This manuscript is a non-peer reviewed preprint, submitted to EarthArXiv, and is yet to be formally accepted in a journal. Subsequent versions of this manuscript may thus have different content.

A new model for fault growth during syn-kinematic deposition

Emma K. Bramham1\*, Tim J. Wright1, and Douglas Paton1

1School of Earth and Environment, University of Leeds, Leeds, UK

\*corresponding author: E.K.Bramham@leeds.ac.uk

**ABSTRACT**

Constraining the mechanisms of fault growth is essential for understanding extensional tectonics. In these dynamic systems the propagation of existing faults through recent syn-kinematic depositions is a poorly understood yet critical process. To understand how underlying structures influence faulting, we examine fault growth in a 10 kyr magmatically-resurfaced region of the Krafla fissure swarm, Iceland. We use a high-resolution digital (0.5 m) elevation model derived from airborne LiDAR to measure 775 fault profiles, with lengths ranging from 15 m to 2 km. For each fault, we measure the ratio of vertical displacement to length (Dmax/L) and the proportion of the fault that is un-displaced (“fissure-like”). We observe that many shorter faults (<200 m) retain fissure-like features with no vertical displacement for substantial parts of their displacement profiles; longer faults (> 200 m) are typically fully displaced and have Dmax/L at the upper end of the global population. We hypothesize that faults initiate at the surface as fissures in resurfaced material as a result of flexural stresses caused by displacements on underlying faults. Faults then accrue vertical displacement following a constant-length model and only grow by linkage or lengthening when they reach a classically-shaped displacement-length profile. This hybrid growth mechanism is repeated with the deposition of each subsequent syn-kinematic layer resulting in a remarkably wide distribution of Dmax/L. Whilst our observations are directly associated with magmatic resurfacing process, our results capture a specific period in the fault slip-deposition cycle that is equally applicable to fault zone characterization in sedimentary basins.

**INTRODUCTION**

Two-end members that explain strain distribution during the evolution of fault systems are i) the isolated model, whereby faults increase in displacement and length (Dmax/L) through radial tip propagation (Walsh and Watterson, 1988; Dawers et al., 1993; Walsh et al., 2003) and ii) the coherent/segment linkage model that involves growth through linking of individual segments (Peacock and Sanderson, 1991; Cartwright et al., 1995). The consensus is that the former is more likely to apply at an early stage where randomly distributed heterogeneities control which faults nucleate, whereas the latter is largely controlled by the presence of underlying faults or heterogeneity at a later stage. This two end member concept, and the associated compilation of global D-L data (Walsh and Watterson, 1988; Peacock and Sanderson, 1991; Cowie and Scholz, 1992; Schlische et al., 1996; Schultz and Fossen, 2002; Walsh et al., 2002; Rotevatn et al., 2019), have been widely used to evaluate quantifiable characteristics of fault populations in a range of tectonic setting including Mid Ocean Ridges, magmatic rift systems and extensional sedimentary basins (Gupta et al., 1998; Bohnenstiehl and Kleinrock, 2000; Clifton and Schlische, 2001; Polun et al., 2018; Rotevatn et al., 2019).

Two problems are associated with these end-members. First, although these models should have distinct distributions within D-L plots, global compilations have significant scatter in data. This is primarily because compilations include multiple datasets from non-comparable settings, spanning multiple throw magnitudes making it impossible to discriminate between them (Cartwright et al., 1995). Second, neither account for the short timescale propagation of a pre-existing fault through a syn-kinematic package that was deposited between slip events.

In this study, we investigate fault growth in syn-kinematic deposits using fault data from the northern Krafla fissure swarm, a region magmatically resurfaced by the Storaviti lava flow ~10 ka (Sæmundsson, 1991; Jóhannesson and Sæmundsson, 1998) and fractured by ~20 subsequent rifting episodes (Björnsson et al., 1979). The data availability provides an unparalleled opportunity to consider a single fault system with D-L spanning two orders of magnitude, while the magmatic rift systems provide a unique opportunity to consider this interplay because an established fault system is near-instantaneously resurfaced by magmatic material.

**KRAFLA FISSURES**

The Krafla fissure swarm (KFS) lies within the Northern Volcanic Zone (NVZ) (Fig. 1a), one of four volcanic rift zones across Iceland (Sigmundsson, 2006). The NVZ extends northwards from the Vatnajökull icecap in central Iceland to the north coast where it meets the Tjörnes Fracture Zone (Einarsson, 1991). Encompassing a series of north-northeast, left-stepping en echelon fissure swarms following the plate boundary through the region (Einarsson, 2008), the NVZ includes five main volcanic systems: Askja, Kverkfjöll, Fremrinámar, Krafla and Theistareykir (Fig. 1b). The KFS covers a 5-10 km wide and 100 km long region and transects the 200 ka active Krafla central volcano and caldera (Sæmundsson, 1991).

The KFS contains structural features ranging from pure extension (tension) fractures through to well-developed normal faults (Hjartardóttir et al., 2012).The main region of deformation is largely confined to a central zone of fissures, commonly flanked by exposed normal faults forming graben structures (Gudmundsson, 1984; Opheim and Gudmundsson, 1989). The resulting fissure swarm consequently forms a set of graben structures with the central graben extending from north of Hverfjall up through the central caldera towards the coast (Angelier et al., 1997), with the density of faults and fissures decreasing with increasing distance from the central caldera (Hjartardóttir et al., 2012).

**DATA AND METHODS**

We use a series of airborne Light Detection And Ranging (LiDAR) surveys, acquired on 7th August 2007 and 5th September 2008 by NERC’s ARSF Dornier aircraft that provide an optimal resolution of ~0.5 m x-y axis and ~0.2 m z-axis, to create a high resolution (0.5 m) digital elevation model (DEM) of the Krafla fissure swarm. Following initial post-processing of the raw LiDAR point cloud data to x, y and z coordinates by ULM, Cambridge, we use a convergent interpolation algorithm (Haecker, 1992) to build the DEM. The DEM provides an unprecedented view of the topographic surface (Fig. 1c and d) and using abrupt changes in surface expression to map hangingwall and footwall cut offs we were able to achieve along fault measurement sample intervals of 2-6 m (average ~4.8 m decreasing to 2 m around fault tips and complex regions). The resulting profiles of vertical displacement and library of displacement profiles allow us to compare faults across the study area which, with the resolution of the data, includes faults that are still primarily extension fractures (<0.5 m vertical displacement). In total, we measured 775 faults with maximum displacement ranging from ~0.5 -37 m and lengths from ~15 m to 2000 m across the area. We extracted the Dmax/L for each measured fault and plotted against the global population (Fig. 2a – inset bottom right).

Given the unified stress system and relatively homogenous basaltic rheology, the resultant Dmax/L should have a fairly narrow distribution. However, there is a remarkable spread of data, particularly at lower displacements. To investigate this wide distribution we develop a quantitative approach for categorizing the fault profiles (Table 1) based on the percentage of fault profiles that have significant vertical displacement (here defined as vertical displacement > 1 m). Category 1 fractures show no vertical displacement through to Category 5 fractures, which show vertical displacements along their entire length (fig. 2a – top inset). Category 5 fractures are further divided into three sub-groups (Table 1 and Fig 2b): fully-displaced faults (5a - Classical), exhibiting a single bell shaped profile; faults with a flat-topped profile (5b – Flat-Top); and faults with local minima (5c - Linked), inferred to represent the regions between the original segments prior to linkage.

We examine where within the range of the measured Dmax/L data each of the categories lies (Fig. 2a - main) and test whether there is a relationship between fault geometry and a fault’s location within the distribution.

**DATA DISTRIBUTION**

Category 1 and 2 fractures, representing fractures that are fissure-like (displacement < 1 m) along 65% or more of their length, are preferentially distributed in the lower portion of the Dmax/L plot, With only 4 exceptions, all fractures with displacements less than 2 m are fissure-like (category 1 or 2), and these span lengths from ~15 – 400 m. Noticeably, the distribution of fissure-like fractures has quite a sharp upper limit in maximum fault length, with only three fissure-like faults having lengths greater than 400 m. Dmax/L for fissure-like fractures spans nearly the full global range (~10-3 to 10-1). Fractures that are predominantly fault-like (category 4 and 5) form a distinct population on the Dmax/L plot, with a much narrower range of Dmax/L (~10-2 to 10-1) and displacements > 2 m for all but X faults. .

This change in the characteristic displacement and shape of fracture profiles implies a model of fault growth in which fractures evolve from being “fissure-like” to “fault-like” as they increase their displacement, without changing their length. We refer to this region of the Dmax/L plot as the “Fissure to Fault Growth Zone” (FFGZ; Figure 2a). The correlation between length and displacement for “fault-like” fractures implies that they can only increase their length once they are fully displaced. We propose that this transition represents the evolution from fissure dominated population to a fault dominated population which we define as the Fault Growth Zone (FGZ Fig. 2a, light grey arrow).

Fractures that have significant displacement along >90% of their length (category 5) have a range of shapes that we, as noted previously, have subdivided into three groups (5a - Classic, 5b – Flat-Top, and 5c - Linked; Fig. 2b). Category 5a faults are most likely to fit along the uppermost limit of the published distribution of Dmax/L, with the Category 5b and 5c showing lower Dmax for their lengths. Category 5c faults have D/L profiles that are consistent with them having been formed by linkage of shorter segments. We have divided a selection of Category 5c faults into their possible pre-linkage fault segments (using their displacement minima, example shown in Fig. 2c – inset), with each fault segment being extrapolated to represent its likely original fault length. We then plot the Dmax/L values for the constituent faults (Fig. 2c). The distribution shows that the Dmax/L estimated for the pre-linkage fault segments are towards the upper limit of the published distribution into the region of the distribution occupied in Fig. 2c by the Category 5a faults, and implies that only once faults are fully displaced vertically are they are able to grow by linkage with other fully displaced faults.

**MODEL FOR FAULT GROWTH**

Our analysis of a population of fissures and faults in the KFS suggests that in this location faults form initially as fissures. They then gradually increase their displacement, both in magnitude and in the percentage of the fracture length that has significant displacement (FFGZ in Figure 2), before entering a phase where both length and displacement increase (FGZ in Figure 2). We hypothesize that this pattern of fault growth is a result of the faults forming above pre-existing faults following the resurfacing caused by the Storaviti lava flow.

Collectively, the observations suggest four stages of fault growth. Initially there is a **Resurfacing Stage** (stage a in Figure 3)**,** in which there is a near-instantaneous episode of deposition of a homogenous package (in this case the Storaviti lava flow) that buries the pre-existing underlying fault. This is followed by the **Initial Fracture Stage** (stage b)**,** where slip on the underlying fault causes tensile bending stresses at the surface, resulting in horizontal opening of isolated fissures, with minimal vertical displacements (< 0.5 m). As time progresses, the fissures enter a **Constant Length Stage** (stage c to d), in which the percentage of each fracture that has displacement increases and the amount of displacement increases until the faults reach a D-L profiles with near-full displacements (category 4 and 5). Faults then enter a **Mature Growth Stage** (Stage d to e) where faults can grow by a combination of increasing both their displacement and length in isolation and by increasing their length by linkage, allowing further growth in their displacement. This final stage data distribution tends towards the higher boundary of the published distribution of Dmax/L. The process will then be repeated following the next phase of resurfacing.

**IMPLICATIONS AND CONCLUSIONS**

The wide distribution of global Dmax/L data in previous compilations has been attributed to differences in tectonic setting, lithology, or maturity of the individual systems (Cartwright et al., 1995). Our results demonstrate that D/L data, even in a very well constrained, single setting has a natural variability. It is the combination of data resolution and the dataset capturing the as yet unrecognized syn-kinematic evolution involving both radial tip-propagation and coherent fault growth that leads to the distribution.

Our findings are most directly applicable to magmatic divergent plate boundaries, including submarine Mid Ocean Ridges and subaerial magmatic systems such as those in Iceland or Afar, Ethiopia. D-L relationships have been widely used to estimate both regional strain and to discriminate strain zones, thus infer crustal scale processes (Gupta and Scholz, 2000; Soliva and Schulz, 2008; Polun et al., 2018). Our results suggest that care must be taken when applying fault position, and distribution of data, on D/L plots to predict fault-controlled mechanisms. Equally, surface fault expression derived from topographic or bathymetric data may be a poor predictor of the nature of the underlying fault structure (Deschamps et al., 2007; Soliva et al., 2008; Carbotte et al., 2015), in particular when slow and fast spreading MORs are compared; the rate of resurfacing versus tectonic strain is not comparable (Shaw and Lin, 1996; Bohnenstiehl and Kleinrock, 2000). These underlying faults also play a critical role in controlling the deeper plumbing of hydrothermal systems in MORs (Hayman & Karson, 2007). Our results suggest that shallow structures must be used with care when attempting to understand/model this plumbing system.

Our observations are also applicable beyond divergent magmatic plate boundaries. Seismic hazard mapping in magmatic and sedimentary systems often relies upon surface fault expression to predict nature of the deeper fault (Scholz and Gupta, 2000), yet this may poorly predict such underlying faults. On longer time-scales, hybrid models have been applied to explain cumulative slip in sedimentary basin evolution (Rotevatn et al., 2019). Our models suggest such processes are present over much shorter timescale of the seismic slip - syn-kinematic deposition cycle. Our observations and new model for fault growth during syn-kinematic deposition should be used when interpreting fault zone architecture using high resolution seismic data or surface observations (Hayman et al.; Baudon and Cartwright, 2008; Welch et al., 2009).

**ACKNOWLEDGEMENTS**

We would like to thank NERC for providing the funds to support this research (NERC grant NE/E007414/1 and a NERC-COMET studentship for EKB through the National Centre of Earth Observation), NERC ARSF for the LiDAR data acquisition, Schlumberger for providing Petrel software to the University of Leeds, Freysteinn Sigmundsson and Asta Rut Hjartardóttir for their knowledge and support whilst in the field in Iceland, Dave Hodgson for his valuable discussion and constructive criticism.

Angelier, J., Bergerat, F., Dauteuil, O., and Villemin, T., 1997, Effective tension-shear relationships in extensional fissure swarms, axial rift zone of northeastern Iceland: Journal of Structural Geology, v. 19, p. 673–685, doi:10.1016/S0191-8141(96)00106-X.

Baudon, C., and Cartwright, J., 2008, The kinematics of reactivation of normal faults using high resolution throw mapping: Journal of Structural Geology, v. 30, p. 1072–1084, doi:10.1016/j.jsg.2008.04.008.

Björnsson, A., Johnsen, G., Sigurdsson, S., Thorbergsson, G., and Tryggvason, E., 1979, Rifting of the plate boundary in north Iceland 1975–1978: Journal of Geophysical Research, v. 84, p. 3029, doi:10.1029/jb084ib06p03029.

Bohnenstiehl, D.R., and Kleinrock, M.C., 2000, Evidence for spreading-rate dependence in the displacement-length ratios of abyssal hill faults at mid-ocean ridges: Geology, v. 28, p. 395–398, doi:10.1130/0091-7613(2000)28<395:EFSDIT>2.0.CO;2.

Carbotte, S.M., Smith, D.K., Cannat, M., and Klein, E.M., 2015, Tectonic and magmatic segmentation of the Global Ocean Ridge System: a synthesis of observations: Geological Society, London, Special Publications, doi:10.1144/SP420.5.

Cartwright, J.A., Trudgill, B.D., and Mansfield, C.S., 1995, Fault growth by segment linkage: an explanation for scatter in maximum displacement and trace length data from the Canyonlands Grabens of SE Utah: Journal of Structural Geology, v. 17, p. 1319–1326, doi:10.1016/0191-8141(95)00033-A.

Clifton, A.E., and Schlische, R.W., 2001, Nucleation, growth, and linkage of faults ,in oblique rift zones: Results from experimental clay models and implications for maximum fault size: Geology, v. 29, p. 455–458, doi:10.1130/0091-7613(2001)029<0455:NGALOF>2.0.CO;2.

Cowie, P.A., and Scholz, C.H., 1992, Displacement-length scaling relationship for faults: data synthesis and discussion: Journal of Structural Geology, v. 14, p. 1149–1156, doi:10.1016/0191-8141(92)90066-6.

Dawers, N.H., Anders, M.H., and Scholz, C.H., 1993, Growth of normal faults: displacement-length scaling: Geology, v. 21, p. 1107–1110, doi:10.1130/0091-7613(1993)021<1107:GONFDL>2.3.CO;2.

Deschamps, A., Tivey, M., Embley, R.W., and Chadwick, W.W., 2007, Quantitative study of the deformation at Southern Explorer Ridge using high-resolution bathymetric data: Earth and Planetary Science Letters, v. 259, p. 1–17, doi:10.1016/j.epsl.2007.04.007.

Einarsson, P., 1991, Earthquakes and present-day tectonism in Iceland: Tectonophysics, v. 189, p. 261–279, doi:10.1016/0040-1951(91)90501-I.

Einarsson, P., 2008, Plate boundaries , rifts and transforms in Iceland: Jokull, v. 58, p. 35–58.

Gudmundsson, A., 1984, Tectonic aspects of dykes in northwestern Iceland.: Jokull, v. 34, p. 81–96.

Gupta, S., Cowie, P.A., Dawers, N.H., and Underhill, J.R., 1998, A mechanism to explain rift-basin subsidence and stratigraphic patterns through fault-array evolution: Geology, v. 26, p. 595–598, doi:10.1130/0091-7613(1998)026<0595:AMTERB>2.3.CO;2.

Gupta, A., and Scholz, C.H., 2000, Brittle strain regime transition in the Afar depression: Implications for fault growth and seafloor spreading: Geology, v. 28, p. 1087, doi:10.1130/0091-7613(2000)28<1087:bsrtit>2.0.co;2.

Haecker, M.A., 1992, Convergent gridding: a new approach to surface reconstruction: Geobyte, v. 7, p. 48–53.

Hayman, N.W., Karson, J.A., Hayman, N.W., and Karson, J.A. Faults and damage zones in fast-spread crust exposed on the north wall of the Hess Deep Rift: Conduits and seals in seafloor hydrothermal systems G 3 G 3 Geochemistry Geophysics Geosystems Geochemistry Geophysics Geosystems:, doi:10.1029/2007GC001623.

Hjartardóttir, Á.R., Einarsson, P., Bramham, E., and Wright, T.J., 2012, The Krafla fissure swarm, Iceland, and its formation by rifting events: Bulletin of Volcanology, v. 74, p. 2139–2153, doi:10.1007/s00445-012-0659-0.

Jóhannesson, H., and Sæmundsson, K., 1998, Geological map of Iceland, 1:500,000, Bedrock Geology:

Opheim, J.A., and Gudmundsson, A., 1989, Formation and geometry of fractures, and related volcanism, of the Krafla fissure swarm, northeast Iceland: Geological Society of America Bulletin, v. 101, p. 1608–1622, doi:10.1130/0016-7606(1989)101<1608:FAGOFA>2.3.CO;2.

Peacock, D.C.P., and Sanderson, D.J., 1991, Displacements, segment linkage and relay ramps in normal fault zones: Journal of Structural Geology, v. 13, p. 721–733, doi:10.1016/0191-8141(91)90033-F.

Polun, S.G., Gomez, F., and Tesfaye, S., 2018, Scaling properties of normal faults in the central Afar, Ethiopia and Djibouti: Implications for strain partitioning during the final stages of continental breakup: Journal of Structural Geology, v. 115, p. 178–189, doi:10.1016/j.jsg.2018.07.018.

Rotevatn, A., Jackson, C.A.L., Tvedt, A.B.M., Bell, R.E., and Blækkan, I., 2019, How do normal faults grow? Journal of Structural Geology, v. 125, p. 174–184, doi:10.1016/j.jsg.2018.08.005.

Sæmundsson, K., 1991, Geology of the Krafla system: Nattura Myvatns: Hid Islenska Natturufraedifelag, Reykjavik, 24–95 p.

Schlische, R.W., Young, S.S., Ackermann, R. V., and Gupta, A., 1996, Geometry and scaling relations of a population of very small rift-related normal faults: Geology, v. 24, p. 683–686, doi:10.1130/0091-7613(1996)024<0683:GASROA>2.3.CO;2.

Scholz, C.H., and Gupta, A., 2000, Fault interactions and seismic hazard: Journal of Geodynamics, v. 29, p. 459–467, doi:10.1016/S0264-3707(99)00040-X.

Schultz, R.A., and Fossen, H., 2002, Displacement-length scaling in three dimensions: The importance of aspect ratio and application to deformation bands: Journal of Structural Geology, v. 24, p. 1389–1411, doi:10.1016/S0191-8141(01)00146-8.

Shaw, W.J., and Lin, J., 1996, Models of ocean ridge lithospheric deformation: Dependence on crustal thickness, spreading rate, and segmentation: Journal of Geophysical Research: Solid Earth, v. 101, p. 17977–17993, doi:10.1029/96jb00949.

Sigmundsson, F., 2006, Iceland geodynamics: crustal deformation and divergent plate tectonics:

Soliva, R., Benedicto, a., Schultz, R. a., Maerten, L., and Micarelli, L., 2008, Displacement and interaction of normal fault segments branched at depth: Implications for fault growth and potential earthquake rupture size: Journal of Structural Geology, v. 30, p. 1288–1299, doi:10.1016/j.jsg.2008.07.005.

Soliva, R., and Schulz, R.A., 2008, Distributed and localized faulting in extensional settings: Insight from the north Ethiopian Rift-Afar transition area: Tectonics, v. 27, doi:10.1029/2007TC002148.

Walsh, J.J., Bailey, W.R., Childs, C., Nicol, A., and Bonson, C.G., 2003, Formation of segmented normal faults: A 3-D perspective: Journal of Structural Geology, v. 25, p. 1251–1262, doi:10.1016/S0191-8141(02)00161-X.

Walsh, J.J., Nicol, A., and Childs, C., 2002, An alternative model for the growth of faults: Journal of Structural Geology, v. 24, p. 1669–1675, doi:10.1016/S0191-8141(01)00165-1.

Walsh, J.J., and Watterson, J., 1988, Analysis of the relationship between displacements and dimensions of faults: Journal of Structural Geology, v. 10, p. 239–247, doi:10.1016/0191-8141(88)90057-0.

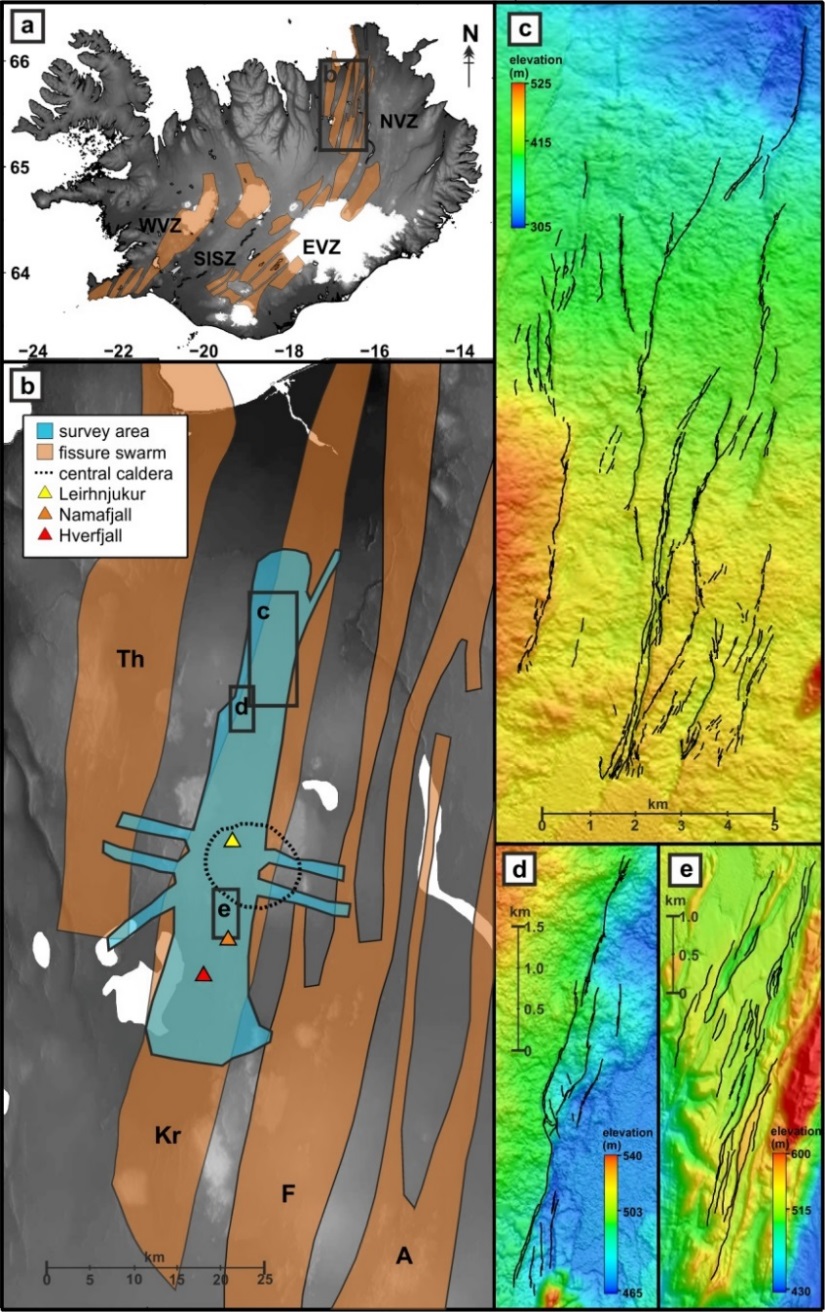
Welch, M.J., Knipe, R.J., Souque, C., and Davies, R.K., 2009, A Quadshear kinematic model for folding and clay smear development in fault zones: Tectonophysics, v. 471, p. 186–202, doi:10.1016/j.tecto.2009.02.008.

Figure 1. a) Location map of Icelandic fissure swarms (orange) and the main volcanic zones: WVZ (Western Volcanic Zone), SISZ (South Iceland Seismic Zone), EVZ (Eastern Volcanic Zone) and NVZ (Northern Volcanic Zone). b) Showing location of the NVZ fissure swarms, Krafla (Kr), Theistareykir (Th), Fremrinamar (F) and Askja (A), with the region covered by the LiDAR survey shown in blue. c), d) and e) show regions of the LiDAR DEM used for fault measurements, with measured faults shown as black lines.

Table 1. Fault categories

Figure 2. a) *bottom inset* showing Dmax/L data for the Krafla faults (red) plotted alongside published Dmax/L data as collated by Bailey et al., 2005; *main section* showing Krafla fault Dmax/L categorised from 1-5 as described in Table 1) with example fault profiles in the *top inset*. The Fracture-to-Fault Growth Zone (FFGZ) and Fault Growth Zone (FGZ) are represented by light and dark grey arrows respectively, with the dotted black line showing an approximate cut-off in maximum fracture length in the FFGZ. b) Category 5a, 5b and 5c faults, as described in Table 1, with example fault prfiles in the top inset. c) Selected linked faults (red), and the Dmax/L of the suggested component segments (turquoise) as estimated from extrapolating each linked section, example shown in the inset.

Figure 3. Model of fault growth shows a) an initial stage of resurfacing; b) initial opening of extensional fracturing; c) growth in isolation from extensional fracture to fault through multiple slip events; d) fully formed fault moving into growth in isolation; and e) continued fault growth through linkage of fully formed faults. Note that the growth stage shown in c) represents the gradual development of a fully formed fault by stage d), in reality this stage may take many more iterations of fault slip before achieving a fully formed fault profile.



|  |  |  |  |
| --- | --- | --- | --- |
| Category | % of fault with vertical displacement | Range (%) | Description |
| 1  2 | 0  ~25 | 0-10  11-35 | Minimal vertical displacement across fault  ~25% of fault showing vertical displacement |
| 3 | ~50 | 36-65 | ~50% of fault showing vertical displacement |
| 4 | ~75 | 66-89 | ~75% of fault showing vertical displacement |
| 5 | 100 | 90-100 | Vertical displacement across the whole fault |
| 5a | 100 |  | Category 5 fault with classical fault profile |
| 5b | 100 |  | Category 5 fault with flattened fault profile |
| 5c | 100 |  | Category 5 fault with linked fault profile |

