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Igneous sills record far-field and near-field stress interactions during volcano construction: Isle of Mull, Scotland

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ABSTRACT

Sill emplacement is typically associated with horizontally mechanically layered host rocks in a near-hydrostatic far-field stress state, where contrasting mechanical properties across the layers promote transitions from dykes, or inclined sheets, to sills. We used detailed field observations from the Loch Scridain Sill Complex (Isle of Mull, UK), and mechanical models to show that layering is not always the dominant control on sill emplacement. The studied sills have consistently shallow dips (1°–25°) and cut vertically bedded and foliated metamorphic basement rocks, and horizontally bedded cover sedimentary rocks and lavas. Horizontal and shallowly-dipping fractures in the host rock were intruded with vertical opening in all cases, whilst steeply-dipping discontinuities within the sequence (i.e. vertical fractures and foliation in the basement, and vertical polygonal joints in the lavas) were not intruded during sill emplacement. Mechanical models of slip tendency, dilation tendency, and fracture susceptibility for local and overall sill geometry data, support a radial horizontal compression during sill emplacement. Our models show that dykes and sills across Mull were emplaced during NW–SE horizontal shortening, related to a far-field tectonic stress state. The dykes generally accommodated phases of NE–SW horizontal tectonic extension, whereas the sills record the superposition of the far-field stress with a near-field stress state, imposed by emplacement of the Mull Central Volcano. We show that through detailed geometric characterisation coupled with mechanical modelling, sills may be used as an indication of fluctuations in the paleostress state.

1. Introduction

Sheet intrusions represent an important and directional volumetric addition to the crust, with dykes accommodating horizontal extension, and sills commonly accommodating vertical thickening. Although vertical and lateral mafic magma transport through the crust is traditionally associated with dykes, recent studies have shown that sills can dominate the transport and storage network (e.g. Airoldi et al., 2011, 2016; Eide et al., 2016; Magee et al., 2016). Dykes and sills are commonly observed in close spatial association with each other, which has led to the interpretation that regional sill complexes are fed by dykes, despite few supporting observations of this transition. Dykes are commonly used to infer crustal extension, with the idealised dyke plane developing perpendicular to the axis of minimum compressive stress (σ_3; here we reckon compressive stress positive, in which $\sigma_1 > \sigma_2 > \sigma_3$), and parallel to the σ_1–σ_2 plane. If sills are fed by dykes then a rotation of principal stress axes is required; from a horizontal σ_3 for dyke emplacement, to a vertical σ_3 for sill emplacement. A vertical σ_3 is typically inferred to be the result of a local stress perturbation at the interface between anisotropic mechanical layers (e.g. Gudmundsson, 2011), rather than a far-field stress state with a horizontal σ_1–σ_2 plane. However, several studies of intrusive systems that include sills have identified the potential for a far-field (tectonic) stress state control on intrusion geometry (e.g. England, 1988; Chaussard and Amelung, 2012; Walker, 2016). This relationship between intrusion geometry and stress state is important for several key reasons: (1) far-field horizontal compression and shortening during intrusion may serve to inhibit vertical ascent of magma (via dyking) toward the surface (e.g. Chaussard and Amelung, 2012); (2) the dominant mechanism for sill emplacement will play an important role in the placement and distribution of intrusions (e.g. Maccaferri et al., 2011); and (3) sills may serve as a record for phases of horizontal shortening in regions that are otherwise considered tectonically inactive (e.g. Walker et al., 2017), or in cases where the scale of observa-

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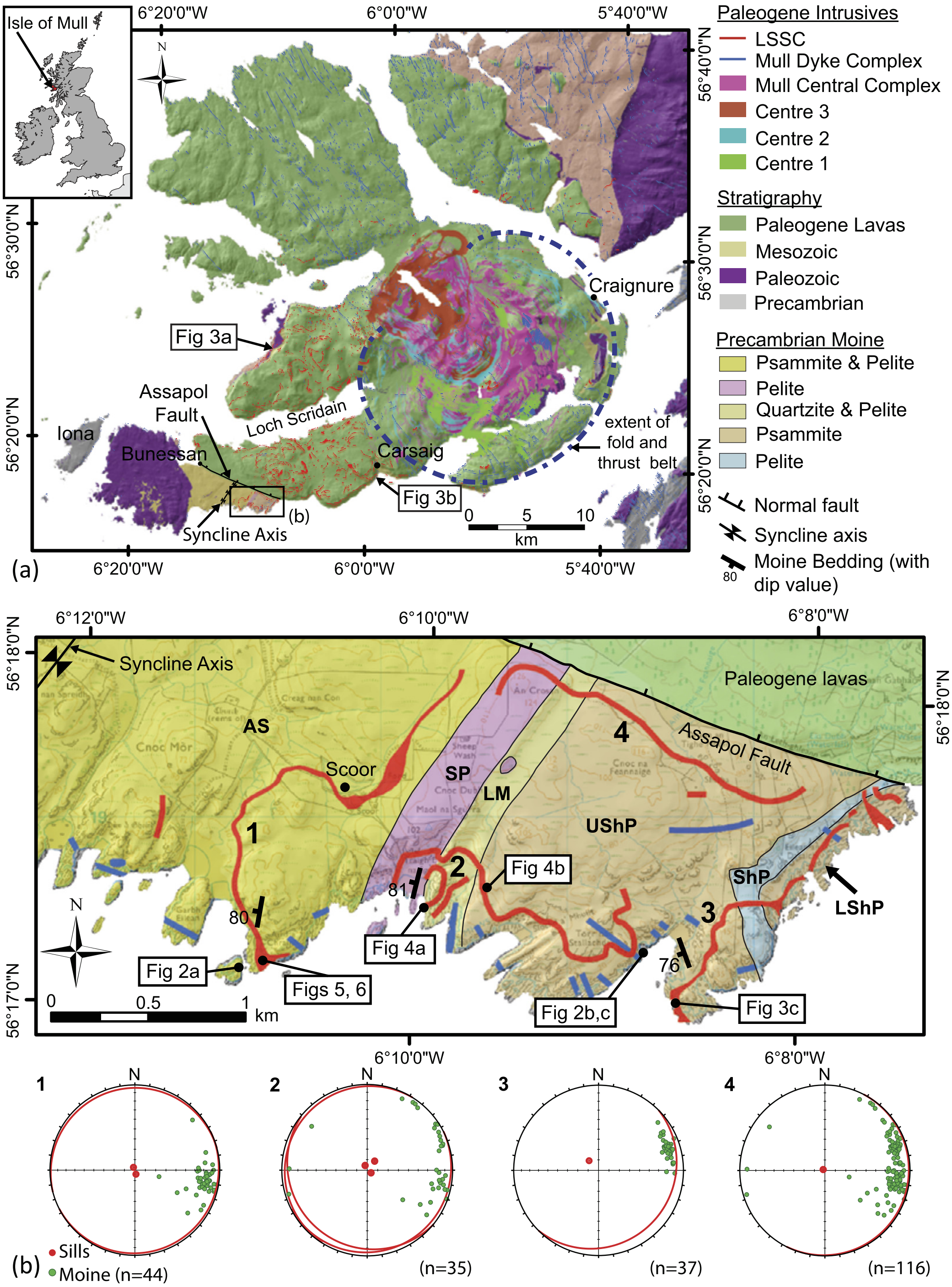

Fig. 1. (a) Geological map of Mull (DiGMapGB-50 a) showing major lithologies and intrusive systems, including the Loch Scridain Sill Complex (LSSC), the Mull dyke swarm and the central complex. The extent of the fold and thrust belt is redrawn from Mathieu and van Wyk de Vries (2009). (b) Geological map (DiGMapGB-50 b; Ordnance Survey 1:25,000 shown as an underlay (OS Scale Colour Raster, 2015)) of the main study area showing only the eastern limb of the Assapol Syncline. Abbreviations indicate the different formations: **LShP**, Lower Shiaba Psammite Formation; **ShP**, Shiaba Pelite Formation; **UShP**, Upper Shiaba Psammite Formation; **LM**, Lagan Mor Formation; **SP**, Scoor Pelite Formation; and **AS**, Ardalanish Striped Formation. Each sill is numbered and corresponds to the equal area, lower hemisphere stereonets below the map. Stereonets show the overall attitude of each sill, as well as the Moine foliation.

tion precludes characterisation of minor strains (e.g. using remote sensing and geophysical imaging techniques).

To consider sill emplacement controls, we present a structural characterisation for sills that cut basement and cover sequences in the Loch Scridain area of western Isle of Mull, Scotland (Fig. 1a): The Loch Scridain Sill Complex. Notably, Precambrian basement rocks in the study area are vertically bedded (e.g. Figs. 2, 3c), whereas the Mesozoic sedimentary, and Paleogene volcanic, cover sequences are horizontally bedded (Fig. 3a, b), presenting a rare opportunity to investigate the role of mechanical layering in controlling sill geometry. For the first time, we use slip tendency, dilation tendency, and fracture susceptibility mechanical modelling, based on field data for intrusions and host rock fractures, to constrain the stress state during sill emplacement. Our field observations and mechanical models reveal that sill emplacement required a radial horizontal shortening, which we attribute to stress