

**The geometry of Karoo dolerite dykes and saucers in the
Highveld Coalfield: constraints on emplacement processes
of mafic magmas in the shallow crust**

by
André Coetzee

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Faculty of Science at Stellenbosch University*



Promoter:
Professor Alexander F.M. Kisters
Department of Earth Sciences
Stellenbosch University

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Declaration

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Abstract

This dissertation is a compilation of two case studies that integrates an extensive underground mining and drilling data set on Karoo dolerite intrusions in the Highveld Coalfield to constrain the emplacement processes of the upper-crustal plumbing system of the Karoo large igneous province.

Chapter 3 describes by means of a three-dimensional strata model the geometry of a regional-scale Karoo-age (ca. 180Ma) saucer complex locally referred to as the number 8 sill. The saucer complex consists of three saucers largely confined to the Karoo Supergroup underlain by a shallow dipping basement feeder. The model demonstrates the lateral emplacement of magma where a single basement feeder gives rise to several split level saucers that subsequently coalesces into one vast saucer complex. Furthermore, these relationships show a strong spatial and geometric dependency of saucers to their underlying feeders. Lithological interfaces and weak layers control and facilitate the lateral emplacement of magma during the development of saucers in the Karoo Supergroup.

The common occurrence of localised dome- and ridge-shaped structures along the flat inner sill of the saucers are likely generated from lobate magma flow processes. Inflation of individual magma lobes induce overlying strata failure along multiple curved faults that facilitates the formation of circular inclined sheets feeding a flat lying roof seated at a higher stratigraphic level.

Chapter 4 examines the spatial and temporal relationships between dolerite dykes and the saucers that make up the larger number 8 sill complex. These dykes have distinct short strike lengths, curved geometries and form interconnected and cross-cutting patterns. Moreover, the dykes are often rooted along the upper surface of underlying saucers and cannot be seen to extend below the base (inner sill) of the saucers. Contact relationships show a mainly coeval or contemporaneous emplacement of dykes to the inner sill and inclined sheets of the

underlying saucer. The dykes can be described as two diverse sets, namely systematic and non-systematic dykes. Systematic dykes form a well-organised interconnected boxwork or ladder-like pattern of two near-orthogonal dyke sets confined to the inner sill of the underlying saucer. The formation of these dykes is related to the uplift and stretch of the strata directly overlying propagating magma lobes along the inner sill of the underlying saucer. Conversely, non-systematic dykes display a more irregular array of structures that not only overlie the inner sill but often cross-cut or extend outwards from the inclined sheets of the saucer. These dykes are likely the product of multi-directional stretch induced during the emplacement of coeval and adjacent saucers forming a so called “cracked lid” similar to field descriptions of stacked saucers in Antarctica. Dyke-saucer relationships of the Highveld Coalfield highlight the influence of magma emplacement processes and the deformation of host strata rather than far-field tectonic stresses.

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Chapter 1: Introduction

1.1 Preface

The Karoo large igneous province represents the continental scale outpouring of basaltic magmas of the Drakensberg Group that capped the sediments of the Karoo Supergroup during the breakup of Gondwana at ca. 180 Ma. The Karoo Basin is characterised by a vast network of intrusive dolerite sills and dykes that rapidly intruded at 183.0 to 182.3Ma (Svensen et al., 2012) and subsequently served as the feeders to the overlying Drakensberg lavas (Cox, 1992; Duncan et al., 1997). Field studies have, however, revealed that these mafic intrusions tend to be geometrically more complex; instead showing a tendency to form networks of regional-scale saucer- or basin-shaped geometries interconnected by several short, localised dykes (Chevallier and Woodford, 1999). It is primarily in the coalfields of South Africa, largely situated to the northeast of the Karoo Basin, where the occurrence of dolerite saucer-dyke complexes is of particular interest. Here, the overall destructive effect of transgressive saucers on the structural integrity of the host strata coupled with the unpredictable nature of dykes and stringers present a serious risk to the coal mining industry. The thermal effect from saucers tends to be more severe, often baking the coal seams over extensive areas and driving volatile gasses into the surrounding wall rocks that can ignite during mining. The high frequency of joint sets and faults near the affected area can also lead to severe roof falls. Furthermore, dense networks of cross-cutting dykes typically compartmentalise the coal seam into small isolated blocks that not only prevents optimal reserve extraction but can also significantly reduce the payable reserve over the life of mine (Du Plessis, 2008).

1.2 Research rationale

Despite the common occurrence of dolerite saucer-dyke complexes throughout the Karoo Basin, little is known about the underlying feeder system and the general emplacement mechanism related to their formation. This is mainly due to the poor exposure of feeder connections along the base of saucer intrusions in the field. Such feeding relationships are critical in understanding the emplacement mechanism that governs the formation of these intrusive complexes in the Karoo Basin. This dissertation uses a large sub-surface data set to constrain the geometry and relationship between saucers, dykes, and their underlying feeders in order to develop a better understanding of the emplacement processes of shallow crustal mafic intrusive complexes not only in the Karoo Basin, but sedimentary basins, in general.

The Secunda Complex, situated in the larger Highveld Coalfield, consists of several coal mines centred around the town of Secunda (Fig. 2.1) that presents a unique view into the occurrence of dolerite saucer-dyke complexes that are not seen elsewhere in the Karoo Basin. The coal mines offer extensive drill hole and mining data sets compiled by several geologists over a period of some 35 years detailing the properties of different dolerite intrusions and the Karoo Supergroup host rocks. Furthermore, the underlying Evander Basin, where mining operations stretches from 200m to 3.5km depth over an area some 300km² beneath the Karoo Supergroup, provides additional information. The data, many obtained from paper logs and core sketches dating from the late 1950's, provide basic descriptions of dolerite intrusions and basement strata belonging to the Witwatersrand, Ventersdorp and Transvaal Supergroups. It is here where two adjacent collieries (Middelbult and Brandspruit) overlap with Evander Gold Mine (Fig. 2.1) that an area of some 500km² was selected to investigate the three-dimensional geometry, wall-rock relationships and emplacement mechanism of a saucer-dyke complex locally referred to as the number 8 dolerite sill.

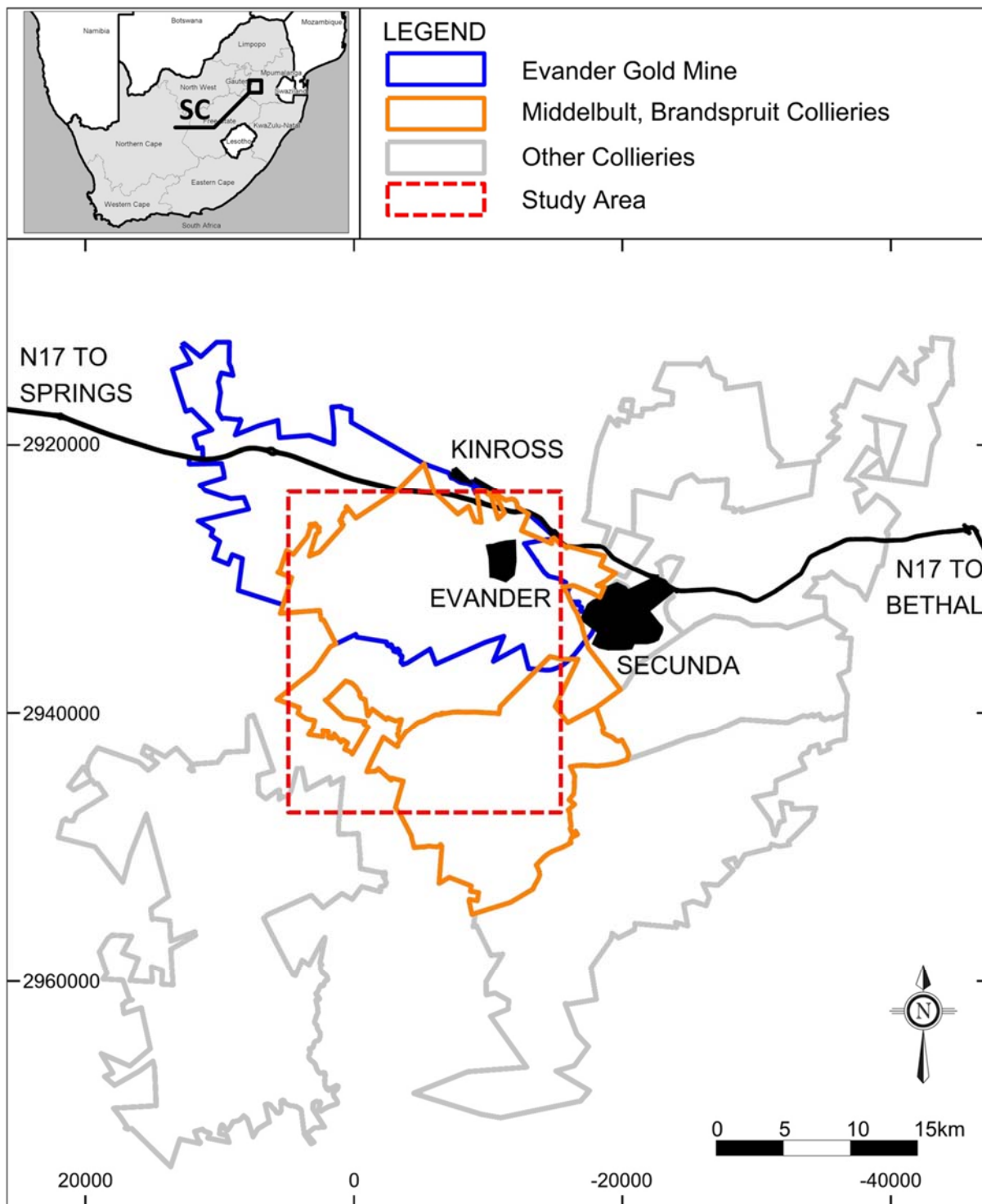


Figure 2.1: A map of the Secunda (coal mine) Complex, Karoo Basin, South Africa. The map shows the mining boundaries of Middelbult and Brandspruit collieries as well as the underlying extent of Evander Gold Mine within the studied area.

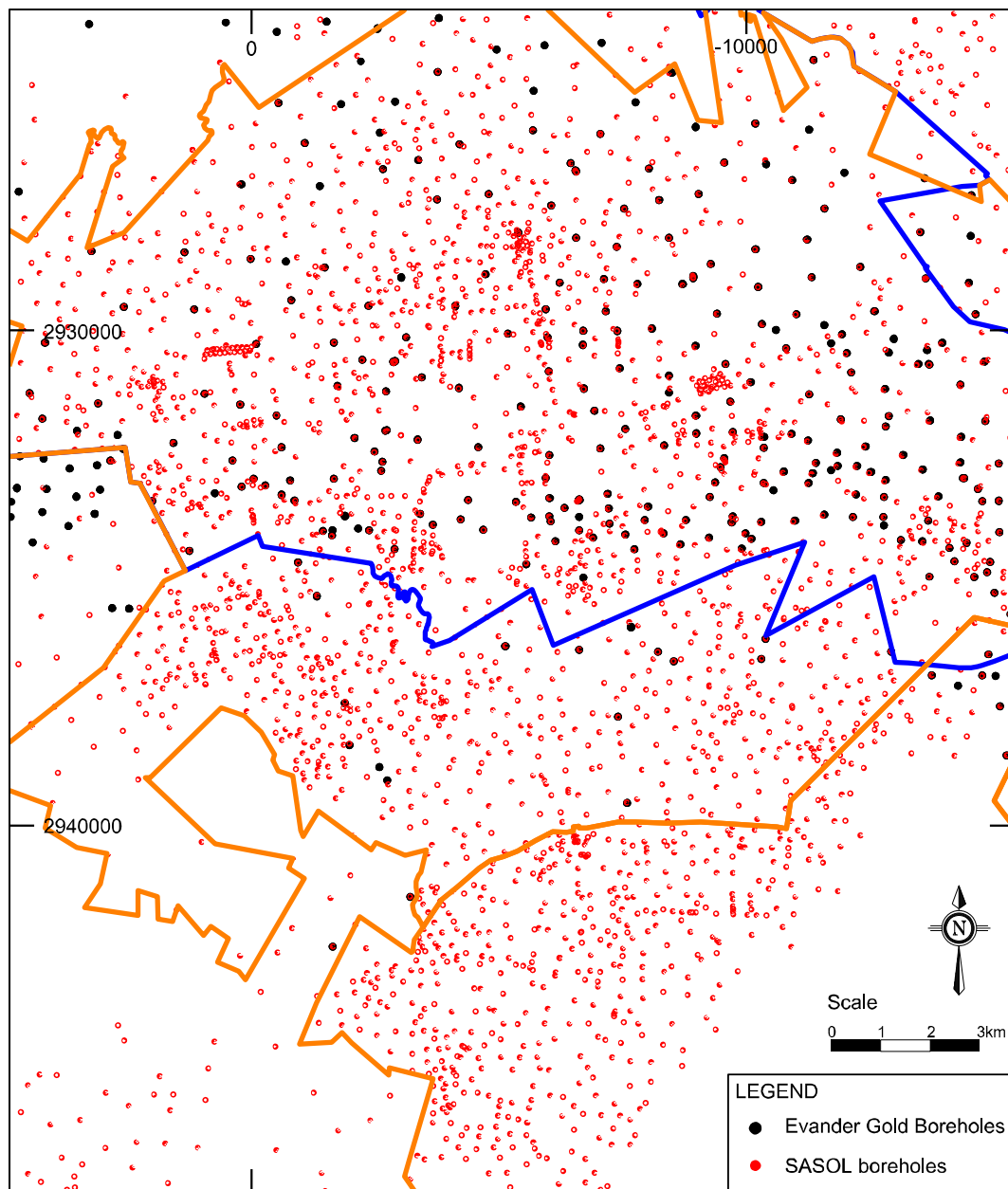


Figure 2.2: The map presents the spatial distribution of the ca. 3100 drill holes used in the 3D modelling of the number 8 sill. Sasol boreholes are drilled up to the base of the Karoo Supergroup whereas gold mine boreholes extend several kilometres into the underlying basement layers.

1.3 Structure of the dissertation

By utilizing the large drill hole and mining data sets this dissertation presents the combined results of two separate projects that consider (1) the 3D modelling of a local saucer complex and the more generic aspects relevant to the emplacement mechanisms of saucers and (2) the geometry, temporal relationship and emplacement mechanism of dykes overlying saucers.

This dissertation is laid out as follows:

- Chapter 2 is a summary of the relevant background information on saucer complexes and emplacement mechanisms in addition to a description of the geological setting of the Secunda Complex.
- Chapter 3 presents an intricate geometric 3D model of a split level saucer complex fed by an underlying sheet seated in the basement layers. This chapter represents published work that appeared in the *Journal of Volcanology and Geothermal Research*.
- Chapter 4 discusses the control of magma flow dynamics of saucer complexes in the emplacement of overlying dykes. This chapter at the time of writing was submitted to the *Journal of Structural Geology* and was undergoing peer review.
- Chapter 5 details the main conclusions and implications of the research and highlights the remaining uncertainties by recommending topics for further investigation.

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Chapter 2: Background

Mafic saucer and dyke complexes are characteristic features in several large igneous provinces, such as the East China Sea Shelf Basin (Rui et al., 2013), Siberian Platform (Prokopyev et al., 2016), Møre and Vøring Basins, Norway (Hansen & Cartwright, 2006), South Victoria Land, Antarctica (Elliot and Fleming, 2000, 2008; Muirhead et al., 2012, 2014) and the Karoo Basin, South Africa (Chevallier and Woodford, 1999; Galerne et al., 2008, 2011; Schofield, 2009; Svensen et al., 2012). In the Karoo Basin dolerite intrusions are primarily represented by stacked interconnected saucer- or basin-shaped sills defined by a central concordant inner sill that links outwards onto a transgressive inclined sheet followed by a flat lying outer sill seated at a higher stratigraphic level (Chevallier and Woodford, 1999). Here, dolerite dykes are also spatially closely associated with the saucers. Contrary to the large regional-scale dykes of the Okavango Dyke Swarm and Lebombo Monocline (Le Gall et al., 2005; Hastie et al., 2014), dykes in the Karoo Basin often form interconnected patterns that show variable strikes, curved geometries and short strike lengths (Duncan et al., 1997; Chevallier and Woodford, 1999; Galerne et al., 2008). The sheer size and frequency of saucers relative to dyke networks in the Karoo Basin seem to suggest saucers play a major part in the lateral transportation of mafic magmas in sedimentary basins and may serve as primary feeders to the overlying Drakensberg lavas (Chevallier and Woodford, 1999; Galerne et al., 2011).

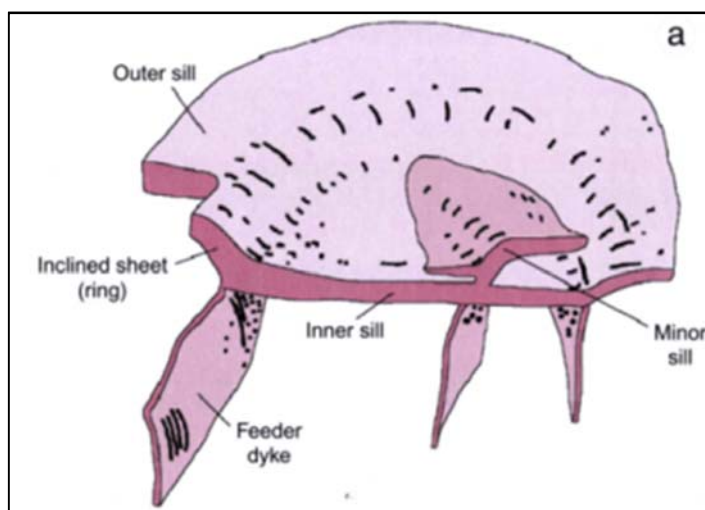


Figure 2.3: The conceptual model of a saucer-shaped sill and proposed feeder dykes after Chevallier and Woodford, 1999.

2.1 Saucer emplacement models

The emplacement mechanisms and the controls on the emplacement level of the saucer-shaped intrusions are poorly understood and still a highly contentious topic. Traditionally emplacement models were based on the conditions that induce dyke to sill transition at shallow crustal levels. Proposed models range from 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-based studies from sedimentary basins in addition to analogue tests show sill formation is strongly controlled by the mechanical properties and anisotropies in the host rock sequence. Since dykes are commonly invoked as the underlying feeder to saucer complexes it was found that the angle of approach of a dyke to a discontinuity is critical in the formation of sills. Gudmundsson (2011) demonstrated a dyke intruding at right angles to a discontinuity is likely to be deflected laterally in all directions whereas a dyke with a shallower angle of approach will intrude only in one direction. In a layered strata sequence, the presence of interfaces only is, however, not sufficient to cause the transition from dykes to sills. This transition is promoted by the presence of competent (high Young's modulus (E)) rock layers overlying less competent layers in addition to weak interfaces (Gudmundsson, 2011; Kavanagh et al., 2006). Even so, dyke-to-sill transition models are not able to explain the geometry and often complex interconnected nature of saucer-shaped intrusions. Two main models have been put forward to explain the emplacement mechanism of saucers by specifically describing the underlying feeder system: (1) dykes or pipes that links along the centre of the inner sill from where magma spreads out-and upwards to form the saucer (Malthe-Sørenssen et al, 2004; Kavanagh et al., 2006; Galland et al., 2009) and (2) one saucer feeds into the base of an overlying saucer in a stacked arrangement (Cartwright & Hansen, 2006; Thomson & Schofield, 2008).

Despite the different magma conduits in the two proposed feeder systems, both models suggest the laccolith-like growth of saucers radially outwards from the inner sill to the inclined sheet followed last by the outer sill (Fig. 2.2). Early inner sill emplacement uplifts and bends the strata directly overlying the sill body. Subsequent inner sill inflation and lateral advance generates extension throughout the roof strata which reaches a maximum above the boundaries of the sill. Once the tensile stress exceeds the tensile strength of the overlying strata failure occurs. Strata failure manifests as steep, inward-dipping, reverse faults along the margins

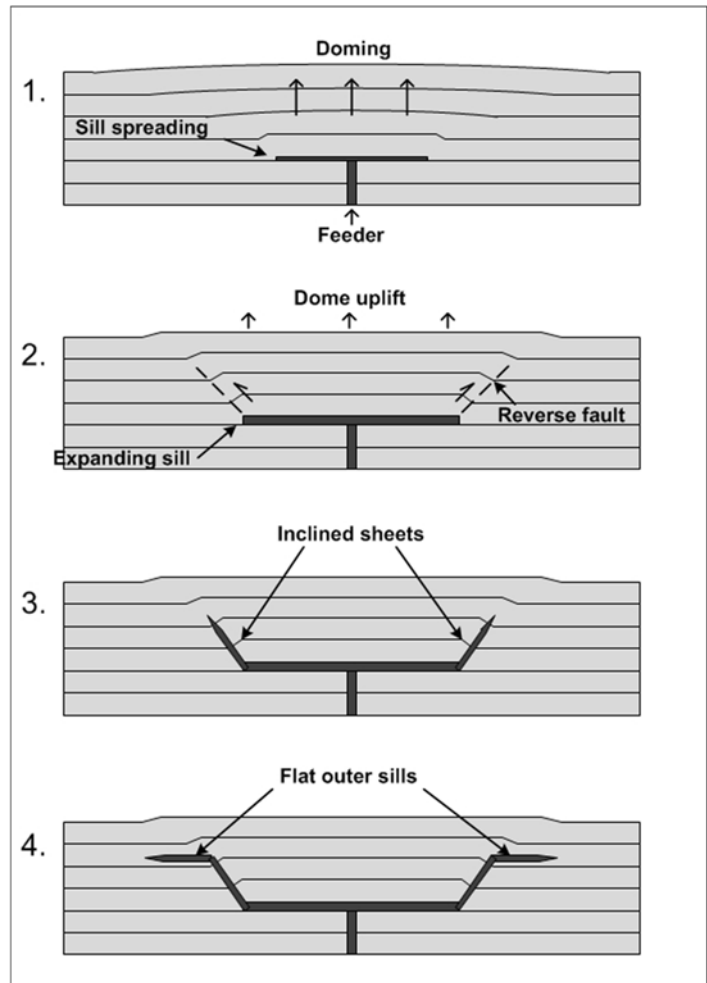


Figure 2.4: The stages in the development of a saucer-shaped sill after Galland et al., 2009. Refer to text for more details.

of the inner sill from where the magma can transgress the stratigraphy to form the inclined sheet. The subsequent drop in magma pressure forces lateral magma propagation along layer anisotropies, thus forming the flat outer sill (Gouly and Schofield, 2008; Mathieu et al., 2008; Galland et al., 2009).

2.2 Lobate magma flow

Saucers typically display lobate structures preserved as elongated tube-like features or fingers ranging in size from 100's of meters to several kilometres that extend radially away from the centre of the inner sill (Pollard et al., 1975; Hansen & Cartwright, 2006; Schofield, 2009;

Schofield et al., 2010; Galerne et al., 2011; Rui et al., 2013). Sill fingers can form due to instabilities in the advancing fracture between a magma sheet and the brittle host rock. Such instabilities arise from host rock heterogeneities where a change in lithological or structural continuity causes the magma front to advance unevenly. Magma will subsequently exploit points of low resistance in the host rock and accelerate ahead of the bulk of the magma sheet in long narrow magma fingers (Pollard et al., 1975). Faster cooling of the small magma fingers from the surrounding wall rocks creates a rigid crust which promotes inflation instead of continued lateral propagation. The continued cycle of lobe growth, crust formation, inflation and renewed magma break-out develops a sequence of ever smaller fingers away from the feeder (Hansen and Cartwright, 2006). Subsequent coalescence of fingers produces a laterally continuous sheet with the vestiges of lobate magma flow preserved as distinct undulations of thinner troughs and thicker ridges in the largely planar magma sheet (e.g., Hansen & Cartwright, 2006; Schofield, 2009; Schofield et al., 2010; Galerne et al., 2011).

2.3 Sill-fed dykes

The emplacement of dykes as an intricate part of saucer complexes are regarded as problematic due to the conflicting stress regimes required for the simultaneous formation of both sills and dykes. Dykes are expected to form in an extensional setting while the formation of saucer-shaped sills is strongly dependent on a neutral or static tectonic setting (Galland et al., 2006). However, Muirhead et al. (2012, 2014) proposed an emplacement mechanism that reconciles these two stress regimes whereby the uplift generated during saucer formation induce extension in the overlying strata. Continuous expansion of the inner sill drives multidirectional stretch and extension in the overlying strata which in turn produces fractures perpendicular to the surface of the sill. Subsequent magma injection into these fractures from

the underlying sill creates a randomly orientated array of dykes above the saucer known as a “cracked lid”.

2.4 Geology of the Secunda Complex

The Karoo Supergroup consisting of the basal Dwyka Group and overlying Eccca Group was deposited over a basement unconformity at 300-180 Ma (Cadle et al, 1993). The Eccca Group is represented by the Vryheid Formation consisting of several sand- and siltstone sequences interrupted by five coal seams of which only a select few are well developed and economically minable. The sub-outcropping basement strata trend east-west and dips at some 15° to the north. Basement strata includes lithologies that belong to the southern lobe of the Bushveld Complex (2.06 Ga), the Transvaal (2.64-2.2 Ga), Ventersdorp (2.7 Ga) and Witwatersrand (2.98-2.7 Ga) (Evander Basin) Supergroups in addition to Meso-Archaean TTG gneisses (>3.1 Ga).

The Karoo igneous event lead to the emplacement of multiple networks of interconnected saucer complexes and dykes in the Secunda Complex at ca. 183 (Duncan et al., 1997; Svensen et al., 2012). Several generations of dolerite saucers can be distinguished in the area, namely a distinct plagiophyric saucer referred to as the number 8 sill and two aphyric saucers termed the number 4 and 7 sills. The oldest of the saucer types are the number 4 sill (Van Niekerk, 1995), a dark green, fine grained dolerite rock that with the exception of a few localised zones occurs near the present day topographic level. The number 7 sill has a similar texture to the number 4 sill but occurs in isolated areas exclusively along the basement-Karoo Supergroup contact. Conversely, the number 8 sill has a porphyritic texture defined by needle-like plagioclase phenocrysts. The number 8 sill represents a single emplacement event across the Secunda Complex and consists of numerous interconnected saucers which frequently transgress and displace the Karoo stratigraphy. Dyke networks are spatially closely

associated with the different sills and often occur as patterns of short, curving and interconnected structures spaced at regular distances.

Regionally continuous normal faults such as the Secunda Graben and Witkleifontein fault post-date the dolerite intrusions and represent displacements of 10's of metres in the sedimentary stratigraphy. These large faults are characterised by numerous localised sympathetic faults often with very short strike lengths and small associated displacements (< 5m).

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Chapter 3: Saucer-feeder geometries

This chapter constitutes a presentation of the published research paper: *The 3D geometry of regional-scale dolerite saucer complexes and their feeders in the Secunda Complex, Karoo Basin*¹ by Coetzee and Kisters.

This paper was first authored by André Coetzee with standard supervision entailing academic guidance and editorial support from Alex Kisters. The following aspects were carried out independently by André Coetzee: (1) mining and drilling data collection, (2) data consolidation, processing and interpretation, (3) 3D modelling and interpretation, (4) preparation and submission of the manuscript and (5) manuscript revision and successful resubmission.

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

André Coetzee^{a,*}, Alexander Kisters^b

^a Geology Department, Sasol Mining (Pty) Ltd, Private Bag X1031, Secunda 2302, South Africa

^b Department of Earth Sciences, University of Stellenbosch, Private Bag X1, Stellenbosch 7602, South Africa

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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 km² 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.

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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

* Corresponding author.

E-mail addresses: acoetzee90@gmail.com, andre.coetzee2@sasol.com (A. Coetzee).

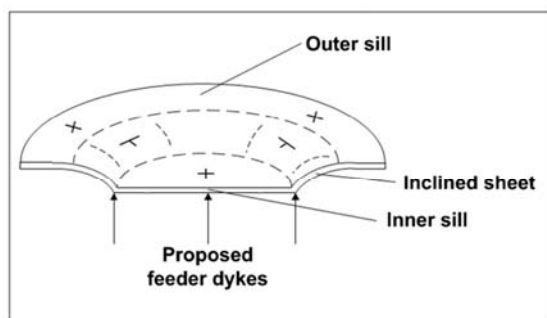


Fig. 1. 3D sketch showing the structural elements of a saucer-shaped sill and proposed feeder dyke positions.

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-Sørensen 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.

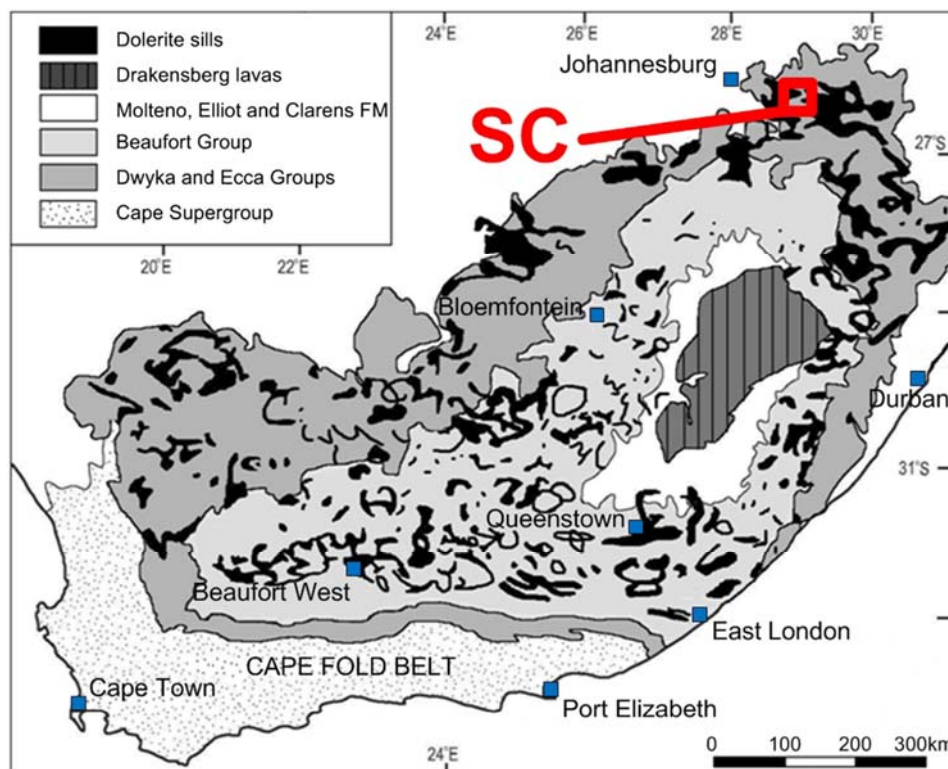


Fig. 2. Simplified geological map of South Africa showing the main Karoo Basin, distribution of Karoo sediments and the main dolerite sills (solid black) (modified from Galerne et al., 2008 and Jeffrey, 2005). The Secunda Complex (SC) is located in the north-easternmost parts of the Karoo Basin.

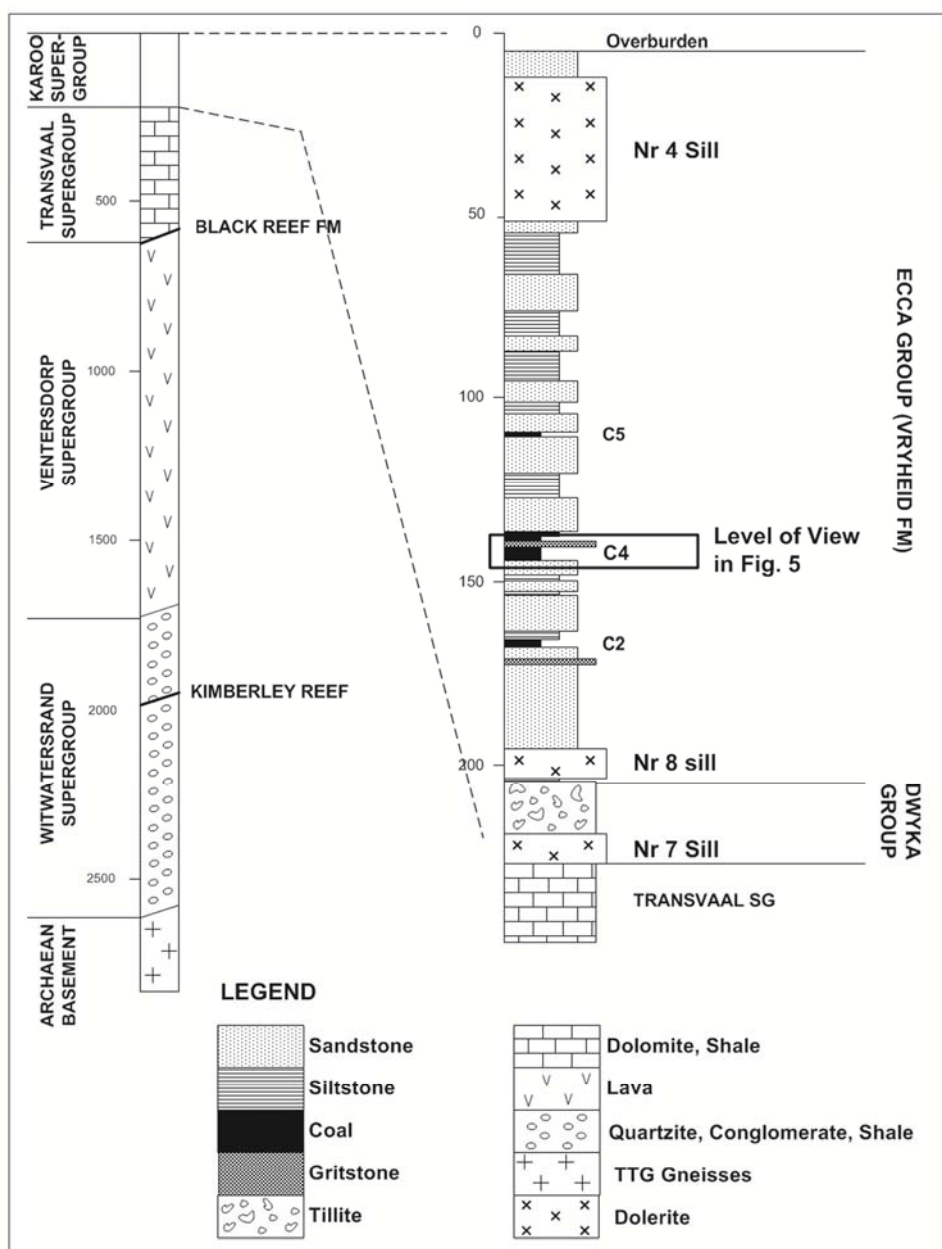


Fig. 3. Generalised stratigraphic column of the area indicating the positions of important lithostratigraphic units such as the Black Reef Formation, the Kimberley reef in the Witwatersrand Supergroup and the C4 coal seam in the Karoo Supergroup in relation to depth (m). The common intrusion levels of the three main dolerite sills (numbers 4, 7, and 8) in the Karoo Supergroup are also shown. Note the stratigraphic level viewed in Fig. 5.

2. Geological setting

The Karoo Supergroup in the northern parts of the main Karoo Basin in South Africa was deposited during the late Carboniferous to early Permian and consists of the basal, glaciogenic Dwyka Group overlain by the siliciclastic Eccca Group (Fig. 3). The Jurassic (c. 180–183 Ma) Karoo magmatism is thought to have been triggered by a mantle plume located to the north-east of South Africa, finding its expression in the emplacement of a vast network of dolerite dykes and sills into the Karoo strata, which formed the plumbing system to the Drakensberg flood basalts (Duncan and Marsh, 2006; Galerne et al., 2008).

Coal measures in the Eccca Group in the northern parts of the Karoo Basin are largely confined to the Vryheid Formation (Johnson et al., 2006) that consists of a 200 m thick paralic sand- and siltstone sequence interlayered with a number of coal seams of which the number 4 (C4) seam is currently mined in the Secunda Complex (Fig. 3). The Karoo Supergroup unconformably overlies a wide range of basement lithologies belonging to the Transvaal (ca. 2.64–2.2 Ga), Ventersdorp (ca. 2.7 Ga) and Witwatersrand (ca. 2.98–2.7 Ga) Supergroups (Evander Basin) in addition to Meso-archaeal (>3.1 Ga) TTG gneisses and plutons (Fig. 4). Sub-outcropping basement strata trend east-west and dip at about 15° to the north as a result of subsequent, but pre-Karoo normal

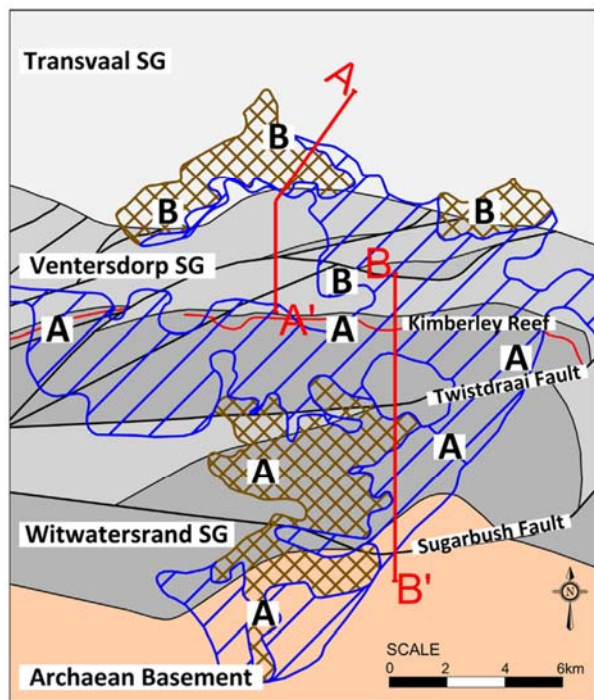


Fig. 4. Geological projection showing the position of basement strata and structures below the Karoo Supergroup. The hatching and cross-hatching respectively represents the occurrence of the number 8 sill (Dolerites A and B indicated) on the Dwyka-Ecca Group contact (blue) and in the basement stratigraphy (brown). The normal faults all have displacements to the south and are indicated in black. The extent of underground mining information from Evander Gold mine is concentrated to the north of the Kimberley reef sub-outcrop. The cross-sections can be viewed in Fig. 6. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

faulting and tilting. The Transvaal and Ventersdorp Supergroups are mainly found in the north and the Witwatersrand Supergroup overlies a TTG basement in the south of the Secunda Complex. The Witwatersrand Supergroup contains several structural discontinuities that predate the Transvaal Supergroup, including mafic dykes and sills, but also reverse and normal faults. Furthermore, numerous pre-Transvaal south dipping normal faults have displaced the Ventersdorp and Witwatersrand Supergroups resulting in large zones of reef loss. The most prominent of these are the east-west trending Twistdraai and Sugarbush faults with throws of up to 700 m (Fig. 4). Karoo magmatism was followed by a prolonged period of extensional tectonic activity during the break-up of Gondwana ca. 175–90 Ma (Watkeys, 2006) that resulted in the formation of late-stage normal faults in the Secunda Complex such as the east-west trending Secunda Graben and Witkleifontein fault with throws of up to 53 m and 20 m, respectively (Fig. 5).

The Secunda Complex (Fig. 2) combines a number of collieries that forms part of the larger Highveld coalfield. The region is characterised by a rolling landscape with little or no rock outcrops except for selected road cuttings and quarries. The three main and regionally developed sill complexes in the Secunda Complex include the number 4, 7 and 8 sills. In the mining terminology, large, shallowly-dipping dolerite sheets are commonly referred to as sills. This alludes to the predominantly concordant nature of the dolerites with respect to the Karoo stratigraphy, but their internal geometry is considerably more complex. The number 4 sill, the oldest of the three (Van Niekerk, 1995), is a 40–50 m thick fine-grained, dark-green sill that occurs primarily near the surface in the upper Ecca Group sandstones. The number 7 sill shows a similar

texture to the number 4 sill, but is confined to stratigraphically lower levels of the Dwyka Group (Fig. 3) and occurs exclusively towards the northwest (Fig. 5). The number 8 sill has a distinct porphyritic texture with lath-like, acicular plagioclase crystals set in a fine-grained matrix. The number 8 sill is by far the most extensive sill complex across the region often forming km-scale saucers that typically transgress and displace the Karoo strata from the Dwyka-Ecca Group contact upwards into the Ecca Group (Fig. 5). The porphyritic texture of the number 8 sill is characteristic for the number 8 sill and facilitates regional correlations across drill holes. Thin, 1–5 m wide, gently curving, but generally E–W trending subvertical dolerite dykes are abundant and spatially closely associated with the larger dolerite saucer complexes. The dykes are fine grained, dark-green to brown-grey coloured rocks with a porphyritic texture similar to that of the number 8 sill. There are no Karoo-aged dolerite intrusions recorded in the underlying Witwatersrand strata and along the Kimberley reef below the Secunda Complex.

3. Spatial data

The studied area, covering approximately 500 km², is centered around Middelbult Colliery in the north and the Brandspruit Colliery to the south (Fig. 5) that mine the largely horizontal C4 coal seam at depths between 80 to 150 m in the upper parts of the Vryheid Formation. The underground workings of Evander Gold mine underlie much of Middelbult Colliery (Figs. 4 and 5), and mining of the Kimberley reef in the lower parts of the Turffontein Subgroup (Central Rand Group) provide underground data from depths between 200 m and 3.5 km. Hence, the combined coal and gold mining operations offer mine and borehole information of intersected Karoo dolerites from an up to 3.5 km vertical section from the Witwatersrand into the Karoo Supergroup (Fig. 6). Geological data from the three mines includes over 3100 drill holes through the entire Karoo Supergroup of which some 395 holes reach as deep as the Kimberley reef. The full set of drill holes was combined with underground mining data relating to the number 8 sill and incorporated into the Datamine Strat3D modelling software package to create a detailed 3D geometric strata model, which includes marker horizons and discontinuities such as the C4 coal seam, the Dwyka Group, the Black Reef Formation at the base of the Transvaal Supergroup and post-Karoo faults (Fig. 6). The following results are a combined analysis of cross-section interpretations based on borehole data and strata modelling.

4. Results of 3D modelling

4.1. Stratigraphic occurrence and 3D geometry of the number 8 sill complex

The number 8 sill is a geometrically composite dolerite complex that consists of three interconnected saucer-like structures confined to the Karoo Supergroup underlain by a shallow dipping sheet in the basement rocks. In order to simplify the description of the characteristics of the number 8 sill complex, the three saucers are referred to as dolerites A, B and C and the basement sheet is referred to as dolerite D (Figs. 6 and 7). Dolerite A and B (green in Fig. 7) are laterally continuous within the Karoo Supergroup stratigraphy. Dolerite C (red in Fig. 7) is stratigraphically higher and shares a short segment with dolerite B. Conversely, dolerite D is the stratigraphically lowest sheet occurring exclusively in the underlying Transvaal and Ventersdorp Supergroups. Dolerite D connects to the base of dolerite B near the position where the Transvaal-Ventersdorp Supergroup contact sub-outcrops below the Karoo stratigraphy (Fig. 6a). There are several minor sheets related to the number 8 sill in the Transvaal Supergroup above dolerite D, but these thinner and discontinuous sheets were not considered in the model as the much thicker and regionally extensive dolerite D was regarded as the main basement dolerite sheet.

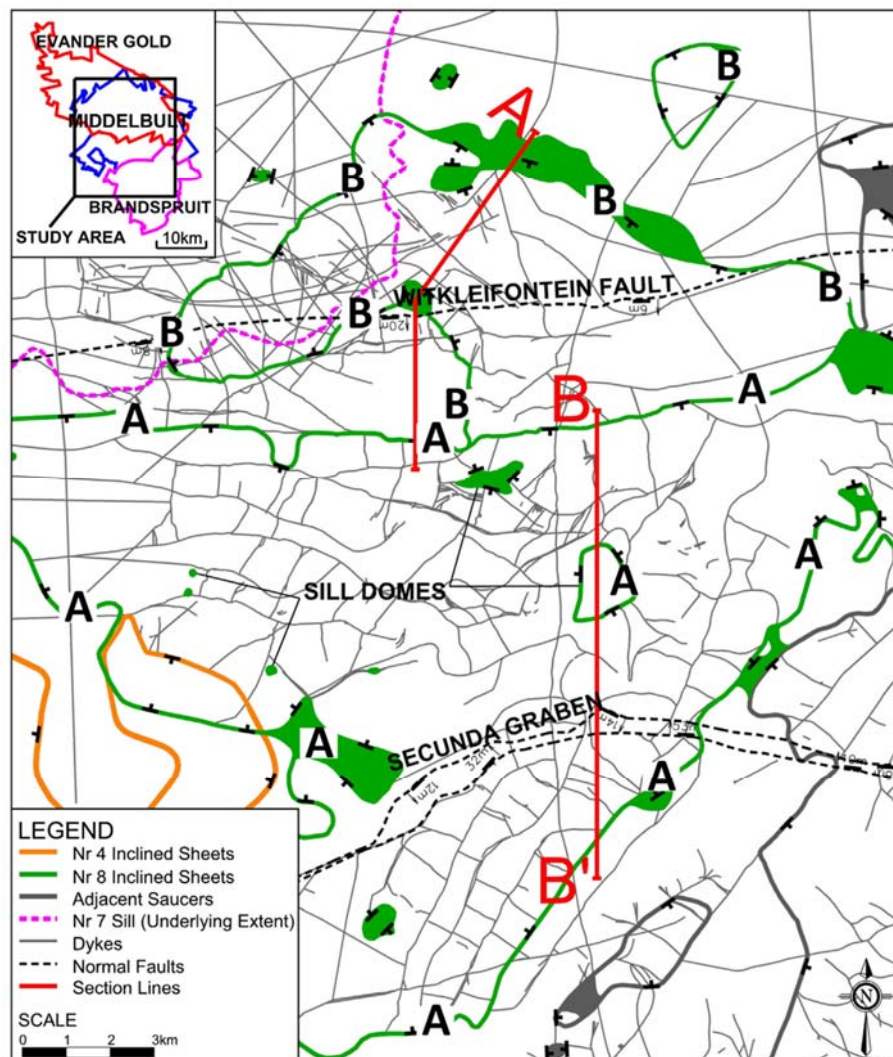


Fig. 5. Geological map of the Secunda Complex projected to the level of the C4 seam, some 80–150 m below surface (see Fig. 3). The indicated structures illustrate the intersection of inclined sheets (lines) and sills (solid) in addition to dykes and normal faults with the C4 seam. The lines of intersection and dips of the dolerite sheets define the occurrence of several intrusive dome and basin structures that cross-cut the C4 horizon. The extent of the number 8 sill (dolerites A and B) used for modelling is shown in green. Grey outlines indicate areas that have not been used in the modelling exercise. The pink dashed line merely delineates the extent of the underlying number 7 sill which does not intersect the C4 seam level.

4.1.1. Dolerite A

Dolerite A forms a saucer-shaped structure, some 18 km in diameter, consisting of a flat inner sill, an inclined sheet and a flat outer sill. The flat-lying inner sill is largely confined to the contact between the Dwyka and Ecca Groups at elevations between 1400–1420 m (A.M.S.L) (Fig. 8a). The centre of the inner sill cuts through the Dwyka Group and below into the basement strata at an elevation of 1360 m. This deep-seated zone has a diameter of 6 km and is centred around the sub-outcrop positions of the east-west trending Twistdraai and Sugarbush normal faults (Fig. 48a).

The inner sill is flanked by three inclined sheets that impart a triangular geometry on the basin (Fig. 8b). Planar, near-vertical sheets in excess of 14 km strike length are developed to the north and south-east of the inner sill showing east-west and NE-SW strikes, respectively. The eastern extent of the northern inclined sheet has been eroded. The northern and south-eastern inclined sheets are not connected in the east and form a so called “open-end” where the inner sill joins adjacent

basin-shaped intrusions to the far east of the studied area (Fig. 8b). Shallower dipping sheets in the south-west transgress the stratigraphy along a very irregular surface, which involves steeper segments with dips of 50° that cross-cut the overlying strata over vertical sections of up to 40 m. The steeper segments alternate with flat, bedding-concordant segments that seem preferentially located along weak layers, particularly the C4 seam (Fig. 9).

Outer sills extend laterally from the inclined sheets at a higher stratigraphic level and mainly occur below the number 4 sill at elevations between 1560–1620 m. The full extent of the outer sills is typically not preserved as the sills terminate against the present day topography. The eastern extent of the outer sill of the northern inclined sheet is eroded in topographic lows.

The thicknesses of the inner sill of dolerite A vary along distinct east-west trending corridors from 9–18 m to 18–27 m (Fig. 10a). These thickness variations are rather gradual, but correspond to the east-west strike of the underlying pre-Karoo Twistdraai and

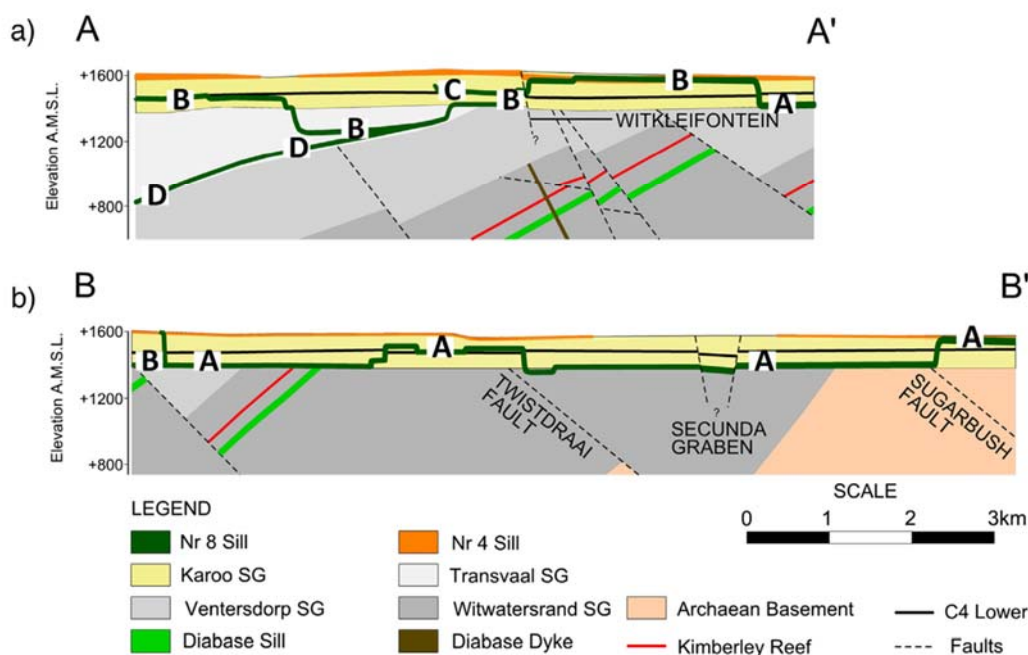


Fig. 6. Geological cross-sections along north-south section lines indicated in Figs. 4 and 6, with a vertical exaggeration factor of 2. a) Cross-section A-A' showing the relationship of dolerites B-D in both the Karoo and basement stratigraphy. b) Cross-section B-B' showing the occurrence of dolerite A mainly along the Dwyka-Ecca Group contact forming an isolated intrusive dome structure at its centre. Note that the Dwyka Ecca Group contact is obscured by the scale due to the low thickness of the Dwyka Group. The near vertical inclined sheet of dolerite A in the north forms the boundary (designated in Fig. 7) with dolerite B.

Sugarbush faults. The Karoo stratigraphy has been uplifted by between 9 and 27 m above dolerite A across the extent of the saucer (Figs. 6 and 9). The inclined sheet thickness corresponds to that of

the connected inner sill with the northern, south-eastern and south-western inclined sheets showing respective thicknesses of 11–15 m, 18–21 m and 21–27 m.

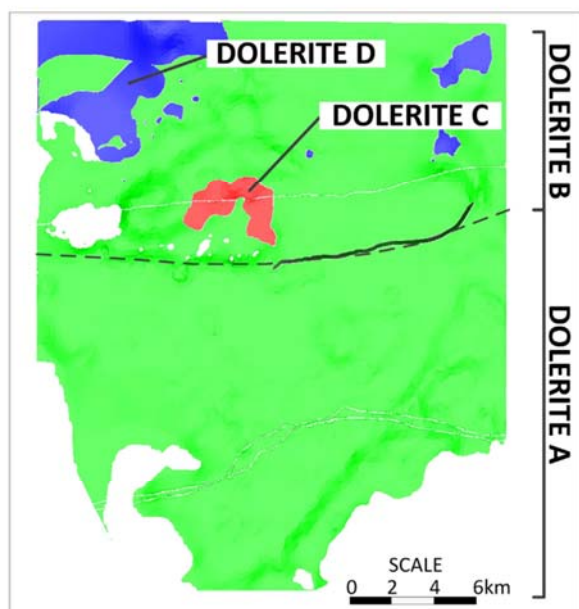


Fig. 7. Geological strip map illustrating the spatial positions and stratigraphic levels in colour of the four number 8 sill segments, dolerites A, B, C, and D. Dolerites A and B (green) primarily occur within the Karoo Supergroup stratigraphy and are overlain by dolerite C in a small localised area (red). Dolerite D (blue) occurs exclusively in the deeper basement strata underneath dolerite B. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.1.2. Dolerite B

The dolerite describes a narrow, 15 × 2 km east-west trending basin-like structure (Fig. 8a) with its long axis parallel to the sub-outcrop of the contact between the Transvaal and Ventersdorp Supergroups beneath the Karoo Supergroup (Fig. 8b). Dolerite B consists of an inner sill (Fig. 8) that progressively climbs from its lowest point (1280 m elevation) at the Transvaal-Ventersdorp Supergroup contact (i.e. Black Reef Formation) onto the Dwyka Ecca Group interface at elevations between 1400–1420 m (Figs. 6a, 8a, 11a).

The rims of the inner sill are defined by inclined sheets climbing from the Dwyka Ecca Group contact to higher stratigraphic levels just below the surface at elevations between 1600 to 1680 m (Fig. 8a). The near-vertical southern and north-western inclined sheets cross-cut the Karoo stratigraphy over 200 m before linking with the flat outer sills (Fig. 8b). In contrast, the north-eastern inclined sheet connects the inner and outer sills through a series of successive 20–40 m upward steps involving steeper segments with dips less than 50° alternating with flat, subhorizontal segments that preferentially follow the C2 and C4 coal horizons (Fig. 9).

The southern and western outer sills occur below the number 4 dolerite sill at an elevation of ca. 1600 m (Fig. 8a). Conversely, the north-eastern outer sill occurs primarily along the C5 horizon (1540 m) from where it steps 20 m downwards with dips <30° to the C4 seam at a level of 1520 m, followed by a steep (50°) upward transgression towards the number 4 sill at 1640 m.

The transition from the inner sill to the inclined sheet of dolerite B coincides with a sharp drop in thickness from 8 to 3 m to the south and north-west and from 8 to 6 m to the north-east (Fig. 10a). The overlying strata has been uplifted by 6–8 m above the inner sill and 3 m above the outer sill of dolerite B.

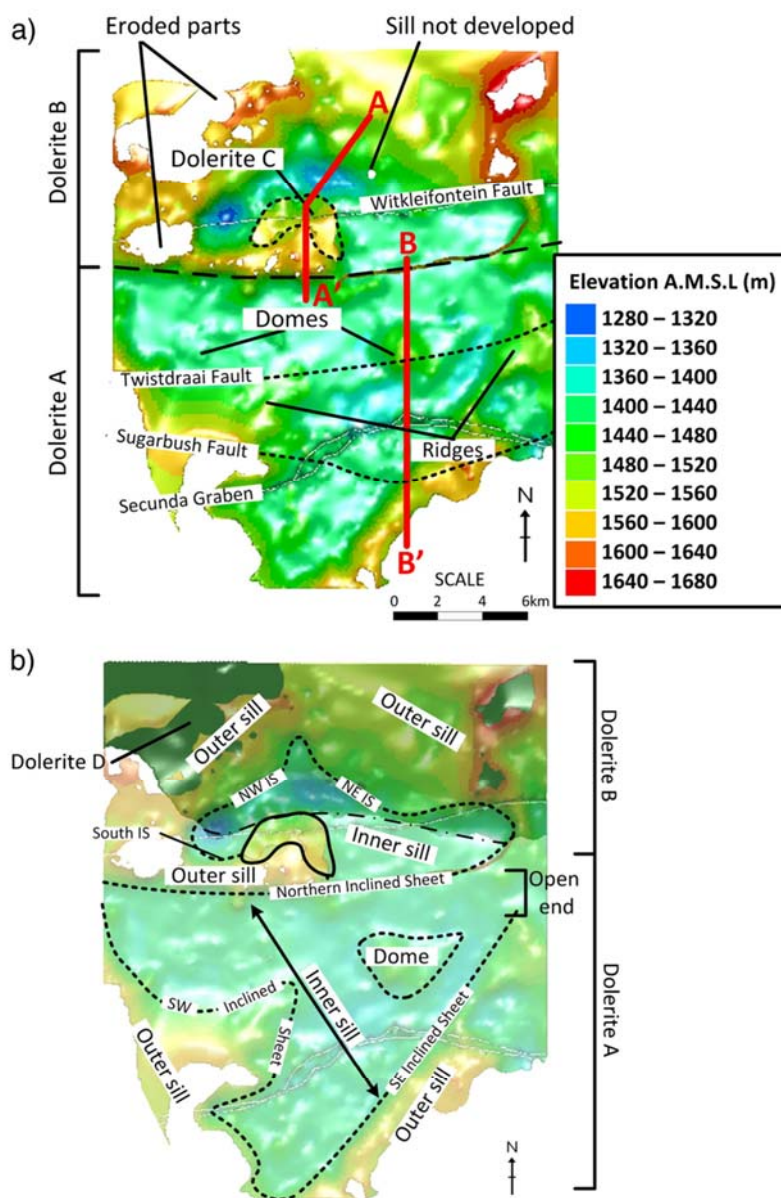


Fig. 8. The plan view diagrams represent three-dimensional geometric models of the number 8 sill with a vertical exaggeration of 5. a) The main features of the three upper level dolerites (A, B and C) are shown together with the dome and structures and pre- and post-Karoo normal faults. The blank areas demarcate zones where the dolerites are either not developed or eroded. (b) Projection of the outlines of the inner sills or start positions of the inclined sheets is shown in dashed lines for dolerites A and B. The inner and outer sills are indicated respectively on the inside and outside of the dashed lines. Refer to the text for descriptions of the different inclined sheets for dolerites A and B. The location of the underlying dolerite D can also be seen in relation to dolerite B with the line of linkage indicated in the broken-dashed line. Note the position of the open-end where a gap exists between the northern and south-eastern inclined sheets.

4.1.3. Dolerite C

A prominent feature of dolerite B is an outgrowth of a smaller saucer, dolerite C, situated along the southern extents of dolerite B. Dolerite C describes a 4×2 km saucer that transgresses the strata independently from dolerite B in a series of 20–40 m steps before linking with the inclined sheet and outer sill of dolerite B in the south (Figs. 6a and 11a).

4.1.4. Dolerite D

Dolerite D largely consists of an 8×20 km flat sheet roughly parallel to the shallow dipping contact between the Transvaal and Ventersdorp

Supergroups (Black Reef Formation in Fig. 11a, b). Along its eastern extent the dolerite sheet steps upward by ca. 400 m at an angle of some 20° into the overlying dolomite succession of the Transvaal Supergroup forming what resembles a flat basin-like structure (Fig. 11c). The Transvaal Ventersdorp Supergroup contact dips north at 15° and sub-outcrops below the Karoo Supergroup along a gently undulating east-west surface (Figs. 8b, 11b). This surface represents the connection between dolerites B and D. Dolerite D attains thicknesses of >10 m in the north that sharply decreases to less than 2 m in the south (Fig. 10b).

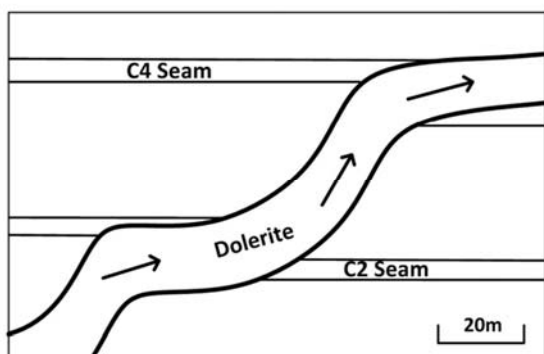


Fig. 9. Cross-sectional view (east-west) of the transgression of the south-western inclined sheet dolerite A consisting of steeper segments that cross-cut the strata alternating with flat, bedding-concordant segments that exploit and displace coal-seam horizons.

4.1.5. "Dome- and ridge-structures"

The inner sill of dolerite A shows several upward steps or protrusions through the stratigraphy that result in dome- or ridge-like

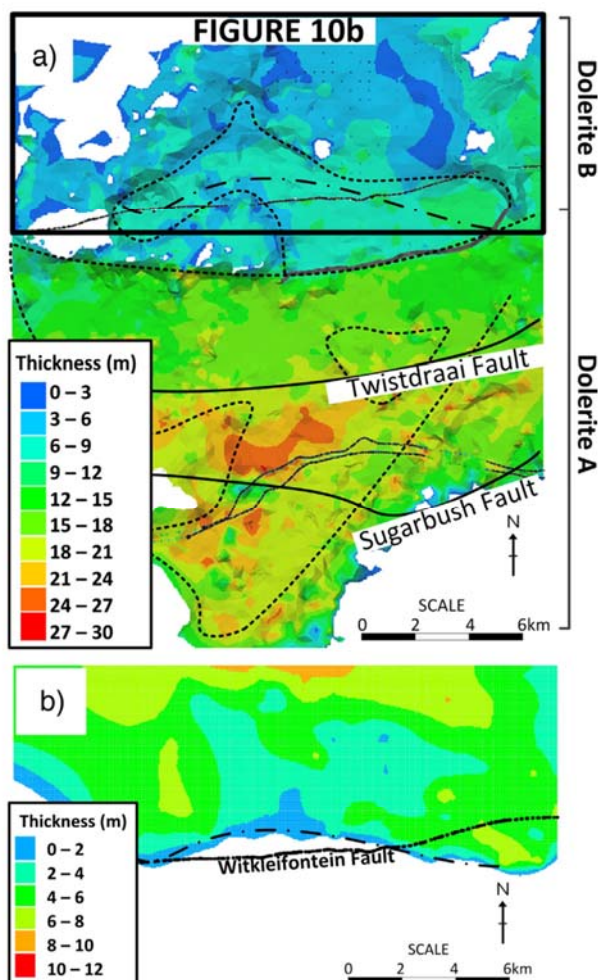


Fig. 10. (a) Thickness contour plot of dolerites A and B is shown on top of their 3D geometry. Also, the inclined sheet positions, pre-Karoo faults and the connection line from dolerite D are shown. (b) Thickness plot of the underlying dolerite D. The position of this figure in the northernmost parts of Fig. 10A is indicated by the black block.

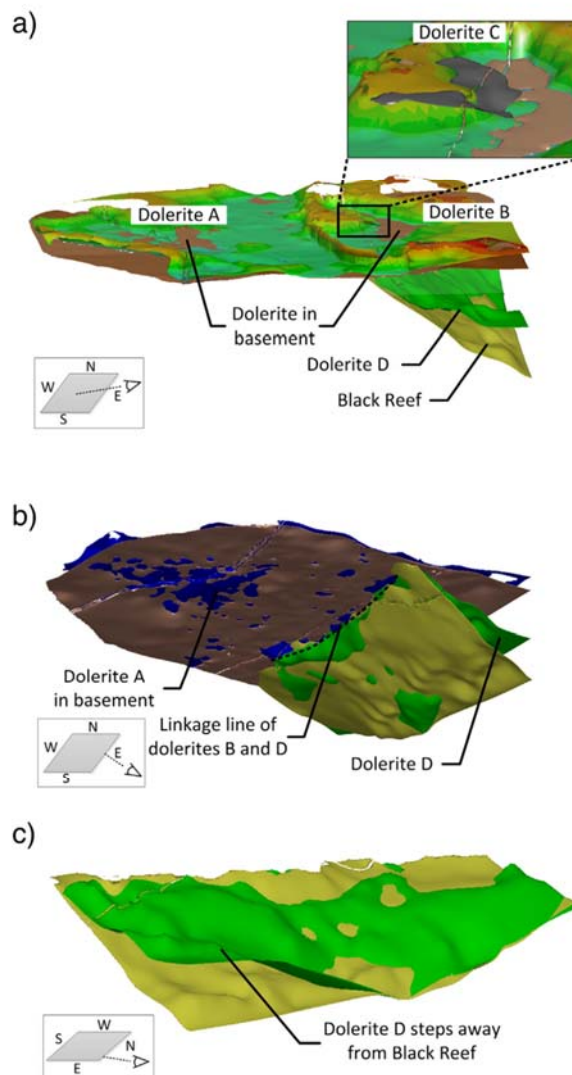


Fig. 11. Three-dimensional models of the number 8 sill using a vertical exaggeration of 5. (a) The positions where dolerites A and B enter the basement are indicated by the overlying Dwyka Group (brown). The relationship between dolerite D, the Transvaal-Ventersdorp Supergroup contact (Black Reef Formation) and the overlying dolerite B can be seen from the east. A zoomed in section illustrates the extent and relationship between dolerites C (grey) and B. (b) Dolerites A and B are shown in blue for better visibility together with the Dwyka Group in brown. Here the areas where the dolerites enter the basement are clearly seen below the Dwyka in relation to dolerite D and the black reef Formation sub-outcrop against the Dwyka Group. The connection (dashed line) between dolerites B and D describes an east–west trending curving plane that follows the sub-outcrop line of the Black Reef Formation. (c) Dolerite D (green) shows an upward step away from the Transvaal-Ventersdorp Supergroup contact (Black Reef Formation) and forms a structure that resembles a flat basin.

structures in the otherwise planar and flat-lying sill (Fig. 12). The upward protrusions range in amplitude from 40 to 130 m above the base of the inner sill with dome diameters ranging from 100's of meters to a maximum of 6 km (Fig. 8a). The smaller domes have round- to oval outlines with diameters from 200–500 m and appear to be concentrated near the somewhat irregular south-western inclined sheet of dolerite A (Fig. 12). These domes are typically bounded by near-vertical sheets that transgress the stratigraphy between 40 and 90 m before flattening within the C2 or C4 horizons (Fig. 6b).

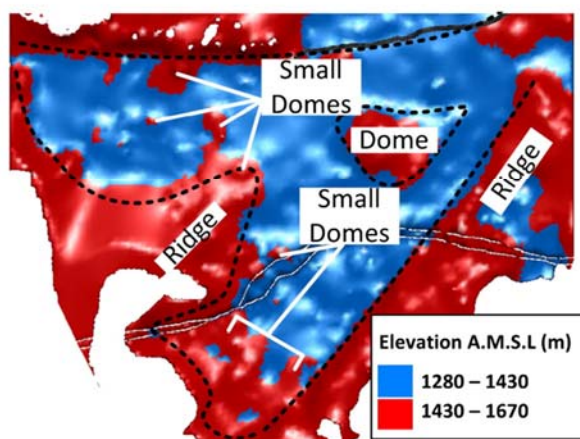


Fig. 12. Elevation contours of dolerite A illustrating the higher lying dome and ridge structures that occur along the inner sill (1400–1430 m) of dolerite A. Note the concentration of smaller domes near the south-western inclined sheet of dolerite A.

Conversely, larger, km-scale domes and ridges occur both within the inner sill and along the inclined sheets of dolerite A (Figs. 8a and 12). The centre of the inner sill is marked by a $4 \times 4 \times 4$ km triangular dome, which together with a 2×4 km ridge along the south-western inclined sheet, appears to separate dolerite A into a northern and a southern half. A further NE–SW trending ridge of 6×3 km occurs along the south-eastern inclined sheet of dolerite A and connects to adjacent saucers situated to the east. These structures are bounded by steeply ($40\text{--}60^\circ$) dipping dolerites that dip away from a central flatter portion that usually exploit the C4 or C5 coal seams (Fig. 6) some 60 to 130 m above the inner sill of dolerite A. Therefore, larger protrusions form ridge-like structures, in plan view, with considerably higher aspect ratios (ca. 45:1); compared to smaller, rather dome-like structures with aspect ratios of ca. 5.5:1.

The dome and ridge structures occurring within dolerite A are neither parallel to any regional pre-Karoo faults nor do they coincide with any appreciable loss or gain in dolerite thickness (Figs. 4 and 10a).

5. Discussion

The borehole and mining data set of the Secunda Complex can be used to demonstrate the geometries, connectivity and spatial relationships between dolerites B, C and D of the number 8 sill complex. Based on the 3D modelling data, the discussion aims to address (1) the saucer-feeder relationships of the number 8 sill, and (2) the formation of dome- and ridge structures within dolerite A, suggesting (3) a tentative emplacement model for the number 8 dolerite sill as a whole.

5.1. Saucer-feeder relationship

5.1.1. Dolerites B, C and D

Experimental models by Galland et al., (2009) and Galerne et al., (2011) suggest the geometry and location of a saucer to be directly related to the geometry of the underlying feeder. A pipe-like feeder will develop into a circular saucer, whereas a linear, dyke-like feeder will result in a more elongate or elliptical saucer. However, in natural systems, seismic data suggests that saucers are not necessarily underlain by and linked to vertical dykes, but are instead fed by vertically stacked sills and magma moving from one sill to the base of an overlying sill (Hansen and Cartwright, 2006; Thomson and Schofield, 2008). Subsequent emplacement of the saucer-shaped sills occurs by roof strata uplift and laccolith-like processes whereby magma, controlled by host rock anisotropies, spreads out- and upwards from the central feeder position (Galland

et al., 2009; Galerne et al., 2011; Malthe-Sørensen et al., 2004) initiating the formation of the inner sill. The incremental growth and inflation of the inner sill induces uplift of the overlying strata until the point of roof strata failure. Roof failure occurs along steep, inward-dipping, reverse faults at the margins of the inner sill from where the magma cuts up the stratigraphy to form the bounding inclined sheets. The resulting drop in magma pressure promotes subsequent magma emplacement along layer-parallel anisotropies giving rise to the overall saucer shape of inner and outer sills connected by transgressive, inclined sheets (Galland et al., 2009; Gouly and Schofield, 2008; Mathieu et al., 2008).

The stratigraphically lowest sheet of dolerite D in the number 8 sill complex is the most likely feeder of the overlying dolerite B in the Karoo strata that, in turn, connected to the smaller saucer of dolerite C (Fig. 11). This spatial relationship between dolerites B, C and D describes two orders of vertically stacked saucers (dolerites B and C) in the Karoo sequence. The saucers are underlain by and connected to a shallowly-dipping, sheet-like feeder (dolerite D) that is largely controlled along the Transvaal-Ventersdorp Supergroup contact in the basement rocks (Fig. 11b). The geometry and east-west strike of feeder dolerite D corresponds with the arched and elongated east-west-trending saucer geometry of the overlying dolerite B (Fig. 8a). This agrees with experimental results that indicate the shape of saucer-shaped intrusions to be primarily influenced by the geometry of their underlying feeders (Galland et al., 2009; Galerne et al., 2011). The spatial relationship between dolerites B and D not only provides strong evidence of magma transport through sill-feeding-sill networks (Cartwright and Hansen, 2006; Thomson and Schofield, 2008), but also illustrates that elongated saucers may develop from shallowly-dipping sheets through mainly lateral magma transport and without the presence of near-vertical feeder dykes.

The deflection of dolerite D into parallelism with the Dwyka Ecca Group contact to form the inner sill of dolerite B stresses the importance of lithological anisotropies and contacts in the Karoo sequence for the lateral propagation and growth of dolerite saucers. The near-vertical inclined sheets that bound the inner sill of dolerite B in the south and in the northwest are likely to have formed during the inflation and resulting roof strata failure around the inner sill. Some of these faults can be shown to cross-cut the entire stratigraphic sequence, whereas others form in a step-wise fashion consisting of bedding-parallel flat and cross-cutting steeper segments. It is particularly the weaker (low Young's modulus) coal seam horizons that seem to localize the formation of flat dolerite segments.

A similar mode of roof strata failure during the inflation of dolerite B is assumed for the formation of dolerite C in which the bounding inclined sheet propagates upwards in a step-wise manner. The flat outer sills are likely to have formed last during this process resulting from the renewed lateral propagation of the dolerite magma fed by inclined sheets and ponding beneath the stratigraphically higher number 4 dolerite sill. The overall out- and upward growth of the dolerite B and C saucers from the inner to the outer sill stage via interconnecting inclined sheets is in good agreement with experimental models of magma emplacement from a central feeder (Galland et al., 2009; Galerne et al., 2011; Malthe-Sørensen et al., 2004).

5.1.2. Dolerite A

Due to the limited depth extent of borehole data from basement rocks in the far south of the study area (Figs. 4, 6) an underlying feeder system to the larger dolerite A cannot be established with certainty. The east-west strike of the northern inclined sheet (Fig. 8b), the pronounced east-west thickness trends (Fig. 10a) and the deeper-seated zone of the inner sill all broadly coincide with the east-west strike and position of underlying pre-Karoo faults such as the Twistdraai and Sugarbush faults (Fig. 4). However, there are no recorded Karoo-aged intrusions in the Witwatersrand Supergroup and along these faults that could have represented the feeders of the overlying saucer.

Furthermore, neither the triangular shape, nor the dome structures of dolerite A conform to the expected geometry of an east-west trending elongated saucer that would have resulted from an underlying feeder sheet that exploited the older basement faults (Galerie et al., 2011). Despite this, the northern inclined sheet trends parallel to these faults and while there is no direct spatial correlation, the parallelism might indicate a control of pre-existing structures on the propagation and inflation of magma sheets in the Karoo Supergroup. Another possibility is that dolerite A was fed laterally and from, for example, an adjacent saucer within the Karoo stratigraphy. Two saucers that can serve as potential feeders are situated directly to the north (dolerite B) and to the east (eastern saucer) of dolerite A connecting along its respective northern and south-eastern inclined sheets (Fig. 8).

Dolerite B is in contact with dolerite A along the full extent of the northern inclined sheet. However, the steep southerly dip of the northern inclined sheet towards the inner sill of dolerite A (Figs. 6, 8) and the significantly higher thickness (15–27 m) of dolerite A compared to dolerite B (6–8 m) (Fig. 10a) implies that intruding magma most likely initiated doming and uplift of the strata above dolerite A independent of dolerite B. Therefore, dolerite B is excluded as a potential magma source to dolerite A. We suggest the saucers lying to the east and extending beyond the studied area to represent alternative and likely lateral feeders to dolerite A. The open-ended structure defined by a gap between the northern and south-eastern inclined sheets to the far east of dolerite A (Fig. 8a) is a narrow feature that links the inner sills of dolerite A and the eastern saucer along the Dwyka Ecca Group contact. This interface acts as a preferred emplacement horizon for the dolerites in the Secunda Complex and would have promoted and facilitated magma ingress into the inner sill of dolerite A from the east.

5.2. The significance of “dome and ridge structures”

The dome- and ridge structures along the inner sill of dolerite A (Figs. 5, 6b, 8) are unique structures that have not been documented elsewhere from dolerites in the Karoo Basin (Chevallier and Woodford, 1999; Galerie et al., 2011; Schofield, 2009). However, analogue experiments on the emplacement of saucer shaped intrusions by Galerie et al. (2011) have yielded very similar dome structures along the inner sill (Galerie et al., 2011, Fig. 7). In other words, dome-like protrusion along the inner sills of mafic saucers has now been documented from both analogue experiments and natural systems. This stresses the likely significance of these structures for our understanding of the emplacement of dolerite saucers. The following is an attempt to account for the formation of these dome-like features based on their occurrence and geometry in the inner sill part of dolerite A.

Magma lobes and fingers are a commonly observed feature in saucer-shaped sills interpreted to represent channels and conduits along the front of the propagating magmas that protrude outwards and ahead of the main magma sheet (Galerie et al., 2011; Hansen and Cartwright, 2006; Pollard et al., 1975; Rui et al., 2013; Schofield, 2009). Subsequent inflation and coalescence of the lobes eventually yields laterally continuous dolerite sheets. The original presence of these lobes and fingers is indicated by the preservation of distinct thickness variations in the form of tube-like structures and thicker ridges separated by thinner troughs in the otherwise planar dolerite sheets (e.g., Galerie et al., 2011; Hansen and Cartwright, 2006; Schofield, 2009). Although these tube-like thickness variations are not observed, the large domes and ridges in the flat parts of the inner sill of dolerite A and, in particular, the high concentration of smaller domes near the south-western inclined sheet (Fig. 12) may represent the vestiges of magma lobes and fingers that facilitated initial magma propagation. As with other documented examples of regional dolerite sills in the Karoo Basin (Chevallier and Woodford, 1999; Galerie et al., 2008; Galerie et al., 2011) dolerite A most likely developed from multiple

magma lobes and fingers propagating in a westerly direction from the lateral feeder at the open-ended structure.

A critical aspect of the suggested emplacement mechanism is the assumption that individual magma lobes and fingers propagating along the inner sill of a larger saucer can initiate overlying strata failure, similar to the process of roof strata failure and inclined sheet propagation above inner sill portions forming the eventual saucer geometries of many dolerite complexes (Chevallier and Woodford, 1999; Galerie et al., 2008; Galerie et al., 2011). The process of dome and ridge formation can be conceptualized in three successive steps. (Fig. 14):

1. Magma propagates laterally along the inner sill of dolerite A of what would become a larger saucer. Instabilities in the magma front initiate the formation of magma lobes propagating ahead of the main magma sheet, similar to processes suggested by, for example, Pollard et al., (1975). The inflation of individual lobes induces failure of the roof strata and results in the injection of magma into the faults to form steeply inclined, oppositely dipping sheets between adjacent lobes (Fig. 14a).
2. Further lobe propagation ahead of the main magma sheet leads to the lateral growth of the two inclined sheets promoting coalescence on the one side.
3. As two adjacent magma lobes expand towards each other and merge, the two inclined sheets also merge causing the steeply dipping sheets to close towards each other forming a circular or ring-like inclined sheet. Following this, the resulting drop in magma pressure at the tips of the ring-like inclined sheet favours horizontal, bedding-parallel propagation of magma thereby forming a closed dome structure with a flat lying roof.

The formation of more elongated ridge structures would involve a similar emplacement mechanism except that the two magma lobes will not coalesce to form the ring-like inclined sheet as shown in step 3 (Fig. 14). Instead, after step 2 (Fig. 14) the magma fingers diverge and propagate in different directions while continuing to feed the existing inclined sheets and the subsequent flat lying roof that define the ridge. We need to emphasize that this mechanism has not undergone a rigorous mechanical analysis and is merely an attempt at explaining the steeply dipping sheets that outline the central flatter portions of the dome and ridge structures.

5.3. Model of emplacement of the number 8 sill complex

5.3.1. Temporal relationship of dolerites A and B

Geometric modelling of the number 8 sill illustrates the spatial relationship of the four connected dolerite segments, namely the three saucers, dolerites A–C, underlain by a basement feeder, dolerite D. Dolerite D along the Transvaal Ventersdorp Supergroup contact has represented the most likely underlying basement feeder to the overlying dolerite B largely hosted by the Karoo Supergroup. Although there are only a few and widely spaced drill holes into the basement stratigraphy, the available information suggest dolerite D and the Transvaal Ventersdorp Supergroup contact are laterally continuous beyond the study area. Assuming the continuation of the Transvaal Ventersdorp Supergroup contact and, by inference, dolerite D further to the east, dolerite D underlies the eastern saucer proposed as the lateral feeder to dolerite A (Fig. 13). Furthermore, given the relationship between dolerites D and B, it is reasonable to assume a similar relationship existed for the eastern saucer whereby the basement feeder, dolerite D, fed into the base of the overlying eastern saucer. Therefore, this saucer-feeder relationship suggests dolerites A and B were independently fed from different locations by the same basement feeder, dolerite D (Fig. 15).

The distinct feeder locations in addition to the non-feeding contact between dolerites A and B indicate that these two dolerites intruded during separate events. Moreover, given that the northern inclined sheet formed through the doming of the strata above dolerite A and that dolerite B subsequently coalesced along this inclined sheet, dolerite

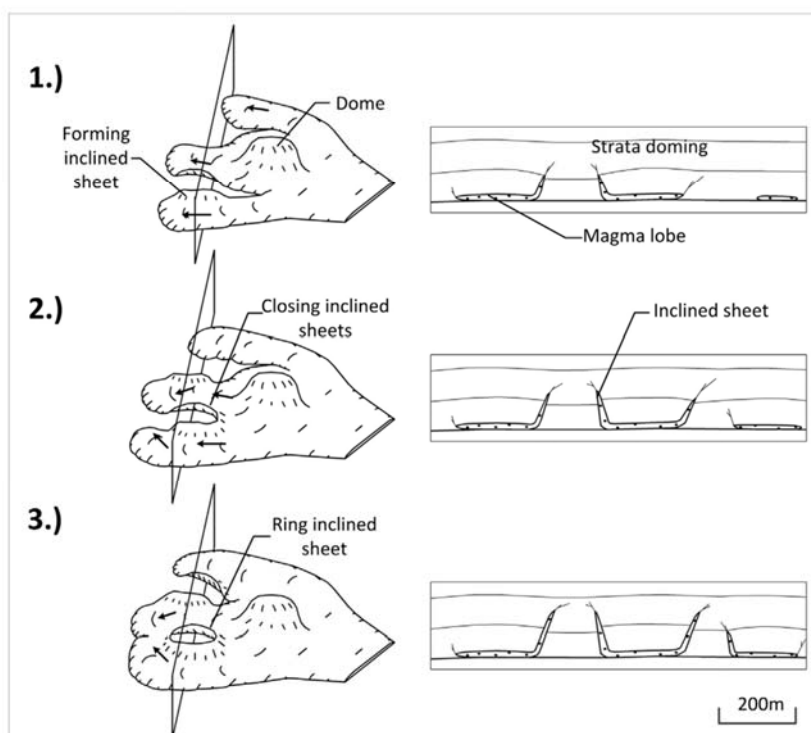


Fig. 13. Diagrammatic sketches illustrating the proposed stages in the development of domes along the inner sills of saucers, such as dolerite A. The arrows indicate magma movement during each stage (nr. 1–2). Cross-sectional views with the section lines are shown for each developmental stage with the magma propagation direction extending into the page. Refer to the text for more information.

A most likely intruded prior to dolerite B. This implies a diachronous propagation of magma along the length of dolerite D and the intersection of the magma front with the Karoo unconformity at different times from east to west as is commonly suggested for advancing sheets undergoing segmentation processes (Hansen and Cartwright, 2006; Pollard et al., 1975). This would, in turn, first have resulted in the formation of the eastern saucer and dolerite A followed later by dolerite B.

5.3.2. Emplacement mechanism

Given the emplacement sequence between dolerites A and B in addition to the feeder relationships and occurrence of lobate magma flow, a likely emplacement mechanism can be deduced for the rest of the number 8 sill in the Karoo stratigraphy. The position and orientation of the triangular dome- and ridge structure that separates the inner sill of dolerite A into two segments (Fig. 8a) may indicate that magma was diverted upon entry through the open-ended structure into two lobes, one moving in a western (lobe 1) and the other in a south-western (lobe 2) direction (Fig. 16).

The following steps are the proposed early stages of development of dolerites A and B (Fig. 16 – encircled numbers in Fig. 16 correspond to stages 1–5 described below):

1. Magma ascent through the basement occurs along dolerite D and enters the inner sill of dolerite A. From here, magma spreads laterally along the Karoo unconformity through the open-ended structure.
2. Instabilities along the propagating magma front create two directions of flow forming lobes 1 and 2. The magma advances laterally along the contact between the Dwyka and Ecca Group that subsequently is the locus of the inner sill of dolerite A.

3. Crystallization of magma along the wall-rock contacts around each magma lobe reduces the rate of lateral propagation and promotes inflation of the magma lobes. Subsequent doming triggers

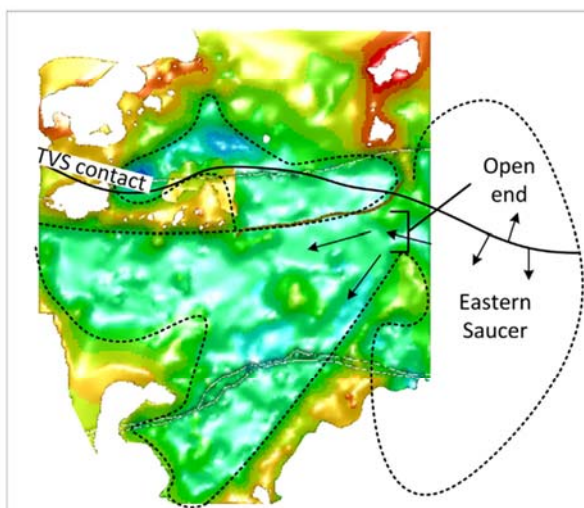


Fig. 14. Simplified map showing the projection of the Transvaal-Ventersdorp Supergroup (TVS) contact below the Karoo Supergroup together with the geometry and outlines of inner sills of dolerites A and B. The arrows indicate the envisaged direction of magma movement for the proposed lateral feeder system of dolerite A. Magma originates from the eastern saucer linked to an extension of dolerite D based on an extrapolation of the Transvaal Ventersdorp Supergroup contact.

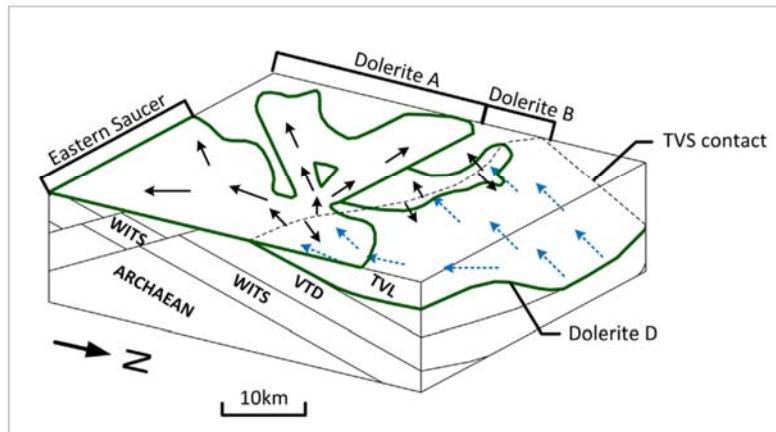


Fig. 15. Simplified block diagram is a simplistic illustration of the feeder relationships and proposed magma flow patterns between dolerites A and D as well as dolerites B and D viewed from the east looking west. The green lines on the upper plane (Karoo-basement contact) delineate the outlines of the inner sills of dolerites A and B in addition to the eastern saucer. The dashed lines and blue arrows indicate the features inside the block while the black arrows represent magma movement on the upper plane. Magma from dolerite D first feeds the eastern saucer and dolerite A followed later by dolerite B. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

strata failure above each lobe and initiates the formation of two separate sets of inclined sheets above each magma lobe. As a consequence, lobes 1 and 2 start forming the respective northern and south-eastern inclined sheets in addition to two steep inclines (red in Fig. 16) that will later define the triangular dome structure (Fig. 8).

At this stage, magma from the underlying dolerite D starts entering the basement-Karoo unconformity in what subsequently becomes the inner sill of dolerite B.

4. Magma break-out from the two lobes coalesces at the centre of the inner sill of dolerite A. This also leads to the coalescence of the steep, inclined sheets (blue in Fig. 14) creating the triangular outline of the dome.

At this stage, magma from the stratigraphically lower feeder of dolerite D intrudes further west and into dolerite B. The inner sill starts expanding north and southwards from the initial injection point by means of lobate magma flow, largely confined to the Dwyka Ecra Group contact.

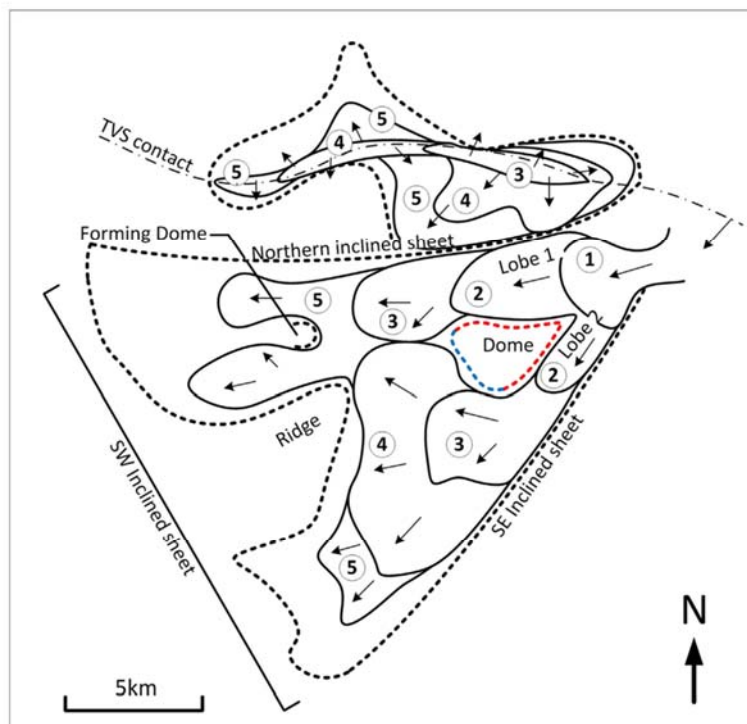


Fig. 16. Diagrammatic sketch showing the proposed stages (stages 1–5) in the early development of dolerite A and B. The arrows indicate the proposed direction of magma movement along each lobe from one stage to the next. The dashed lines indicate the outlines of the inner sills and areas of strata transgression that form the final inclined sheets and dome structures. Refer to the text for more information. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

5. The movement of magma away from the centre towards the west initiates another set of steep inclines that outline the shape of the ridge structure along the south-western inclined sheet. Following this, the formation of smaller magma fingers during the lateral propagation of the main magma sheet result in the formation of the small domes near the south-western inclined sheet.

Magma continues to intrude further westward along the Karoo basement contact, feeding dolerite B and causing the inner sill to grow laterally. In the east the inner sill of dolerite B terminates against the northern inclined sheet of dolerite A that formed earlier.

There are several key questions remaining. This includes the reasons for the sharp increase in thicknesses to the south of dolerite A (Fig. 10a) and the cause for the inner sill of dolerite A to intrude downwards from the Dwyka Ecca Group contact into the basement strata (Fig. 11a) during a lateral emplacement process. This model emphasizes the role of lobate magma flow for the propagation and emplacement of saucer-shaped Karoo dolerites. It also highlights gaps or uncertainties in our understanding of the emplacement processes and the need for more intricate experimental and theoretical work but also field-based 3D studies of complex emplacement geometries and their contacts to better understand the emplacement controls of low viscosity intrusions in sedimentary basins.

6. Conclusions

The following conclusions can be drawn from cross-section and modelling analyses on the relationships between saucer-shaped sills and their feeders in the Secunda Complex:

1. The study has shown that although dolerites constituting the large number 8 sill are in contact with each other, these contacts do not necessarily represent feeding connections. The connections between dolerites B–C and D represent a sill-feeding-sill relationship and display similarities to those described by Cartwright and Hansen (2006) and Thomson and Schofield (2008) whereby one saucer feeds into the base of an overlying saucer creating a vertically stacked sill network. Furthermore, it seems likely that dolerite A and B were fed from separate points along dolerite D leading to a split level sill complex that subsequently coalesced within the Karoo Supergroup stratigraphy.
2. The feeder positions and dolerite geometries suggest a lateral emplacement process and inflation by roof uplift for dolerite A and B respectively. Magma moved exclusively from east to the west along the inner sill of dolerite A, in contrast to magma flowing out- and upwards from the centre of the inner sill of dolerite B.
3. Dolerites A and B describe two unique geometries, namely a triangular and an elongated saucer. The geometry of dolerite B has a remarkably similar trend to the position and linear shape of dolerite D along the sub-outcrop of the Transvaal-Ventersdorp Supergroup. In contrast, the geometry of dolerite A shows no direct relation to dolerite D and the adjacent saucers that facilitated magma ingress. These relationships only partly support the findings of analogue models (Galland et al., 2009; Galerne et al., 2011) that show a strong geometric and spatial dependency of saucers to their underlying feeders.
4. The stratigraphic controls of the number 8 sill along the Transvaal Ventersdorp Supergroup and Dwyka-Ecca Group contacts underline the significance of lithological interfaces or regional unconformities for the emplacement and lateral propagation of magma. Furthermore, weak layers, in particular the coal seam horizons, were influential in facilitating lateral movement of magma during its upward ascent through the Karoo Supergroup.
5. Lobate magma flow that initiates localised roof strata failure is invoked as a likely emplacement mechanism to explain the occurrence of intrusive dome- and ridge structures along the inner sill of dolerite A. Magma lobes, propagating in different directions ahead of the main magma sheet, undergo successive episodes of lobe arrest and inflation, which induce strata uplift and failure manifested as steep 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. However, the theoretical emplacement model whereby individual lobes simultaneously form flat inner sills together with steeply inclined sheets is mechanically problematic.
6. The application and use of strata modelling software when integrating very large and diverse 3D data sets is crucial for the visualization of complex dolerite geometries.

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Chapter 4: Dyke-saucer relationships

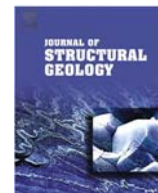
This chapter constitutes a presentation of the submitted research paper: *Dyke-saucer relationships in Karoo dolerites as indicators of propagation and emplacement processes of mafic magmas in the shallow crust*¹ by Coetzee and Kisters.

This paper was first authored by André Coetzee with standard supervision entailing academic guidance and editorial support from Alex Kisters. The following aspects were carried out independently by André Coetzee: (1) mining and drilling data collection, (2) data consolidation, processing and interpretation, (3) 3D modelling and interpretation, (4) preparation and submission of the manuscript.

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Dyke-saucer relationships in Karoo dolerites as indicators of propagation and emplacement processes of mafic magmas in the shallow crust

André Coetzee^a, Alexander Kisters^a^a Department of Earth Sciences, University of Stellenbosch, Private Bag XI, Stellenbosch 7602, South Africa

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Dyke patterns

ABSTRACT

This paper describes the spatial and temporal relationships between Karoo-age (ca. 180 Ma) dolerite dykes and a regional-scale saucer-sill complex from the Secunda (coal mine) Complex in the northeastern parts of the Karoo Basin of South Africa. Unlike parallel dyke swarms of regional extensional settings, mafic dykes commonly show curved geometries and highly variable orientations, short strike extents and complex cross-cutting and intersecting relationships. Importantly, the dyke networks originate from the upper contacts of the first-order dolerite sill-saucer structure and are not the feeders of the saucer complex. Cross-cutting relationships indicate the largely contemporaneous formation of dykes and the inner sill and inclined sheets of the underlying saucer. Systematic dykes form a distinct boxwork-type pattern of two high-angle, interconnected dyke sets. The formation and orientation of this dyke set is related to the stretch of roof strata above elongated magma lobes that facilitated the propagation of the inner sill. Other dykes form more irregular dyke patterns related to the multidirectional stretch of roof strata above the inner sill, similar to the “cracked lid” model described for large saucer complexes in Antarctica. Dyke patterns generally reflect the saucer emplacement process and the associated deformation of wall rocks rather than far-field regional stresses.

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1. Introduction

Mafic dykes typically form part of larger, regional-scale (>100–1000 km strike length) parallel or radial dyke swarms that accommodate the transfer of mantle derived magmas through the continental crust, mainly during periods of lithospheric stretching, thinning and associated mantle upwelling (Ernst and Buchan, 2003; Hastie et al., 2014; Saunders et al., 2007). Dyke propagation is commonly inferred to occur normal to the least compressive stress (σ_3 , with $\sigma_1 \geq \sigma_2 \geq \sigma_3$) so that the orientation of dykes and dyke swarms is widely used to infer paleo-stress directions during dyke emplacement. The consistent orientation of dyke swarms over large distances underlines the controls of regional, far-field stresses for the emplacement of parallel dykes swarms, in particular (Le Gall et al., 2005; Hastie et al., 2014).

Dolerite dykes in the Karoo Basin of South Africa are considered part of the primary plumbing system that facilitated the ascent of the mantle-derived magmas for the Drakensberg flood basalts, heralding the break-up of Gondwana during the Jurassic (ca. 180 Ma) in this part of southern Africa (Cox, 1992; Duncan et al., 1997; Svensen et al., 2012). Karoo dykes generally form tabular, up to tens of meters wide intrusive bodies with variable strike lengths, but

high aspect ratios typical for the low viscosity mafic magmas. Regional dyke swarms such as the Okavango Dyke Swarm or dykes of the Lebombo Monocline are developed in the north-eastern parts of the Karoo Igneous Province (Le Gall et al., 2005; Klausen, 2009; Hastie et al., 2014). For the most part, however, Karoo dykes show variable orientations, even over short lateral distances. Cross-cutting and intersecting relationships are complex and very unlike the parallel dyke swarms found in extensional settings and continental interiors. Notably, most Karoo dykes and dyke networks are spatially closely associated with kilometre-scale sill- or saucer complexes (Chevallier and Woodford, 1999; Duncan et al., 1997; Galerne et al., 2008). These saucer complexes consist of stacked, interconnected inner and outer sills connected by transgressive, inclined sheets. The abundance and sheer size of these saucer structures indicate a significant component of lateral magma transfer at and close to the emplacement level in the Karoo stratigraphy (Chevallier and Woodford, 1999; Coetzee and Kisters, 2016).

Similar, highly irregular dyke patterns from the Ferrar Large Igneous Province in Antarctica have recently been ascribed to local extension and failure of roof rocks above large-scale saucer structures (Muirhead et al., 2012, 2014). These intricate saucer-

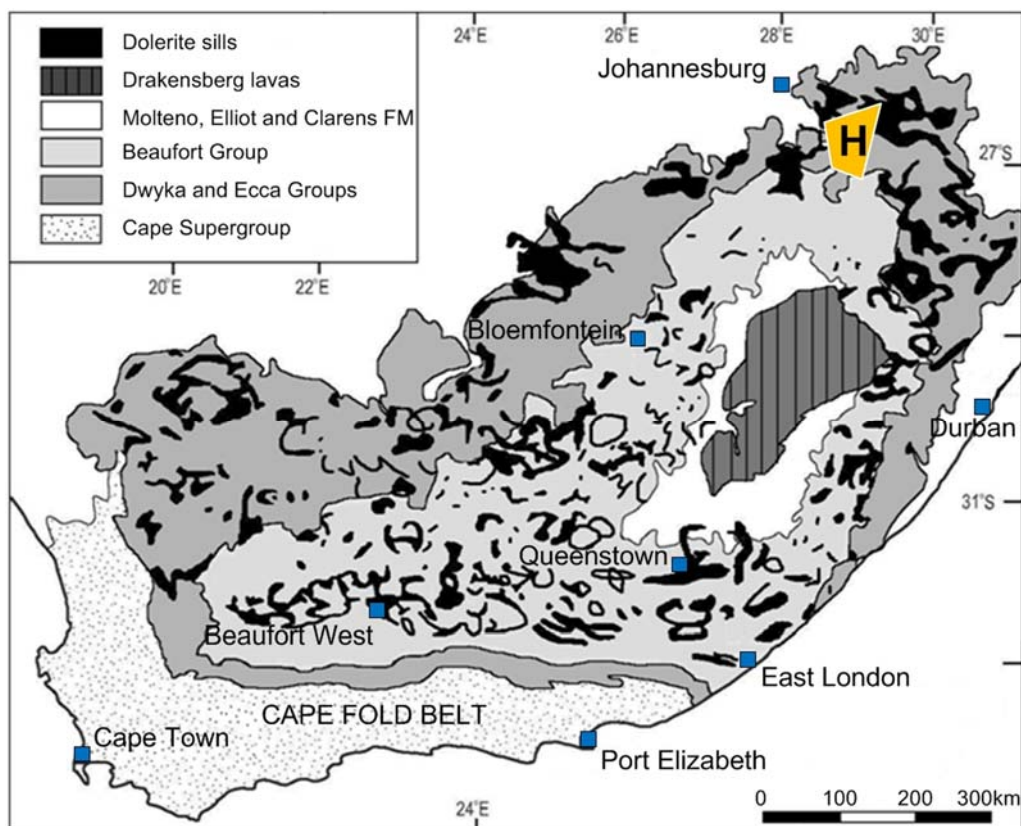


Fig. 1. A geological map of the main Karoo Basin showing the distribution of Karoo sediments and dolerite saucers (solid black) (modified from Galeme et al., 2008 and Jeffrey, 2005). The Highveld Coalfield (H) is located in the north-eastern parts of the Karoo basin.

dyke relationships highlight the complexity of magma transfer and feeding relationships of mafic magma systems in the upper crust.

The seemingly random and unpredictable occurrence and orientation of dykes also pose serious challenges for the large coal mining operations in the north-western parts of the Karoo basin. Dykes, in particular, cross cut and often displace the coal seams and devolatilise or burn the surrounding coal. This not only reduces the structural integrity of the rock, but also increases the joint density and the occurrence of methane pockets, all contributing factors to potential fall-of-ground or gas ignition incidents during mining (Du Plessis, 2008). All this requires a more profound understanding of dyke emplacement and the controls of dyke intrusion that was evidently largely independent of regional tectonic stresses during or prior to continental break up and associated Karoo volcanism.

This paper presents evidence on the spatial and inferred temporal relationship of saucer-shaped sills and overlying dykes based on drill hole data and underground mining from the Secunda Complex of the Highveld Coalfield in the north-eastern parts of the Karoo Basin of South Africa (Fig. 1). We have analysed the distribution and intrusive relationships of dolerite dykes over an area of some 500 km² covered by Brandspruit and Middelbult collieries. The extensive 3D data set of drill hole information combined with underground developments from gold and coal mining operations offer a unique view into the occurrence of dolerite dykes in the Karoo stratigraphy that would otherwise not be available from outcrop studies. Dykes in the Secunda Complex show curved geometries, short strike lengths, varying orientations and a particular interconnected pattern that do not seem to conform to our

classic view of vertical, planar intrusions with large strike lengths and relatively consistent orientations. This study focuses on describing the geometry, orientations and connectivity of dykes with the specific aim of understanding the origin of the complex dyke patterns, also in relation to the regional-scale sill complexes in the area.

2. Geological Setting

The northern extent of the main Karoo Basin consists of a ca. 200m thick, subhorizontal sedimentary sequence deposited onto a basement unconformity during the late Carboniferous to early Permian. The Karoo Supergroup is characterised by the basal Dwyka and overlying Ecca Group with coal seams largely confined to the Vryheid Formation of the Ecca Group (Fig. 1, 2). Sub-outcropping basement rocks trend east-west, with dips of ca. 15° to the north. Basement strata include, from north to south, rocks of the Transvaal (ca. 2.64-2.2 Ga), Ventersdorp (ca. 2.7 Ga) and Witwatersrand (ca. 2.98-2.7 Ga) Supergroups (Evander Basin), all underlain by Meso-Archaeon (>3.1 Ga) TTG gneisses and plutons. The basement structure of the Evander Basin is complicated by predominantly northwest-southeast trending reverse faults and east-west striking normal faults exploited by several pre-Ventersdorp (>2.7Ga) diabase dykes and sills.

The Karoo magmatism towards the end of the Karoo sedimentation resulted in the emplacement of a vast network of interconnected saucer complexes and dykes throughout the sedimentary sequences of the Karoo Basin (Duncan et al., 1997). This close spatial

relationship between dolerite dykes and regional-scale saucer complexes is well developed in the Secunda Complex of the Highveld Coalfield (Fig. 3a), details of which will be discussed further below. Post-Karoo normal faults in the region include the east-west trending Secunda Graben and Witkleifontein fault that displace the dolerite intrusives and Karoo stratigraphy by a maximum of 53m and 20m, respectively (Fig 3a).

3. Dolerite intrusions

3.1 Spatial Data

The Brandspruit and Middelbult collieries in the Secunda Complex mine and develop along the largely horizontal number 4 (C4) coal seam of the Vryheid Formation at depths between 80 and 150m. The collieries are underlain by gold mining operations that exploit the Kimberley reef of the Neo-Archaean Central Rand Group at depths between 200 m and 3.5 km. The extent of the Kimberley reef is limited to the northern half of the study block and is largely mined out across the region. Current underground development along the C4 horizon covers about 50 percent of the total study area (Fig. 3b). Dykes are mainly located by means of in-seam drilling from existing underground operations and typically cover distances up to 1000 m ahead of mining. Additionally, surface-based directional drilling is performed for longer term mine planning by exploring several kilometres ahead of primary mining developments (Fig. 3b). Dykes beyond the mined-out and drilled areas are typically extrapolations from known positions or interpretations from aeromagnetic surveys. Taken in conjunction, the coal and gold mining operations offer an unique, up to 3.5 km vertical section from the Witwatersrand into the Karoo Supergroup documenting the distribution, geometry and connectivity of Karoo-aged dolerite intrusions.

3.2 Dolerite Petrography

Different generations of Karoo dolerites can be distinguished mainly on textural grounds. Most dolerites are fine grained and dark-green to grey in colour made up of plagioclase and augite, as the main constituents, together with variable amounts of either olivine or quartz, alkali feldspar and opaque minerals. Secondary phases include mainly chlorite and muscovite and carbonate. Many dolerites have a porphyritic texture defined by lath-like plagioclase phenocrysts with little or no preferred orientation. Plagioclase phenocrysts vary in abundance and dolerites may also contain only few or no phenocrysts. This is an important criterion in the distinction of dolerites in underground exposure or in borehole core. Dyke contacts against wall rocks are sharp and steep to vertical. Chilled margins are well-developed and often associated with higher concentrations of plagioclase phenocrysts. Sandstone and siltstone of the wall rocks are commonly baked to a pale-grey colour and friable texture that very easily disintegrates in wet conditions. Also, dense joint sets as well as calcite and pyrite veins frequently occur on both sides of dyke contacts.

3.3 Spatial and temporal relations of dolerite geometries

The largest dolerite structures in the Brandspruit and Middelbult collieries are flat-lying, largely concordant, but locally discordant and stepping saucer-like structures that are similarly described from elsewhere in the Karoo Basin (Chevallier and Woodford, 1999;

Galerie et al., 2008). These saucers form geometrically complex and partly interconnected first-order dolerite structures that underlie areas of up to 170 km² (Coetzee and Kisters, 2016). Sharply discordant, steeply inclined dolerite dykes are common, but are typically much smaller compared to the saucers structures. Based on their occurrence and size, regional dykes can be distinguished from more local dykes. Dykes show a close spatial and also temporal association with the regional saucer structures, so that we provide a brief description of the saucers first, followed by the more detailed characterisation of dykes.

3.4 Dolerite Saucers

The main saucer complexes in the Secunda Complex are referred to as the number 4, 7 and 8 sills in the local mining terminology (Coetzee and Kisters, 2016) (Fig. 2, 3a, 4a). The term “sill” emphasizes the generally flat lying, concordant to sub-concordant attitude of the dolerites, but the geometries are more complex. The first-order, composite sill complexes typically comprise a number of interconnected saucer-shaped dolerite sheets that consist of a central inner sill, an inclined sheet and a flat outer sill. In the following, we focus on dyke-saucer geometries related to the very large number 8 sill.

Throughout its extent, the number 8 sill is characterized by a uniformly developed fine grained, dark green and plagioclase porphyritic texture. The composition and textures of the number 8 sill are similar to those of dolerite dykes in the area. In detail, the number 8 sill complex consists of three saucer-shaped intrusions that mainly occur within the Karoo Supergroup, namely dolerite A, B and C (Fig. 4a, b). These saucers are underlain and fed by a shallowly dipping sheet confined to the basement rocks of the Transvaal and Ventersdorp Supergroups, locally referred to as dolerite D (Fig. 3a, 4a). For better clarity and in order to minimize the potential effects that overlapping or adjacent saucers may have on dyke emplacement, the following descriptions of dyke-saucer relationships focus exclusively on dykes associated with the saucer of dolerite A (Fig. 3a, 4b). The discussion will be extended to include other dyke-saucer relationships in the region.

Dolerite A defines a triangular saucer with a diameter of some 18 km in its central parts. The central inner sill occurs primarily along the subhorizontal Dwyka-Ecca Group contact (Fig. 2, Fig. 4b). The inner sill is not developed as a smooth and flat, bedding-parallel sheet, but contains a number of elongate dome- or ridge-like structures that are the result of upward steps of the dolerite across the stratigraphy. These ridges reach amplitudes of some 130 m above the inner sill with lengths ranging from 100's of meters to several kilometres (Fig. 3a, 4b). The formation of these ridges relates to the propagation of the inner sill as magma lobes ahead of the main magma sheet (e.g. Galerie et al., 2011; Hansen & Cartwright, 2006; Pollard et al., 1975; Rui et al., 2013; Schofield, 2009). Magma propagation along these lobes is episodic, characterised by the successive arrest and renewed inflation of the lobes that eventually coalesce to form the inner sill. The inner sill of dolerite A is bounded by steep, near-vertical inclined sheets, both to the north and south-east, with a shallowly dipping inclined sheet in the south-west (Fig. 3a, 4b). The gap between the northern and south-eastern inclined sheets creates an ‘open-end’ structure, which connects dolerite A to adjacent saucers situated to the far east (Fig. 3a). The three inclined sheets connect to stratigraphically higher,

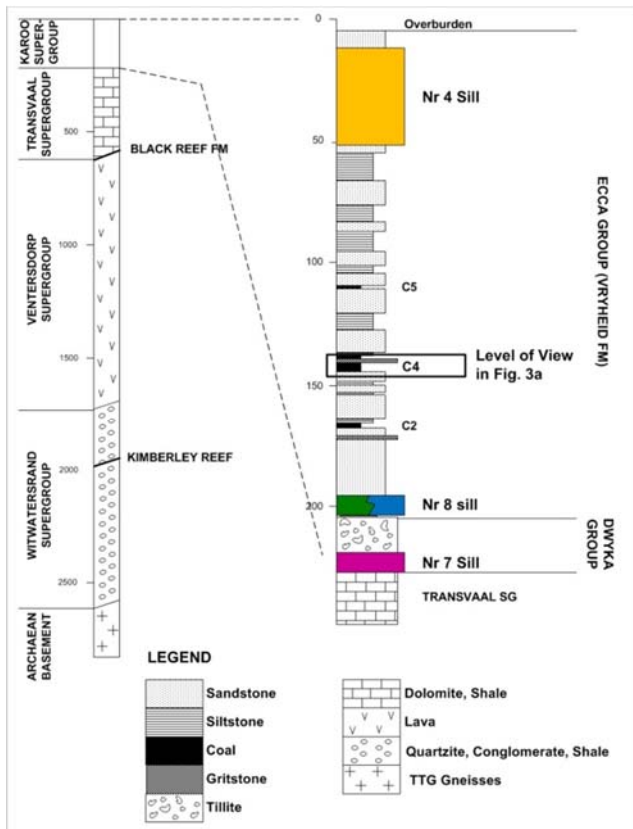


Fig. 2. Generalised stratigraphic column of the area indicating the positions of important lithostratigraphic units such as the Kimberly reef in the Witwatersrand Supergroup and the C4 coal seam in the Karoo Supergroup in relation to depth (m). The common intrusion levels of the three main dolerite sills (numbers 4, 7, and 8) in the Karoo Supergroup are also shown in the same colours as in figure 3a. Note the stratigraphic level viewed in figure 3a.

flatlying outer sills that, for the most part, are preserved near the present-day surface and some 180m above the inner sill (Fig. 4a, b). This geometry of an inner sill, bounded by inclined transgressive sheets connected to upper sills forms the characteristic saucer structure of Karoo dolerites (e.g., Chevallier and Woodford, 1999). A more detailed account of the geometry and controls of the saucer structures can be found in Coetzee and Kisters (2016).

3.5 Dolerite dykes associated with dolerite A

We will first give an account of the dyke patterns immediately overlying the dolerite A saucer (Fig. 3a, 4b). Dykes in the Secunda Complex can be grouped into systematic and other dykes based on their orientation, occurrence and intersecting or cross-cutting relationships amongst each other, but also with respect to the inner sill and inclined sheet of the dolerite A saucer.

3.5.1 Systematic dykes

The majority of dykes overlying dolerite A are systematic dykes with a more regular spacing and preferred orientations compared to other dykes. Systematic dykes describe a characteristic boxwork-type pattern that consists of two orders of high-angle, interconnected dykes (Fig. 3a). Major dykes can be distinguished

from minor dykes in this dyke network (Fig. 5a, b). Major dykes show strike lengths of 6 – 11 km and widths of 4-5 m. In places, major dykes consist of two or three closely spaced (< 50 m) dykes trending parallel for several kilometres before merging into one coeval dyke (Fig. 5a). Major dykes show systematic variations in their orientation and commonly curved trajectories (Fig. 5b). Easterly trending major dykes are developed in the north (Fig. 3a), confined to a ca. 4x10 km corridor, subparallel to the respective northern inclined sheet of the dolerite A saucer (Fig. 5a). In contrast, major dykes show north-easterly trends in the south (Fig. 3a), subparallel to the southeastern inclined sheet of dolerite A. The two sets of major dykes converge towards the east near the “open-end” structure which connects dolerite A to adjacent saucers situated to the far east (Fig. 3a). This results in an overall fan-like geometry of major dykes that closely follows the outline of the inner sill and bounding inclined sheets of the first-order dolerite A saucer.

Minor dykes show strike lengths of 0.7 – 2 km and widths of 0.5 – 2m, spaced at intervals of between 600 m to 1.6 km. The dykes terminate abruptly and mostly at right angles against major dykes without forming any cross-cutting contacts (Fig. 3a, 4a, b). In numerous cases, the right-angle terminations are achieved by the systematic reorientation of minor dykes normal to the strike of major dykes within 100 - 500 m of the contacts between the two dyke sets (Fig. 5a). There is neither a bulging nor deflection of minor dykes near these terminations that would indicate the ponding of the mafic magmas or dyke deflection along these contacts. This pattern of longer major dykes and interconnecting high-angle minor dykes forms the characteristic boxwork-type geometry of systematic dykes. In this pattern, minor dykes may also consist of not one, but several shorter interconnected dyke segments (Fig. 5a). Also, many of these minor dykes can be seen to link at one end to a major dyke, while the other end tapers out seemingly failing to connect to the next major dyke (Fig. 5a).

Both major and minor dykes originate from the top of the inner sill of dolerite A and the dykes do not extend below the inner sill of the dolerite A saucer. Karoo-age dykes are also virtually absent from the Witwatersrand strata below the Karoo Supergroup, consistent with the notion that the dykes are rooted in the underlying dolerite A saucer. Similarly, all major and minor dykes terminate laterally along the inside of the inclined sheets of dolerite A and cannot be observed to cross-cut the inclined sheets (Fig. 3a, 4b).

3.5.2 Other dykes

The occurrence of other dykes is more sporadic compared to systematic dykes. Other dykes do not seem to define any preferred orientations and cross-cutting relationships between different dyke sets are inconsistent. Based on cross-cutting relationships, three main other dyke sets can be distinguished including regional dykes, as well as more locally developed dykes, henceforth referred to as protruding and oblique dykes.

Regional dykes include four gently curving dykes that can be traced for over 20 km along strike, showing thicknesses of 2 to 8m (Fig. 3a). These dykes occur across the area in variable orientations, such as north-south, north-east and east-southeast. The north-south trending dykes, in particular, display sharply cross-cutting relationships with the dolerite A saucer.

Protruding dykes include shorter, 1 to 7 km long dykes that originate and protrude outwards from the outer margin of the inclined sheet of the dolerite A saucer without any underlying sill

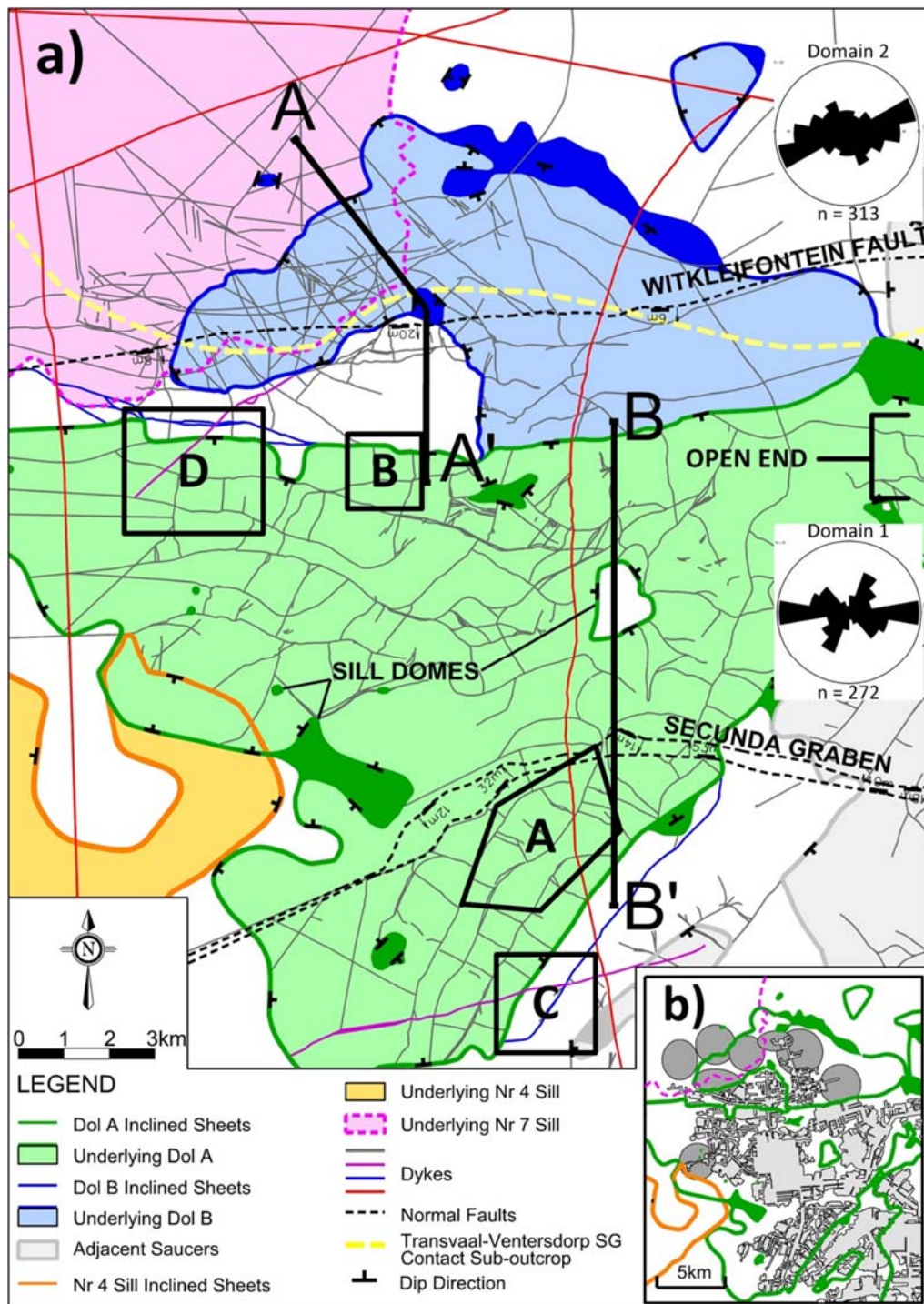


Fig. 3. (a) Geological map of the study area within the larger Secunda Complex projected to the level of the C4 seam, some 80 - 150 m below surface (see figure 2). The indicated structures illustrate the intersection of inclined sheets (lines) and sills (solid) in addition to dykes and normal faults with the C4 seam as encountered during mining or interpreted from drilling information. The underlying extent of each of the saucers is indicated by the shaded colours (blue, green, etc.) within the inclined sheets or outer limits of the underlying sill (pink broken line around number 7 sill). Therefore, the areas with no shading represent zones where no underlying sill occurs within the Karoo Supergroup. The sub-outcrop line of the Transvaal-Ventersdorp Supergroup contact (yellow) designates the line along which dolerite D links with the base of dolerite B. Dykes are indicated in grey with the exception of special dykes, such as regional (red), protruding (blue) and oblique (purple) dykes. The rose diagrams illustrate the dyke orientations overlying dolerite A (domain 1) and the area to the north mostly overlying dolerite B (domain 2). The cross-sections A-A' and B-B' are shown in figure 4. The demarcated zones A, B, C and D are the areas presented in figure 5. (b) The diagram visually illustrates where in-seam geological information is available either from actual mining developments or directional drilling. These areas marked in grey are where dyke properties and geometries are established with certainty. The dykes outside these zones are either interpretations from aeromagnetic data or extrapolations from known positions.

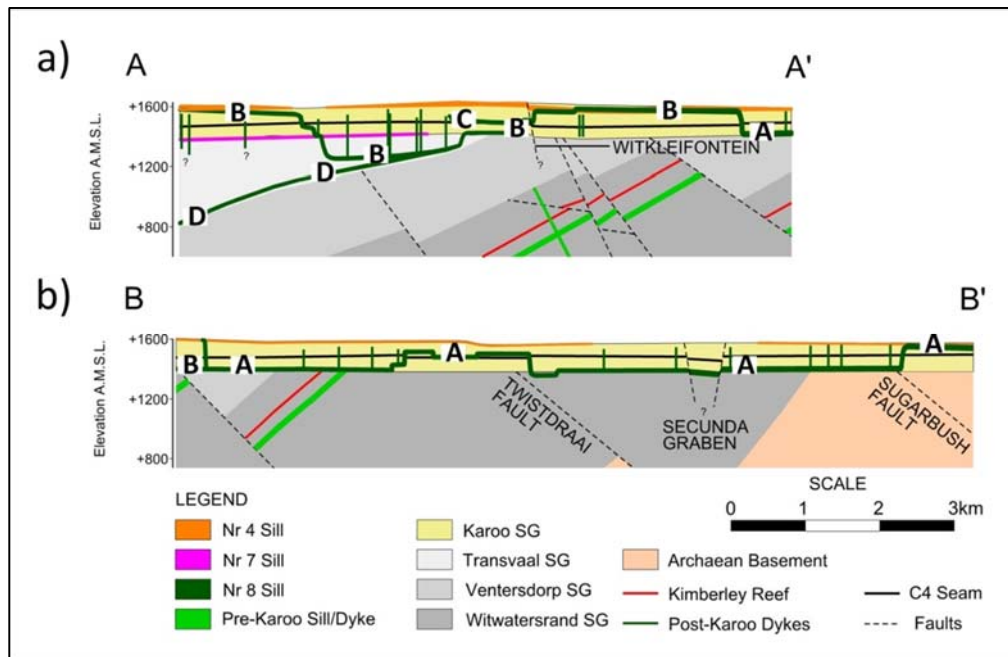


Fig. 4. Stratigraphic cross-sections along north-south section lines indicated on Figure 3a, with a vertical exaggeration factor of 2. a) Cross-section A-A' showing the relationship of dolerites B – D and the number 7 sill in both the Karoo and basement stratigraphy. The roots of the overlying dykes are unclear due to the many overlapping sills in the area. b) Cross-section B-B' illustrates the occurrence of the first order dolerite A saucer mainly along the Dwyka-Ecca Group contact forming an isolated dome structure at its centre. The overlying dykes are all rooted in the underlying inner sill.

(Fig. 3a, 4c). From the borehole data it is not evident whether these dykes are connected at their upper ends to the overlying outer sills of dolerite A (Fig. 5c). Protruding dykes are 2 – 3 m wide and have east-west and north-easterly strikes along the respective northern and south-eastern inclined sheets (Fig. 3a, 4c). The dykes originate at high angles to the respective inclined sheet they are connected to, but rotate into parallelism with the inclined sheets within some 300-500m (Fig. 5c) or by linking to sharp bends in the inclined sheets (Fig. 3a).

In contrast to the protruding dykes, oblique dykes not only occur outside the confines of dolerite A, but also cross-cut the inclined sheets and extend into the saucer. Oblique dykes, some 4 m thick, are found along the far west and south-western extents of dolerite A and cross-cut the respective northern and south-eastern inclined sheets at high angles (Fig. 3a, 4c, d).

3.6 Cross-cutting and temporal relationships between intrusions

The cross-cutting relationships and terminations observed between the different dyke sets and dolerite A provide insight into the relative timing of their emplacement. The most characteristic features of the dyke networks analysed here are the abrupt terminations of commonly high-angle dyke sets against each other and the curved traces of dykes resulting from the rotation of dykes to near-orthogonal orientations along dyke intersections or contacts (Fig. 5a,c). These features are particularly prominent in the systematic dyke sets where minor dykes connect at high angle to major dykes, forming the characteristic boxwork-type dyke pattern. Actual cross-cutting relationships in the systematic dyke sets are conspicuous by their absence. These spatial relationship between major and minor dykes closely resemble the geometry of joint patterns where shorter cross joints extend in the intervals between

and connect to larger systematic joints (e.g., Dyer, 1988; Engelder and Gross, 1993; Gross 1993). The curvature of minor dykes and their commonly right-angle terminations against major dykes reflects perturbations of the local stress field around the latter (e.g., Dyer, 1988). This implies the intrusion of major dykes prior to the emplacement of minor dykes. However, the sharp terminations and lack of cross-cutting relationships suggest that the two sets were interconnected and broadly formed at the same time, although in succession and before major dykes had fully crystallized.

Similarly, both major and minor dykes terminate against the inclined sheets of the dolerite A saucer which indicates an earlier emplacement of the inclined sheets. However, the lack of cross-cutting contacts or deflections of systematic dykes against the inclined sheets of dolerite A further indicates the broadly contemporaneous emplacement of the dykes and the bounding inclined sheet.

In contrast, regional dykes are commonly intersected by systematic dykes. There is a notable exception where one major dyke terminate against the north-south regional dyke at the centre of dolerite A saucer (Fig. 3a, 4a). Also, regional dykes have a tendency to cross-cut the inclined sheets of the dolerite A saucer.

The majority of oblique dykes cross-cut both the regional dykes and also systematic dykes. However, an oblique dyke to the north of dolerite A terminates abruptly against one of the systematic dykes (Fig. 5d), therefore indicating a later intrusion period for these dykes. Protruding dykes also tend to cross-cut the regional dykes (Fig. 3a). The origin and linking relationship of protruding dykes with the main inclined sheets also suggests the broadly coeval timing between the two, but with protruding dykes shortly following the emplacement of the inclined sheets.

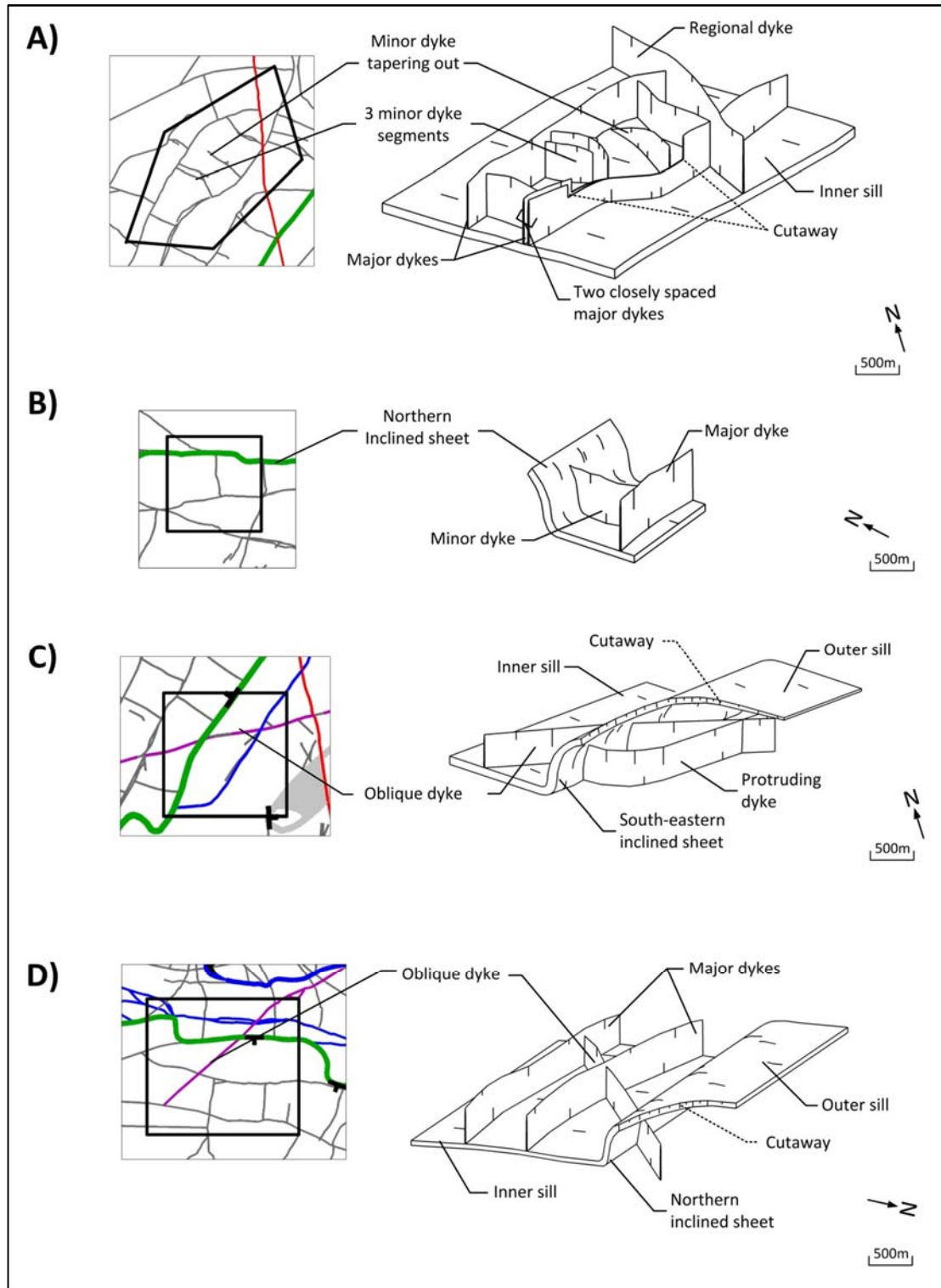


Fig. 5. Three-dimensional diagrams of the different dyke-saucer interrelationships along zones A, B, C and D as shown in figure 3a. Refer to the text for more information.

In summary, cross-cutting relationships allow a general sequence of saucer and dyke emplacement to be established. Emplacement of the inner sill of dolerite A was followed in close succession by the regional dykes, systematic dykes (major and then minor dykes) and later the inclined sheets. Subsequent to the inclined sheets were the

protruding dykes and later the oblique dykes. Importantly, the characteristic sharp terminations of dyke sets against each other and/or the inclined sheets point to the broadly contemporaneous emplacement of dykes during saucer formation and before full crystallization of individual dyke sets. This also indicates that

different dolerite geometries of the first-order saucer, systematic and other dykes were, for the most part, interconnected.

3.7 Wall-rock displacement along dykes

Several dykes across the area are associated with displacement of the host strata by a few meters along one side of the dyke (Fig. 6). The type of displacement, i.e. normal or reverse, could not be established with certainty due to the near-vertical dip of most dykes. Larger displacements of some 3 to 6 m are characteristic of the thicker regional dykes with throws to the south-west, north-west and west. Measurable displacement of strata along a select few systematic dykes is between 0.5 and 2 m with throws in a north-easterly and south-easterly direction. The throws along two major dykes overlying dolerite A are exclusively in a northerly to north-easterly direction and decrease from a maximum of 2 m in the west to 0 m in the east. The displacement of wall-rock strata illustrates that the emplacement of dykes is not necessarily into purely extensional (mode I) fractures, but into shear fractures, wherever an actual wall-rock displacement could be established with certainty. Notably, displacements do not point to a unidirectional or regional extension, but rather a multidirectional stretch given the contemporaneity of dyke emplacement.

4. Discussion

Complex dyke networks made up of interconnected and commonly curving dykes overlying dolerite sills or saucers are common across the Karoo basin (Chevallier and Woodford, 1999; Galerne et al., 2008). This points to a fundamentally different emplacement mechanism of these dykes as opposed to conventional dykes in extensional settings. The 3D data set from the Secunda Complex highlights a number of features that are pertinent for our understanding of dyke-sill relationships of Karoo dolerites. The spatial data demonstrate that dolerite dykes are rooted in and originate from the underlying dolerite A. This agrees with the textural and petrographic similarities between dykes and the underlying dolerite A. Dyke terminations also indicate the successive, but broadly contemporaneous emplacement of dykes. Moreover, the inconsistent directions of wall-rock displacement indicate a multidirectional stretch of strata above the dolerite A saucer.

4.1 Models for dyke-saucer/sill relationships

The Jurassic Ferrar Large Igneous Province in Antarctica is the time-equivalent of the Karoo Igneous Province in southern Africa (Elliot and Fleming, 2000). Similar to Karoo dolerites, the mafic magmatism in the Ferrar Igneous Province is dominated by large sill complexes made up of several overlying and laterally interconnected saucer-shaped intrusions that are, for the most part, emplaced into subhorizontal sedimentary rocks of the Permo-Triassic Victoria Group (Elliot and Fleming, 2008). Recently, Muirhead et al. (2012, 2014) discussed the formation of highly irregular, almost randomly orientated dyke networks originating from and fed by underlying sills of the Ferrar Large Igneous Province. Muirhead et al. (2012) suggested the sill-fed dykes to form as a result of localised extension of strata overlying the sills generated by the uplift and doming of the roof rocks during sill emplacement and inflation. The doming and stretching of the roof

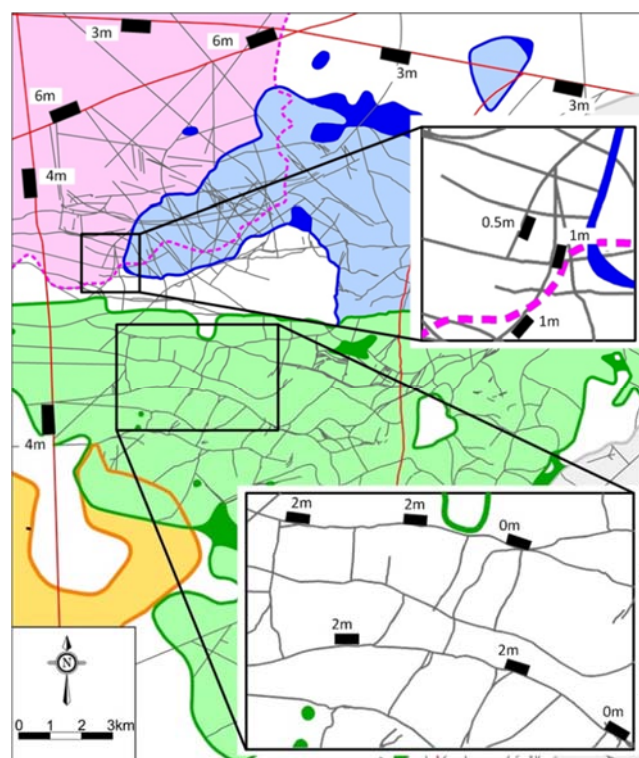


Fig. 6. The geological map indicates the variable directions of displacement along several dykes in the study area. Refer to the text for more information.

strata give rise to fractures that enable the vertical ascent of magma from the sill surface into the overlying stratigraphy, thereby creating an array of dykes linked to an underlying sill. This “cracked lid” model (Muirhead et al., 2014) accounts for the seemingly random orientation of dyke networks overlying feeder sills. Dyke formation and propagation are induced by the emplacement and inflation of the underlying sills and not related to regional stresses.

4.2 Dyke-saucer relationships in the Secunda Complex

The dyke network developed above dolerite A saucer closely resembles the “cracked lid” dykes described by Muirhead et al. (2012, 2014) for mafic sills in Antarctica, but with distinct differences. Instead of the random dyke orientations Muirhead et al. (2014), the systematic dykes above the dolerite A saucer, in particular, describe a distinct boxwork- or ladder-type pattern of interconnected high-angle dykes with systematic changes in their orientation. We suggest this pattern to be related to the emplacement processes and dynamics of the first-order saucer structure. The lateral growth of sills is commonly interpreted to occur via the propagation of magma lobes and fingers ahead of the main magma front (Pollard et al., 1975; Hansen & Cartwright, 2006; Schofield, 2009; Galerne et al., 2011; Rui et al., 2013). The propagation of magma lobes is thought to be an episodic process, driven by the repeated arrest and reactivation of magma lobes depending on the magma supply from the feeder sill or dyke and, thus, magma pressures within the lobes (Hansen and Cartwright, 2006). The lateral amalgamation and coalescence of individual magma lobes in the plane of propagation eventually forms the throughgoing sill (Galerne et al., 2011; Hansen & Cartwright, 2006;

Pollard et al., 1975; Schofield, 2009).

Coetzee and Kisters (2016) suggested that dolerite A was most likely fed indirectly from a steeply-inclined sheet, dolerite D, in the basement. The basement feeder gave rise to the eastern saucer which in turn fed magma laterally into the inner sill of dolerite A via the “open-end” structure (Fig. 3a, 7). From here, lateral, bedding-parallel magma propagation was through two main lobes. This includes a western and a south-western magma lobe with flow directions from the east to the west and southwest, respectively, parallel to and along the respective northern and south-eastern edges of the saucer (Fig. 7). The magma lobes have long aspect ratios, a width and height of some 2.5 km and 20 m, respectively, and lengths in excess of 10 km. The systematically changing orientation of major dykes and characteristic orthogonal boxwork pattern defined by the overlying major and minor dykes reflect this emplacement pattern and the presence of two main magma lobes contained in the inner sill of dolerite A. Notably, the convergence of major dykes in the northeast and towards the entry point (“open-end”) form a partial radial pattern (Fig. 3a) and the major dykes are parallel to the magma flow path and propagation direction of the two main magma lobes that constitute the inner sill of dolerite A (Fig. 7) (Coetzee and Kisters, 2016).

The major dyke fractures are most likely the result of extensional stresses generated in the uplifted roof strata normal to the long axis geometry of the expanding magma lobes (Fig. 8a). The bending of strata along the flanks of the lobe and the prevailing growth of these magma lobes in length rather than width would ensure that the major dyke fractures are continuously driven parallel to the advancing magma lobes. Magma from the propagating lobes may eventually exploit the longitudinal fractures and, thus, form the major dykes (Fig. 8a). The ladder-like pattern of minor dykes linking at regular intervals between major dykes (Fig. 5a) suggests extension was also induced parallel to the magma lobes (Fig. 8b). In this case, extensional stresses can be conceived to be a result of the maximum bending and stretching of the immediate roof rocks ahead of the 15 – 20 m thick propagating magma lobe. This would lead to orthogonal fractures that terminate against the earlier formed major dyke fractures (Fig. 8b). It is conceivable that bending and associated stretching of roof rocks followed by fracturing of the roof strata and magma infilling may lead to the episodic arrest of the magma lobe. Dykes extending from the magma lobe into the roof will result in a drop in driving magma pressure and, thus, arrest of the magma front. Further growth and propagation is only accomplished once magma is replenished and further fed from the main feeder. This may contribute to the episodic arrest and reactivation of magma lobes as described by Hansen & Cartwright (2006) and Rui et al. (2013).

Once the inner sill has reached its maximum diameter for a certain overburden thickness (Malthe-Sørensen et al., 2004; Goultly and Schofield, 2008) the overlying strata can no longer accommodate the concordant advance of the sill by simple bending and fracturing. At this stage multiple fractures trending parallel to the advancing magma front coalesce to form a reverse fault along the edges of the inner sill (Goultly and Schofield, 2008; Galland et al., 2009).

Reverse faulting and upward displacement of roof strata is accompanied by the intrusion of magma from the inner sill to develop the inclined sheets bounding the inner sill of dolerite A (Fig. 9a). At this stage, the development of major-minor dyke fractures ceases and the intruding dykes terminate against the

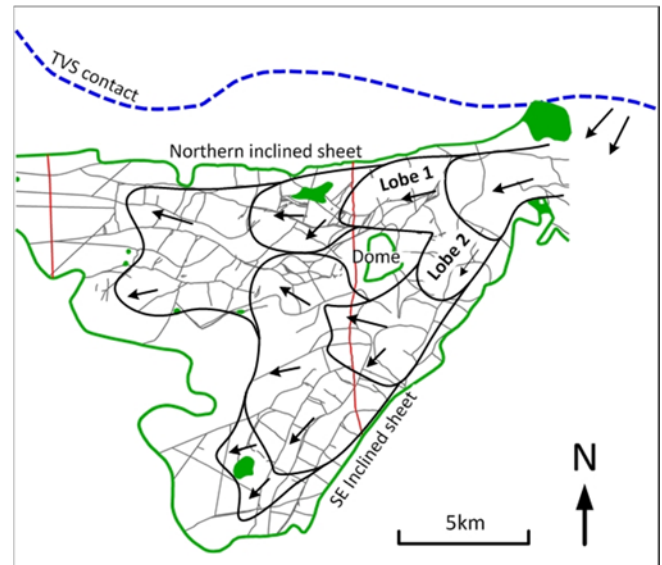


Fig. 7. Diagrammatic sketch with arrows showing the proposed movement of magma along the inner sill of dolerite A after Coetzee and Kisters (2016). Magma originating from dolerite D along the Transvaal-Ventersdorp (TVS) contact intrudes via adjacent saucers situated to the east through the “open-end” structure and into dolerite A.

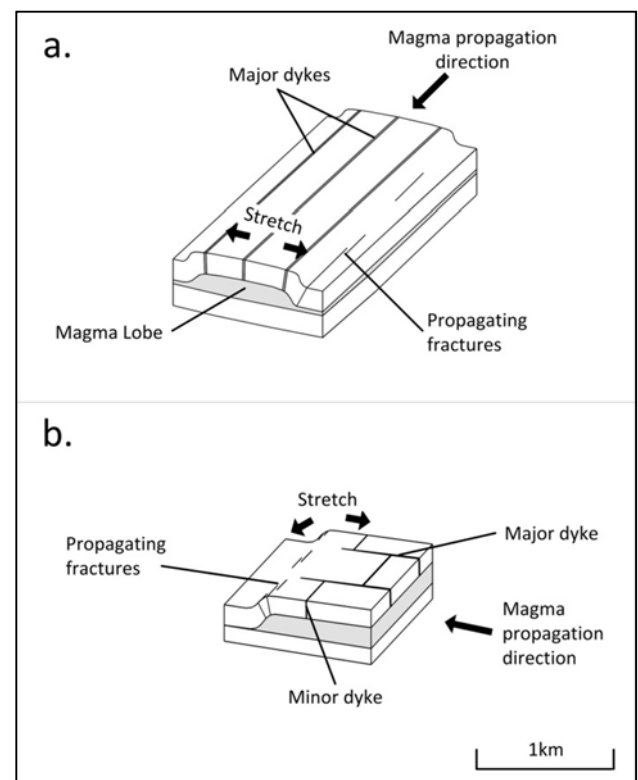


Fig. 8. Schematic diagrams outlining the proposed deformation structures and associated stresses in the strata overlying an elongated magma lobe. (a) Major dyke fractures forming parallel to the long axis of the magma lobe due to roof strata doming. Rising magma subsequently exploit fractures to form major dykes. (b) Minor dyke fractures form parallel to the advancing magma front due to bending of overlying strata. These fractures terminate against the major dyke fractures to form a ladder-like pattern.

infilled inclined sheets (Fig. 9b). This sequence of spatially and temporally closely associated saucer and dyke formation accounts for the boxwork dyke pattern to be confined to the inner sill of the dolerite A saucer (Fig. 9c).

Contrary to the systematic boxwork dyke pattern, the other dykes are not readily explained by doming and fracturing of the roof strata directly above the magma lobes. The contemporaneous timing and interconnected geometry indicates the regional dykes are related to the major-minor dykes. However, emplacement of the regional

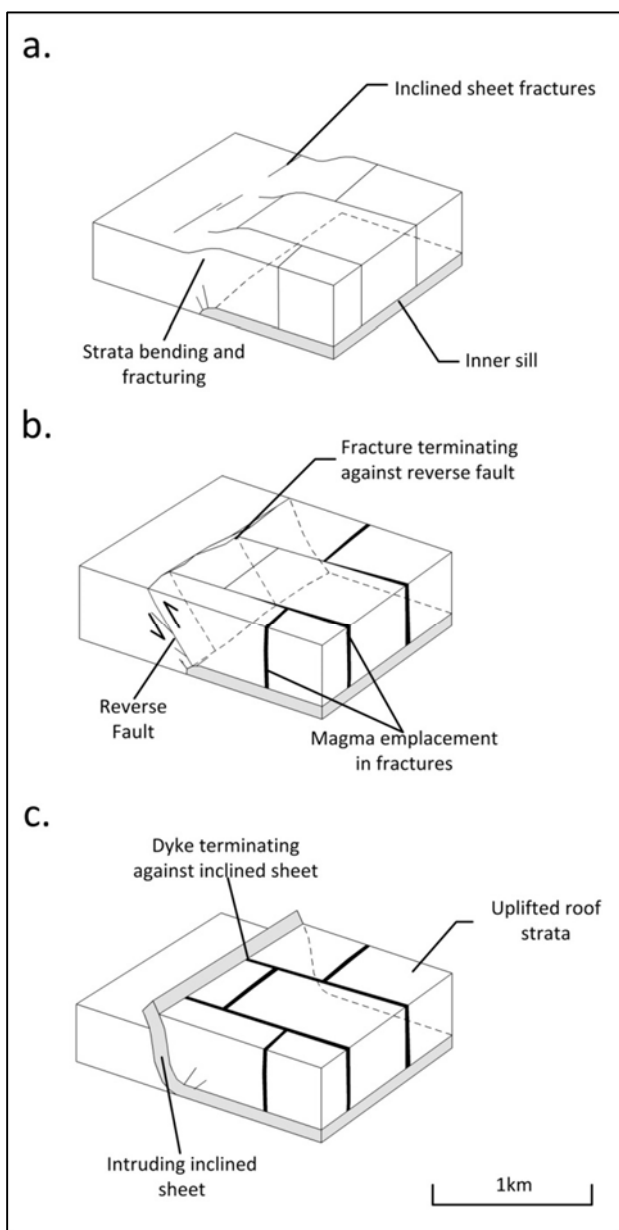


Fig. 9. The block diagram shows the steps in the formation of an inclined sheet from the failure of the overlying strata above an inner sill. (a) Multiple fracturing develops parallel to the magma front (b) Fractures coalesce into a reverse fault which facilitates the upwards displacement of roof strata (c) Magma exploits the fault plane to form a transgressive inclined sheet. All major pre-existing fractures and intruding dykes terminate against the surface of the inclined sheet limiting the boxwork dyke pattern to the inner sill of the saucer.

dykes is not limited to the confines of the dolerite A saucer. This suggests that the regional dykes are possibly the product of a more complex emplacement mechanism, perhaps influenced by the doming and fracturing of roof strata associated with the intrusion of the adjacent and coeval dolerite B saucer and underlying feeder (Coetzee and Kisters, 2016).

Protruding dykes originate from the outside of inclined sheets and project into strata without underlying feeder sills. Although coeval, this implies a different control of emplacement than those associated with the uplift of strata above the inner sill and bounding inclined sheets of the dolerite A saucer. The occurrence of protruding dykes originating at high-angles at points of sharp curvature along the inclined sheets facing away from the saucer suggests a lateral component of stretch parallel to the outside of the inclined sheets (Fig. 10a). The additional volume of the 15 – 20 m thick inclined sheet injected into the strata creates a membrane effect whereby the wider circumference along the outer surface of the sheet induce extension in the immediate wall rocks and the formation of fractures facing away from the outside of the saucer (Fig. 10a). Subsequently, magma pressure drives the infilling and lateral propagation of the fractures further away from the inclined sheets (Fig. 10a, b). In this scenario multiple propagating fractures may be drawn towards each other and later coalesce to form dykes that both originate and terminate against the outside of the saucer (Fig. 10b).

The distinct orientation and the general cross-cutting relationships

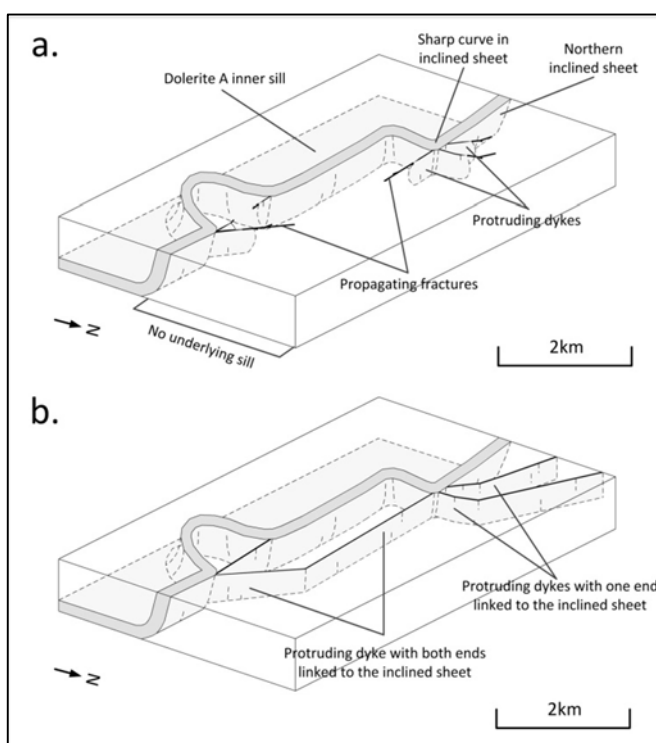


Fig. 10. The sketch illustrates the proposed formation of protruding dykes as seen north of the dolerite A saucer in Fig. 3a. (a) The membrane effect along the outer surface of the inclined sheet induces fractures extending away from the saucer. (b) Magma pressure infills and drives the fractures further into the wall rocks. Multiple fractures later coalesce forming protruding dykes with both ends linked to the inclined sheet of the saucer.

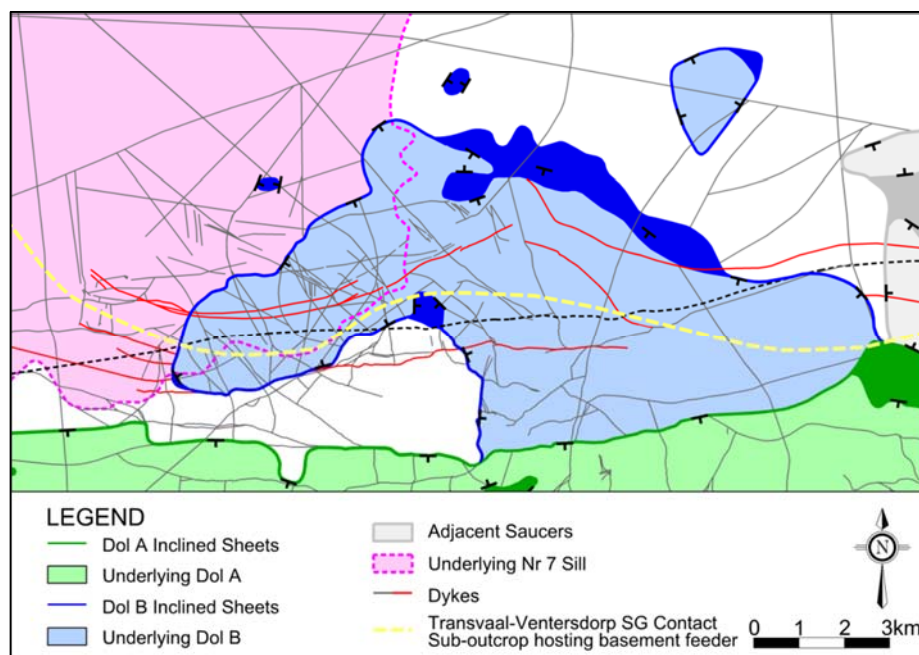


Fig. 11. A geological map of the area directly north of the dolerite A saucer showing the complex interconnected dyke patterns overlying the number 7 sill as well the dolerite B saucer and underlying basement feeder, dolerite D. Refer to the text for more information.

of the oblique dykes seem to suggest they are unrelated to the saucer and may possibly be emplaced from a coeval magma source located outside the dolerite A saucer. The interpretations of regional, protruding and oblique dykes at this stage remains speculative but indicates that dyke formation need not be limited to vertical magma ascent from an underlying feeder. Rather they highlight localised extension and subsequent dyke formation in the absence of a regional stress field that follows the multidirectional stretch on top of the dolerite A saucer.

4.3 Complexities arising from overlapping sills

The distinct dyke patterns and geometries overlying the dolerite A saucer are regarded as the basic model for dyke-saucer relationships above a single saucer (Fig. 3a, 4b). However, intrusive relationships are likely to be more complicated with the occurrence of spatially and temporally overlapping saucers and the resulting interference of dykes related to different saucer structures. This is especially the case to the north of dolerite A where the number 7 sill not only represents a different emplacement age but also spatially underlies and overlies the respective dolerite B saucer and basement feeder, dolerite D. In these examples of temporally distinct and spatially overlapping saucer emplacement, several episodes of dyke intrusion must be expected, each forming its own unique pattern of systematic and other dykes and resulting in the complex network of cross-cutting intrusions as it is developed north of dolerite A (Fig. 3a). This is evident in the less organised dyke pattern developed to the north that are seemingly not constrained by the inclined sheets of the dolerite B saucer. The dyke pattern overlying dolerite B consisting of several long, 8 to 10 km, dykes (red in Fig. 11) cross-cut by numerous shorter (2 to 5 km) high-angle dykes gives way to a noticeably denser and more scattered

4. Conclusions

The extensive underground and borehole information available on dolerite intrusions in the Secunda Complex offer a unique insight into the feeding and geometric relationships between dolerite saucer complexes and the complex dyke networks of the Karoo Basin. The main conclusions of the three-dimensional dyke-saucer relationships described here are summarized below:

1. Mining and drill hole data has shown that the geometrically complex dyke networks are rooted in underlying sill and /or saucer structures. The dykes do not represent the feeders of the larger saucer structures.
2. The distinct interconnected pattern of systematic dykes forms a cracked lid atop the underlying dolerite A saucer. The connections between the commonly curving trends of dykes point to the successive, but broadly coeval emplacement of dykes of different orientations.
3. The orientation and intersecting relationships of systematic dykes can be related to the actual emplacement processes and magma flow dynamics responsible for the formation and propagation of the underlying first-order saucer structure. The characteristic boxwork pattern displayed by systematic dykes forms as a result of the infilling of magma into extensional fractures created in the roof strata during the propagation and emplacement of elongated magma lobes during the advance of the inner sill of the dolerite A saucer. The interconnected boxwork pattern consisting of laterally extensive major dykes linked by short orthogonal minor dykes form during localised bending and fracturing of the roof strata at the magma

fronts. The formation of dykes above the inner sill ceases with the formation of the bounding inclined sheet, which confines the dyke pattern to the inner sill of the saucer.

4. The occurrence of other dykes is not directly related to the doming above the magma lobes forming the concordant inner sill of the dolerite A saucer. Rather these dykes are most likely influenced by multi-directional extension induced in the roof strata by adjacent and coeval saucers. Moreover, the membrane effect most likely initiates extensional fractures in the wall rocks outside the inclined sheets which allows for lateral dyke emplacement and the protrusion of dykes away from the saucer.

5. Acknowledgments

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Chapter 5: Conclusion and outlook

The case studies herein highlight the dominant role of dyke-saucer complexes in the emplacement of mafic magmas at shallow crustal levels by documenting:

- Regional and local scale magma emplacement mechanisms of saucer complexes
- The effect of lithological interfaces and unconformities on the emplacement and geometry of saucers
- The influence of saucer growth and strata uplift on the formation of overlying dykes

These points have been addressed by the interpretation and consolidation of mining and drill hole data sets from gold and coal mining operations into the 3D geometric strata model of the number 8 sill complex. Despite the more detailed findings summarized in chapters 3 and 4, the following overarching conclusions can be drawn.

5.1 Conclusion

Dolerite intrusions of the Highveld Coalfield, Karoo Basin represent an interconnected dyke-saucer complex that largely extends up to 200m depth. The sill-feeding-sill model demonstrated in this thesis suggests predominantly lateral magma transport at the high crustal level of the Karoo Supergroup. Lateral magma transport at this relatively shallow crustal level is corroborated by the lack of potential feeders in the basement. Moreover, the intense roof rock deformation associated with saucer growth and the emplacement of numerous interconnected dyke patterns, as seen in the Secunda Complex, would be expected at prevailing shallow emplacement depths. The effective formation of “cracked lids” atop saucers in the absence of far-field tectonic stresses accommodates a small degree of vertical

magma ascent in addition to the mostly horizontal flow of magma through saucer complexes. However, the sheer voluminous dominance of saucers compared to dykes in the Karoo Supergroup implies that saucers most likely served as the main plumbing system to the Drakensberg flood basalts. Therefore, the Karoo large igneous province is likely fed by a dense network of saucer complexes confined to the Karoo Supergroup which in turn is fed by only a few isolated feeders in the underlying basement strata. This highlights the role of the subhorizontally layered Karoo Supergroup and associated strata anisotropies for the lateral spreading of the magmas over tens and possibly hundreds of kilometres.

5.2 Future outlook

The data presented in this thesis has crucially shed new light on the contentious matter of saucer feeder systems. The intricate sill-feeding-sill relationships identified here with underlying feeders that may be off-set some distance away from the saucer without linking directly along the base of the inner sill highlights the shortcomings of analogue models. Experimental models have certainly improved our understanding of the general emplacement mechanism of saucers but the commonly invoked dyke-based feeder systems are not seen in reality and question the validity and continued use of these models. Analogue models have to find ways to better replicate the strong control of layer anisotropies as shown in this thesis in addition to the contrasts in temperature and density between the host rock and injected fluid. This would produce more accurate and realistic representations of mafic intrusions and allow us to better constrain magma emplacement process in the brittle upper crust.

The lobate flow emplacement mechanisms proposed for various unusual features observed in the dolerite dyke-saucer complexes are mechanically problematic and require a great deal of further investigation. Here, too, the current inability of analogue models to mimic the “real

world” constraints on magma emplacement will prove inadequate for testing such complex magma flow dynamics. Numeric models as performed by Kavanagh et al. (2004) could serve as a viable alternative if the models can be further constrained by sufficient and well sampled numeric field data. Therefore, until such time, we will have to rely on similar studies or significant advances in geophysical technology to visualize and improve our understanding of these complex intrusive systems.

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Appendix A: Research outputs

Peer-reviewed article:

Coetzee, A., Kisters, A.F..M. (2016). *The 3D geometry of regional-scale dolerite saucer complexes and their feeders in the Secunda Complex, Karoo Basin*. Journal of Volcanology and Geothermal Research, 317, 66–79.

Article under review:

Coetzee, A., Kisters, A.F..M., (assigned manuscript no: SG-D-16-00200). *Dyke-saucer relationships in Karoo dolerites as indicators of propagation and emplacement processes of mafic magmas in the shallow crust*.