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The 3D geometry of regional-scale dolerite saucer complexes and their feeders in the Secunda Complex, Karoo Basin

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ABSTRACT

Dolerites in the Karoo Basin of South Africa commonly represent kilometre-scale, interconnected saucer-shaped structures that consist of inner sills, bounded by inclined sheets connected to stratigraphically higher outer sills. Based on information from over 3000 boreholes and mining operations extending over an area of ca. 500 km^2 and covering a >3 km vertical section from Karoo strata into underlying basement rocks, this paper presents the results of a 3D modelling exercise that describes the geometry and spatial relationships of a regional-scale saucer complex, locally referred to as the number 8 sill, from the Secunda (coal mine) Complex in the northern parts of the Karoo Basin.

The composite number 8 sill complex consists of three main dolerite saucers (dolerites A to C). These dolerite saucers are hosted by the Karoo Supergroup and the connectivity and geometry of the saucers support a lateral, sill-feeding-sill relationship between dolerite saucers A, B and C. The saucers are underlain and fed by a shallowly-dipping sheet (dolerite D) in the basement rocks below the Karoo sequence. The 3D geometric strata model agrees well with experimental results of saucer formation from underlying feeders in sedimentary basins, but demonstrates a more intricate relationship where a single feeder can give rise to several split level saucers in one regionally extensive saucer complex.

More localised dome- or ridge-shape protrusions are common in the flat lying sill parts of the regional-scale saucers. We suggest a mode of emplacement for these kilometre-scale dome- and ridge structures having formed as a result of lobate magma flow processes. Magma lobes, propagating in different directions ahead of the main magma sheet, undergo successive episodes of lobe arrest and inflation. The inflation of lobes initiates failure of the overlying strata and the formation of curved faults. Magma exploiting these faults transgresses the stratigraphy and coalesces to form a ring-like inclined sheet that subsequently feeds a central flat lying roof at a higher stratigraphic level.

On a regional scale, the kilometre-size saucer geometries reflect the lateral migration and transport of mafic magmas close to or at the level of the Karoo Supergroup, fed by only isolated feeders in the basement. On a more local scale, the complex internal geometries within saucers mainly reflect the flow pattern of the magmas and wall-rock accommodation structures.

1. Introduction

Karoo dolerites typically form laterally extensive, composite sill complexes that intruded across Southern Africa prior to the break-up of Gondwana c.180–183 Ma (Duncan and Marsh, 2006; Galerne et al., 2008). In most cases, these dolerite intrusions form networks of interconnected saucer- or basin-shaped sheets that commonly consist of an inner sill, a steeply inclined sheet and a flat outer sill (Fig. 1) (Chevallier and Woodford, 1999; Galerne et al., 2008). The emplacement mechanisms and the controls on the emplacement level of the saucer-shaped intrusions are, however, still a contentious topic. Models for magma ascent and emplacement focus primarily on conditions that induce the dyke to sill transition in the upper crust. These models consider factors like abrupt changes in the stress field, discontinuities and rigidity contrasts (Pollard, 1973; Kavanagh et al., 2006), zones of equipotential pressure (Bradley, 1965) and neutral buoyancy (Francis, 1982). Field observations from other sedimentary basins and analogue models propose sill formation to be primarily influenced by mechanical characteristics and anisotropies in the layered host-rock sequence (Chevallier and Woodford, 1999; Galland et al., 2009; Galerne et al., 2011; Muirhead et al., 2012). Rigidity contrasts between stiffer or competent units (high Young's modulus (E)) and softer units with a lower Young's modulus, in particular, provide preferential horizons for the deflection of feeder dykes into sills. This effect is magnified in the presence of well-developed bedding plane contacts that represent

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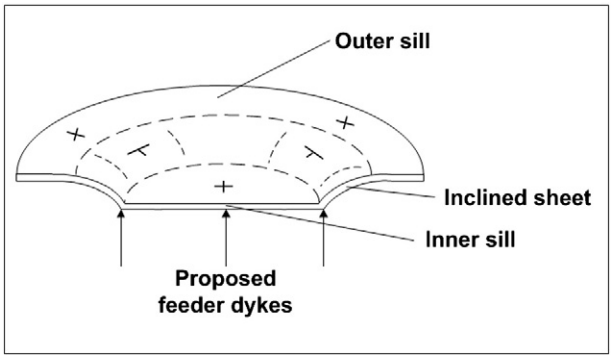

Fig. 1. 3D sketch showing the structural elements of a saucer-shaped sill and proposed feeder dyke positions.
After Chevallier and Woodford (1999), Galland et al. (2009), Galerne et al. (2011), and Kavanagh et al. (2006).

weak interfaces along which the emplacement of sills is facilitated (e.g., Gudmundsson, 2011; Kavanagh et al., 2006). However, models for the dyke-to-sill transition and arrest of magmas typically do not account for the complex saucer-shaped geometries of mafic sill complexes observed in the field. Two main feeder models have been proposed specifically for saucer-shaped intrusions: (1) dykes feeding sills either along the rim (Chevallier and Woodford, 1999) or near the centre of the inner sill (Fig. 1) (Galland et al., 2009; Kavanagh et al., 2006), and (2) sills feeding sills whereby the inclined-sheet of one saucer-shaped sill feeds into the base of an overlying saucer forming a nested sill complex (Cartwright and Hansen, 2006; Thomson and Schofield, 2008).

This paper presents a three-dimensional geometric strata model based on an extensive set of mining and drill hole data of dolerite sheets in the Secunda (coal mine) Complex (Fig. 2) with the primary aim of investigating the relationship between saucers and their feeders. Although similar studies were done at other locations in the Karoo Basin (Chevallier and Woodford, 1999; Galerne et al., 2008; Galerne et al., 2011) this study provides a significantly larger 3D data set, utilizing lithological and structural information from over 3100 boreholes and extensive underground mine development. The data obtained from coal and gold mining operations covers an area of ca. 500 km² and provide insights into a variety of basement rocks in addition to the overlying Karoo strata. The region contains three main, regionally extensive dolerite complexes. This study focuses on one of these complexes, referred to locally as the number 8 sill. The number 8 sill complex was selected for its unique interconnected geometry that consists of several connected saucers in the Karoo stratigraphy underlain by a deeper-seated feeder in basement rocks below the Karoo Supergroup. The three-dimensional data set allows for (1) detailed descriptions of the occurrence, geometry and connectivity of the dolerite complex, and (2) the identification of lithologic and structural controls on dolerite emplacement. The spatial and contact relationships between the saucers and the underlying feeder are used to better constrain the likely emplacement mechanisms of the dolerite sheets, also before the background of existing models of dolerite emplacement in the Karoo Basin (Chevallier and Woodford, 1999; Galerne et al., 2008) and experimental models (Malthe-Sørenssen et al., 2004; Galland et al., 2009; Galerne et al., 2011). These constraints are intended to contribute towards our understanding of sill-feeder geometries and emplacement processes of high-level mafic intrusive rocks not only in the Karoo coalfields, but sedimentary basins, in general.

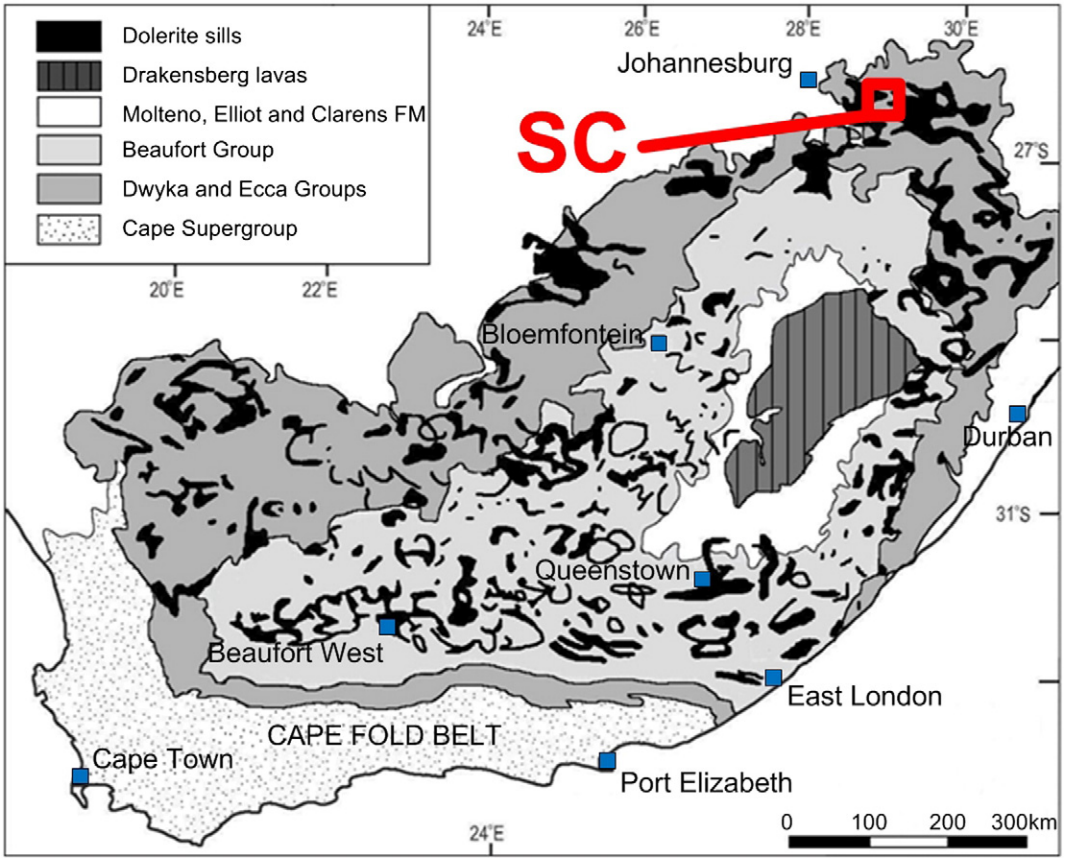

Fig. 2. Simplified geological map of South Africa showing the main Karoo Basin, distribution of Karoo sediments and the main dolerite sills (solid black) (modified from Galerne et al., 2008 and Jeffrey, 2005). The Secunda Complex (SC) is located in the north-easternmost parts of the Karoo Basin.