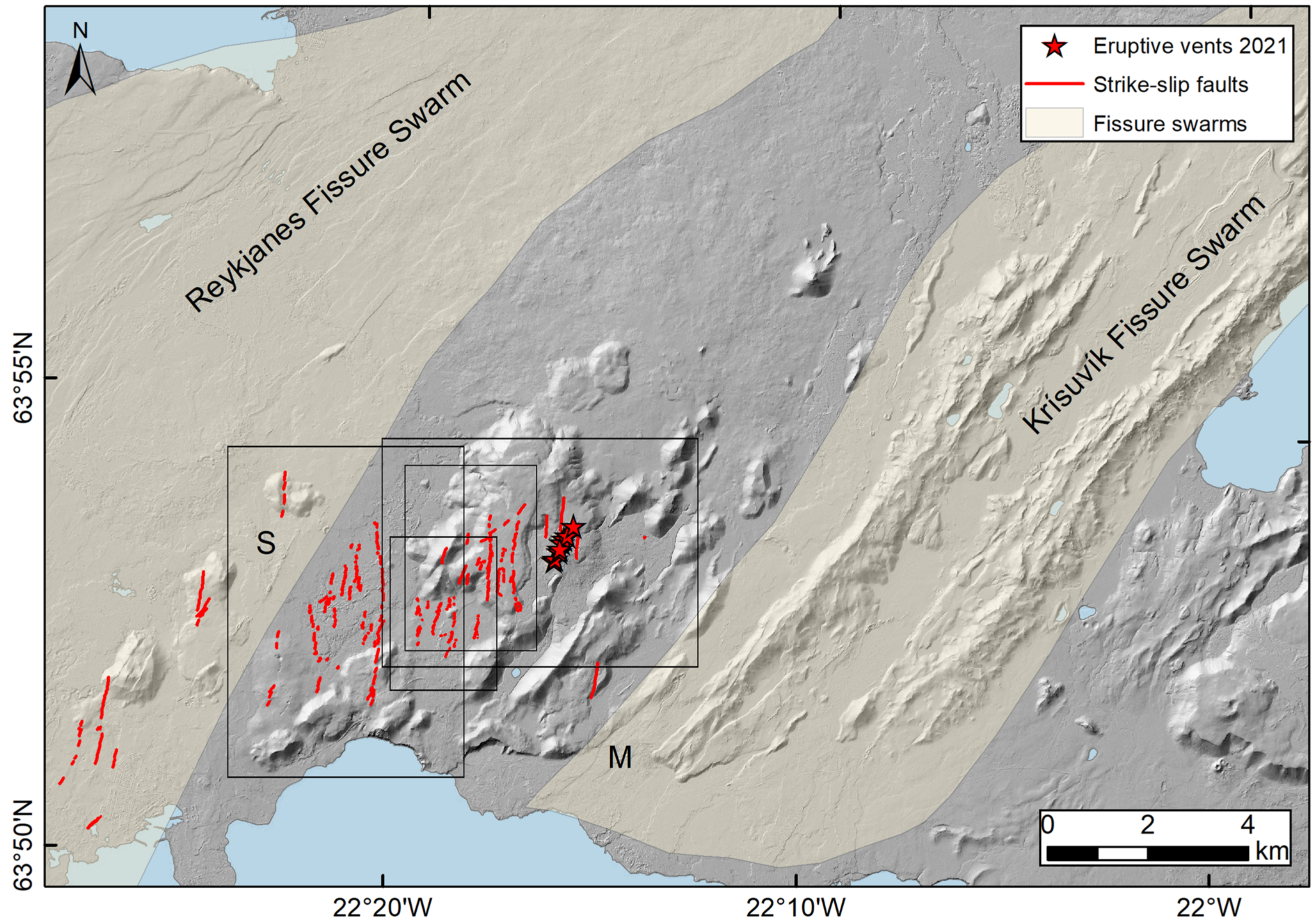

Fig. 2 The location of the Fagradalsfjall volcanic segment between the Reykjanes-Svartsengi Fissure Swarm in the west and the Krísuvík Fissure Swarm in the east. Mapped N-S faults are shown in red. Stars mark the eruption sites of the 2021 eruption. The Sundhnúkar eruptive fissure is marked with S, and the Méltunnuklif normal fault is marked with M. The Fagradalsfjall volcanic system occupies the area between the two fissure swarms. The four rectangles show the study areas of Figs. 4–7. The base map for this figure and subsequent Fig. 4–7 is the digital elevation model of the Icelandic Land Survey (Landmælingar Íslands)

westernmost fracture array of our study area is exposed in the 12,500–14,500 years old Vatnsheiði picrite lava shield (Fig. 4), but the next five fracture arrays are exposed in the Dalahraun lava field. Each fracture array is described below.

Da01. The Vatnsheiði lava shield (D-8 of Jónsson 1978) is one of the oldest known post-glacial eruptive units on the Reykjanes Peninsula. The summit elevation is only about 100 m, and the total volume was estimated to be 0.4 km^3 by Jónsson (1978). The lava appears to have issued from three sources, aligned in a N-S direction. The surface fractures identified in this system also follow this N-S axis. The fracture array consists of elongated depressions and open fissures and is about 2 km long.

Da02. This array is exposed in three lavas of different age, Dalahraun, Sundhnúkahraun, and Vatnsheiði, for a distance of about 2 km (Fig. 4). The exposed structures in the youngest lava consist mostly of narrow fissures, a few tens of cm wide, whereas the Dalahraun section includes rather impressive push-up structures. This may be taken as evidence for repeated activity on the underlying fault.

Da03. This array is only exposed in a very rough part of the Dalahraun lava. The distinction between lava flow structures and tectonic fractures is difficult in a number of places. The identification of the fracture array is, however, beyond doubt. Its length exceeds 1 km.

Da04. This array is also exposed in a rough part of the Dalahraun lava. It can be traced almost continuously for 0.7 km. If a separate, offset segment to the SE is taken as part of the system, its length reaches 1 km.

Da05. This fracture array can be traced almost continuously from its northern end for more than 1 km. It becomes less

Fig. 3 **a** A field example of the relationship between a dilatational fracture, shown by the line of disturbed rock surface in the foreground, and a push-up in the background, displacing the fracture array to the left. Picture taken near the northern end of fracture array Da06. **b** A typical push-up of crushed rock in a relatively smooth lava surface. **c** A fracture array (Fa07) on top of Fagradalsfjall is marked by elongated depressions (right), formed in the loose surface material above extensional fractures, and a row of prominent push-ups in the background. Fresh soil crack from the 2021 activity is seen in the depression. **d** A row of sinkholes marks an underlying extensional fracture in Meradalir, Ge05. The photograph was taken shortly before the fresh lava in the background covered this area

distinct as it enters the rough part of Dalahraun. The array can be traced south of the lava, towards the hyaloclastite hills to the south, where it may merge with the next fracture array to the east, Da06.

Da06. The array is located about 0.55 km west of the westernmost point of Fagradalsfjall. The northern part of the array is marked by a line of hillocks and en echelon fractures, which can be traced continuously for about 1 km across a relatively smooth lava surface (Fig. 3a). Push-up structures can also be seen almost continuously along this segment. They consist of high piles of crushed rock, sometimes as high as 5 m. The orientation of this linear structure is about 355°. The area east of the fracture array has subsided with respect to the western side, 1–5 m. It is marked as a normal fault on the geological map of Saemundsson et al. (2016). A continuation of this system can be discerned as a disturbance on the digital elevation model, extending southwards for additional 3 km (Fig. 4).

The Nátthagakriki fracture arrays

The Nátthagakriki valley, SW of Fagradalsfjall, is covered with several small lava flows of local origin, several of which have issued from craters on the slopes and top plateau of Fagradalsfjall. The largest is Borgarhraun (H-45 of Jonsson 1978) of age between 8000 and 11,500 years (Saemundsson et al. 2016). All the lavas here appear to be of similar age. The lavas are cut by at least four fracture arrays that extend from the northern slope of the valley for about 1.5 km into the lava plain (Fig. 5).

Na01. This array is exposed as fissures and push-ups in the lava near the cinder cone Bleikshóll, (H-44 of Jónsson 1978). This lava is more than 8000 years old (Saemundsson et al. 2016). The fracture system can be traced for at least 1 km.

Na02. This array is very well exposed on the lava plain west of the hyaloclastite hill Einbúi (Fig. 5), marked by

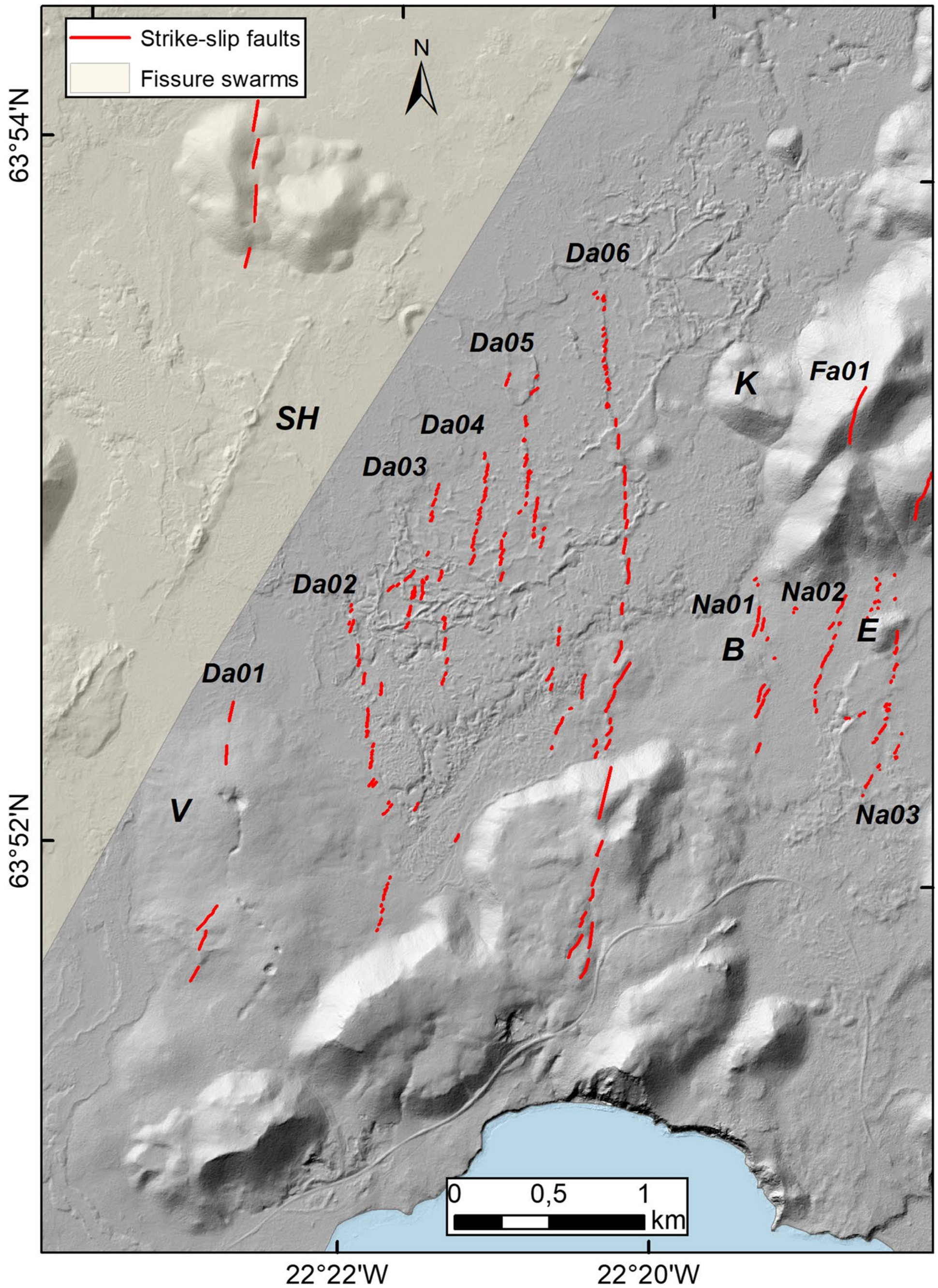

Fig. 4 The Dalahraun fracture arrays, Da01–Da06. V marks the Vatnsheiði picrite lava shield, SH the Sundhnúkar eruptive fissure, B the Bleikhóll cinder cone, E the Einbúi hyaloclastite hill, and K the Kast hyaloclastite hill, part of Fagradalsfjall

extensional fissures arranged en echelon, with push-up hills between their ends. It can be traced for 1.0 km on the plain, but if fractures in a small valley in the mountain to the north (Fa01) are counted as a part of this system, its length would exceed 3 km.

Na03. This array extends east and south of the small hill Einbúi and consists of many fractures arranged en echelon. The system has a clear continuation (Fa02) on top of the Fagradalsfjall mountain, making the length 2.5 km.

Na04. The easternmost of the fracture systems is marked by a few modest push-ups and indistinct fractures between them. It is about 1.5 km long but may have a continuation on the top plateau of Fagradalsfjall to the north (Fa03), making it 1.7 km long.

The Fagradalsfjall fracture arrays

The Fagradalsfjall mountain forms the central part of the volcanic system. It was formed by eruptions beneath a

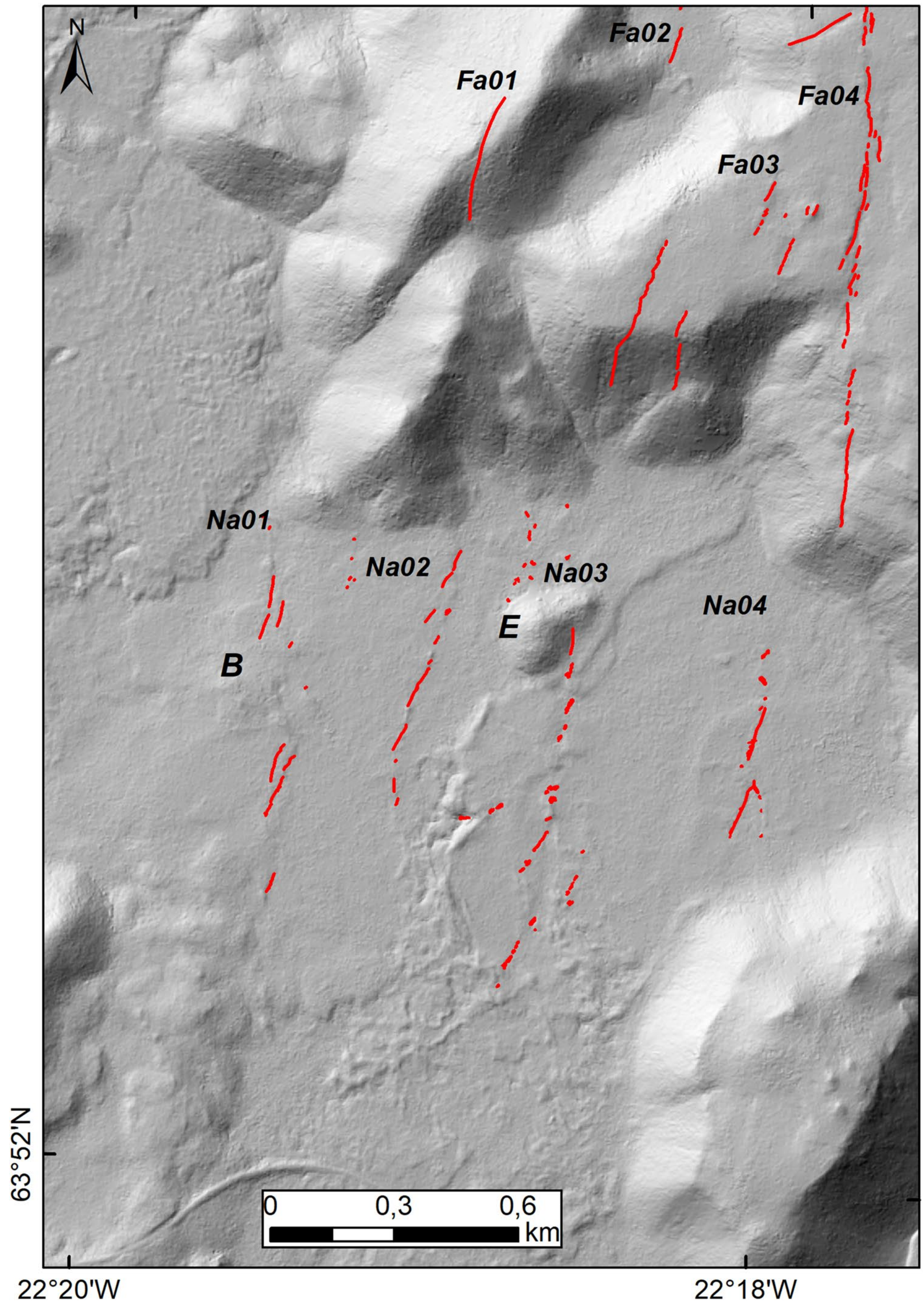

Fig. 5 Fracture arrays of the Nátthagakriki valley, Na01–Na04. B marks the Bleikhóll cinder cone and E the Einbúi hyaloclastite hill

glacier, probably more than one. The main body of the mountain is made of pillow lava and other hyaloclastites formed in contact with water, but the plateau on top is lava, formed by subaerial effusive activity. Most of the plateau has been glaciated. The mountain could be classified as a complex tuya according to the morphometric scheme of Pedersen and Grosse (2014). The plateau and surrounding formations are cut by seven fracture arrays that are particularly well preserved on the flat lava plateau (Fig. 6). Small patches of lava of Holocene age can be found in association with some of the fractures and appear to have erupted from them. More detailed descriptions of these fracture arrays are found in Eyjólfsson (1998).

Fa01. This array is marked by a prominent depression on the SE-slope of Kast, a hyaloclastite hill on the W-side of Fagradalsfjall. It may be regarded as the northernmost part

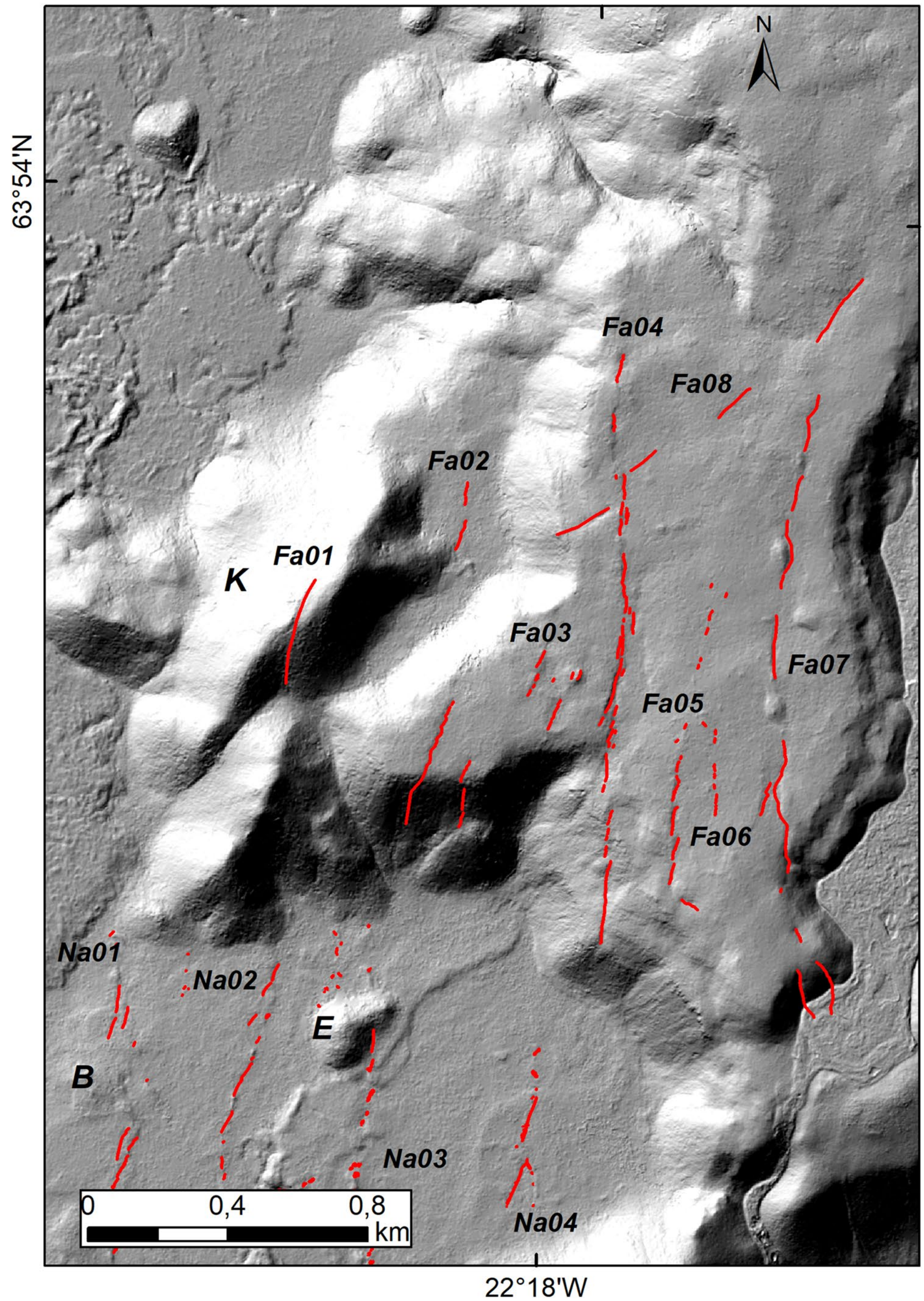

Fig. 6 The fracture arrays on top of Fagradalsfjall, Fa01–Fa08. K marks Kast, a hyaloclastite hill on the western side of Fagradalsfjall. B and E as in Fig. 4

of fracture array Na02 on the Nátthagakriki plain to the south, see above.

Fa02. This array can be traced along the western side of Fagradalsfjall southwards into the Nátthagakriki valley, where it merges with array Na03. A small spatter cone is found near the bottom of the slope into Nátthagakriki where arrays Fa02 and Na03 merge. Another small spatter cone is found in the valley east of Kast, with a lava flowing northward. These lava features are spatially linked with the fracture arrays and may originate from them. The total length of both systems is more than 3 km.

Fa03. This array consists of a 0.3-km-long cluster of fractures near the southern edge of the lava plateau of Fagradalsfjall. The cluster includes a spatter cone, a source of a thin Holocene lava flow that flowed down the mountainsides, both to the west towards Dalahraun lava, and to the south into Nátthagakriki to merge with Borgarhraun lava. A large Holocene spatter cone is at the foot of the slope SSW of array Fa03.

Fa04. This array is exposed on the top plateau, along the western edge of Fagradalsfjall, where a few small spatter cones have fed thin lava flows down the western slopes of the mountain, also to the south into Nátthagakriki. The fracture array continues obliquely down the eastern slopes of Nátthagakriki valley, where it is well visible from a distance as vegetated, elongate depressions. The length of the visible array is about 1.7 km.

Fa05. This is a short array just above the southern edge of the plateau, marked by two small push-ups and a series of fractures. The implied fault has a small throw of about 1 m, down on the east side. Push-up structures and en echelon fractures interact and form a sinuous, semi-continuous rubble zone along the fault trace, resembling lion's paws. Such features appear to be characteristic for oblique faults with both normal and strike-slip displacement (see, e.g., Einarsson et al. 2018). The length of the array is about 0.5 km.

Fa06. This array is about 120 m east of Fa05 and parallel to it. Both arrays are about equally long. Fa06 consists of rather immature looking fractures, however. The fractures are narrow; there are few and small push-ups, and the array is discontinuous.

Fa07. This is the longest fracture array that can be traced on the Fagradalsfjall plateau, a total of 2.8 km long. It is marked by a very regular pattern of several N-S depressions, the surface expressions of underlying fissures, and large push-ups (Fig. 3c). The en echelon arrangement of the fissures, together with the location of the push-ups, is consistent with right-lateral strike slip on an underlying fault. The eastern side has subsided with respect to the western side, indicating a component of normal faulting as well. The southern end of the array extends beneath the lava from the 2021 eruption. The whole array Fa07 was reactivated during the intense earthquake swarm that preceded the eruption (Sigmundsson et al. 2022) but has not been active since then. The fresh lava is unfractured.

Fa08. This array is the only evidence for a possible conjugate fault we have identified in the Fagradalsfjall area. The westernmost segment is accentuated by erosion, and the easternmost one is connected to a push-up on the N-S system Fa07, which is not an uncommon relationship observed in the South Iceland Seismic Zone (Clifton and Einarsson 2005). Apart from the westernmost lineament, the en echelon arrangement of the fracture segments indicates left-lateral slip on the potential underlying fault.

Geldingadalir area lineaments

The area east of Fagradalsfjall is quite different from the previously described areas (Fig. 7). Prior to the new lava from the 2021 eruption, there were no lavas on the surface, unlike the Pleistocene lavas of the top plateau of Fagradalsfjall and the Holocene lavas west of the mountain. The surface formations consist of individual hyaloclastite mounts and closed

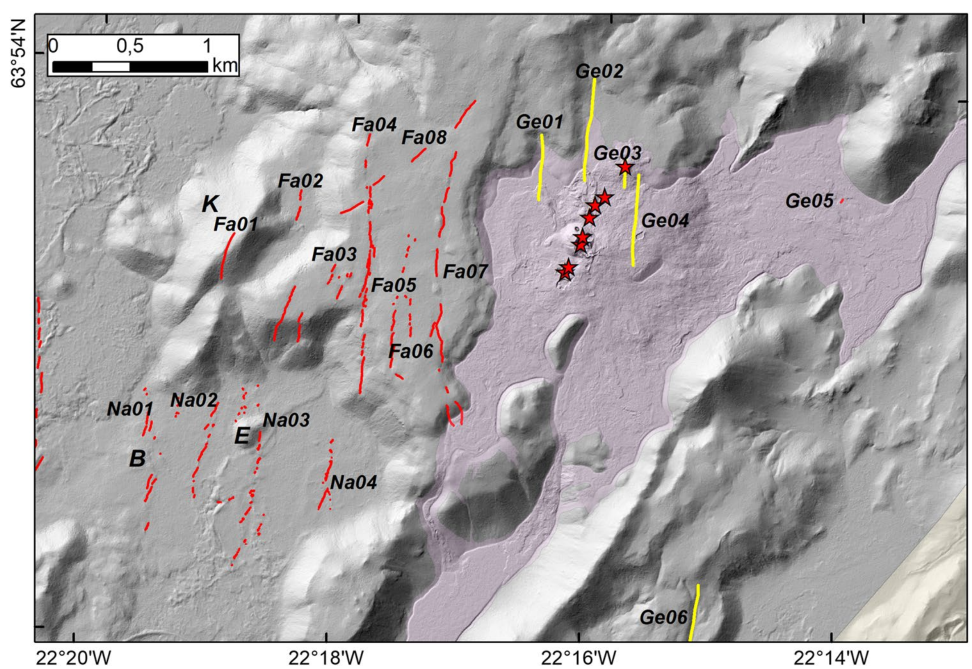

Fig. 7 Structural lineaments in the Geldingadalir area, Ge01–Ge06 (yellow). The map covers the landscape after the emplacement of the 2021 eruption lava. Parts of fractures and lineaments have been covered by the new lava and are no longer visible. Stars mark the eruption sites of the 2021 eruption. The 2021 lava is shown in purple. B, K, and E are as shown in Fig. 4

valleys between them, collecting sediments. Surface cracks and fractures are therefore not preserved. Strong hints of underlying faults are seen in the area, however, mostly N-S trending straight valleys and depressions. These are the most prominent ones.

Ge01. The northern end of the Geldingadalir valley forms a strong N-S lineament, about 0.5 km long.

Ge02. A similar N-S valley is about 0.3 km east of Ge01 and parallel to it, cutting into the eastern slopes of Fagradalsfjall. This lineament is 0.9 km long. Two of the eruption sites of the 2021 eruption are located on the southern prolongation of this lineament, including the main crater responsible for a large majority of the lava production.

Ge03. A N-S trending lineament, about 0.3 km east of Ga02, contained the two northernmost eruption sites active in April 2021. The lineament can be traced for 0.5 km.

Ge04. Immediately, east of Ge03 another N-S lineament can be identified, about the same length but extending farther south. This lineament is now completely covered by the new lava of 2021.

Ge05. An elongated sinkhole in the Meradalir valley is visible on aerial photographs taken before the 2021 eruption filled this valley with lava (Fig. 3d). Another large sinkhole was formed during the earthquakes preceding the eruption, about 1.2 km directly north of this hole, possibly belonging to a common fracture array.

Ge06. A clear NNE-SSW trending lineament, about 1 km long, is identified in the SE part of the Fagradalsfjall area. A connection to some of the other arrays on the map is not obvious.

Discussion

Definition of the Fagradalsfjall volcanic system

Historically, the definition of a basaltic volcanic system in a rift zone goes back to the work of George Walker in the Tertiary basalt formations in Eastern Iceland (Walker 1974, 1993). Areas of enhanced volcanism were shown to be accompanied by dike swarms extending for tens of kilometers along paleorifts. The modern expressions of these structural units were identified as central volcanoes such as Askja and Krafla of the Northern Volcanic Zone and their fissure swarms (Sæmundsson 1978). Central volcanoes typically contain characteristics like formations of silicic rocks, calderas, geothermal systems, and one or more fissure swarms extending from these areas of enhanced volcanism. The definition was modified by Jakobsson (1979) to "… a spatial grouping of eruption sites, including upper crustal feeder dikes, active within a relatively short time period of time and with certain limited tectonic, petrographic and geochemical characteristics."

There are problems applying this concept of volcanic systems to the volcanism of the Reykjanes Peninsula branch of the plate boundary. There are prominent fissure swarms, and each of them has a high-temperature geothermal system and a reasonably well defined center of volcanic activity. They lack, however, evolved silicic rock formations, calderas, and other indications of mature crustal magma chambers. Yet, in spite of these shortcomings, these systems have been accepted as volcanic systems similar to those of, e.g., Askja and Krafla (Sæmundsson 1978; Einarsson and Sæmundsson 1987). This set of volcanic systems includes Hengill, Brennisteinsfjöll, Krísuvík, and Reykjanes (Fig. 1). Subsequent studies led to separation of the geothermal system of two of these volcanic systems into smaller sub-systems. It has consequently been customary recently to divide the Reykjanes volcanic system in two: The Reykjanes and Svartsengi systems (e.g., Sæmundsson et al. 2020) and the Krísuvík system into the Krísuvík and Trölladyngja volcanic systems (e.g., Hjartarson 2009).

One volcanically active area, the Fagradalsfjall volcanic area, falls outside these previously defined systems (Fig. 2). It is located between the fissure swarms of Svartsengi (Reykjanes) and Trölladyngja (Krísuvík) and lacks two additional characteristics to fulfill the criteria of a volcanic system. Even if it contains a central area of high volcanic productivity, it does not host a geothermal system and it does not have a fissure swarm. The dike that fed the 2021 eruption had the orientation of a typical NE-SW trending fissure swarm but no fissures with that orientation were formed at the surface except in the immediate proximity of the eruptive vents. The vents were located near the intersections of the dike with the N-S strike-slip structures, as is also the case with older eruption sites at Fagradalsfjall (Eyjólfsson 1998).

The central area of high productivity is the volcanic edifice of Fagradalsfjall, a flat-topped hyaloclastite edifice of 250–350 m elevation with the form of a tuya. The main volume is formed by subglacial eruptions, but it is capped by subaerial lava flows with glacial striations. The lava platform is cut by several parallel, N-S striking, right-lateral strike-slip faults. The area around the main edifice is covered by volcanic products, mostly of small to medium size eruptions (e.g., Jónsson 1978). East of the mountain they are mostly of subglacial origin, forming cone-shaped hyaloclastite hills separated by valleys without drainage. The age of two of these hills has been estimated by paleomagnetic methods to be about 94 ka (Jicha et al. 2011). The area west of the mountain is covered by post-glacial lava flows, some of which originate in craters on the slopes of Fagradalsfjall. All these lavas are older than 7000 years, judged from tephra found on their surface (Sæmundsson et al. 2016). The only post-glacial lava flow of large volume is the Þráinsskjöldur lava shield originating a few kilometers NE of Fagradalsfjall. It was formed at the end of the last glacial period, about 14,000 years ago, during the retreat of glacial ice from the peninsula (Sæmundsson 1995b). All the volcanic formations with known chemical composition have the signature of primitive mantle origin (Jakobsson et al. 1978; Gee 1998; Gee et al. 1998; Halldórsson et al. 2022). The depth to the mantle in this area is about 15 km (Weir et al. 2001).

The location of this volcanism outside the prominent volcanic systems and the tectonic and petrological characteristics prompted the definition of an additional volcanic system, the Fagradalsfjall volcanic system (Sæmundsson and Sigurgeirsson 2013), despite its lack of most of the characteristics normally used to define such systems. The outlines of the Fagradalsfjall system are shown in Fig. 2. Its extent along the plate boundary is defined to be limited by the outermost fractures or boundary faults of the adjacent fissure swarms of Svartsengi and Krísuvík.

Faults and stress field

The fractures and lineaments identified in the Fagradalsfjall area are shown in Figs. 2–7. From theses maps, it is evident that this area is quite different from other parts of the Reykjanes Peninsula Oblique Rift, where the structural grain of the NE-SW fissure swarms is dominating, with long normal faults, open fissures, and eruptive fissures. All fracture structures around Fagradalsfjall, on the other hand, are short and fall into arrays with N-S trend. Most fractures have a NNE-SSW to N-S strike and are arranged en echelon within these arrays. Push-up structures are common, often bridging the gap between adjacent open fractures. This structural relationship is common along strike-slip faults in the transform zone of South Iceland (e.g., Einarsson et al. 1981; Einarsson et al. 2010). Similar structures have also been identified along the eastern part of the Reykjanes Peninsula Oblique Rift, between the Brennisteinsfjöll and Hengill Fissure Swarms (Erlendsson and Einarsson 1996; Einarsson et al. 2018). We similarly interpret these fracture arrays as the surface expression of strike-slip faults with right-lateral slip, sometimes with a smaller component of normal faulting.

Early studies of earthquake focal mechanisms along the Reykjanes Rift revealed a consistent horizontal and NW–SE orientation of the least compressive principal stress axis, σ_3. The maximum principal stress, σ_1, fluctuated between the vertical and horizontal NE-SW orientation (Klein et al. 1973, 1977). This result was confirmed by Keiding et al. (2009) and was found to be consistent with surface strain measurements.

In the absence of fluid, the crust may fail under shear stress along a set of conjugate faults, i.e., with fault planes containing the intermediate principal stress axis and under an angle of about 60° to the minimum pricipal stress axis. In the case of horizontal σ_1 on the Reykjanes Peninsula Oblique Rift, these would be strike-slip faults, right-lateral faults striking about N to N15°E, or left-lateral faults striking about N60°E to N75°E. The northerly striking faults are consistent with the fault pattern we see at Fagradalsfjall. We have been unable to verify the left-lateral, conjugate fault set at the surface, except in the case of Fa08 on the top plateau of Fagradalsfjall (Fig. 6). Active faults with this orientation (N˜60°E) have, however, been seen in the distribution of earthquakes and aftershocks, both beneath Fagradalsfjall (Hjaltadóttir and Vogfjörð 2006) and in the easternmost part of the Reykjanes plate boundary where it connects with the Western Volcanic Zone and the South Iceland Seismic Zone in the Hengill Triple Junction (Parameswaran et al. 2020).

Dikes preferentially open up against the minimum compressive stress, σ_3, In the case of the Reykjanes Peninsula Oblique Rift stress field, they would therefore be vertical and strike NE-SW (Fig. 8). We may apply this physical concept to the situation at Fagradalsfjall in the beginning of a magmatic episode, when magmatic fluid is introduced into a prestressed crust with high differential stress $\sigma_1 - \sigma_3$. If the dike propagates to shallower levels where the crust is more brittle, the flow may be diverted into pre-existing strike-slip faults with N-S strike before it leads to eruptions. Introducing fluid into these fractures is likely to trigger faulting before the pressure builds up to eruptable levels. Such pre-eruption earthquakes were observed prior to the outbreak of

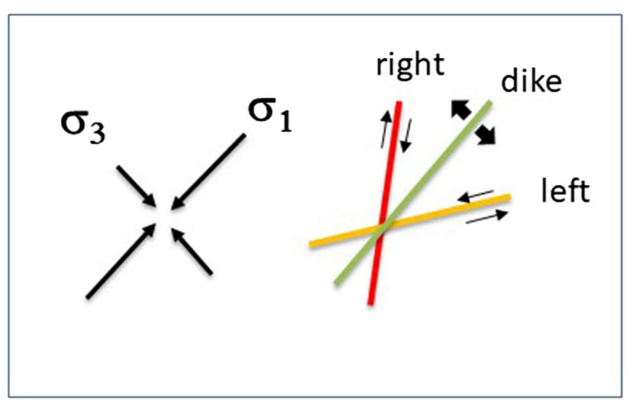

Fig. 8 Crustal stress field with maximum principal stress oriented NE-SW and minimum principal stress in NW–SE leads to conjugate strike-slip faults in a northerly (right-lateral) and east-north easterly direction (left-lateral). Dikes are preferentially formed perpendicular to the least principal stress

the Fagradalsfjall eruptions on March 19, 2021 (Sigmundsson et al. 2022) and August 3, 2022.

Faulting between overlapping rifting structures

Rifting in the rift zones of Iceland occurs within fissure swarms, apparently mostly by diking during rifting episodes. Modern examples of this type of activity include the Krafla rifting episode of 1975–1984 (Wright et al. 2012; Buck et al. 2006; Einarsson and Brandsdóttir 2021; Hjartardóttir et al. 2012) and the Bárðarbunga dike of 2014 (Sigmundsson et al. 2015; Gudmundsson et al. 2016; Hjartardóttir et al. 2016). Each rift zone includes several fissure swarms that are arranged within the zone parallel to each other or en echelon. Each dike or rifting event may only affect a limited length of one fissure swarm. This leads to accumulated horizontal shear stress between adjacent fissure swarms that is released in some kind of transfer motion. Two examples of such tectonism exist in the Icelandic rifts. The persistent seismicity east of the Askja volcano in the Northern Volcanic Zone (Green et al. 2014; Greenfield et al. 2018; Einarsson and Brandsdóttir 2021) occurs between the fissure swarms of the Kverkfjöll and Askja Volcanic Systems. Similarly, at the eastern end of the Reykjanes Peninsula Oblique Rift, there is an ENE-WSW zone of seismicity between the fissure swarms of Hengill-Hrómundartindur and the Brennisteinsfjöll Volcanic Systems (Parameswaran et al. 2020). The seismicity in both areas is caused by strike-slip on conjugate fault systems. The orientation of the inferred least principal stress is horizontal and in the general direction of plate spreading. Although the situation is not exactly the same, the Fagradalsfjall strike-slip faults are situated between the fissure swarms of Reykjanes (Svartsengi) and Krísuvík Volcanic Systems.

Bookshelf faulting

The Fagradalsfjall section of the Reykjanes Peninsula Oblique Rift is characterized by a series of strike-slip faults with a N-S strike, arranged side-by-side along the plate boundary. Similar faults also exist in other section of the oblique rift and are there superimposed on structures of the fissure swarms of the other volcanic systems (Clifton and Kattenhorn 2006; Einarsson 2008; Einarsson et al. 2018). These structural units sometimes merge into each other and are often difficult to separate in the field. Structures resembling the fissure swarms are absent at Fagradalsfjall. The dike intrusion that preceded the eruption of 2021 did not lead to surface fracturing of the type observed during the eruptive activity of Krafla 1975–1984 or Bárðarbunga-Holuhraun in 2014–2015 (e.g., Einarsson 1991b; Hjartardóttir et al. 2012). Instead, the relative plate velocity at Fagradalsfjall is largely taken up by bookshelf faulting on faults oriented at high angle to the boundary.

Since its introduction of this concept in the eighties (e.g., Einarsson et al. 1981; Einarsson and Eiríksson 1982; McKenzie 1986; Mandl 1987), bookshelf faulting has been identified in several tectonic areas. The type example in Iceland is the transform zone where the Reykjanes Peninsula Oblique Rift is connected with the Eastern Volcanic Zone by transform faulting via the South Iceland Seismic Zone. Most of the main earthquakes in this E-W zone are generated by faulting on a system of N-S strike-slip faults (Einarsson 2008, 2010). The conjugate set of faults is represented in that zone but always in a subordinate role. Along the mid-oceanic ridge system, bookshelf faulting appears to be linked with overlapping spreading centers, in particular in connection with rift propagation and migrating transform zones, such as along the Galapagos Ridge (Morgan and Kleinrock 1991; Wetzel et al. 1993). A similar setting is documented for bookshelf faults in southern Afar between the overlapping Ghoubbet-Asal-Manda-Inakir rift and the Manda Hararo-Abhe Bad rift (Tapponier et al. 1990). Bookshelf faulting is also documented in the convergent plate boundary setting of Nicaragua, where the trench-parallel strike-slip component of the oblique plate convergence is taken up by a set of transverse faults (LaFemina et al. 2002). Bookshelf-type tectonism is not limited to plate boundary settings. It was also found to be active in the intraplate earthquake of 2017 (M 5.8) in the Intermountain Seismic Belt in Montana, USA (Smith et al. 2021). Aftershocks of the earthquake illuminated a set of several parallel faults consistent with bookshelf faulting across the area.

Taken together, bookshelf faulting is found in various tectonic settings, at divergent, convergent and transform plate boundaries, and intraplate as well. All the examples above occur in areas that are in some way anomalous. The plate boundaries are oblique, migrating, or unstable. This is certainly the case with the Reykjanes Peninsula Oblique Rift. It is presumed to have been formed in response to a ridge jump that began about 7 Ma when the divergent plate boundary jumped from the previous location at Snæfellsnes Rift to the Western Volcanic Zone that was to be the main locus of rifting for the following 4 million years (Kristjánsson and Jónsson 1998; Khodayar and Einarsson 2002).

Kinematically, the bookshelf faulting model only allows a finite and small displacement across a plate boundary. The associated rotation of the blocks between the faults finally locks the faults. New faults have to form to take up the motion. A continuation of this process must lead to a crushed zone and finally to a through-going continuous fault taking up the relative motion across the boundary, a proper transform fault.

Conclusions

The Fagradalsfjall eruption 2021 took place within a highly oblique segment of the Mid-Atlantic plate boundary, the Reykjanes Peninsula Oblique Rift. The orientation of the plate boundary is about 70°, whereas the vector of relative motion of the Eurasia Plate with respect to the North America Plate is about 105°. The angle of obliquidy is therefore 35°. Four swarms of extensional structures like fissures, eruptive fissures, and normal faults are arranged en echelon along the plate boundary. In addition, numerous strike-slip structures exist along the peninsula.

The 2021 eruption was located between two of the fissure swarms, the Krísuvík fissure swarm in the east and the Svartsengi fissure swarm in the west. Tectonic structures in this area are almost exclusively strike-slip faults. We have identified more than 20 faults by their surface expressions that consist mostly of short fissures and fractures, and push-up hillocks. The average spacing between the faults is about 0.4 km. They are oriented N-S, i.e., transverse to the plate boundary, and the sense of motion is right-lateral. They apparently take up the transcurrent, left-lateral component of the plate motion vector across the plate boundary by a mechanism often termed bookshelf faulting, i.e., by right-lateral displacement on a series of transverse faults and counterclockwise rotation of the blocks between them.

Most volcanic vents in the Fagradalsfjall area are located on or very near the strike-slip bookshelf faults. This applies to the eruptive vents of the recent eruption of 2021, in particular.

Bookshelf faulting is found throughout the Reykjanes Peninsula Oblique Rift. In other segments of this rift, the N-S faults are superimposed on conventional rift structures like fissure swarms. Bookshelf faulting continues eastwards, beyond the Hengill Triple Junction, along the South Iceland Seismic Zone, where rift structures and Holocene volcanism are absent. Faulting on the set of faults conjugate to the bookshelf faults does occur, but it is mostly in a subordinate role. These branches of the plate boundary are highly oblique to the vector of relative plate movements and became active in the last 3–7 million years in response to eastwards jumps of the Icelandic divergent zone. Several other examples of bookshelf faulting appear to have similar origin at unstable plate boundaries.

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