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Numerical modelling of dykes deflected into sills to form a magma chamber

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ABSTRACT

Most shallow magma chambers are thought to evolve from sills. For this to happen, several conditions must be met. (1) There must be a discontinuity, normally a contact, that deflects a dyke (or an inclined sheet) into a sill. (2) The initial sill must have a considerable thickness, normally (depending on dyke injection rates) not less than some tens of metres. (3) The resulting sill must receive magma (through dykes) frequently enough so as to stay liquid and expand into a chamber. (4) The resulting magma chamber must remain at least partially molten and receive multiple magma injections over a given period of time to build up a volcano on the surface above. In this paper we present numerical models based upon field data and geophysical data as to how sills are emplaced and may subsequently evolve into shallow magma chambers. We suggest that most sills form when dykes meet contacts, particularly weak ones, which are unfavourable to dyke propagation. A contact may halt (arrest) a dyke altogether or, alternatively, deflect the dyke into the contact. The three main mechanisms for dyke deflection into a contact are (1) the Cook–Gordon debonding or delamination, (2) rotation of the principal stresses, generating a stress barrier, and (3) an elastic mismatch across a contact between adjacent layers. Elastic mismatch means that the layers have contrasting Young's moduli and varying material toughness. Once a sill is initiated, the developing magma chamber may take various forms. Many shallow magma chambers, however, tend to maintain a straight sill-like or somewhat flat (oblate) ellipsoidal geometry during their lifetimes. For a sill to evolve into a magma chamber there must be elastic-plastic deformation of the overburden and, to some extent, of the underburden. So long as the sill stays liquid, subsequent dyke injections become arrested on meeting the sill. Some magma chambers develop from sill complexes. For the sill complex to remain partially molten it must receive a constant replenishment of magma, implying a high dyke-injection rate. Alternatively, an initial comparatively thick sill may absorb much of the magma of the dykes that meet it and evolve into a single shallow magma chamber.

1. Introduction

Dykes and inclined sheets are easily identified in outcrops: they are subvertical (dykes) to steeply or gently dipping (sheets) planar intrusions that dissect the strata (commonly lava flows, pyroclasticlayers, and sedimentary layers). Thus in contrast to sills, which are mostly concordant, dykes and inclined sheets are mostly discordant to bedding or any horizontal features (Fig. 1a). A dyke has normally a large length-thickness (or aspect) ratio, commonly 10^{2-4} (Gudmundsson, 2011a). Dyke is thus a tabular intrusion with common strike and dip dimensions ranging from kilometres to tens of kilometres, while the longest dykes reach strike dimensions of thousand kilometres or more. The dip dimensions are necessarily limited by the depths to the source magma chambers or reservoirs. Dyke thicknesses are mostly in the range from tens of centimetres to tens of metres, while some dykes are as thin as a few centimetres and the thickest ones many hundred metres (cf. Baer and Heimann, 1995).

Sills, on the other hand, are commonly a little harder to distinguish from their host rocks, particularly when hosted by a lava pile, as they are concordant (Fig. 1b) and in many ways similar to lava flows. However, there are several criteria which can be used to distinguish between the two. These include (e.g. Gudmundsson, 2011a):

1. sills normally have much better developed sets of columnar joints than lava flows;
2. sills have a chilled selvage on the upper and lower margins (the roof and floor), also known as glassy margins, whereas lava flows have chilled selvage (if at all) only at the lower margin;
3. sills have little or no scoria at their margins, whereas lava flows (particularly aa lava flows) have zones of scoria at their upper (commonly weathered) and lower margins;
4. vesicles are smaller, less angular, and less widely distributed in sills than in lava flows;

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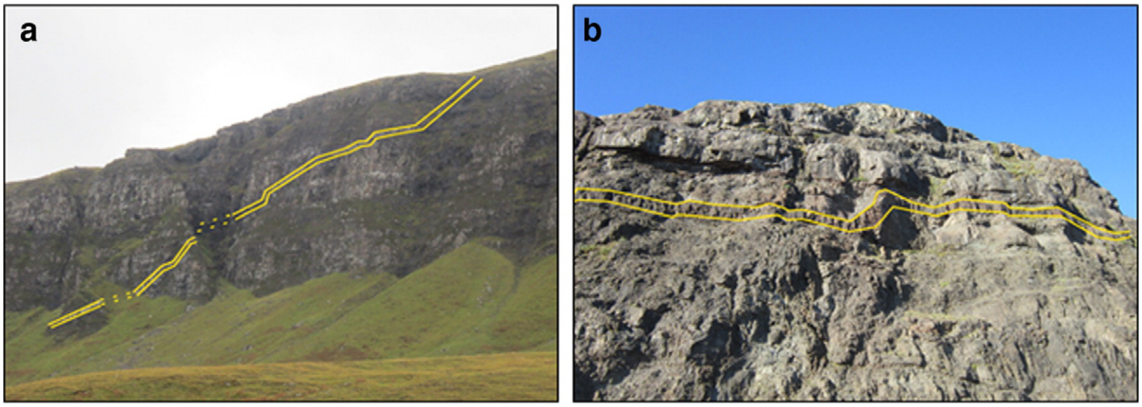

Fig. 1. a) View south, the inclined sheet is approximately 3 m thick and cuts through a basaltic lava pile on the Isle of Mull, Inner Hebrides, Scotland. b) View north, the sill is about 1 m thick and cut through a basaltic host rock, SE Iceland.

5. sills are commonly stepped (Fig. 1b), that is, change their elevation within the pile, and may increase their dips so as to become inclined sheets or dykes, neither of which applies to lava flows;
6. some lava flows gradually change into pillow lavas (others are formed directly as pillow lavas), which do not happen to sills.

Both dykes and sills are primarily fluid-driven extension fractures and, more specifically, hydrofractures. Hydrofractures propagate as a result of internal fluid overpressure (driving pressure, net pressure). Overpressure is the combined effect of the initial excess pressure in the magma chamber at the time of rupture (and dyke injection) and buoyancy. Excess pressure is the fluid pressure in a magma chamber in excess of the overburden pressure or lithostatic stress. When the chamber ruptures and injects a dyke (or an inclined sheet), the excess pressure is normally roughly equal to the in situ tensile strength of the host rock, or a few mega-pascals (Gudmundsson, 2011a). The buoyancy is due to the difference in the density between the fluid (here the magma) and the rock through which the fracture (here a dyke, an inclined sheet, or a sill) propagates. Since the fluid density can be higher, the same, or lower than the host-rock density, the buoyancy effect can be negative, neutral, or positive. Generally, many and probably most hydrofractures, even those subject to positive buoyancy effects, do not reach the surface but rather stall or become arrested or deflected along contacts at varying depths or stratigraphic levels within the crust (Menand, 2011; Gudmundsson, 2011b).

Sill emplacement has been studied in the field and also through geophysical measurements both as regards sill geometries as seen, for example, in seismic lines in sedimentary basins, as well as during active sill emplacement in volcanoes. Examples of direct field studies include those on the Midland Valley Sill and the Whin Sill in Britain (Francis, 1982), as well as those of sills in the Faroe Islands (Hansen et al., 2011), in the Karoo Basin, South Africa (Chevallier and Woodford, 1999; Malthe-Sørenssen et al., 2004; Galerne et al., 2008; Polteau et al., 2008; Arnes et al., 2011; Galerne et al., 2011), in the Henry Mountains, Utah (Pollard and Johnson, 1973), and in the Theron Mountains and North Victoria Land, Antarctica (Leat et al., 2006; Berner et al., 2009). Seismic studies of sill geometries and depths in sedimentary basins include those of sills in the Vøring Basin and the Møre Basin, both offshore Norway (Planke et al., 2005; Hansen and Cartwright, 2006; Fjeldskaar et al., 2008), in the North Rockall Trough (Thomson and Hutton, 2004), in the eastern Northern Yellow Sea Basin and Bohai Bay Basin, both in China (Lee et al., 2006; Cukur et al., 2010; Wang et al., 2011) and in the Neuquén Basin in Argentina (Rossello et al., 2002). Sill emplacement (fed by dykes) has also been detected through geophysical (seismic and GPS/InSAR studies) in active volcanoes, such as for several years prior to the March 2010 eruption in Eyjafjallajökull in Iceland (Sigmundsson et al., 2010; Gudmundsson et al., 2012). Another example is the sill (and dyke) emplacement during the 2011–12 eruption of (offshore) El Hierro, Canary Islands (Becerril et al., 2013; Marti et al., 2013).

Sill formation was initially explained through the concept 'level of neutral buoyancy' (Bradley, 1965; Francis, 1982; Corry, 1988), a mechanism also known as the hydrostatic hypothesis. This hypothesis suggests that when a magma-driven fracture, a dyke, meets a layer with the same density as that of the magma—namely, meets a level of neutral buoyancy—the dyke becomes deflected into a sill along that layer/level (or its contact with adjacent layers). Field and theoretical studies, however, show that this hypothesis is not tenable (Maccaferri et al., 2010, 2011; Gudmundsson, 2012a). More specifically, field studies such as of sill complexes in the Karoo Basin and 3D seismic data analysis (Cartwright and Hansen, 2006; Galerne et al., 2008; Menand, 2008; Galerne et al., 2011) and studies in Antarctica and elsewhere (Muirhead et al., 2011) indicate that neutral buoyancy is not a major controlling factor in the formation of sills. In sill complexes, the sills are stacked at different levels within the upper crust or in sedimentary basins (e.g., Planke et al., 2005; Muirhead et al., 2011), indicating that magma can travel vertically through many neutral-buoyancy layers as sill complexes form an interconnected network.

These results are in agreement with general results as to dyke and sill emplacement. The average rock density of the uppermost several hundred metres of a volcano-tectonically active rift zone anywhere in the world is typically around 2500 kg m^{-3} or less (Gudmundsson, 2012a). By contrast, basaltic magma commonly has densities of 2600 kg m^{-3} to 2750 kg m^{-3} (Murase and McBirney, 1973; Kilburn, 2000; Spera, 2000). It follows that to reach the surface, basaltic magma must normally propagate through crustal layers of densities that are less than that of the magma. This propagation happens everywhere in the world where basaltic volcanism takes place. Most of the basaltic dykes must pass through many 'neutral buoyancy' layers on their paths to the surface (Gudmundsson, 2012b). It follows that neither do dykes normally deflect into sills at levels of neutral buoyancy nor do neutral buoyancy layers/units halt or arrest the vertical propagation of the dykes.

The principal aim of this paper is to explore the conditions for sill emplacement at shallow depths. The focus is on the conditions for dyke deflection along a weak contact. Particular attention is given to the main mechanism of dyke deflection. A second aim is to analyse and explore the conditions that favour the development of an individual sill or a sill complex into a shallow magma chamber. Here the focus is on new numerical models with application to field examples from Iceland and Scotland. While applied to these particular areas, the mechanical results presented here are completely general and apply to sill emplacement and magma-chamber development in volcanic areas worldwide.