



Multiple, isotopically heterogeneous plagioclase populations in the Bushveld Complex suggest mush intrusion



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ABSTRACT

The Bushveld Complex and other layered intrusions show significant initial isotopic heterogeneity, both between and within co-existing cumulate minerals. Various processes have been proposed to account for this, including (i) intrusion of variably contaminated crystal mushes from deeper staging chambers, (ii) blending of semi-consolidated crystal mushes as a result of subsidence during cooling, (iii) variable infiltration of contaminants into a partially solidified crystal mush, (iv) density-driven mixing of minerals from isotopically distinct magma pulses, (v) contamination of crystals at the roof of the intrusion and mechanical incorporation of such contaminated crystals into the lower crystallisation front as a result of gravitational instability at the upper crystallisation front, and (vi) late-stage metasomatic processes. In order to assess the likely process(es) responsible for initial isotopic heterogeneities within the Bushveld Complex, we analysed core and rim domains of 12 plagioclase crystals from the Main and Upper zones of the Bushveld Complex for their Sr-isotopic compositions. The data show the presence of multiple, isotopically heterogeneous populations of plagioclase occurring within the same rocks. The data presented here are best explained through the intrusion of variably contaminated crystal mushes derived from a sub-compartmentalized, sub-Bushveld staging chamber that underwent different degrees of contamination with crustal rocks of the Kaapvaal craton.

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1. Introduction

Much of the early isotopic work performed on the Bushveld Complex and other layered intrusions focused on whole-rock and specific bulk mineral separate data as proxies for whole-rock isotopic compositions to comment, for instance, on aspects related to magma recharge, crustal contamination, parental magma compositions and the nature of mantle source regions. It has long been recognised, especially in volcanic systems, that co-existing minerals may exhibit isotopic disequilibrium, both between (intergranular isotopic disequilibrium) and within (intragranular isotopic disequilibrium) rock-forming minerals (Davidson and Tepley, 1997; Tepley et al., 1999, 2000). Recent work on the Bushveld Complex and other layered intrusions as described below has shown the presence of significant isotopic heterogeneity, both between and within co-existing cumulate minerals.

Various processes have been proposed to account for this. The blending of semi-consolidated crystal mushes as a result of

subsidence during cooling was proposed by Yang et al. (2013) to explain both inter- and intracrystalline Sr-isotopic disequilibrium in plagioclase from the Upper Critical Zone of the Bushveld Complex (see also Maier et al., 2013), whereas Prevec et al. (2005) chose to explain Nd-isotopic disequilibrium between plagioclase and orthopyroxene in the Upper Critical Zone as being the result of the density-driven mixing of minerals from isotopically distinct magma pulses. Chutas et al. (2012) using micro-drilling and progressive leaching experiments proposed that variable infiltration of contaminants into a partially solidified crystal mush was responsible for Sr- and Pb-isotopic disequilibrium in plagioclase and orthopyroxene from the Lower, Critical and Upper Zones of the Bushveld Complex. The intrusion of variably contaminated crystal mushes from deeper, crustal staging chambers was proposed by Roelofse and Ashwal (2012) to explain significant Sr-isotopic disequilibrium between plagioclase and orthopyroxene in the Main Zone of the Bushveld Complex. For the Rum Intrusion, Tepley and Davidson (2003) preferred a model to explain both inter- and intracrystalline Sr-isotopic variations between plagioclase and clinopyroxene in which it was argued that contamination of crystals at the roof of the intrusion were mechanically incorporated into the lower crystallisation front as a result of gravitational instabil-

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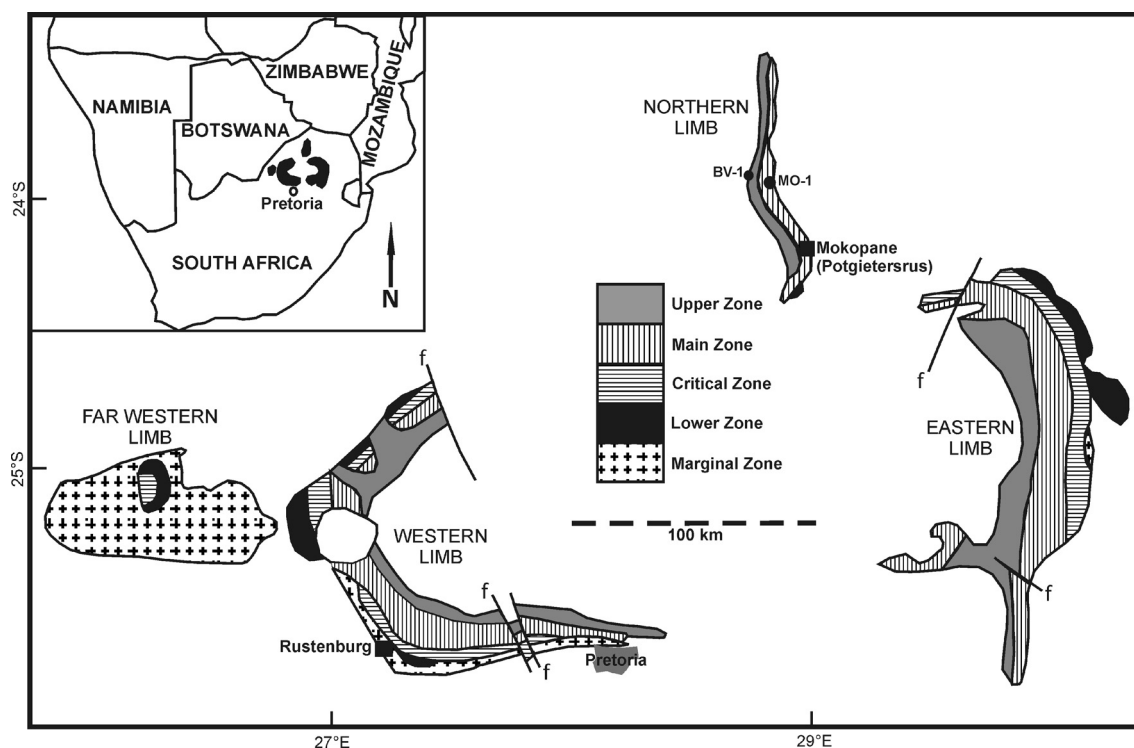


Fig. 1. Geological map of the Bushveld Complex showing the locations of the various limbs and the positions of the BV-1 and MO-1 drill holes. Inset shows the location of the Bushveld Complex within South Africa.

ity at the upper crystallisation front. [McBirney and Creaser \(2003\)](#) explained Sr- and Nd-isotopic disequilibrium in the Skaergaard Intrusion as being the result of late-stage metasomatic processes.

The realisation that isotopic disequilibrium is also present within layered intrusions and not confined to volcanic systems necessitates not only new methodological approaches for the study of cumulate rocks but also a fundamental reassessment of what we thought we knew about the petrogenesis of layered intrusions in general. This study reports the results of a detailed Sr-isotopic investigation performed on manually separated core and rim domains of cumulate plagioclase crystals from the Main and Upper zones of the Northern Limb of the Bushveld Complex as sampled by the Bellevue (BV-1) and Moordkopje (MO-1) drill holes, that was performed in order to test the competing hypotheses proposed for the existence of isotopic disequilibrium as presented above.

2. Geological setting

[Eales and Cawthorn \(1996\)](#) provided an excellent review of the geology and petrology of the Rustenburg Layered Suite (RLS) of the Bushveld Complex ([Fig. 1](#)), the world's largest layered intrusion, with an areal extent of >65,000 km², and the world's largest host of Cr, V and platinum-group elements ([Kruger, 2005](#)). The sequence of mafic layered rocks comprising the RLS has thicknesses of 7–9 km and occurs in five discrete limbs known as the Western, Eastern, Far Western, Northern and Southern limbs ([Eales and Cawthorn, 1996](#)). The RLS was intruded into Palaeoproterozoic (2.5–2.06 Ga) supracrustal rocks of the Transvaal Supergroup at 2054.4 ± 1.3 Ma ([Ashwal et al., 2005](#); [Scoates and Friedman, 2008](#)). Most researchers argue based on Sr, Nd and Os whole-rock isotopic data that the magmas that gave rise to the RLS underwent significant amounts of contamination with crustal rocks of the Kaapvaal craton ([Kruger and Marsh, 1982](#); [McCandless et al., 1999](#); [Maier et al., 2000](#); [Harris et al., 2005](#)). Some, however, argue for contamination of mantle-derived magmas with a sub-continental

lithospheric mantle component ([Richardson and Shirey, 2008](#)). A large body of evidence suggests that contamination took place within a sub-Bushveld staging chamber and not within the main Bushveld Complex magma chamber as is seen exposed today ([Maier et al., 2000](#); [Eales, 2002](#); [Ashwal et al., 2005](#); [McDonald and Holwell, 2007](#); [Barnes et al., 2009](#); [McDonald et al., 2009](#); [Holwell et al., 2011](#); [Roelofse and Ashwal, 2012](#); [Lehloenyana and Roelofse, 2013](#); [McDonald et al., 2009](#); [Holwell et al., 2011](#); [Roelofse and Ashwal, 2012](#); [Lehloenyana and Roelofse, 2013](#)), as well as to the inference that magmas may have been intruded as crystal mushes instead of aphyric liquids, especially in the gabbroic Main Zone of the RLS ([Maier and Barnes, 1998](#); [Maier et al., 2001](#); [Eales, 2002](#); [Barnes et al., 2004, 2009](#); [Holwell et al., 2011](#); [Roelofse and Ashwal, 2012](#); [Lehloenyana and Roelofse, 2013](#)).

Samples analyzed during the present study originated from the 2950 m deep Bellevue (BV-1) and the 1563 m deep Moordkopje (MO-1) drill holes drilled on the Northern Limb of the Bushveld Complex. The former sampled the entire Upper Zone of the Rustenburg Layered Suite and the upper Main Zone, whereas the latter sampled the lower Main Zone, the Platreef and its granitic footwall. A detailed account of the geology of BV-1 and MO-1 was given by [Ashwal et al. \(2005\)](#) and [Roelofse and Ashwal \(2012\)](#), respectively.

3. Analytical methodology

Polished thin sections on the order of 150–190 μm thick were prepared from rocks sampled from the Bellevue and Moordkopje drill cores ([Fig. 2](#)). Subhedral and presumably cumulus plagioclase crystals were selected using a petrographic microscope to ensure that altered areas were excluded. Material around selected crystals was removed using a dental drill equipped with different drill bits and the crystals were subsequently removed from the thin section through immersion in acetone. The individual plagioclase crystals were then broken using a surgical blade into a core domain and several rim domains that were combined for subsequent

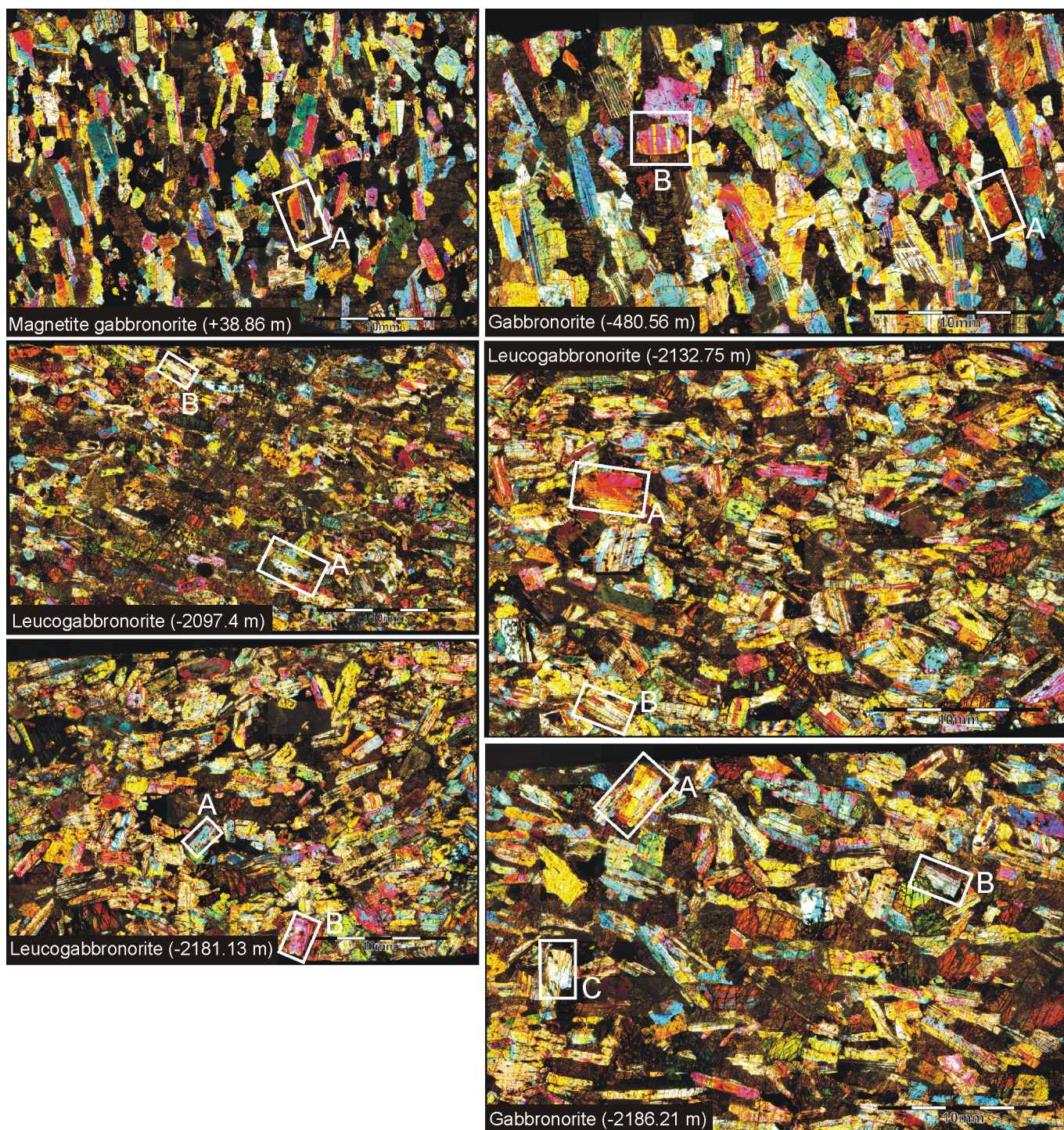


Fig. 2. Photomicrograph collages of polished thick sections showing plagioclase crystals sampled as part of this study. Cross polarized, transmitted light.

analysis. The resultant samples were cleaned using dilute nitric acid. After addition of a mixed ^{87}Rb - ^{84}Sr tracer, plagioclase crystals were digested in hydrofluoric acid on a hotplate at 160°C overnight. Digested samples were dried and taken up in 2N hydrochloric acid. Rb and Sr were separated using cation ion-exchange chromatography (Romer et al., 2005). The samples were loaded on Ta single-filaments using a mixture of hydrochloric and phosphoric acid and analysed on a Thermo-Triton mass-spectrometer at the GFZ German Research Centre for Geosciences, Potsdam. Rb and Sr were analyzed by static multicollection and dynamic multicollection, respectively. The obtained $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were

normalised to $^{86}\text{Sr}/^{88}\text{Sr}=0.1194$ and corrected for tracer contribution. Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were then calculated for an age of 2054.4 Ma (Scoates and Friedman, 2008). During the measurement period, Sr reference material NBS 987 gave a value of 0.701250 ± 18 (2σ , $n=10$). All analytical uncertainties are expressed at the $2\sigma_m$ level.

4. Results

Sr-isotopic data obtained on the studied core and rim domains of plagioclase crystals are presented in Table 1 and compared

Table 1
Sr isotopic data for plagioclase core and rim domains.

Elevation (m)	Lithology	Crystal	Core/Rim	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$ (2054.4 Ma)
+38.86	Magnetite gabbroonorite	A	C	0.707798 ± 48	3.9E-05	0.707796 ± 48
−480.56	Gabbroonorite	A	C	0.708321 ± 40	1.7E-03	0.708272 ± 44
		A	R	0.707249 ± 32	9.6E-04	0.707220 ± 33
		B	R	0.706891 ± 14	1.6E-03	0.706843 ± 16
		B	C	0.706914 ± 20	1.2E-03	0.706880 ± 22
−2097.4	Leucogabbroonorite	A	R	0.710813 ± 18	8.6E-05	0.710810 ± 18
		A	C	0.711724 ± 16	4.4E-05	0.711723 ± 16
		B	R	0.709174 ± 12	2.8E-04	0.709166 ± 14
		B	C	0.709483 ± 54	6.1E-05	0.709481 ± 54
		A	R	0.708441 ± 16	3.1E-05	0.708440 ± 16
−2132.75	Leucogabbroonorite	A	C	0.709869 ± 19	6.2E-06	0.709869 ± 19
		B	R	0.709372 ± 76	1.3E-05	0.709371 ± 76
		B	C	0.708692 ± 16	2.9E-05	0.708691 ± 16
		A	R	0.708300 ± 32	4.4E-04	0.708287 ± 34
−2181.13	Leucogabbroonorite	A	C	0.708442 ± 18	1.6E-04	0.708438 ± 18
		B	R	0.713588 ± 38	3.3E-04	0.713578 ± 39
		B	C	0.710338 ± 20	1.4E-05	0.710338 ± 20
		A	R	0.707515 ± 20	3.5E-03	0.707410 ± 20
−2186.21	Gabbroonorite	A	C	0.710717 ± 38	1.1E-03	0.710684 ± 40
		B	C	0.707576 ± 14	4.3E-03	0.707449 ± 16
		C	C	0.708562 ± 95	6.1E-04	0.708544 ± 98

Elevation reported relative to Upper Zone – Main Zone boundary.

Table 2
Mineral chemistry of plagioclase as determined by Ashwal et al. (2005) and Roelofse and Ashwal (2012). Numbers reported are the averages of the total number of analyses performed per sample (n). Depths are reported relative to the Upper Zone–Main Zone boundary.

Depth (m)	SiO ₂	Al ₂ O ₃	FeO	CaO	Na ₂ O	K ₂ O	Total	An% (min)	An% (max)	An% (ave)	An% (1-σ SD)	n
+38.86	54.01	30.81	0.62	11.32	5.06	0.32	102.93	51.6	60.2	56.6	–	11
−480.56	52.78	30.63	0.43	12.14	4.78	0.30	101.28	54.5	59.3	58.4	–	10
−2097.4	49.22	32.20	0.33	15.07	3.06	0.18	100.06	67.6	74.5	72.4	2.1	11
−2132.75	51.32	30.53	0.36	13.75	3.08	0.18	99.22	67.2	72.9	70.4	1.8	9
−2181.13	51.22	30.86	0.40	13.97	2.98	0.16	99.59	68.9	73.1	71.5	1.4	9
−2186.21	51.47	30.97	0.36	14.04	2.92	0.14	99.90	67.5	74.6	72.0	2.6	9

graphically to variations in modal mineralogy and plagioclase composition (given in Table 2) with varying depth in the BV-1 and MO-1 drill cores in Fig. 3. A sample from the upper part of the Main Zone above the troctolite layer (see Fig. 3 for location of the troctolite layer), occurring 480.56 m below the Upper Zone–Main Zone boundary shows both isotopically homogenous plagioclase with initial $^{87}\text{Sr}/^{86}\text{Sr}$ of ~ 0.7068 and heterogeneous plagioclase with a rim considerably less radiogenic than its core (~ 0.7072 vs ~ 0.7083). Much larger spreads of initial $^{87}\text{Sr}/^{86}\text{Sr}$ are seen both between individual plagioclase crystals and between core and rim domains in samples occurring in the lower Main Zone below the troctolite layer. For instance, in a sample from 2097.4 m below the Upper Zone–Main Zone boundary, one plagioclase crystal showed a rim with an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of ~ 0.7092 and a core with an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of ~ 0.7095 , co-existing with plagioclase with a rim exhibiting an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of ~ 0.7108 and a core with an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of ~ 0.7117 . In other samples, for example those from 2132.75 m and 2181.13 m below the Upper Zone–Main Zone boundary, the cores of some plagioclase crystals are less radiogenic than the rims, whereas in other plagioclase crystals occurring within the same rocks, the rims are less radiogenic than the cores. Furthermore, the spread in initial $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic compositions (~ 0.7069 – ~ 0.7136) determined for plagioclase core and rim domains in the present study is in stark contrast to the more-or-less uniform values found for the Main (~ 0.7085) and Upper (~ 0.7075) zones when analysing whole-rocks or plagioclase mineral separates (Kruger, 2001), demonstrating how the complexity of isotopic disequilibrium between and within cumulate crystals can be missed in bulk analysis.

5. Discussion

5.1. A model to account for Sr isotopic disequilibrium in plagioclase

Recent work (Roelofse and Ashwal, 2012) on the lower Main Zone within the Northern Limb of the Bushveld Complex has shown the presence of distinct Sr-isotopic disequilibrium between co-existing plagioclase and orthopyroxene, with the former typically showing initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of ~ 0.708 and the latter up to ~ 0.711 . The fact that these values were obtained on bulk mineral separates merely suggests an average $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.708 for plagioclase within these rocks, which masks the significant inter- and intragranular Sr-isotopic variations that we report in this study.

Roelofse and Ashwal (2012) showed convincingly that the isotopic composition of the Main Zone could not be modelled using any of the immediate country rocks to the RLS as contaminants. Additionally, various crystalline basement rocks could also be excluded as potential contaminants. The only likely contaminants based on geochemical considerations appeared to be upper and lower crust of the Kaapvaal craton as exposed within the Vredefort Dome, represented by the Outer Granite Gneiss (OGG) and the Inlandsee Leucogranofels (ILG), respectively.

The model of Roelofse and Ashwal (2012) assumed that the mantle at 2054.4 Ma had $^{87}\text{Sr}/^{86}\text{Sr} = 0.702$ and $\epsilon_{\text{Nd}} = +2.0$, in line with the choice of Maier et al. (2000). To gain an understanding of the variation of Sr and Nd concentrations in mantle derived melts, they used the pMELTS software package of Ghiorso et al. (2002) and the composition of a spinel peridotite as reported by McDonough (1990) as

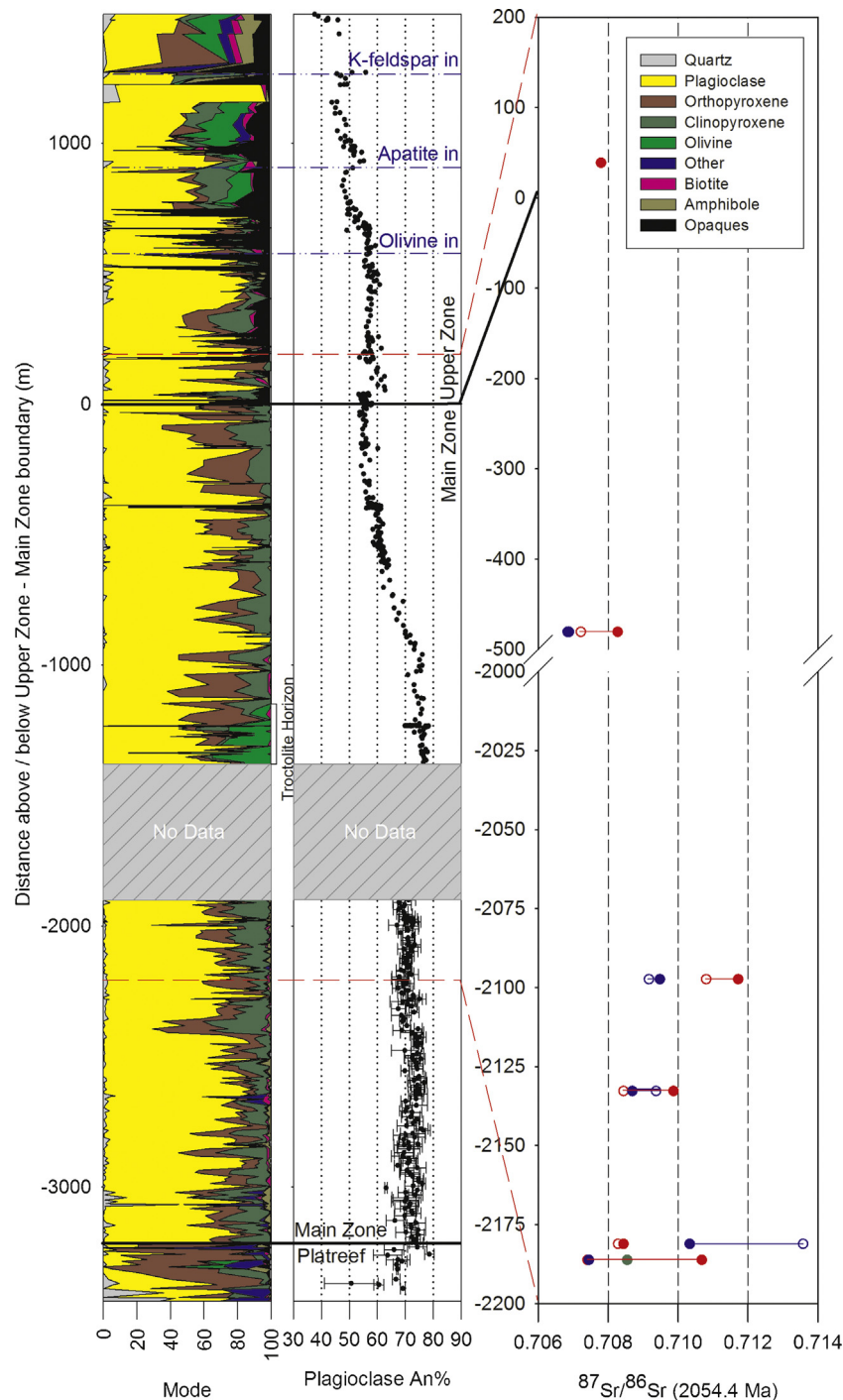


Fig. 3. Summary showing variation in modal mineralogy, plagioclase An% (Ashwal et al., 2005; Roelofse and Ashwal, 2012) (with 1σ errors for some analyses) and $^{87}\text{Sr}/^{86}\text{Sr}$ for core (solid circles) and rim (open circles) domains of plagioclase crystals analysed isotopically in this study. Error bars ($2\sigma_m$) for $^{87}\text{Sr}/^{86}\text{Sr}$ are smaller than the symbols used. Depths (in metres) are reported relative to the Upper Zone–Main Zone boundary.

starting composition. The mineralogical compositions of the refractory restites were used to calculate bulk partition coefficients using the equations of Shaw (1970) for the case of equilibrium melting and the partition coefficients for Sr and Nd as reported by Arndt et al. (1993). Sr and Nd concentrations in melts generated by different degrees of partial melting were then calculated using the Sr and Nd concentrations of primitive mantle as reported by Hofmann (1988). For the generation of partial melts of the Vredefort crustal end-members, the approach of Maier et al. (2000) was followed using the results of Patino-Douce and Beard (1995) for the isobaric

melting behavior of synthetic biotite-gneiss at a pressure of 10 kbar. Additional information pertaining to the model can be found in Roelofse and Ashwal (2012).

The ILG and OGG have (on average) similar major and trace element and Nd isotopic compositions, which may explain the lack of significant heterogeneities between and within minerals occurring within the RLS when considering the major element, trace element and Nd isotopic data (Roelofse and Ashwal, 2012). The present model (Fig. 4) suggests that the rocks of the lower Main Zone of the RLS represent the products of mantle-derived

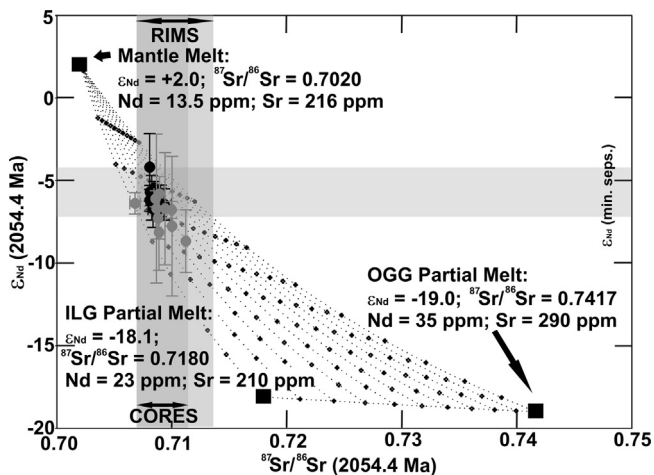


Fig. 4. Isotopic mixing model showing how the isotopic compositions of plagioclase core and rim domains are consistent with interaction between a primary mantle melt and partial melts derived from the Kaapvaal craton, represented by rocks exposed in the Vredefort dome. Isotopic data for plagioclase (large black dots) and orthopyroxene (grey dots) obtained on mineral separates (Roelofse and Ashwal, 2012) are shown for comparison. Vertical shaded areas show the ranges in $^{87}\text{Sr}/^{86}\text{Sr}$ for plagioclase core and rim domains from the current study and horizontal shaded area the range of ϵ_{Nd} values obtained on plagioclase mineral separates (Roelofse and Ashwal, 2012) that may be used as a proxy for ϵ_{Nd} values for plagioclase cores and rims. The derivation of the model has been explained in detail by Roelofse and Ashwal (2012).

magmas that were intruded into a sub-compartmentalized staging chamber in which these magmas were contaminated by between 20% and 30% of mixtures of upper and lower crustal material whilst fractionating, followed by subsequent blending of crystal mushes derived from these sub-compartments en-route to final emplacement. The fact that plagioclase bulk mineral separates typically yield initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of $\sim 0.708\text{--}0.709$ (Roelofse and Ashwal, 2012) suggests that most of the plagioclase that entered the presently exposed Bushveld Complex magma chamber crystallised in a sub-compartment contaminated mostly by lower-crustal derived melts, with a much smaller contribution of plagioclase from a sub-compartment contaminated by more radiogenic, upper-crustal derived melts. Fig. 5 shows a schematic representation of the morphology of the postulated sub-Bushveld staging chamber, which is a refinement of the model proposed by Roelofse and Ashwal (2012), taking into account the present data set.

It should be noted that the model developed here assumes bulk melting and mixing of crustal end-members of the Kaapvaal craton (see Maier et al., 2000 and Roelofse and Ashwal, 2012). The model

is therefore an over-simplification. It applies for the relative contributions of the various end-members to the Sr budget, but it does not necessarily reflect the relative amount of assimilated rocks, because of two reasons: (i) the content and Sr-isotopic composition of the contaminating end-members may vary through time and (ii) the content of Sr in the mantle-derived magma may vary temporally as well. Anatexis preferentially yields melts enriched in certain low-melting constituents and its chemical and isotopic fingerprint may vary in relation to both the degree of partial melting and the previous history of melt extraction. Thus, end-members dominated by anatectic melts may show varied chemical and isotopic composition due to progressive melting and repeated melt extraction (Zeng et al., 2005; Vasquez et al., 2009). Furthermore, the timing of magma contamination is important, as crystallization of plagioclase retracts Sr from the melt and, thus, for a given amount of contamination, the Sr-isotopic composition of plagioclase from a melt with low Sr content will be more strongly shifted towards the composition of the contaminant than plagioclase from a melt with high Sr content. Each magma compartment has its own history of crystallization and contamination, behaving as an open system and having compositionally variable contaminating components. Complications like selective mobilization of elements during anatexis, however, will likely only affect the degrees of contamination required for modelling of the present results, whilst still maintaining the validity of the proposed model.

5.2. Competing hypotheses

The fact that some plagioclase crystals have rims more radiogenic than cores, whereas in others (occurring within the same rock) the reverse is true, argues against the operation of late-stage metasomatic processes or the percolation of residual liquids with isotopic compositions different from that of the compacting crystal mush, as have been proposed by McBirney and Creaser (2003) and Chutas et al. (2012) to account for isotopic disequilibrium within the Skaergaard Intrusion and the Lower, Critical and Upper zones of the Bushveld Complex, respectively. The present results, therefore, do not appear to be reconcilable with the operation of metasomatic processes in the Main and Upper zones of the Northern Limb of the Bushveld Complex.

The Sr-isotopic composition of the RLS can neither be explained satisfactorily by melts derived from contemporaneous depleted mantle ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7021$; DePaolo and Wasserburg, 1977) that were contaminated by the immediate country rocks to the presently exposed part of the RLS (see Prevec et al., 2005; Roelofse and Ashwal, 2012; Chutas et al., 2012; Yang et al., 2013). This suggests that isotopic heterogeneities were not caused as a result of an interplay between wall/roof rock contamination and magma cham-

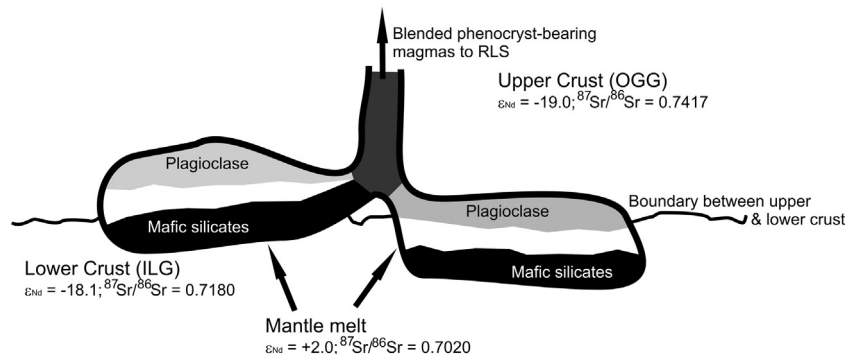


Fig. 5. Schematic representation showing a possible morphology for a sub-Bushveld staging chamber that may explain the current dataset. Isotopic values are calculated for an age of 2054.4 Ma (Scoates and Friedman, 2008). The present model represents a refinement of the model proposed by Roelofse and Ashwal (2012). (ILG = Lower crust and OGG = upper crust as exposed in the Vredefort Dome).

ber dynamics within the RLS, as was argued to be the case for the Rum Intrusion by [Tepley and Davidson \(2003\)](#).

Furthermore, isotopic heterogeneity of plagioclase cannot be explained through interaction of mantle-derived magma with sub-continental lithospheric mantle, as plagioclase would not have been stable at the required depths for such interactions to take place ([James et al., 2001](#)), and will hence only be able to record isotopic disequilibrium at shallower, most likely, crustal levels of emplacement. The present results cannot exclude the involvement of a sub-continental lithospheric mantle component for the magmas that gave rise to the RLS ([Richardson and Shirey, 2008](#)), but the results nevertheless show that at least some crustal contamination would have been needed to result in the observed isotopic heterogeneities.

Models to account for isotopic heterogeneity within the RLS that invoke the mixing of crystal mushes as a result of subsidence during cooling ([Yang et al., 2013](#)) or the density-driven mixing of minerals from isotopically distinct magma pulses ([Prevec et al., 2005](#)) (as has mostly been applied to explain isotopic heterogeneity within the Upper Critical Zone of the RLS) rest on the assumption that magma pulses that entered the Bushveld Complex had different isotopic compositions prior to emplacement, that the magmas crystallised their respective liquidus phases without mixing as a result of significant density contrasts and that the minerals that crystallised then became incorporated into the same rocks. Such models appear untenable for the Main Zone of the RLS, where compositionally very similar magma pulses would have been prone to mixing. This would have tended to result in isotopically homogenous mineral compositions. Similarly, the degree of mixing experienced by successive layers should have been near constant (which appears highly unlikely), for otherwise, taking into account the large spread in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios encountered in the present study, whole-rock $^{87}\text{Sr}/^{86}\text{Sr}$ ratios should show considerably larger variations within the Main Zone if such processes were operational than what is the case (see [Kruger, 2001](#); [Roelofse and Ashwal, 2012](#)).

5.3. Further implications for layered intrusion studies and ore formation processes

The existence of both inter- and intragranular isotopic disequilibrium shows that caution should be exercised when isotopically analysing bulk mineral separates or whole-rocks and even when inferences are drawn from progressive leaching experiments ([Chutas et al., 2012](#)), when studying the rocks of layered mafic intrusions. Furthermore, the present results suggest that the Bushveld Complex, and potentially other layered mafic intrusions, most likely do not represent simple systems undergoing differentiation in-situ, but are rather intricately complex products of mantle melting followed by varying degrees of crustal contamination within multi-level staging chambers in which magmas fractionate to varying degrees prior to final emplacement. Layered intrusions, therefore, represent snapshots within the development of magmatic mush columns ([Marsh, 2004, 2006, 2013](#)). Importantly, the petrogenetic model proposed above for the Main Zone of the Northern Limb of the Bushveld Complex suggests that the Main Zone could not have been the source of the Ni-Cu-PGE mineralisation of the Platreef, which lends additional support for the notion that PGE-rich sulfides were entrained from deeper levels in the magma that gave rise to the Platreef (cf. [McDonald and Holwell, 2007](#); [McDonald et al., 2009](#); [Holwell et al., 2011](#)).

6. Conclusions

The present study shows the existence of multiple, isotopically heterogeneous populations of plagioclase occurring within

the Main Zone of the Northern Limb of the RLS. Our results cannot be satisfactorily explained with reference to models invoking gravity-driven mixing of isotopically distinct minerals within the RLS magma chamber, or models invoking metasomatism or advection of contaminants moving through crystal piles within the RLS magma chamber. The present dataset, however, is consistent with a model in which the lower Main Zone of the RLS represents the products of mantle-derived magmas that were intruded into a sub-compartmentalized staging chamber in which the magmas were contaminated by mixtures of upper and lower crustal material whilst fractionating, followed by subsequent blending of crystal mushes derived from these sub-compartments en-route to final emplacement. The RLS of the Bushveld Complex, in our opinion, may therefore be regarded as a high-level snapshot of a developing magmatic mush column. Additionally, the existence of both inter- and intragranular isotopic disequilibrium in rocks of the RLS suggests that extreme caution should be exercised in the interpretation of isotopic data obtained from progressive leaching experiments and that proper in-situ analytical methods (e.g., micro-drilling or LA-ICP-MS) should rather be utilised.

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