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The mechanics and dynamics of sills in layered elastic rocks and their implications for the growth of laccoliths and other igneous complexes

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Abstract

The recent experimental work by Kavanagh et al. [Kavanagh, J.L., Menand, T. and Sparks, R.S.J. (2006). An experimental investigation of sill formation and propagation in layered elastic media. Earth Planet. Sci. Lett. 245, 799–813.] shows that lithological discontinuities and rigidity contrasts can control the formation and dynamics of sills at interfaces separating upper, rigid strata from lower, weaker strata. The present paper extends this work and focuses on its implications in terms of the length- and time-scales associated with the development of laccoliths and other igneous complexes. Sill formation controlled by rigidity contrasts is shown to provide a growth mechanism for laccoliths. The formation of a sill provides favourable rigidity anisotropy for the emplacement of subsequent sills so that laccoliths grow by over-accretion, under-accretion or even mid-accretion of successive sills. In accord with field data, this model predicts that laccoliths grow mainly by vertical expansion, representing the cumulative thickness of their internal sills, while maintaining a comparatively constant lateral extend. The model also predicts that the time-scale over which laccoliths form is essentially determined by the cumulative time between successive sill intrusions. Also, sill dynamics are controlled by viscous dissipation of the fluid along their length, which have consequences for the size and shape of sills. Viscously-controlled dynamics would enable sills to propagate further and thus to grow thicker than dykes of similar magmas. These dynamics would also enable sills to propagate faster and thus to induce non-elastic deformations in surrounding rocks that could deviate them from the interface they originally follow. This would allow them to feed new sills along other interfaces and could assist in the formation of the step structures and saucer-shapes that are commonly observed in sill complexes.

Keywords: sills; laccoliths; plutons; emplacement; igneous complexes

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1. Introduction

Igneous intrusions represent a major mechanism for the construction and evolution of the Earth's crust. Much of the research on magmatic intrusions has focused on the mechanics and dynamics of dykes, which are the main agent for the vertical transport of magma through the crust (e.g. Lister and Kerr, 1991; Rubin, 1995; Menand and Tait, 2002). In comparison, most of the research on sills (sensu lato) has focused mainly on the mechanical and dynamical aspects of the propagation of sills that have already formed, and on the deformation induced by sill intrusions (Pollard, 1973; Pollard and Holzhausen, 1979; Fialko et al., 2001; Malthe-Sørenssen et al., 2004) but the questions of how and why sills form in the first place and where they are observed have not been studied to the same extent. Yet, geological evidence, conceptual reasoning and numerical models suggest that sills, laccoliths and plutons represent a more fundamental mode of emplacement, and that they are an important mechanism by which chemical differentiation of magma occurs within the crust (Blundy and Gardner, 1997; Annen and Sparks, 2002; Annen et al., 2006).

The crust is layered in density, composition, physical properties and strength (Fountain et al., 1992; Orcutt et al., 1976), with a vertical stratification from a mainly mafic lower crust to a

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more granitic upper crust (Rudnicki and Fountain, 1995). This cannot have developed by vertical intrusions. Instead, horizontal seismic layering of the lower crust is consistent with the development of sill complexes (Fountain et al., 1992; Chmielowski et al., 1981; Al-Kindi et al., 2003; Nedimović et al., 2005). There is also a growing body of evidence that magma chambers and plutons develop and grow by amalgamation of numerous but distinct episodes of sill intrusion (Coleman et al., 2004; Glazner et al., 2004). Also, sills increase the petroleum prospectivity of sedimentary basins (Schutter, 2003a,b), are associated with ore deposits (Ramirez et al., 2006) and geothermal systems (Wohletz and Heiken, 1986), and are part of diamond-bearing Kimberlite complexes (Mitchell, 1986; Sparks et al., 2006). Yet, despite their importance and the wealth of available field data, the mechanics and dynamics of sill formation are still poorly understood.

Extensive geological and geophysical data constrain the size of sills and their rate of emplacement. Field measurements of the geometry and dimensions of sills, laccoliths and plutons show that a generic, continuous link exists between the thickness and length of these intrusions. But, as shown by Cruden and McCaffrey (2002) and McCaffrey and Cruden (2002) (see also Breitkreuz and Petford, 2004), this scaling relationship does not follow a single power law. Sills grow mainly by lateral propagation whereas laccoliths seem to grow by vertical thickening before extending laterally again as plutons and batholiths (Fig. 1). This suggests the existence of different growth processes that are related to the length-scale of the intrusions.

Many field and geochronological data indicate that laccoliths, plutons and magma chambers develop and grow by amalgamation of numerous sill intrusions. For instance, ages from U–Pb data from the Tuolumne Intrusive Suite in California show that it was emplaced within 10 Myrs. However this is in contradiction with simple thermal considerations. For instance, a pluton the size of the Half Dome Granodiorite, which is part of the Tuolumne Intrusive Suite, should cool down and solidify in less than 1 Myr if one assumes it represents a single discrete igneous event. Geochronological data, however, reveal that the Half Dome Granodiorite was emplaced in at least 4 Myrs. This result implies that its formation involved multiple igneous events, which is in accord with field observations of the pluton being composed of numerous dykes and sills (Coleman et al., 2004; Glazner et al., 2004). Field studies of smaller plutons suggest even shorter emplacement time-scales, perhaps less than 100 years in the case of the Black Mesa bysmalith in the Henry Mountains in Utah (Habert and de Saint-Blanquat, 2004; de Saint-Blanquat et al., 2006). Therefore, as well as their length-scale, the time-scale for the growth of laccoliths and plutons seems to be dependent on the size of the intrusion considered.

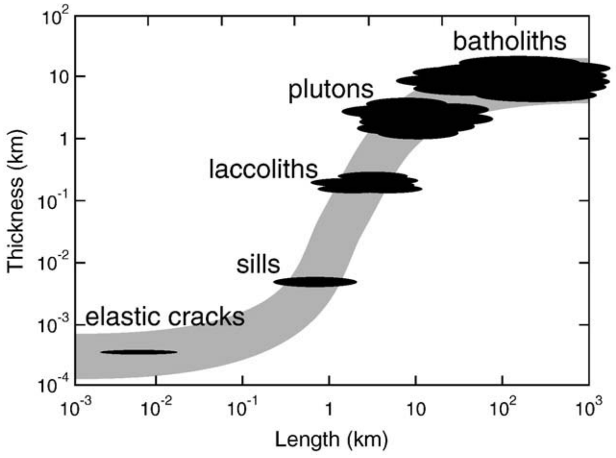

Fig. 1. Schematic diagram showing the scaling relationship between sills, laccoliths, plutons and batholiths based on Cruden and McCaffrey (2002) and McCaffrey and Cruden (2002). Each type of intrusion appears to be linked to the others following an S-shaped growth law over several orders of magnitude.

The main hypotheses for sill formation invoke either a buoyancy (Corry, 1988) or a tectonic stress orientation (Roberts, 1970) control. However, the concept of sill emplacement at the level of neutral buoyancy seems in contradiction with field observations and 3D seismic data of individual sills intruding successively different stratigraphic levels and yet feeding one another (Thomson and Hutton, 2004; Cartwright and Hansen, 2006; Thomson, 2007); if one of these stratigraphic levels represents a level of neutral buoyancy then the intrusion of other stratigraphic levels by the same sills must be controlled by other mechanisms. Alternatively, magmatic intrusions tend to orient themselves parallel to the minimum compressive stress (Anderson, 1951). Therefore a transition from dyke to sill would be expected when the minimum compressive stress changes from horizontal to vertical. This could occur either because of the presence of stress anisotropy or due to stress rotation induced by magmatic intrusions, as shown by Roman et al. (2004, 2006). In the latter case, dyke injection could potentially induce the subsequent formation of a sill by switching stresses such that σ_3 becomes σ_1 due to magma pressure and σ_2 (vertical) becomes σ_3.

Field investigations have led to the view that sills form mostly in more compliant strata such as shales, mudstones or hyaloclastites (e.g. Mudge, 1968; Fridleifsson, 1977; Antonellini and Cambray, 1992). The opposite situation has also been observed, however, with dykes being arrested and sills forming at the interface between a lower more compliant and an upper more rigid strata such as sandstones, limestones or lavas (Fridleifsson, 1977; Hyndman and Alt, 1987; Gudmundsson and Brenner, 2001; Holness and Humphreys, 2003). The soft shales and hyaloclastites that cap some sills may have been ductile at the time of sill emplacement (Mudge, 1968), in which case the rheology contrast with a lower brittle strata would have helped stop the feeder dykes (Parsons et al., 1992). It has also been suggested that stress redistribution in layered elastic media would strengthen some strata relative to others; when a multilayer is subjected to horizontal compression, stiffer layers take up most of the compressive stress, whereas when the same multilayer is subjected to a horizontal extension, softer layers will experience a lower reduction in compressive stress and thus appear, comparatively, to be more horizontally compressive (Gudmundsson, 1986; Gudmundsson and Brenner, 2001). Recently, Kavanagh et al. (2006) showed that in the absence of tectonic stresses sills can form only at the interface between lower more compliant and upper more rigid elastic strata. Thus these studies suggest that, assuming elastic rock behaviour,