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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.

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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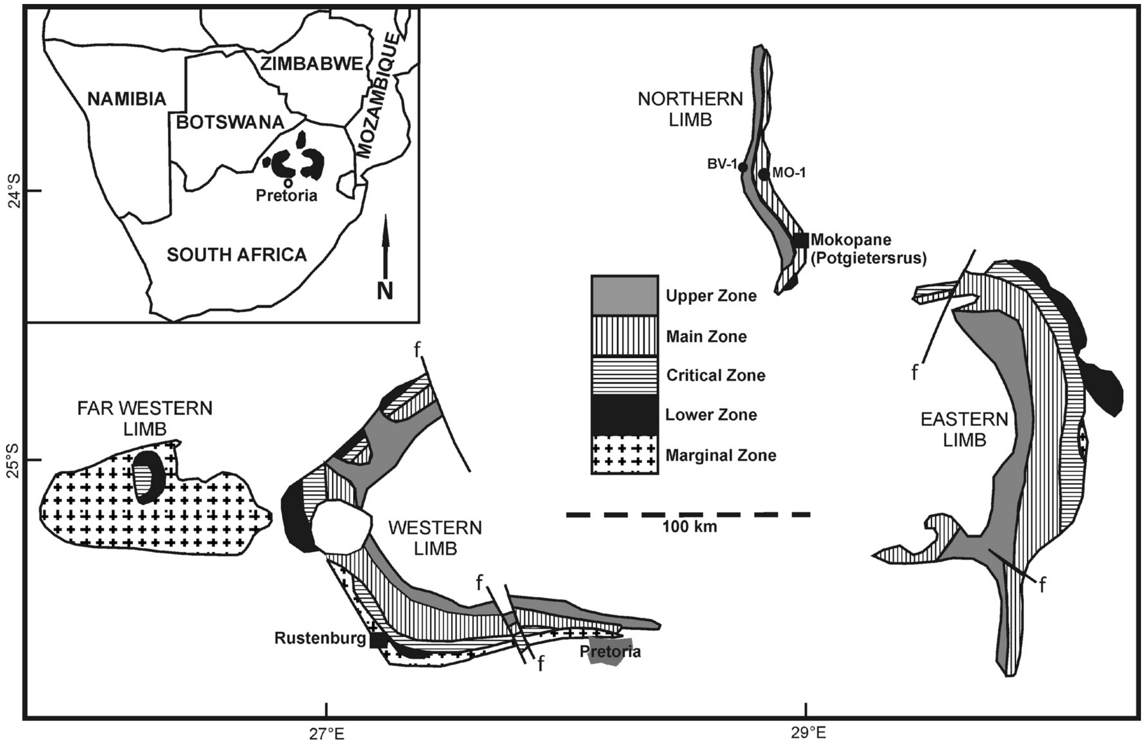

Fig. 1. Geological map of the Bushveld Complex showing the locations of the various limbs and the positions of the BV-1 and MO-1 drill holes. Inset shows the location of the Bushveld Complex within South Africa.

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 km^2, 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; Lehloenya and Roelofse, 2013 McDonald et al., 2009; Holwell et al., 2011; Roelofse and Ashwal, 2012; Lehloenya 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; Lehloenya and Roelofse, 2013).

Samples analyzed during the present study originated from the 2950 m deep Bellevue (BV-1) and the 1563 m deep Moorkopje (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