Forum Comment

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A new model for the growth of normal faults developed above pre-existing structures

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The Iceland rift is worldwide one of the best monitored and documented system of volcanic growth faults (e.g., Müller et al., 2017; Bonali et al., 2019; Weismüller et al., 2019; Iezzi et al., 2020; and references in each of these). The data presented by Bramham et al. (2021) lie in a length scale between that of Google Earth™ and unmanned aerial vehicle and therefore only partially resolve some of the well-established complexities that are required for interpreting the surface manifestation of fault zones in this setting (Holland et al., 2006; Kettermann et al., 2016, 2019). For example, the interpretations presented by Bramham et al. of individual faults only consider $D_{\max}$ and *L* and *D* variation over the length of a fault. Other recognized (and in our opinion) important measurable attributes not considered or discussed include opening width at the surface, presence of tilted blocks, cooling joint geometry, collapsed basalt relays, infills of snow or sediment, and vegetation (Holland et al., 2006; Bubeck et al. 2017a). As a result, Bramham et al. arrive at an over-simplified and, in our opinion, flawed model of fault and fissure development. The worldwide *L-D* data set reproduced and added to by the authors gives useful constraints on the geometry and development of faults in rocks. However, it is increasingly recognized that the substantial scatter in the data set is caused by a wide range of additional variables that affect the position and evolution path of any given fault in this diagram. These parameters include (1) mechanical properties, failure mode, spatial heterogeneity of properties, anisotropy (the Iceland basalts are heterogeneous and orthotropic) and the stress field. (2) Spatial relationships in a fault network (abutting, synthetic-antithetic, and boundary conditions). If the spatial location of a given fault in the network (Bubeck et al., 2017b, 2018) is not considered, there is a danger that the choice of where to locate the tips of a fault and its segments becomes increasingly arbitrary, especially considering the length scale of heterogeneities in basalts. (3) For volcanic growth faults, the addition of magma changes the properties of the fault as it is filled with magma from above or below, reorganizing and the asperities (Holland et al., 2011).

Bramham et al. present a model for fault growth, where movement on the subsurface fault (A) results in a long and shallow fracture opening on the surface (Ferrill and Morris, 2003; Abe et al., 2011) (B), which then develops throw and propagates down (C), until the whole initial length of the fracture has developed throw inside the new lava (D), finally to connect up with the master fault at depth. They base this model on observations that parts of the faults with intermediate throw (their Categories 2 and 3) contain a section with little or no throw. The outcrop of the Krafla fissure swarm is the sum of ~10 increments of the displacement field over 10,000 years after resurfacing. One may assume that the base of the lava had a similar structure as the surface does now, with massively dilatant faults and fissures filled with magma. The model does not specify a length scale but this can be inferred from the depth at which Bramham et al. show the master fault dip becoming shallower, caused by the shear stress being sufficiently high to allow shear fracturing of intact basalt. Using this inferred length scale, the proposed thickness of the resurfacing basalt is seen to be >500 m, although to us this seems far too thick. The thickness of the new lava will inevitably have a large effect on the evolution of later faults and fractures. Lava thickness is variable in the Krafla graben, so the faults and fissures analyzed will very likely contain variance due to lava thickness changes. In the model presented by Bramham et al., the basement fault does not propagate upward, which is inconsistent with published physical and numerical models (Abe et al., 2011). More fundamentally, Bramham et al.'s model implicitly assumes that all fissures develop into faults, although experimental and modeling studies have shown that the majority of fissures that open early do not go on to develop throw. Based on this, we propose an alternative interpretation of the graphs in Bramham et al.'s figure 3, where only some of the fissures develop throw, some over their entire length, some growing in length, and some over part of their length. Including measurements of the opening vector of each fault and fissure would have allowed the dip of the master fault at depth to be estimated, which could then be used to explain additional variance in the plots.

In summary, we are concerned that parts of the interpretation made by Bramham et al. are artifacts, and others are clouded by measurement error because they have not considered all the attributes and variables that characterize the specific geologic setting in Iceland. These affect both the position and path of a given fault on a *L-D* diagram and may account for much of the observed variance in the data. In our opinion, for progress to be made in understanding this multiscale and multiparameter dynamic system, one needs integrated, multiscale, and multiparameter data.

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