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# Sub-volcanic Intrusions in the Karoo Basin, South Africa

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## Abstract

The Karoo Basin in South Africa contains the world's best exposed sub-volcanic part of a Large Igneous Province. Dolerite sills and dikes crop out across the 630,000 km<sup>2</sup> large basin, from base to top of the stratigraphy. We present data from a compilation of 32 boreholes drilled since the 1960's, showing that the sill percentage in the stratigraphy for individual boreholes varies from 0 to 54 %. Borehole depth is the key factor determining the sill proportion in specific regions, as shorter boreholes give higher sill proportions. When focusing on eight boreholes that were drilled through almost complete stratigraphic sections, the cumulative sill content is between 250 and 720 meters (average 440 m), yielding a proportion of sills to total thickness of 32 %. Using this average number as a proxy for the average sill content in the basin, the resulting sill volume is on the order of 250,000 to 300,000 km<sup>3</sup> when extrapolating to basin scale. The volume of dikes remains unknown, but all are quite thin and so have relatively small volume, estimated to less than 15 % of the sill volume. The sills may have been a thermal source for the generation of oil and gas, as well as leading to their volatilization and escape to the Early Jurassic atmosphere.

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## 1 Introduction

Outcrops and boreholes in the Karoo Basin provide a unique opportunity to study the processes and consequences of shallow sub-volcanic intrusions related to a Large Igneous Province (LIP). The intrusions were emplaced in clastic sedimentary rocks and led to contact metamorphic aureole formation, changes in the maturity state of the host organic matter, devolatilization and fluid expulsion, and mineral reactions and

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compaction. The emplacement of the sub-volcanic complex was a major event that affected rheology and fluid generation at the time of emplacement in the Early Jurassic and onwards (Chevallier and Woodford 1999; Jamtveit et al. 2004; Svensen et al. 2006, 2007; Aarnes et al. 2011). However, previous work on the sills has mainly focussed on outcrops, not boreholes. In this contribution, we present a new compilation of borehole data from the Karoo Basin. The aim is to improve the understanding of the distributions and thicknesses of the sub-volcanic part of the Karoo LIP.

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## 2 The Karoo Basin and the Sub-volcanic Complex

The Upper Carboniferous to Triassic Karoo Supergroup in South Africa is divided in five groups (the Dwyka, Ecca, Beaufort, Stormberg and Drakensberg groups) with a postulated maximum cumulative thickness of 12 km and a preserved maximum thickness of 5.5 km (Tankard et al. 2009). The current area with outcropping Karoo sedimentary rocks in South Africa is about 630,000 km<sup>2</sup> (Fig. 1). The depositional environments range from marine and glacial (the Dwyka Group), marine to deltaic (the Ecca Group), to fluvial (the Beaufort Group) and finally eolian (the Stormberg Group) (Cattaneo et al. 1998). The Karoo Basin is overlain by 1.65 km of preserved volcanic rocks of the Drakensberg Group, consisting mainly of stacked basalt flows erupted in a continental and dry environment (e.g., Bristow and Saggerson 1983; Duncan et al. 1984; Duncan and Marsh 2006). The plumbing system of the Karoo continental flood basalts is a basin-scale intrusive complex consisting of sills and dykes of varying thickness (Figs. 1, 2, 3 and 4) (du Toit 1920; Walker and Poldervaart 1949; Marsh and Eales 1984; Chevallier and Woodford 1999). The sills were emplaced at about 182.6 Ma (Svensen et al. 2012). The composition of the sills is tholeiitic with minor volumes of more evolved andesitic

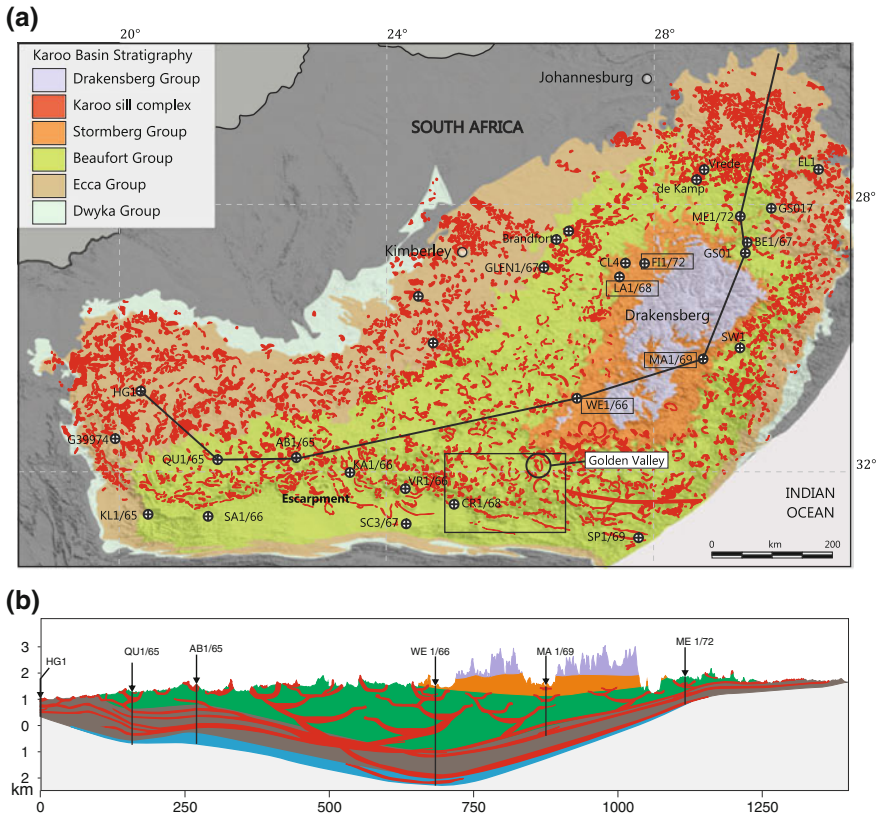
intrusions (Marsh and Eales 1984). Most of the thicker sills in the basin show internal compositional variations due to mild differentiation, a few of the thickest showing strong fractionation, such as the Mount Ayliff, Birds River, and New Amalfi complexes. The Mount Ayliff Complex near Kokstad, with its four lobes (Insizwa, Tabankulu, Tonti and Ingeli) is over 1,000 m thick, and represents an anomaly and has not been included in our compilation (Marsh et al. 2003).

Hundreds of breccia pipes and hydrothermal vent complexes are rooted in the contact aureoles of intrusions in the Karoo Basin and formed as a consequence of pressure build-up related to devolatilization reactions or boiling (Jamtveit et al. 2004; Svensen et al. 2007; Aarnes et al. 2012). The resulting release of carbon-rich gases is proposed as a major source of the <sup>12</sup>C-enriched carbon required to explain the Toarcian negative carbon isotope excursion and global environmental change (e.g., Svensen et al. 2007; Mazzini et al. 2010). The status of this hypothesis, and new data from contact aureoles in the Karoo Basin, is presented in Sect 9.2.

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## 3 Methods

Surface geology is given by the 1:1,000,000 bedrock lithostratigraphical map from the Council of Geoscience through [onegeology.org](http://onegeology.org). The regional profile presented in Fig. 1b is constructed using borehole and surface geology data. We have compiled data from 32 boreholes, including several that intersect the basement below the Karoo sequence (Table 1). 27 of the boreholes contain sills and 18 of those logs are presented in Fig. 5. The logs were obtained from the Council for Geoscience in Pretoria and from our own core studies. When compiling sill thicknesses, we assumed that none of the drilled dolerites represent inclined dykes and that the sill thicknesses in the boreholes represent the real thicknesses. Histograms and percentile calculations were done using the PAST software (Hammer et al. 2001).



**Fig. 1** **a** Geological map of the Karoo Basin showing the distribution of sill intrusions and the locations of the boreholes used in this study. The line across the basin is the trace of the profile presented below. See Fig. 2 for a close-up image of the rectangle in the southern Karoo

**Basin. b** Composite profile across the basin based on surface geology and borehole data. The schematic subsurface geology between the boreholes is constructed based on the typical sill geometries in the Ecca and Beaufort groups. Note the ~22 times vertical exaggeration

## 4 Results

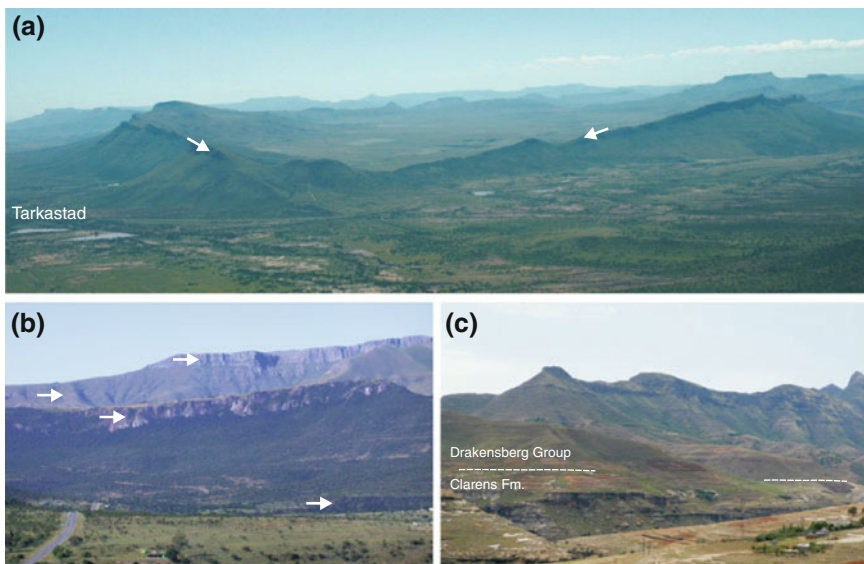
The sill geometries in the Karoo Basin vary with the depth of emplacement. Sills in the Ecca Group are laterally extensive, whereas sills in the Beaufort Group commonly have saucer-like morphologies with climbing limbs that cut across the horizontal stratigraphy of the sedimentary rocks (Figs. 2, 3 and 4) (Polteau et al. 2008a). Sills are rare in the Stormberg Group although dykes are common. Contact aureoles around the sills are well developed and are characterized by bleached hornfels with organic carbon contents approaching zero (Svensen et al. 2007; Aarnes et al. 2011).

The parameters we have extracted from the Karoo Basin logs include sediment thickness to base Dwyka Group (or base Ecca Group if Dwyka is absent), total sill thickness, the number of sills, the percent of sills (defined as the total thickness of sills divided by total thickness of sills plus sedimentary rocks), the thickest sill, and the emplacement levels (Table 1). As seen in the compiled logs in Fig. 5, the sill thicknesses vary considerably between boreholes and within the various stratigraphic units. For the 197 sills in our database, the average thickness is 35 m with most less than 90 m thick (Table 1). The thickest sill in our database is 282 m (GS017), but note that this represents a minimum thickness as the collar of the borehole was located within the sill.



**Fig. 2** Satellite image of the escarpment in the southern parts of the Karoo Basin. The escarpment is defined by *thick sill* intrusions emplaced in the Beaufort Group. Few sills are

present south of the escarpment. The locations of the 4,658 m deep CR1/68 borehole, the Golden Valley saucer (Fig. 3a), and the Nico Malan Pass (Fig. 3b) are also shown

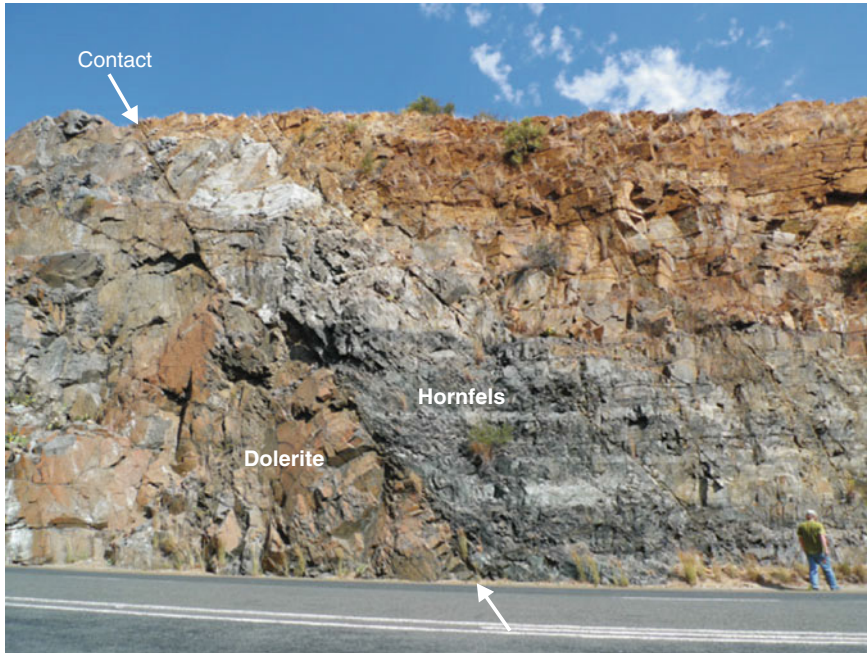


**Fig. 3** **a** The Golden Valley sill complex with characteristic inclined sheets (*white arrows*). The saucer-shaped sill is about 100 m thick and the complex is up to 11 km wide. **b** The escarpment near the Nico Malan Pass seen towards the north. Four sills are present at various levels

in the landscape (*arrows*). **c** The Karoo Basin was flooded by basalt in the Early Jurassic covering the landscape with at least 1.65 km of basalt. Here is the contact between the Clarens Formation (Stormberg Group) and the Drakensberg Group lava exposed in northern Lesotho

We cannot exclude the possibility that some of the sills represent composite sills, although these are rarely seen in the field. The sill thicknesses in

the boreholes are highly variable with an average value of 21 %. SW1/67 contains the highest number of sills (33) and the Vrede borehole the



**Fig. 4** Transgressive sills are common in the Beaufort Group sedimentary rocks and form an important feature of the saucer-shaped intrusions in the basin. Here we see the sill contact north-east of Beaufort West. Sandstone and

siltstone are transformed to hornfels in the contact aureole. Note the oxidized weathering profile in the upper part of the hornfels

highest content (54 %) when comparing with the sediment thickness. We stress that the sill content variation across the basin is heterogeneous and that is not possible to draw sensible contour maps as done by Winter and Venter (1970).

An important finding is that the percentage of sills varies with borehole depth and location relative to the escarpment (Fig. 6a). Also, the intuitive positive relationship between the number of sills and the total content of sills shows that sill thicknesses are evenly distributed among the boreholes (Fig. 6). Short boreholes (and those intersecting only the lowermost stratigraphy) contain a high percentage of sills but also few meters in total. Figure 7 shows the importance of the total stratigraphic succession intersected for understanding the sill content in the boreholes. When plotting the sill content in meters versus percent, the dataset falls mainly along two trends. By differentiating between short boreholes (<1,000 m) and long boreholes (>1,000 m), we show that short boreholes are skewed towards a higher percentage of sills.

A well-known aspect of the sill distribution in the Karoo Basin is the scarcity of sills located south of the Karoo escarpment (see Fig. 1). This can be seen in the logs in Figs. 5 and 8, where the sill content is plotted against the perpendicular distance from the escarpment.

The histograms in Fig. 9 show that the sill thicknesses vary according to emplacement level. The Beaufort Group has a higher abundance of both thin sills (<30 m) and thick sills (90–150 m) than the Ecca Group. The predominance of thin sills in our data set is demonstrated in Fig. 10, showing that most sills (60 %) are less than 30 m thick. In Fig. 11 we show how much sills with thicknesses within 20 m bins contribute to the cumulative sill thicknesses. For instance, even the thinnest sills (<20 m in thickness) in our database sum to 659 m. Sills in the 20–40 m range sum up to almost the same cumulative thickness as the sills in the 40–60, 60–80, and 80–100 m ranges. Note that the few sills thicker than 140 m result in 1:1 relationship between cumulative sill thickness and bin size in cases

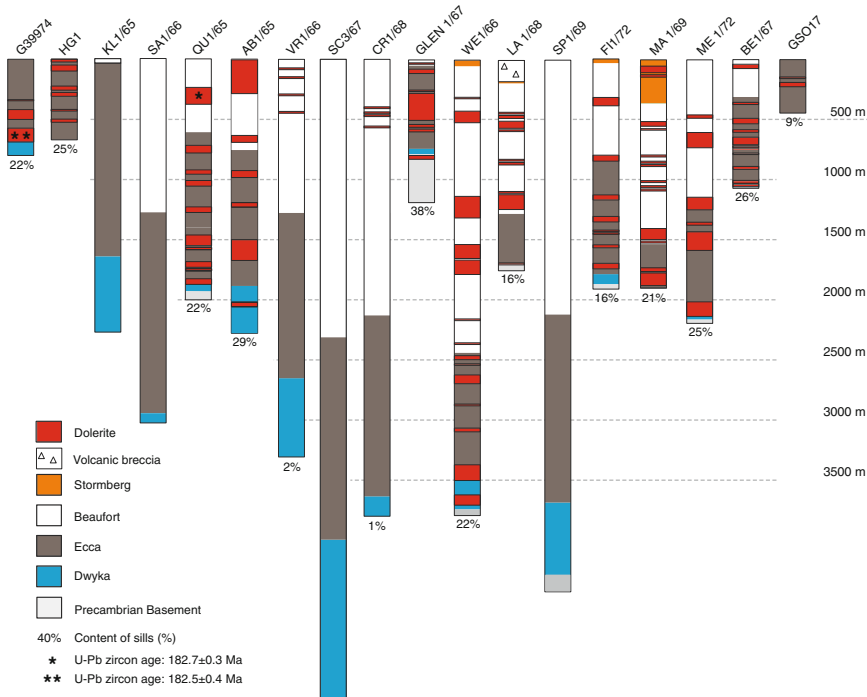
**Table 1** Overview of cores and sill thicknesses

Core	Farm	Lat	Long	TD/ BK	Sediments	Sills	Sills	Volume	Thickest
					m	m	#	%	m
QU1/65	Quagga's Fontein 357	-31,83	21,44	1935	1516	419	10	28	128
WE1/66	Weltevreden 117	-30,90	26,84	3732	2911	821	14	28	129
BE1/67	Bergville	-28,57	29,38	1045	772	273	16	35	64
HG1	Hans Gat 249	-30,80	20,29	672	503	169	6	34	44
LA1/68	Olney 280 (Ladybrand)	-29,09	27,48	1710	1444	266	11	18	127
GLEN1/67		-28,95	26,33	769	450	291	7	61	221
VREDE1/66		-32,26	24,25	3310	3256	54	4	2	42
MA1/69		-30,30	28,72	1892	1502	390	22	26	129
FI1/72	Ficksburg Township 75	-28,89	27,85	1873	1582	291	8	18	21
ME1/72	Meijers Geluk	-28,19	29,28	1037	779	258	6	33	70
AB1/65	Abrahams Kraal 206	-31,80	22,62	2298	1640	658	6	40	282
CR1/68	Drooge Rivier	-32,48	25,00	4658	4631	27	4	0,6	9
KL1/78	Klein Kareelaagte 168	-29,38	24,45	140	125	15	1	12	15
BE1/67	Bergville	-28,73	29,35	1045	772	273	16	35,4	64
GSO17	Hanover 2964	-28,06	29,75	442	403	39	2	9,7	36
	Brandfort	-28,53	26,52	723	607	117	10	19	47
CL4	Clockolan	-28,88	27,55	892	895	95	5	13	
SW1	Swartberg	-30,15	29,27	2805	2090	717	33	34	199
KA1	Kareebosch	-32,02	23,42	2516	2404	112	3	5	76
	Kliprivier			685	510	175	3	34	127
	Petrusville	-30,08	24,67	711	577	133	3	23	62
		28,77	30,32	1857	1608	248	8	15	97
SO1	Somkele	-28,35	32,10	2291	1730	561		32	
	de Kamp	-27,63	28,62	722	425	300	6	70	111
	Vrede	-27,48	28,73	650	298	352	3	118	168
EL1	Elandsnek	-27,47	30,45	576	396	189		45	
	Theunissen	-28,40	26,70	482	428	54	1	13	54
G39974	Kopoas Fontein	-31,49	19,89	1016	807	209	3	26	116
KL1/65	Klipdrift 156	-31,38	20,45	2034	1864	170		9	

where only one sill is present. In total, the sills in the database sum to a thickness of 6,647 m.

We use our database to constrain the volume of sills in the whole Karoo Basin. The approach we use is to extract the average thickness and standard deviation of the sill content in the 12 deep boreholes (>1,000 m). These boreholes are listed in Table 1, and the average is  $426 \pm 211$  m. When scaling to the size of the Karoo Basin (630,000 km<sup>2</sup>), the resulting sill volume is  $270,000 \pm 130,000$  km<sup>3</sup>. Note that (1) the 12

deep boreholes are the best representation of the sill content in the basin, (2) the lack of sills in the Ecca Group south of the Escarpment has not been taken into account, (3) we assume that the entire Karoo stratigraphy, including the Stormberg Group, was present across the present-day size of the basin, and (4) the sill volume is likely significantly underestimated considering the presence of Karoo LIP sills outside South Africa. The volume of dykes in the Karoo Basin remains unknown as there are no studies on dyke



**Fig. 5** Lithological logs from 18 of the 32 studied boreholes. The boreholes are sorted according to longitude. Note that only four boreholes contain complete Ecca and Beaufort Group stratigraphy (LA1/68, MA1/69, FI1/72, and WE1/66). The thickest sill is found in the AB1/65

borehole (at least 282 m). Sills are rare in the Dwyka Group and only one sill is emplaced exclusively in basement rocks (GLEN1/67). The boreholes without sills are all from areas near the southern escarpment

statistics. However, with a few exceptions, most outcropping dykes are thin (1–10 m). If we turn all sills in our database into 5 m wide dykes, the cumulative dike width becomes 985 m (197 × 5) or 15 % of the cumulative sill thickness.

182.3 ± 0.6 Ma. Both the U-Pb and Ar/Ar ages are shown in the compilation in Fig. 12. Monte Carlo simulations of the emplacement duration based on the new U-Pb ages suggests that 95 % of the sills were emplaced within 0.47 m.y. (Svensen et al. 2012).

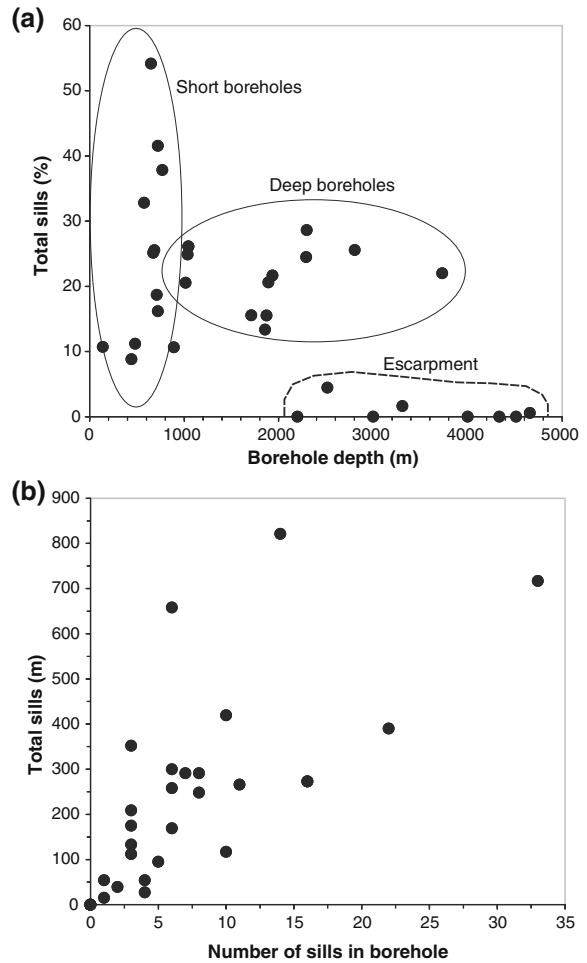
## 5 Discussion

### 5.1 Age and Geochemistry of the Karoo Dolerites

Based on an <sup>40</sup>Ar/<sup>39</sup>Ar study of 15 sills in the eastern Karoo Basin, it was concluded that the Karoo sills were emplaced over a sustained period of some 3 m.y. (Jourdan et al. 2008). A recent study presented 15 U-Pb zircon ages of sills across the whole Karoo Basin which gave overlapping ages within small errors (Svensen et al. 2012), ranging from 183.0 ± 0.5 to

The ages of the lavas, in contrast, are poorly constrained. The geochronology of the basal flood basalt, the Mosheshe’s Ford unit, is characterized by variable and uncertain ages: 184.8 ± 2.6 Ma (K–Ar; Moulin et al. 2011), 186.5 ± 1.1 Ma (uncorrected <sup>40</sup>Ar/<sup>39</sup>Ar plateau age; Duncan et al. 1997), and 181.0 ± 2.0 Ma (<sup>40</sup>Ar/<sup>39</sup>Ar plateau age from the lowermost flow in Lesotho; Jourdan et al. 2007). There have been many attempts to find zircons in both the basal lavas and other flows in South Africa and Lesotho, without success. Thus so far, the direct link between Karoo sills and lavas relies on the geochemical fingerprinting of sills, dykes and lavas (Marsh et al. 1997).

**Fig. 6** Systematics of the 27 boreholes in the database containing sills. **a** The percentage of sills versus the depth to the base of the borehole or top of the basement. Most boreholes contain more than 10 % sills, except the boreholes drilled near the escarpment in the south. **b** The number of sills in each borehole varies from 1 to 33. Generally, boreholes with many sills (>10) have a high proportion of sills on the basis of total sill thickness

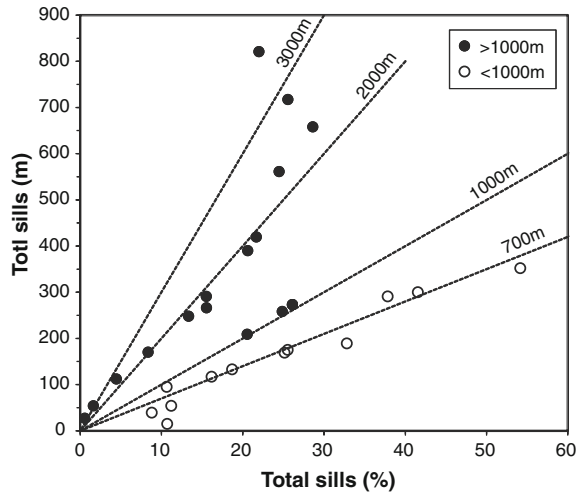


There is no systematic variation in sill geochemistry from base to top in the basin (Neumann et al. 2011 and Chap. 7 of this book). Figure 13 shows a compilation of sill analyses from two boreholes that were drilled through the Ecca and Beaufort groups (LA1/68 and QU1/65). The MgO content is fairly consistent, clustering between 5 and 8 wt. %. Previous studies based on fieldwork in various regions in the basin have given similar results. However, a high-resolution study from the Golden Valley sill complex suggested that variations between sills can be substantial in terms of trace element concentrations, both due to internal processes within each sill and due to sills sourced from reservoirs with slightly different chemistry (Galerie et al. 2008; Neumann et al. 2011).

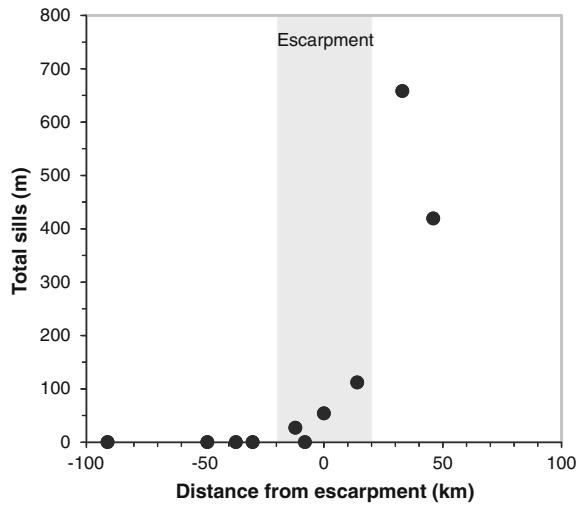
## 5.2 Sill Distribution and Thicknesses

The escarpment in the southern Karoo is defined by more than 1,000 m elevation difference and by the presence of thick sills emplaced in the middle Beaufort Group (Fig. 2). There are few sills emplaced south of the escarpment, and they are thin and not present everywhere. The thick sills cropping out in the upper part of the escarpment (Fig. 3b) likely extended southwards towards the Cape Fold Belt, but are now eroded due to the northward migration of the escarpment. The reason for the general absence of sills south of the escarpment below the middle Beaufort Group is debated. The Cape Fold Belt is suggested to have reduced the ability of horizontal migration of magma deep in the basin

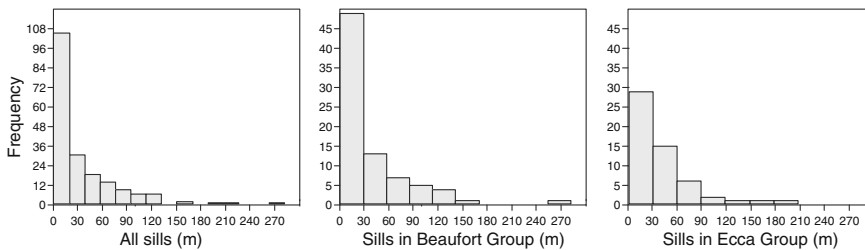




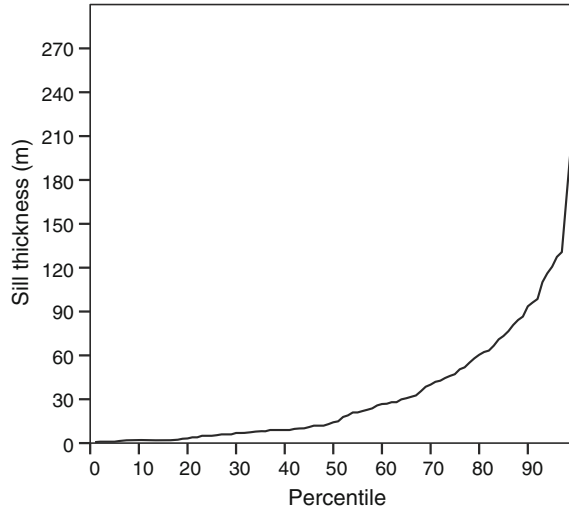
**Fig. 7** The relationship between sill content in percent and total thickness (m). The two trends in the data can be explained when distinguishing between short (*open circles*) and long boreholes (*filled circles*). The *stippled lines* show the theoretical systematics of boreholes in which the total depth and the sill content is varied systematically



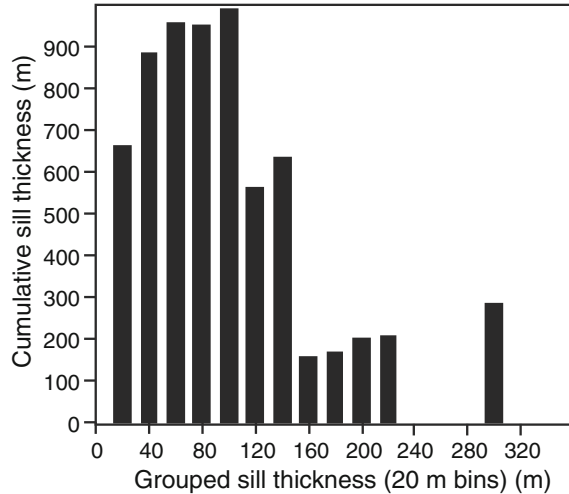
**Fig. 8** The sill content in meters as a function of distance from the southern escarpment along a longitudinal band. Sill are absent in the south and start to appear near the escarpment. Note that the escarpment is a gradual feature in the terrain, usually confined to a ~40 km wide zone. This zone is shown as a *grey band*



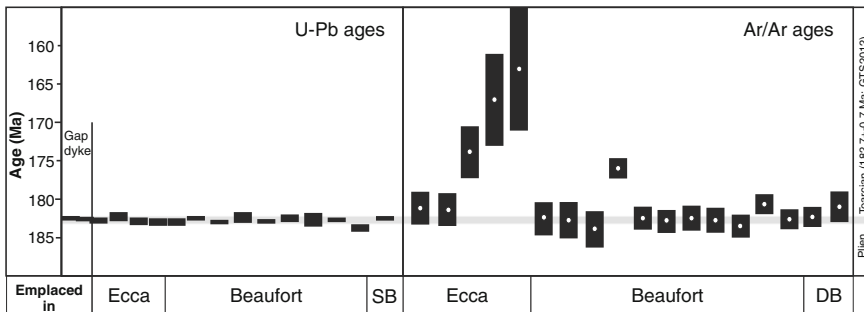
**Fig. 9** Histograms of all sill thicknesses (**a**), sills in the Beaufort Group (**b**), and the Eccca Group (**c**). The major difference between **b** and **c** is the higher abundance of both thin sills (<30 m) and thick sills (90–150 m) in the Beaufort Group



**Fig. 10** Percentile plot showing the distribution of sill thicknesses scaled to 100 %. For instance, 60 % of the sills are thinner than 30 m



**Fig. 11** Cumulative sill thicknesses summarized within 20 m sill thickness bins. Note the high cumulative sill thickness even for sills <20 m thick and the minor contribution from rare >140 m thick sills



**Fig. 12** Published sill ages from the Karoo Basin. The U-Pb zircon ages are compiled from Svensen et al. (2012) and the Ar/Ar sill ages from Jourdan et al. (2007, 2008). The extrapolated GTS2012 age of the Pliensbachian-

Toarcian boundary is also shown. Note that the age of the huge Gap dyke, the only dyke dated by zircons in the basin, is identical to the sill ages. SB: Stormberg Group. DB: Drakensberg Group

(Winter and Venter 1970). Our data support this view as the lower part of the Beaufort Group and the entire Ecca and Dwyka groups in this region are depleted of sills as well (Figs. 5 and 8).

There is an east-west trending zone to the east of Kimberley where the basement has been deformed upward with the result that the thickness of Karoo sedimentary rocks is anomalously thin. In one hole, GLEN1/67, there is a single sill that is 221 m thick (the second thickest of all recorded sills). These two facts result in this one hole yielding a sill content of 38 %, but note that the borehole is less than 1,000 m deep and thus not representative for the full stratigraphy in that area. If this one value were to be ignored then the greatest sill content would appear to be in the northeast of the Karoo Basin. However, in this region only the lowermost rocks (mainly the Ecca Formation) have survived erosion. The boreholes that ring Lesotho (shown in boxes in Fig. 1) show a higher sill content than the other deep boreholes and so do not support the conclusions by earlier workers (Winter and Venter 1970).

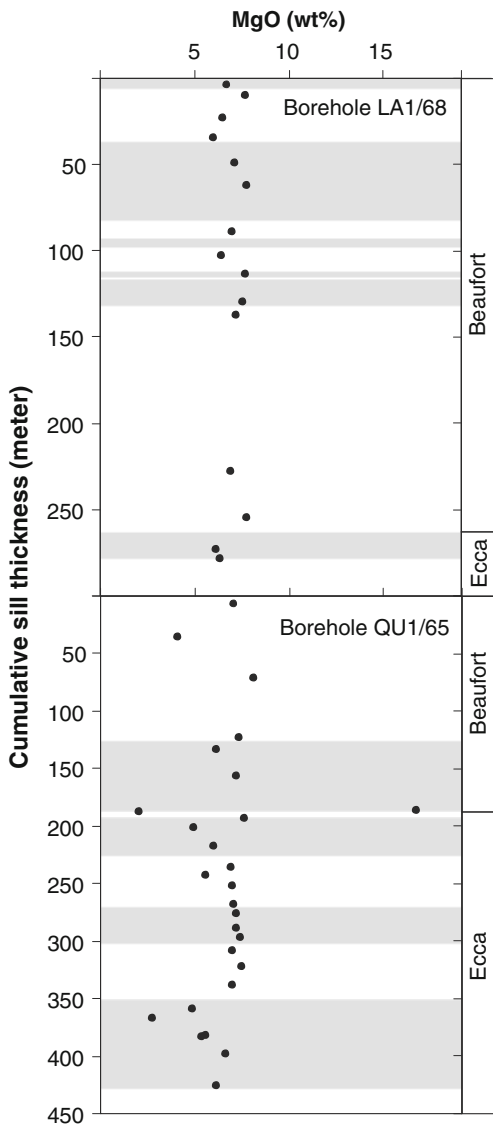
The 12 deep boreholes containing sills may hold the key to quantifying the basin-scale sill volume. These boreholes minimize the skewed data from short and un-representative boreholes, and the effect of erosion and removal of the upper parts of the sedimentary sequences. Our sill volume estimate is  $270,000 \pm 130,000 \text{ km}^3$ . Alternative methods include map view outcrop estimates and integrated cross sections. The latter method was used by Svensen et al. (2012), where the sill volume in a cross-section similar to the one in Fig. 1b was extrapolated to the entire basin giving a volume of  $340,000 \text{ km}^3$ .

### 5.3 The Emplacement of a Sill

The cross-section of the Karoo Basin (Fig. 1b) graphically presents two fundamental aspects: (1) individual sills in the Ecca Group may be laterally extensive (across 100s of kilometres), and (2) the sills in the Beaufort Group do not necessarily form extensive sheets that can be mapped for great distances, but form saucers. This

implies that the tradition of giving individual sills names, such as in the Tunguska Basin in Siberia, does not make sense for the Karoo as sills transgress, pinch out, merge with inclined dykes, and form an intricate network throughout the basin. This is demonstrated in a series of publications from the Golden Valley Sill Complex project, where a large number of geochemical profiles were made together with detailed geochemical fingerprinting of magma batches and detailed fieldwork (Galerne et al. 2008, 2010; Polteau et al. 2008a, b).

The boreholes we have studied have records of the different emplacement from the region in which they were drilled. This means that the question of how many of the 197 sill intersections we have recorded represent the same intrusions is impossible to answer. Extensive sills should in theory be overrepresented in the dataset if these were penetrated by several boreholes. Our data shows that the 60 % of the sills are thinner than about 30 m (Fig. 10), although thin sills should intuitively be the least laterally extensive. Figure 11 shows that the sills thinner than 40 m contribute as much to the cumulative thickness as those in the 40–140 m range (Fig. 11). The reason for the higher abundance of thin sills (<30 m) in the Beaufort Group compared to in the Ecca Group (Fig. 9) is unclear. A possible explanation is that sill thickness is partly controlled by host rock properties (sandstone versus shale) or the depth of emplacement. For instance, a detailed borehole study of saucer-shaped sills has shown that sill offshoots are common near the transgressive segments of thick sills (Chevallier and Woodford 1999). This is potentially an explanation for the many thin sills in the vicinity of thick sills in our borehole compilation (Fig. 5). Moreover, there is apparently a higher proportion of thick sills (90–150 m) in the Beaufort Group compared to in the Ecca Group (Fig. 9), possibly due to emplacement depth, inflation processes, or variations in the melt emplacement flux. Whether the sills were emplaced in time sequence from the base upward, downwards or randomly is unresolvable, but the flux was likely highly variable over the ~500 ky emplacement duration.



**Fig. 13** Whole-rock wt. % MgO data from sills analysed from core material in the LA1/68 and QU1/65 boreholes. The plot shows the stacked sills from the two boreholes without including the sedimentary rocks. Individual sills are shown as alternating white and grey bands. The MgO content is rather consistent throughout the stratigraphy and does not show any specific trends. Note that some of the spread in the data can be due to internal differentiation, as sampling was not restricted to the chilled margins where the primary composition of the magma is likely recorded. Data from Neumann et al. (2011)

## 5.4 Consequences of Sill Emplacement

When South African companies explored the petroleum potential in the Karoo Basin during the 1960s and 1970s, many were concerned about the influence of sills on the petroleum systems. Rowsell and De Swart (1976) compiled borehole data demonstrating the temperature effect of sills on clay minerals and petroleum systems. For instance, the LA1/68 borehole contained dry gas in the lower half of the hole, whereas oil shows were common in the upper part. Both the thermal input from the sills and the weight of the overlying lava pile must have played a key role in the petroleum generation, as the sedimentary sequence in LA1/68 is only 1,444 m thick (Table 1). Even with a very high thermal gradient, this is insufficient for generating temperatures needed for oil and gas generation unless the effect of the lava pile was significant.

During the last decade, contact metamorphism of organic-rich shale in the Karoo Basin has been linked to methane degassing and the Toarcian climate perturbations (Svensen et al. 2007; Aarnes et al. 2011). These studies applied a combination of field investigations, borehole studies, and numerical modelling, and show that methane was generated in sufficient quantities within the Eccla Group contact aureoles to have had an environmental effect if vented to the atmosphere. These findings are moreover important for the outlook for shale gas in the Karoo Basin. New borehole information and gas geochemistry from the Eccla Group, with and without sills, are needed to resolve if sills in a particular region have been beneficial or destructive for the local petroleum systems.

## 6 Conclusions

The Karoo Basin contains the world's best exposed sub-volcanic part of a LIP. Both borehole data and exposed sills have great potential

for addressing detailed processes related to sill geochemistry and emplacement, and contact aureole processes. We conclude that:

- Sills form an integral part of the Karoo stratigraphy, and comprise up to 54 % of the local stratigraphy, but for the 27 boreholes with sills we have studied, the average sill content is 21 %.
- Thin sills (<30 m) are more abundant than thick sill and represent 60 % of a total of 197 individual sill intersections in our database. The Beaufort Group contains more sills in the 90–150 m range than the Ecca Group, possibly reflecting a combination of emplacement processes and host rock lithology.
- Borehole data are crucial for understanding the sill distribution in a sedimentary basin. However, short boreholes may give artificially higher sill percentages than deep boreholes.
- Boreholes from around the Karoo escarpment suggest a tectonic explanation for the absence of sills in the Dwyka and Ecca groups south of the escarpment.
- The Karoo sills represent the best geochronologically constrained subvolcanic part of a LIP. A recent study of 15 dated sills suggested a very rapid emplacement around 182.6 Ma. The lavas are only dated by the  $^{40}\text{Ar}/^{39}\text{Ar}$  and K–Ar methods with a considerable age scatter around 183 Ma, and a revision is critically needed.

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