Reactivation of Magma Pathways: Insights From Field Observations, Geochronology, Geomechanical Tests, and Numerical Models

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Abstract Field observations and unmanned aerial vehicle surveys from Caldera Taburiente (La Palma, Canary Islands, Spain) show that pre-existing dykes can capture and re-direct younger ones to form multiple dyke composites. Chill margins suggest that the older dykes were solidified and cooled when this occurred. In one multiple dyke example, an $^{40}$Ar/$^{39}$Ar age difference of 200 kyr was determined between co-located dykes. Petrography and geomechanical measurements (ultrasonic pulse and Brazilian disc tests) show that a microscopic preferred alignment of plagioclase laths and sheet-like structures formed by non-randomly distributed vesicles give the solidified dykes anisotropic elastic moduli and fracture toughness. We hypothesize that this anisotropy led to the development of margin-parallel joints within the dykes, during subsequent volcanic loading. Finite element models also suggest that the elastic contrast between solidified dykes and their host rock elevated and re-oriented the stresses that governed subsequent dyke propagation. Thus, the margin-parallel joints, combined with local concentration and rotation of stresses, favored the deflection of subsequent magma-filled fractures by up to 60° to form the multiple dykes. At the edifice scale, the capture and deflection of active intrusions by older ones could change the organization of volcanic magma plumbing systems and cause unexpected propagation paths relative to the regional stress. We suggest that reactivation of older dykes by this mechanism gives the volcanic edifice a structural memory of past stress states, potentially encouraging the re-use of older vents and deflecting intrusions along volcanic rift zones or toward shallow magma reservoirs.

1. Introduction

Dykes are a common means of magma transport in magma plumbing systems (Rivalta et al., 2015). Individual dyking events can transport magma laterally up to tens to hundreds of kilometers from its point of origin (e.g., Neal et al., 2018; Sigmundsson et al., 2014), and vertical magma transport through dykes is often inferred to explain recharge of shallow magma chambers (Karlstrom et al., 2010). Understanding likely propagation paths of future dykes is therefore an important component of hazard assessment in volcanic areas.

Dykes propagate as fluid-driven fractures (Gudmundsson, 2011). Their propagation and or arrest is controlled by: (1) the magma pressure and buoyancy; (2) the mechanical properties and structure of the host rock; (3) the stress field into which they intrude; and (4) the temperature and rheology of the magma (Rivalta et al., 2015). Theoretical and field studies of dyke propagation have highlighted the importance of pre-existing structures in the host rock. For example, it is well established that contacts between units of different elastic stiffness (e.g., lava flows vs. pyroclastic layers) promote dyke arrest and the formation of sills (Gudmundsson, 2005a, 2011; Kavanagh et al., 2006). Similarly, many authors have suggested that dykes tend to propagate along regional and volcanic faults (e.g., Browning & Gudmundsson, 2015; Gaffney et al., 2007; Valentine & Krogh, 2006; van den Hove et al., 2017).

Dykes formed from two or more parallel and co-located intrusions are also commonly observed in volcanic regions. Extreme examples of these include sheeted dyke complexes exposed in ophiolites (Gass, 1968), mid-ocean ridges (Stewart et al., 2002), and ocean-island volcanoes (Walker, 1992), in which dykes intrude so densely that they comprise >90% of the rock mass, often making it impossible to distinguish individual
dykes. In less extreme cases, internal chilled margins or compositional variations are most simply explained by multiple co-located magma injections. These dykes are commonly referred to as “multiple dykes” (known as “composite dykes” when the different injections have contrasting compositions), although for brevity and to avoid grammatical confusion we prefer to use the term “multi-dyke.

While geochemical variations within multi-dykes have been widely studied (e.g., Ehlers & Ehlers, 1977; Esteve et al., 2014; Gibson & Walker, 1963; Kanaris-Sotiriou & Gibb, 1985; Sun et al., 2013), literature on the mechanics of their formation is lacking. Indeed, it is commonly assumed that multi-dykes form either because the initial dyke did not have time to solidify completely before the subsequent injection, or because the solidified dyke or its chilled margin were weaker than the host rock it intruded (Ehlers & Ehlers, 1977; Esteve et al., 2014; Gudmundsson, 1984; Guppy & Hawkes, 1925; Marinoni & Gudmundsson, 2000; Platten, 2000; Walker, 1992).

Here we present observations of exceptionally well-exposed multi-dykes on the island of La Palma (Canary Islands, Spain) that appear not to have formed by either of these mechanisms.

2. The Taburiente Dyke Swarm

The Taburiente dyke swarm is found within the ~2–0.5 Ma Volcán Taburiente (Carracedo et al., 1999), a large basaltic edifice that forms the northern portion of the island of La Palma (Canary Islands, Spain; Figure 1a). At the heart of this edifice a deeply incised and eroded collapse-scarp forms a bowl-like depression, Caldera Taburiente, bounded by spectacular cliffs up to ~1 km high. This highly eroded landscape provides exceptional exposure of the volcano’s shallow plumbing system, revealing a complete stratigraphic section through the most recent eruptive products to the edifice basement.

The Taburiente dykes radiate from a focal point in the southern part of the caldera, as described in detail in Thiele et al. (2020). Along the northern side of the caldera these dykes crosscut an earlier NE striking and shallower-dipping (~45–60°) dyke set interpreted to have formed relatively early in the growth of Volcán Taburiente (Thiele et al., 2020). Flow lineations indicate sub-horizontal flow both toward and away from the focal point, suggesting that ascending dykes became radially oriented as they interacted with topographic loading below the Taburiente edifice and then began to flow laterally to form blade-shaped dykes (Thiele et al., 2020).

3. Field Observations and Mapping

To gain access to the steep and unstable exposures within Caldera Taburiente, images collected via unmanned aerial vehicle (UAV) were used to construct three-dimensional (3-D) digital outcrop models using a structure-from-motion multi-view-stereo photogrammetric workflow (SfM-MvS; cf. Bemis et al., 2014; Dering et al., 2019). These digital outcrop models and details of the methods used to construct them are described in (Thiele et al., 2019, 2020). For this study, we focus on three surveys from a site known locally as Hoyo Verde (Figure 1a), where dykes of different orientations intersect to form multi-dykes (Figure 1b).

The dykes at Hoyo Verde intrude volcaniclastic breccia deposits (Figure 1c), welded scoria (Figure 1d) and finely laminated palagonite tuffs (Figure 1e). Multi-dykes were observed in all of these lithologies. The volcaniclastic breccias occur in >10 m thick, polylithic, poorly sorted, and matrix-rich beds toward the bottom of the section, but become finer-grained and more well-sorted toward the middle of the section. The breccias are overlain by thick-bedded scoria deposits. Beds of laminated palagonite tuff of 1–20 m thickness occur in both the breccia and scoria units, and dip ~20–30° north-west.

Mapping of the dyke network (Figure 2) shows that older, more shallowly dipping (~45°) dykes appear to capture younger intrusions and re-orient them by up to 60°, forming thick multi-dyke bundles typically characterized by complex cross-cutting relationships. While some of the captured dykes propagate along the contact of the older dyke, many also propagate along dyke cores. Although the resolution of the models is not sufficient to accurately track individual dykes through these bundles, dykes are observed to re-emerge from the tops of the bundles after tens of meters, suggesting that in some cases the capture is transient.
The dykes are basaltic, variably vesiculated and sometimes crosscut by 5–15 cm spaced cooling joints (Figure 3). Some dykes, typically those with fewer cooling joints, are also crosscut by well-developed sets of internal margin-parallel joints (MPJs). These MPJs are orthogonal to the cooling joints, and can be observed in dykes throughout La Palma, though their length and spacing varies greatly: some form shale-like fracture cleavages (Figure 3a) while others persist laterally over many meters and are closely (Figures 3b and 3c) to widely spaced (Figure 3d). Similar sets of MPJs have also been observed in basaltic dykes from other volcanic islands (Delcamp et al., 2012; Porreca et al., 2006) and the Troodos ophiolite (Kidd & Cann, 1974), and are probably common; our fieldwork suggests they are present in ~40% of the dykes on La Palma.
The margin-parallel orientation of these joints suggests they are not related to the thermal stresses that form cooling joints, which should propagate inwards and parallel to the thermal gradient to form joints perpendicular to the dyke margin (Budkewitsch & Robin, 1994). Hence, their formation remains unexplained, although Porreca et al. (2006) tentatively suggested that similar joints observed on Mount Somma-Vesuvio could result from elevated stresses within the dykes during volcanic loading.

Many of the dykes contain non-randomly distributed vesicles, which form margin-parallel sheets at regularly spaced intervals near the dyke margins (Figures 4a and 4b) or as a single sheet in the dyke core (Figure 4c). MPJs commonly link vesicles within these sheets (Figure 4d); similar structures in dykes on Tenerife have been described by Delcamp et al. (2012). These authors attribute these vesicle sheets to preferential
degassing pathways that form along straight bands parallel to the dyke margins, although we speculate that such sheets could form when vesicles adhere to solidifying dyke margins during periods of lower magma pressure or flux, and in the case of sheets within dyke cores, during the final stages of dyke activity. Regardless of the mechanism of their formation, sheet-like concentrations of vesicles would significantly weaken these parts of the dyke and promote fracture growth, especially if they have been stretched into non-spherical shapes during cooling (Bubeck et al., 2017; Delcamp et al., 2012).

Finally, internal contacts within multi-dykes at many locations have distinct glassy chilled margins up to ~5 mm thick (Figures 5a–5c), suggesting that the external dyke cooled prior to the injection of the subsequent intrusion. Some of the external dykes at Hoyo Verde also show peperitic margins (Figure 5d), indicating that the host rocks were water-saturated during the emplacement of the earliest intrusions.

**Figure 3.** A selection of different margin-parallel joint styles observed in dykes throughout La Palma, ranging from shale-like fracture cleavages (a) to persistent (b) and sometimes imbricated joints (c) and more widely spaced but highly persistent (tens of meters) “tram-track” joints (d). High resolution versions of these images can be downloaded from FigShare (Thiele, 2020) for closer inspection.
To test our interpretation that the external dykes cooled completely prior to intrusion of the internal ones, two samples were collected from an accessible multi-dyke at Hoyo Verde for ⁴⁰Ar/³⁹Ar geochronology. This location was chosen because (1) neither dyke showed any sign of alteration and (2) both the internal and external dykes could be sampled several meters from the point where they intersect, minimizing the potential for thermal overprinting of the external dyke by the internal one. Studies of dyke cooling (e.g., Bonneville & Capolsini, 1999) suggest that temperatures at distances of greater than a few meters from a ∼1 m thick dyke should not exceed the closure temperature of the potassium-argon system, especially if host rock pore-fluids rapidly advect heat away from the dyke.

Following petrographic inspection (Figures 6a and 6b), groundmass concentrates were separated from crushed samples of HV4 (external dyke) and HV6 (internal dyke) and irradiated according to standard ⁴⁰Ar/³⁹Ar techniques (see Supporting information for details). Aliquots of irradiated groundmass were analyzed via the ⁴⁰Ar/³⁹Ar step-heating method following procedures described by Matchan and Phillips (2014). Samples from HV4 and HV6 yielded plateau ages of 796 ± 4 ka (MSWD = 0.75; P = 0.67) and 596 ± 8 ka (MSWD = 0.53; P = 0.71) respectively (Figures 6c–6f). These values are interpreted as the emplacement ages of the dykes. The ∼200 kyr difference indicates that the external dyke had completely solidified and cooled before it was intruded by the younger dyke. A detailed analysis of the robustness and significance of these Ar-Ar plateau ages is included in the Supporting Information.

3.2. Dyke Microstructure and Mechanical Properties

To gain further insight into the formation of the MPJs and multi-dykes, oriented samples from the cores and margins of 10 different dykes were collected at four locations (Figure 1a). Thin sections (n = 26) oriented perpendicular to the dyke margins were prepared, along with ∼22 mm³ ultrasonic pulse specimens (n = 25) and pairs of 25 mm thick and 45 mm diameter Brazilian discs (n = 17 pairs). The ultrasonic pulse and Brazilian disc specimens were selected to represent intact rock, taking care to avoid cooling joints and MPJs.

Inspection of the thin sections reveals that most of the dykes contain preferentially aligned and ∼0.5 mm long plagioclase laths (Figure 7a). Near the margins of some dykes, rotation of plagioclase laths relative to this preferential alignment suggests the presence of small shear-bands (Figure 7b). Imbrication of (and shearing between) domains of aligned minerals is commonly observed at the margins of igneous intrusions, and generally attributed to shearing during magma flow (Holness & Humphreys, 2003).

MPJs are generally parallel to the plagioclase alignment, although in some cases they appear to have formed along the (older) shear-bands instead (e.g., Figures 7a and 7b). The MPJs show no evidence for significant shear offset which, combined with the irregular fracture surfaces, suggests that they formed as predominantly Mode I fractures. Where vesicle bands are present, MPJs link closely spaced vesicles (Figure 7c).
These plagioclase alignments and MPJs are similar to those observed in basaltic dykes in the Azores (Moreira et al., 2015), Tenerife (Delcamp et al., 2012) and sills on the Isle of Mull (Holness & Humphreys, 2003). Delcamp et al. (2012) interpret that these alignments give basaltic dykes on Tenerife a preferential parting direction, which they also relate to MPJs. Our observations corroborate this hypothesis.

Results from the ultrasonic pulse tests indicate that the dykes have anisotropic elastic properties (Figure 8), which we attribute to the plagioclase alignment and vesicle distribution, although other structures such as microfractures could also play a role. P- and S-wave velocities were calculated in three perpendicular directions by measuring the travel time of 50 kHz ultrasonic pulses over distances of ~20 mm. Proper coupling between the ultrasonic pulse transmitter and each sample was ensured using a coupling agent and by applying a small force to the transmitter and receiver pads. As the flow direction of the dykes are unknown.

Figure 5. Black, glassy chill margins (a, b, c) suggesting the exterior dyke was cooled prior to intrusion of the interior one. Black arrows point toward glassy chill margins. The external dyke in (c) contains abundant vesicles, unlike the interior one. External dyke margins are also glassy (d), and locally develop peperitic textures. The pen used for scale in (c) and (d) is ~14 cm long.
Figure 6. Cross-polarised (XP) photomicrographs of the two dykes sampled for geochronology, HV4 (a) and HV6 (b). The resulting heating spectra show that emplacement (plateau) ages of the external (c) and internal (d) dykes are separated by ∼200 ka. Plateau steps are green, rejected steps are cyan. Inverse isochron diagrams (e, f) are also shown for each dyke. Uncertainties are all 2σ.
and likely variable, measurements in the dyke-parallel direction (which we refer to as L and X) represent an arbitrary coordinate system within the flow-plane, while the dyke-perpendicular measurements (P-direction) is consistently perpendicular to the dyke margin (and flow direction).

The ultrasonic pressure- and shear-wave velocities \( V_P \) and \( V_S \) were used to estimate the Young’s (\( E \)) and shear (\( G \)) moduli in each of these directions, using Equations 1 and 2. Bulk-density (\( p \)) values for this calculation were obtained by calculating the buoyancy of each sample in water, as described in detail by Houghton and Wilson (1989).

\[
E = \frac{V_S^2 (3V_P^2 - 4V_S^2)}{V_P^2 - V_S^2}
\]

(1)

\[
G = pv_S^2
\]

(2)

Paired t-tests found no significant difference between the L- and X-directions, but comparisons with the P-direction suggest significant differences in both \( E \) and, to a lesser extent, \( G \) (Table 1). This indicates that the dykes are an average of \( \sim 8\% \) stiffer under dyke-parallel strains than dyke-perpendicular ones, with anisotropies of up to 25% measured on individual samples. Anisotropy of Poisson’s ratio, which has been shown to control stress rotation in anisotropic materials (Faulkner et al., 2006; Healy, 2008), is also \( \sim 8\% \) on average and up to 30% for individual samples.

The Brazilian tests also show significant differences between dyke-perpendicular and dyke-parallel directions (Table 1), with lower tensile strength (unconfined tensile strength, UTS) and fracture toughness (\( K \)) generally observed for failure parallel to the dyke margins (Figure 8). Each pair of Brazilian discs were loaded at 0.02 mm/sec in an Instron 5982 100 kN testing machine fitted with Brazilian frames such that one sample failed parallel to the dyke margin (in the L-X plane) and the other perpendicular to it (X-P plane). Three pairs of samples were discarded as invalid, as one or both samples did not fail along the disc axis but instead underwent a mixture of shear and tensile fracturing. Peak stress \( \sigma_{peak} \) was recorded and used to estimate the ultimate tensile strength (UTS) in the direction of loading using Equation 3 and measurements of the samples’ diameter \( D \) (45 mm) and thickness \( t \) (±25 mm).

\[
UTS = \frac{2 \times \sigma_{peak}}{\pi \times D \times t}
\]

(3)
Post-failure residual stress was also recorded and, using the methodology and calibration curves presented by Guo et al. (1993), the magnitude of the stress-drop at failure of the Brazilian disc was used to estimate $K$. While this method does not give as accurate a measure of $K$ as more conventional tests (e.g., three-point bend; Kuruppu et al., 2014), it is sufficient to provide a qualitative comparison of $K$ in dyke-perpendicular and dyke-parallel directions.

Specimens with MPJs were not tested due to the practical difficulty of preparing samples containing fractures, however other studies have shown that fracturing induces significant elastic anisotropy (e.g., Heap
et al., 2009; Heap et al., 2010), and it seems reasonable to assume that a similar or even more pronounced effect may be expected for fracture toughness and tensile strength.

4. Discussion

Based on our observations at Hoyo Verde, we hypothesize that (1) solidified dykes form important mechanical discontinuities in basaltic volcanoes, and (2) the mechanical contrast between these dykes and the rocks they intrude can explain the formation of the MPJs and multi-dykes. Mechanical layering and anisotropy in volcanic rocks has previously been recognised as a significant control on dyke propagation and volcano deformation (Gudmundsson, 2005b, 2012; Gudmundsson & Brenner, 2001; Kavanagh et al., 2006). Given this context, we use our observations to evaluate hypotheses (1) and (2) in the following sections, and present some preliminary modeling results that explore their physical plausibility. Finally, we suggest that multi-dykes represent reactivated magma pathways, and explore implications of this reactivation for the organization of volcanic plumbing systems and the distribution of volcanic risks.

4.1. Stress-Concentration, Rotation, and the Formation of MPJs

The dykes at Hoyo Verde are much stiffer than the generally compliant breccia and pyroclastic tuff they cross-cut. These volcanogenic rocks were not directly tested, but similar tuffs and scoria from Gran Canaria and Tenerife have Young’s moduli of <1–20 GPa and shear moduli of <1–8 GPa (de Vallejo et al., 2008; Rodríguez-Losada et al., 2009), making them ~3–15 times more compliant than the dykes (\(E \approx 35–70\) GPa, \(G \approx 15–25\) GPa; Section 3.2). This elastic contrast will cause stress concentration within the dykes during volcanic inflation-deflation cycles and progressive gravitational loading, and, due to their oblique orientation, rotation of the principal compressive stress (\(\sigma_1\)) toward parallelism with the dyke margins (Figure 9).

The tendency for the surrounding, poorly cemented, granular rocks such as tuff and volcanic breccia to undergo inelastic deformation (de Vallejo et al., 2008; Heap et al., 2014; J. S. Lee et al., 2012) would exaggerate this effect, as would the dykes’ elastic anisotropy (Section 3.2). The distribution of stress within a stiff, interconnected network of solidified dykes embedded in 3-D within more compliant host rock is thus expected to result in a complex and heterogeneous distribution of stress, akin to engineered composite materials.

As previously suggested by Porreca et al. (2006), we hypothesize that the stress concentration is sufficient to initiate and drive joint propagation parallel to the dyke margins, facilitated by internal margin-parallel structures such as plagioclase alignments and vesicle sheets. The formation of these initial fractures would have enhanced the dyke’s elastic anisotropy, further rotating the maximum compressive stress (Faulkner et al., 2006; Heap et al., 2009, 2010) toward parallelism with the dyke margins.

Interestingly, dykes with well-developed cooling joints were rarely observed to have MPJs. This suggests that the presence of cooling joints inhibits the rotation of the principal compressive stress by reducing the

| Table 1 | Paired t-Tests Comparing Dyke-Parallel Versus Dyke-Perpendicular Elastic Moduli, Tensile Strength, and Fracture Toughness |
|---------|-------------------------------------------------------------|
|          | Mean difference | Mean anisotropy | Standard deviation | \(p\)-value |
| Young’s modulus (\(E\)) | | | | |
| X       | 4.6 GPa         | 9%             | 4.9 GPa            | \(2.3 \times 10^{-4}\) |
| L       | 4.4 GPa         | 8%             | 3.75 GPa           | \(1.4 \times 10^{-5}\) |
| Shear modulus (\(G\)) | | | | |
| X       | 1.6 GPa         | 9%             | 2.2 GPa            | 0.002        |
| L       | 1.35 GPa        | 7%             | 1.69 GPa           | 0.003        |
| Tensile strength (UTS) | 3.5 MPa         | 26%            | 2.4 MPa            | \(6.6 \times 10^{-5}\) |
| Fracture toughness (\(K\)) | 0.35 MPa.m\(^{0.5}\) | 17%            | 0.44 MPa.m\(^{0.5}\) | 0.02 |

Note. Differences are all significant at a 0.05 level based on \(p\)-values produced from the paired t-tests.
bulk stiffness of the dyke, while blunting of MPJ fracture tips along margin-perpendicular cooling joints would further suppress their growth.

4.2. Anisotropy and the Formation of Multi-Dykes

Regardless of their mechanism of formation, the MPJs reduce the dyke-parallel fracture toughness while encouraging the arrest of dyke-cross-cutting fractures. Similar anisotropy of fracture toughness has been well documented in shales, and is known to divert fractures along the fabric (Chandler et al., 2016; Forbes Inskip et al., 2018; H. P. Lee et al., 2015). Microstructural layering has also been shown to increase the fracture toughness and strength of mollusc shells by several orders of magnitude, due to the arrest or deflection of cross-cutting fractures (Kamat et al., 2000).

This anisotropy, combined with the rotation and increase of \( \sigma_1 \) described in Section 4.1, can explain the observed capture and re-orientation of new dykes along older ones. Where dyke margins were weak, increased stress within the older dyke would have encouraged the arrest of the cross-cutting dyke followed by propagation along the older dyke's margin (e.g., the left-hand dyke in Figure 2c). Where dyke margins were well-bonded, the favored propagation path may instead have followed MPJs within the dyke, to form a multi-dyke with internal chill-margins (e.g., Figure 5), perhaps encouraged by delamination and opening of the MPJs (Cook & Gordon, 1964). The abundance of multi-dykes on La Palma (and elsewhere in the Canary Islands) suggest that intrusions can remain captured over long distances (10^2–10^3 m).

4.3. Numerical Modeling

As a preliminary investigation of these hypotheses, we have used Irazu (Lisjak et al., 2018) to construct 2-D plane-strain finite element (FE) models that evaluate the stresses within and around 2 m thick solidified dykes within a 100 × 50 m domain. The dykes dip at angles of 30–75° (Figure 9) and were given a Young's modulus of 25 GPa, 2.5 times stiffer than the surrounding host rocks (10 GPa). A Poisson's ratio of 0.25 was used for both the dyke and host rock. Boundary conditions correspond to the lithostatic stress at ~1 km depth, producing lateral confinement and 25 MPa overburden pressure). The corresponding stress field under the given boundary conditions is obtained through the FE models.

Next, the propagation of a new fracture through this initial stress field was simulated using the boundary-element linear-elastic fracture mechanics code developed by Zhang et al. (2014) and initial stress fields obtained by FE models. New magma was injected at 0.01 m^3/sec per unit of dyke thickness along an initially 10 m long vertical fracture at the base of the model. The distribution of fluid pressure within the new dyke and corresponding elastic stress induced in the surrounding host rock was calculated at each timestep, and
fracture growth triggered when the maximum stress intensity factor in one orientation reaches a critical value equal to the mode I fracture toughness, which we set at 10 MPa·m$^{0.5}$ for both the dyke and the host rock. Due to numerical limitations, we use relatively low elastic contrasts (2.5 times) and magma viscosity (1 Pa·sec). These models also do not include the previously described anisotropic elastic properties or fracture toughness, so give minimum estimates for the amount of deflection that might be expected. In addition, actual magma injection conditions are likely to vary in rate and overpressure with time, but a constant injection rate is used in this study.

Despite these simplifications, the models clearly show that (1) stress is concentrated and rotated in the solidified dyke, and (2) this causes deflection of the cross-cutting fracture (Figure 9). The amount of deflection varies from ~1 to >10 m depending on the dip of the solidified dyke, with smaller intersection angles causing longer offsets. Browning and Gudmundsson (2015) developed a similar mechanical model to show that stiff dykes within compliant fault damage zones can also capture intrusions by this mechanism.

The modeled geometries generally match those observed in the field, although with an order of magnitude less offset (Figure 2). We attribute this difference to the influence of (1) larger elastic contrasts, (2) elastic anisotropy enhancing rotation of the principal stress, and (3) blunting and deflection of the cross-cutting dyke tip along MPJs. The 2-D plane-strain geometry used in our model is also a significant simplification, as most of the dykes we observed showed evidence of lateral propagation (Thiele et al., 2020). Nevertheless, the results suggest that a mechanical explanation for the multi-dyke formation (Section 4.2) is reasonable.

4.4. Implications of Reactivation for Magma Transport and Associated Hazards

By influencing the propagation path of intrusions and other fractures, solidified dykes give volcanic edifices a “structural memory” of past stress states. Deflection of active dykes along older ones (i.e., reactivation) will cause them to become misoriented with respect to regional or topographic far-field stress, and hence lead to unexpected propagation paths. This reactivation will also encourage the self-organization of the magma plumbing system, promoting re-use of older vents and directing dykes along rift zones or toward shallow magma reservoirs.

The importance of dykes as structural discontinuities that favor strain localization onto volcanic rift zones has been proposed by several authors. While discussing volcanic rift zones in the Canary Islands, Carracedo (1994) suggested that solidified dykes in the core of rift zones force active ones into parallelism with the rift. Similarly, Walker (1992) suggested that dyke margins form structural weaknesses that provide preferential propagation pathways in the densely packed dyke-swarms beneath rift zones in the Hawaiian islands. While the mechanics of our model for multi-dyke formation are somewhat different, treating dykes as mechanically competent units rather than structural weaknesses, the overall effect will be the same: dykes will tend to be re-directed along earlier volcanic rift zone dykes.

Similarly, multi-dykes formed by the mechanisms proposed above could focus dykes into shallow magma chambers. Due to their greater stiffness, solidified dykes will carry stresses induced by a pressurized magma chamber to a greater distance than more-compliant host rock, guiding dykes toward the chamber (Karlstrom et al., 2009). Reactivation of older dykes to form multi-dykes would further enhance these processes, assuming the older dykes also intersect the chamber. By increasing the probability of magma recharge in this manner, a volcano might support smaller shallow magma chambers than otherwise expected. Similarly, the chance of a batch of magma interacting with or assimilating older magma would also increase, allowing for greater geochemical diversity of erupted products.

We speculate that it is also possible that dykes reactivating older intrusions to form multi-dykes are less likely to be arrested at bedding interfaces, because the stiff pre-existing intrusion (and local stress field within it) reduces the stress change experienced by the younger dyke as it passes between stratigraphic units with different mechanical properties. A partially arrested dyke was observed at one location (Figure 10), corroborating this hypothesis. Many studies have demonstrated that an anisotropy oriented at a high angle to the dyke propagation direction (e.g., bedding) increases the chance of dyke arrest (e.g., Gudmundsson, 2005a, 2005b). However, to our knowledge, the effect of stiff mechanical discontinuities with similar orientation to the propagation direction (e.g., older, solidified dykes) has received much less attention. If the presence of these older intrusions reduces the chance of dyke arrest, then eruption (rather than arrest)
becomes more likely in areas that have already been extensively intruded, such as along rift zones, promoting localization of eruptive activity. Conversely, if the accommodation of previous intrusions increases the stress contrast between stiff and compliant stratigraphic units, then dyke arrest becomes likely and eruption from previously intruded regions is inhibited due to the formation of a “stress plug” (cf., Thiele et al., 2020). We suggest that the interactions between concordant (bedding parallel) and discordant (highly oblique) mechanical discontinuities, and their influence on dyke propagation, is a fertile avenue for future research. Finally, an intrusion propagating along an older, solidified feeder-dyke might be expected to erupt in close proximity to old vents. Vents and fissures formed during the Holuhraun eruption (Iceland) sometime between 1794 and 1864 were re-used by the 2014 Bárdarbunga eruption (Sigmundsson et al., 2014), which Ruch et al. (2016) argue is evidence that the dyke that fed the eruption intersected and was captured by a pre-existing fissure. While indistinguishable based on the available evidence, these observations could equally be explained by the formation of a multi-dyke. Similarly, Carracedo et al. (1996) describe the 1677 Fuencaliente eruption, during which the main Strombolian vent formed on the much older (>3.3 ka) San Antonio scoria cone. Although plausibly a coincidence, the location of this vent could also be elegantly explained by the presence of a multi-dyke.

5. Conclusions

We propose that solidified dykes form highly discordant mechanical discontinuities in volcanic edifices. Where dykes are stiffer than the material they intrude, local stress concentration and re-orientation can favor the formation of dyke-parallel fractures, including MPJs and multi-dykes. Plagioclase alignments and other internal structures in the solidified dykes, including MPJs that form during volcanic inflation/deflation cycles, result in significant mechanical anisotropy that further encourages reactivation to form multi-dykes. Field observations of dykes on La Palma suggest that these processes can result in the capture and re-orientation of dykes by up to 60°. Multi-dykes formed in this way are thus a type of mechanical memory, as dykes intruded during previous volcanic activity and potentially different stress fields can influence future dyke-propagation paths. Over longer timescales these processes influence the emergent structure of shallow volcanic plumbing systems by capturing and redirecting dykes along rift zones, toward shallow magma chambers, and possibly even old vents.

Figure 10. Photograph (a) and interpretation (b) of a partially arrested multi-dyke. The first dyke was arrested after propagating through compliant bedded scoria into a stiff lava flow. A younger intrusion that propagated along the older dyke (to form a multi-dyke) was not arrested, possibly because the older dyke reduced the stiffness contrast as it crossed the interface. For a 3-D view of this outcrop the reviewer is referred to the digital outcrop models described by Thiele et al. (2020), and available for download on Figshare (Thiele, Cruden, & Micklethwaite, 2019).
Data Availability Statement

The geomechanical and geochronology datasets presented in this work are available in the Supplementary Material. UAV surveys and the derived digital outcrop models can be downloaded from https://doi.org/10.26180/5d688c17f2ed2. Geomechanical and geochronology data can be downloaded from https://doi.org/10.6084/m9.figshare.13332815.v3.

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