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Segment tip geometry of sheet intrusions: a dynamic model for the evolving conditions of emplacement

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Magmatic sheet intrusions are commonly segmented, across multiple scales, with preserved segments typically interpreted as representing an early stage of intrusion growth. Intrusion propagation has long been associated with linear elastic host rock deformation, associated with tapered or elliptical tip zones. Many studies have identified intrusive segments with non-tapered (e.g., superelliptical) tip geometries, associated with a variety of non-brittle host rock deformation. This has led to development of several anelastic propagation models, including fluidisation, viscous indentation, brittle faulting, and ductile faulting and flow. These models are commonly inferred to represent the propagation mechanism throughout intrusion growth, in host rocks with constant material properties. However, non-brittle host rock deformation may overprint earlier emplacement mechanisms, hence tip geometries observed in the field may not be indicative of the entire emplacement process.

Here we present a quantitative field study of segment tip geometry and associated host rock deformation using a segmented basaltic sill network at Neist Point, Isle of Skye, UK (part of the Little Minch Sill Complex), and static Finite Element (FE) Models of intrusion tip stress distributions, to define a new conceptual model for intrusion growth. The FE models highlight that as tip geometry changes from elliptical to rectangular, tensile and shear stress maxima move increasingly out-of-plane following the positions of maximum tip curvature, as would be expected for non-brittle propagation and matching field observations of host rock deformation. The studied sill segments are hosted in interbedded limestone, sandstone, siltstone, and mudstone units, and are mostly thin (<2 m thickness) with each hosted in a single unit; two of the studied intrusions are thick (>2 m) and their tips transect multiple units. We identified 39 segments in total, 26 of which were geometrically characterised, and a total of 43 tips were measured. Segments with tapered tips were commonly associated with host rock bending (elastic-brittle emplacement), while superelliptical segments show a variety of host rock deformation (e.g., brecciation, faulting). Notably, this deformation is limited to the preserved segment tips, with no such features recorded along the length of the intrusions. Tip geometry and host rock deformation style are not linked to

host rock lithology: local conditions of emplacement evolve to facilitate varying deformation mechanisms within a single intrusive network. Changes to magma viscosity (via crystallisation, volatile/heat loss) and host rock properties (heating, brecciation, fluidisation) may inhibit elastic-brittle fracture, and promote segment inflation and non-brittle propagation.

We propose a multiphase conceptual model for basaltic segments in an initially brittle host. Segments are emplaced initially via elastic-brittle fracture followed by a transitional phase of segment inflation, tip rounding, and modification to the conditions of emplacement leading to a non-brittle propagation phase. Our model accounts for multiple segment geometries and styles of host rock deformation observed across many intrusive complexes and across an array of host rock lithologies. Intrusive segments preserved in outcrop primarily represent the final conditions of emplacement, rather than their growth.