Geological setting and concentration of scandium in the Flatreef and eastern limb chromitites of the Bushveld Complex

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Synopsis

Scandium is an important industrial metal for which demand is projected to increase in the future. Although many Sc deposits are secondary, Sc is scavenged by clinopyroxene during fractional crystallization of primary, mafic-ultramafic magmas. Sc may thus occur in sub-economic concentrations in mafic-ultramafic intrusions. In this work, we present new data on the concentration of Sc in the Bushveld Complex (BC) of South Africa. The eastern and western limbs of the BC are considered to be largely pristine, primary magmatic deposits, whereas the northern limb shows evidence of large-scale, localized crustal contamination. Samples from the primary magmatic cumulates of the eastern limb, from the mineralized Flatreef of the northern limb, and from the crustal-contaminated Footwall Assimilation Zone (FAZ) of the Flatreef were analysed for Sc. Despite the FAZ containing abundant clinopyroxene, interpreted to have recrystallized from the original cumulates in the presence of melted sedimentary rocks, no significant differences are seen in the concentration of Sc compared to other cumulate rocks of the BC containing less-abundant clinopyroxene. The concentration of Sc in the analysed samples is mainly controlled by mineralogy, with anorthosites, chromitites, and harzburgites containing under 20 ppm, and norites and pyroxenites containing 20–40 ppm. The parapyroxenites of the FAZ are less enriched in Sc than expected, suggesting that Sc may have been lost during alteration and recrystallization.

Keywords

scandium, Flatreef, Bushveld Complex, rare earth elements, igneous processes.

Introduction

The Bushveld Complex (BC) (Figure 1), which is located in the north of South Africa, is a gigantic assemblage of intrusive magmatic and associated rocks (e.g. Willemse, 1966) estimated to be 2.055 billion years old (Zeh et al., 2015). The mafic to ultramafic phase of the BC is termed the Rustenburg Layered Suite (RLS) (Willemse, 1966; Cawthorn and Webb, 2001; Cawthorn et al., 2006; Kruger, 2005). Associated with the RLS are the later acid suites (the Lebowa Granite and Rashoop Granophyrc suites) (Von Gruenewaldt, Sharpe, and Hatton, 1985; Van Tongeren, Mathez, and Kelemen, 2010), as well as smaller intrusive bodies (sills, dykes and magmatic pipes) (e.g. Tarkian and Stumpf, 1973; Harmer and Sharpe, 1985; Viljoen and Scoon, 1985; Scoon and Mitchell, 1994; 2004).

The BC boasts many different types of economic mineralization. It is the world’s largest single repository of the six platinum group elements (PGE) (e.g. Cawthorn et al., 2002; Arndt et al., 2005), with the pyroxenitic Merensky Reef accounting for much of the PGE production (e.g. Cousins, 1966; Lee, 1996; Cawthorn et al., 2002). Also closely associated with the PGE are the laterally continuous chromitite layers (e.g. Von Gruenewaldt, Hatton, and Merkle et al., 1986; Lee and Parry, 1988; Kinnaird et al., 2002; Oberthür et al., 2015), a major source of the world’s chromium (e.g. Cameron & Desborough, 1966; Teigler and Eales, 1993; Cawthorn et al., 2006). Grades of PGE in the chromitite layers range from below 0.5 ppm up to 10 ppm in the UG-2 chromitite (Von Gruenewaldt et al., 1986; Lee & Parry, 1988; Lee, 1996; Kinnaird et al., 2002; Arndt et al., 2005). The Main Magnetite Layer (MML) is exploited for vanadium (Cawthorn and Webb, 2001) and also hosts titanium resources that may be exploitable in the future (Cawthorn et al., 2006; Harney and Von Gruenewaldt, 1995). The BC is also a source of the base metals Co, Cu and Ni (e.g. Cramer, 2001; Jones, 2005) as well as gold (e.g. Godel, Barnes, Maier, 2007; Van der Merwe, Viljoen, and Knoper et al., 2012) all of which are closely associated with the PGE and are typically separated from them during mineral processing to be sold as secondary commodities (e.g. Jones, 2005; Jacobs, 2006). Tin has also been mined from intrusive pipes associated with the granites of the BC (Von Gruenewaldt and Strydom, 1985; Coetzee and Twist, 1989; Kinnaird and McDonald, 2005).
Geological setting and concentration of scandium

Figure 1—(a) The outcropping rocks of the Rustenburg Layered Suite of the BC, indicating the three main limbs (north, east and west) of the Complex. (b) Magnified view of the southern part of the northern limb where samples originated on the properties of Turfspruit and Macalacaskop (modified after Grobler et al., 2019)

Despite all it has produced so far, the BC may still be host to metal and other commodities that have yet to be exploited.

Scandium

Due to its similar applications in industry, similar chemical properties, and occurrence alongside the lanthanides, scandium may be classified as one of the rare earth elements (REE) (Williams-Jones and Vasyukova, 2018; Wang et al., 2021; Xie et al., 2014). Sc concentrates are traded alongside REE concentrates, but most REE deposits are not significantly enriched in Sc (Williams-Jones and Vasyukova, 2018). However, Sc is mainly mined as a by-product from deposits that primarily exploit the other REE (Xiao et al., 2020; Wang et al., 2021).

Scandium is considered a valuable metal because of its uses in current technological developments. One of the main uses is to reduce the mass of aircraft and vehicles, which may be accomplished by substituting a lightweight, strong alloy of Sc and Al for other metals (Williams-Jones and Vasyukova, 2018; Hughes, Andersen, and Driscoll, 2021; Wang et al., 2021). It is also used for solid oxide fuel cells (Hughes, Andersen, and Driscoll, 2021; European Commission, 2021; Wang et al., 2021), which can be used to produce electricity on scales ranging from portable battery chargers to generators for fuel plants (Minh, 2004). Scandium is traded globally alongside the rare earth elements as well as ‘minor’ metals such as tellurium, antimony, and bismuth (Shanghai Metals Market, 2022). According to the European Commission (2021), the main world producers of Sc are China, Russia, and the Ukraine, with China producing over two-thirds of the world’s supply. With global events trending as they are, the Sc supply chain from Russia and the Ukraine is particularly at risk. Disruption of supply could result in shortages of all commodities supplied by these two countries, having wide-ranging effects on the various industries which rely upon them (e.g. Burke, 2022; Johnston, 2022; Kahn, 2022). In the case of Sc, these industries include the manufacture of semiconductors and batteries, as well as the aeronautics and renewable energy sectors.

Unlike the other REE, Sc is compatible with early rock-forming minerals. In the 3+ oxidation state, it may substitute for Mg and Fe in minerals such as pyroxene and amphibole (Williams-Jones and Vasyukova, 2018). Sc is known to be compatible with clinopyroxene during crystallization, but less compatible with orthopyroxene and incompatible with plagioclase and olivine (Allègre et al., 1977; Morimoto et al., 1988; Nielsen, Gallaham, and Newberger, 1992; Williams-Jones and Vasyukova, 2018). There exists a clinopyroxene that contains Sc as an essential element, namely jervisite (NaScSiO₅) (Hawthorne and Grundy, 1973; Morimoto et al., 1988; Deer, Howie, Howie, and Zussman, 2013; Williams-Jones & Vasyukova, 2018). In the world’s largest single resource of Sc, China’s Bayan Obo deposit, Sc is found in aegirine of hydrothermal origin (Williams-Jones and Vasyukova, 2018). However, Sc may be found enriched in any of the clinopyroxenes associated with mafic-ultramafic intrusive deposits, such as augite and hedenbergite, where it may substitute for Mg or Fe in the M-site (Morimoto et al., 1988; Williams-Jones and Vasyukova, 2018; Wang et al., 2021). The first stage of Sc enrichment in any deposit may be considered to be fractional crystallization, which produces Sc-enriched clinopyroxene in rocks of mafic to ultramafic composition (Wang et al., 2021). Further stages of Sc enrichment may include hydrothermal activity, or surficial weathering in lateritic environments such as the bauxite deposits in Madagascar or Ni-Co laterites of New Caledonia (Taylor et al., 2005; Williams-Jones and Vasyukova, 2018; Teitler et al., 2019; Wang et al., 2021). Lateritic Sc enrichment commonly occurs in iron oxide deposits overlying ultramafic intrusive pipes (Ural-Alaskan type intrusions), which is the case for the New Caledonian deposits (Teitler et al., 2019) and for the Sunrise Ni-Co laterite of Australia, which is sporadically enriched in Pt as well as Sc (SRK Consulting, 2018).

The methods used to extract Sc are mainly hydrometallurgical (Xiao et al., 2020). Like the other rare earth elements, Sc may be roasted to produce a concentrate which is then leached by acids such as HCl, HNO₃, and H₂SO₄ (Xie et al., 2014). At Bayan Obo, Sc is extracted from tailings that have already been processed for Fe and the other REE (Williams-Jones and Vasyukova, 2018; Wang et al., 2021). Aegirine at Bayan Obo is roasted before leaching to decompose it (Williams-Jones and Vasyukova, 2018). Scandium occurring in oxidized deposits such as Ni-Co laterites is particularly suited to hydrometallurgical extraction since it has already been weathered out of the silicates and occurs in oxide minerals such as goethite (Teitler et al., 2019).

Since Sc is mainly produced as a by-product to other elements (Xiao et al., 2020), cut-off grades vary considerably between operations. According to Williams-Jones and Vasyukova, (2018) the average grade of Sc in currently exploited as well as reserve
deposits across the world varies from 50–200 ppm. Teitler et al. (2019) consider high-grade lateritic Sc deposits to be those over 300 ppm, while those of 100 ppm and below are generally too low to be exploited, except for Sc as a by-product. Concentrations of Sc in pyroxenitic rocks of notable mafic-ultramafic intrusions such as the Russian Urals and similar intrusions in China range from 54 to 135 ppm (Wang et al., 2021).

Although Sc is usually not significantly enriched in layered intrusions (Wang et al., 2021), it is of both scientific and economic interest to investigate this element in the BC, particularly the ore-bearing horizons of the Flatreef and their footwalls, the latter being significantly contaminated with crustal material (Keir-Sage et al., 2021; Maier et al., 2021) and are not considered to represent a typical igneous BC cumulate.

The Flatreef

The northern limb (see Figure 1b) of the BC lacks the consistent and ubiquitous mineral layering of the RLS of the western and eastern limbs, although it does host PGE mineralization in a horizon of sulphide-bearing pyroxenite broadly similar to the Merensky Reef, which is known as the Flatreef (Kinnaird and McDonald, 2005; Van der Merwe, Viljoen and Knoper, 2012). The Flatreef represents a thick, almost horizontal, laterally continuous down-dip extension of the Flatreef (Hutchinson and Kinnaird, 2005; Maier et al., 2021) which hosts economic grades of PGE (average grade of 3.8 ppm Pt+Pd+Rh+Au) over a lithological interval which may be up to 90 m thick (Grobler et al., 2019). It was only recently discovered (Maier et al., 2021), and development is under way to exploit this reef for PGE, Au, Ni, and Cu (Grobler et al., 2019; McFall et al., 2019).

The ‘reef’ portion of these rocks, representing the main target for exploitation of PGE and other metals, consists of sulphide-mineralized layers of dunite, harzburgite, and pyroxenite containing chromite stringers of no more than ca. 2 cm thick (Yudovskaya et al., 2017; Grobler et al., 2019). However, PGE mineralization associated with Ni- and Cu-bearing sulphides may extend below the reef for tens of metres into the footwall (Yudovskaya et al., 2017; Grobler et al., 2019). These rocks were emplaced upon the older Transvaal Supergrroup sediments, and therefore they have a much greater degree of contamination (Keir-Sage et al., 2021), though the Flatreef is generally considered to be less contaminated than the up-dip Flatreef (Grobler et al., 2019; Maier et al., 2021).

Directly below the Flatreef, sporadic sulphide mineralization appears in a pile of rocks that may contain sedimentary xenoliths (Kinnaird and McDonald, 2005; Yudovskaya et al., 2017; Grobler et al., 2019). The original composition of these xenoliths ranges from carbonate (dolostone) to pelitic (shale) and quartzitic, and also includes evaporitic rocks (Hutchinson and Kinnaird, 2005; Grobler et al., 2019). The rocks of this pile are layered and may be overlain by a chromitite seam recognized as correlating with the UG-2 elsewhere in the BC (Grobler et al., 2019; Langa et al., 2021). Where sedimentary xenoliths are not abundant, this zone is termed the Footwall Cyclic Unit (FCU) (Grobler et al., 2019).

In the central region of the Flatreef Project area, the most sedimentary xenoliths may be found in the FCU (Yudovskaya et al., 2017; Grobler et al., 2019). In this region, the FCU is also more variable, consisting of abundant pegmatitic mafic and ultramafic rocks, and some rock types appear to have been altered (Grobler et al., 2019). These rocks, where interaction of magma with sediment is highly evident, are termed the Footwall Assimilation Zone (FAZ) (Grobler et al., 2019; Mayer et al., 2021).

Xenoliths found in this zone are often metamorphosed and recrystallized; for example, argillite is often altered to hornfels and dolostones or limestones form marble and localized skarn assemblages (Grobler et al., 2019). Sporadic zones of pegmatoidal ‘parapyroxenite’ and serpentinitized ‘paraharzburgite’ occur in these rocks (Yudovskaya et al., 2017; Grobler et al., 2019). They represent an alteration of the normal mafic-ultramafic assemblage, and may be interpreted as products of an ultramafic magma that was contaminated (with Ca originating from dolostone/limestone) by the sediments, and crystallized in the presence of volatiles resulting from melting of sedimentary xenoliths (Grobler et al., 2019).

Below the entire Flatreef sequence, silts of dunite, pyroxenite, and harzburgite may be found intruding the Transvaal Supergroup (Grobler et al., 2019; Yudovskaya et al., 2021). The package of rocks from the lower chromitite seam up to the noritic cyclic units above the Flatreef shows better mineral layering with less contamination than the Flatreef, and can be well correlated with the interval from the UG-2 up to the Bastard Reef (above the Merensky Reef) in the western and eastern limbs of the BC (Grobler et al., 2019; Beukes et al., 2021; Mayer et al., 2021).

In parts of the FAZ, as is evident from several exploration boreholes drilled by Ivanplats for the Flatreef Project, pegmatoidal clinopyroxenite is well developed over many metres of depth. This clinopyroxenite belongs to the parapyroxenite lithologies that have been affected by contamination with sedimentary material (Grobler et al., 2019). It occurs close to the footwall of the Flatreef mineralized zone and therefore provides an important starting point when studying the Sc content of the BC, since this metal is almost always mined as a by-product to other commodities.

The purpose of this paper is not only to evaluate the scandium content of the Flatreef, but also to provide an overview of existing Sc data for the Critical Zone (CZ) of the Rustenburg Layered Suite of the BC. This is then compared to global deposits and the average Sc contents of mafic to ultramafic igneous rocks. The authors intend this paper to serve as a repository of knowledge as well as a discussion of possibilities pertaining to the economic potential of existing South African mineral ores.

Samples and methods

Samples analysed for scandium in this study include clinopyroxenites from the Flatreef (described below), as well as chromitite and associated silicate rocks (pyroxenite, norite, anorthosite) of the Critical Zone of the eastern BC (see Figure 1a). Preceding Sc analysis, major elements in all samples were analysed by XRF and the normative mineralogy was calculated. The eastern BC samples originate from borehole WV-30 drilled on the Winterveld property of Samancor’s Eastern Chrome Mine. A thorough petrological and mineralogical overview of these samples, as well as their location relative to the eastern limb of the BC, is given in Kotzé and Gauert (2020). Figures 2a–d show typical mineral and textural characteristics of these samples. Sample WV52.1 (Figure 2b) represents the first anorthosite of the Critical Zone, which marks the start of the Upper Critical Zone (UCZ), which is defined by the presence of cumulus plagioclase (e.g. Kinnaird et al., 2002). Sample WV-65 is a massive, nearly nonmonomineralic chromitite with variable grain size from the LG-6, which is mined for Cr at Winterveld. All of the samples from the eastern Bushveld used in this study represent a relatively unaltered, nearly pristine magmatic assemblage that is likely representative of equivalent rocks throughout the eastern and southern limbs of the BC.
Geological setting and concentration of scandium as described in Yudovskaya were judged to be representative of typical lower reef facies (pegmatoidal orthopyroxenite, M1-upper). These two samples respectively of harzburgite (M1-lower) and pyroxenite for this study are all mineralized with regard to PGE and the base Peters by Ivanplats. The methodology for these analyses is described in IV. Assays of Pt, Pd, Rh, Au, Cr, Ni, Cu, and S were provided in Figure 1b. The borehole numbers may be found in Tables III the northern limb where these boreholes were drilled is illustrated boreholes, which are described in Grobler et al. (2019). Both samples contain visible disseminated sulphide mineralization, with the main sulphide minerals being pentlandite, pyrrhotite, and chalcopyrite. The pyroxenite sample (KO32) contains abundant green clinopyroxene. The harzburgite sample (KO2) is relatively high-grade with total Pt+Pd+Rh+Au ca. 5.5 ppm. The pyroxenite, on the other hand, is of lower grade, with Pt+Pd+Rh+Au ca. 1 ppm. The pyroxenite also contains about 0.4 w% Cr, likely from minor chromite, but possibly also in clinopyroxene. The harzburgite contains only 0.5 ppm Cr. Textures and mineralogy of these two samples are depicted in Figure 3a-d. Notably, these samples are much more altered compared to the eastern limb samples, with abundant serpentinization of olivine (Figure 3a), and abundant biotite and chlorite. Plagioclase also displays alteration along microfractures, most likely to sericite (Figure 3b).

Two samples originated from the FCU just below the Flatreef. These consist of pyroxenite and norite, respectively. The pyroxenite (KO14) contains both ortho- and clinopyroxene, and hosts inclusions of what are probably sedimentary xenoliths. The norite sample (KO6) also contains abundant clinopyroxene, and has a pegmatitic texture. The norite contains relatively high-grade PGE mineralization (ca. 6 ppm Pt+Pd+Rh+Au) and abundant disseminated sulphide, whereas the pyroxenite is only sparsely mineralized with respect to BMS and contains slightly less than 0.5 ppm Pt+Pd+Rh+Au. Textures and mineralogy of these samples are depicted in Figures 4a-b. These footwall samples show greater alteration compared to the samples from the Flatreef. There are abundant masses of mica and clay, along with occasional crystal growth of secondary minerals. Both macroscopically and microscopically, the mineral grains display irregular, rounded edges, suggesting possible postmagmatic re-melting and alteration (Figures 4a).

Two samples were taken from the UG-2 equivalent chromitite seam below the Flatreef. Sample KO35-Cr represents the chromitite portion of the seam, and KO25-Px is a pegmatoidal pyroxenite very similar to the pyroxenite which underlies the UG-2 chromitite in the eastern and western limbs. The PGE content of both pyroxenite and chromitite together is given as around 3 ppm. Textures and mineralogy of these samples are depicted in Figure 5.

Figure 2—Textures of samples originating from the eastern limb of the BC. (a) Massive chromitite from the LG-3, once beneficiated for Cr. (b) Anorthosite just above the MG-2; first appearance of cumulus plagioclase in the Critical Zone. (c) Norite of the UCZ. Plagioclase and orthopyroxene (white and brown) are enclosed within a large clinopyroxene oikocryst (dark blue). (d) Rare example of hydrothermal alteration in the WV samples. Base metal sulphide, identified as pyrrhotite (black) occurs along a micro-vein in UCZ norite. Muscovite (pale pink) and biotite (orange) are associated with the sulphide. To the right (black), a large orthopyroxene grain is heavily altered. (b–d) Photomicrographs taken under cross-polarized (CPL), transmitted light.
are shown in Figures 4c–d. The degree of alteration of these samples is similar to those from the Flatreef, and is limited to the pyroxenite rather than the chromitite. Macroscopically, the chromitite appears to have been disturbed by the surrounding silicate layers; individual seams are broken and discontinuous (Figure 4c).

In total, seven samples from the FAZ were analysed. Samples KO33 to KO38 are well mineralized with respect to PGE, with total Pt+Pd+Rh+Au ranging from ca. 3 to ca. 7 ppm. Sample KO7 is exceptionally high grade, with Pt+Pd+Rh+Au just over 9 ppm. For these samples, sulphide-mineralized horizons with appreciable PGE content and abundant visible clinopyroxene were specifically targeted. Textures and mineralogy may be seen in Figures 5a–d. All samples consist of parapyroxenite, with textures similar to the irregular, rounded grain edges of lithologies in the FCU above (Figure 5a). However, in the FAZ, the grains appear much less well ordered. The pyroxenite is very coarse-grained, and contains abundant visible sulphide (Figure 5a). Also visible are veins infilled with quartz or calcite (Figure 5b). These are often associated with large clusters of sulphide. Microscopically, evidence of re-melted pyroxene grains can be seen (Figure 5d), as well as the typical micaceous alteration. In contrast to the Flatreef, where alteration occurs along mineral fractures, in the FAZ there is clear evidence of infilled veins (Figures 5b–c).

Sc analysis

All 22 samples were analysed at the University of the Free State, South Africa, on pressed powder pellets using a Rigaku ZSX Primus IV wavelength-dispersive X-ray fluorescence (XRF) spectrometer. A custom calibration method was set up using a...
set of standards that covered the range of known rock types. The standard reference materials used consisted of SARM, GSJ, CCRM, and USGS rock powders of appropriate compositions. Standards with appropriate Sc values were tracked down by querying the GeoReM database by imputing the desired value ranges of Sc, as described by Jochum et al. (2005). The database provides measured values of any element, as well as recommended, compiled, and certified values. Because Sc has no certified value for any of the available standards, compiled Sc values from Govindaraju (1994) were used for each standard in the calibration after using GeoReM for lookup and reference. After the calibration was set up, each standard was analysed as a sample to test the precision of the calibration, which was found to be excellent (Table I). Duplicate samples were included in analytical runs to ensure accuracy, which was within acceptable limits (10%).

The lower limit of detection was 2 ppm, and the lower limit of quantification was 3 ppm for Sc.

The analysed values for the Eastern Bushveld chromitites and associated lithologies can be found in Table II. The results for the Flatreef, UG-2 equivalent in the northern limb, and FCU samples are in Table III. Sc results for samples originating from the FAZ are in Table IV.

Results and discussion

Sc in the Main and Critical Zones

Despite Sc being used as a trace element to track igneous processes such as fractional crystallization and partial melting, particularly in relation to vanadium, (Allègre et al., 1977; Lee et al., 2005), assay values for Sc in the BC are relatively sparse. No reference information can be found regarding concentrations in Sc in the Critical Zone of the RLS below the Merensky Reef, hence Sc concentrations of chromitites and associated lithologies that we present in this paper appear to be the first of their kind.

The concentration of Sc in the primitive mantle is calculated to be about 16.5 ppm (Lee et al., 2005). In pyroxenitic igneous rocks, as has been discussed above, Sc may reach (sub-)economic concentrations of 50 ppm or above. Looking at the standard reference materials described in Govindaraju (1994), basalts and gabbros such as the USGS standard BHVO-1 and the CCRM standard MRG-1 typically contain about 20–50 ppm Sc (see Table I). Anorthositic rocks, however, do not preferentially concentrate Sc and have much lower concentrations (15 ppm or below) (see e.g. Mitchell 1986; Boudreau 2016).

One of the main sources for Sc concentrations in the Main Zone of the BC (above the level of the Bastard Reef) is Mitchell (1986), who found Sc concentrations to vary from 5 ppm (in anorthosite) to 40 ppm (in pyroxenite). Scandium was strongly correlated with clinopyroxene. Arndt et al. (2005) determined Sc along with other trace elements in the Merensky Reef unit and associated rocks. The concentration of Sc varied from 9 to 22 ppm, which is relatively low. Notably, the Merensky Reef samples in this study are mineralogically dominated by orthopyroxene and plagioclase, with almost no clinopyroxene.

The Lower Main Zone and Platreef of the northern limb (Roelofse and Ashwal, 2012) show a slightly higher average, with Sc ranging from 20–36 ppm in gabbroic and noritic lithologies, excluding outliers. Anorthosite and leuconorite, as expected, have lower concentrations (10–18 ppm Sc).

The analysed values of Sc presented in Table II closely approximate the exact ranges in the Main Zone, Merensky Reef, and Platreef as discussed above, with maximum concentrations ranging above the Merensky Sc concentrations as given by Arndt et al. (2005). The two massive chromitites from the LG-6

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**Table I**

<table>
<thead>
<tr>
<th>Standard name</th>
<th>Rock type</th>
<th>Compiled value* (Govindaraju, 1994)</th>
<th>Analysed value</th>
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<tr>
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<td>Basalt</td>
<td>31</td>
<td>30</td>
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<td>JB-2</td>
<td>Basalt</td>
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<td>Gabbro</td>
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<td>MRG-1</td>
<td>Gabbro</td>
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<td>Norite</td>
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<td>SARM-5 (NIM-P)</td>
<td>Pyroxenite</td>
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</table>
and LG-3, as well as the only anorthosite sample, contain Sc concentrations below the limit of quantification. Considering the rest of the results, this is clearly due to the fact that these horizons contain almost no pyroxene – all three of these samples can be said to be monomineralic, with the chromitites strongly excluding any mineral but chromite, and the anorthosite with only Ca-plagioclase and no visible pyroxene. Sc consistently correlates with rock type, with the melanorites and pyroxenites ranging from about 20 to 40 ppm, while anorthosite and leuconorite have concentrations below 20 ppm. Variations between individual layers may simply be due to the amount of clinopyroxene versus orthopyroxene. In the Lower Critical Zone (LCZ), orthopyroxene is the most important cumulus phase, and correspondingly the LCZ pyroxenite (WV62) in Table II has Sc of just below 20 ppm. The very low Sc content in the chromitiferous melanorite of the MG-5 (sample WV30; 6 ppm) can be explained by the high concentration of Cr₂O₃ (40%) in this sample, indicating high chromite content, in addition to the fact that it contains mainly orthopyroxene rather than clinopyroxene. These results agree with the theory that Sc preferentially associates with clinopyroxene above all other minerals. Based on these results, Sc does not appear to be compatible with chromite.
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**Sc in the Flatreef**

The values from the Flatreef, UG-2- equivalent and FCU shown in Table III correspond to the ranges in the previous results. Again, Sc correlates closely to rock type, with olivine-rich harzburgite of the Flatreef showing low values (8 ppm) and the clinopyroxene-rich pyroxenites of the reef and footwall with higher values (up to 40 ppm). The analysed value for pyroxenite associated with the UG-2 fits in with values found for pyroxenite of the Critical Zone in the eastern limb.

Values of Sc found in the FAZ fit into the ranges for the BC discussed so far, but interestingly, despite clinopyroxene-rich lithologies being targeted for analysis, including two samples (KO34 and KO35) with an estimated 71–73% modal clinopyroxene, the values actually trend lower than those found in the unaltered eastern limb and the relatively unaltered Flatreef, with the lowest value being 9 ppm and the highest 28 ppm. This may be a sign that the extensive alteration found in the FAZ might have redistributed scandium that was originally concentrated in the clinopyroxenes. Alteration of clinopyroxene to mica would mean that Sc, incompatible in the crystal structure of mica, might partition into a hydrothermal fluid. If so, the eventual fate of the Sc is still unknown, since no likely reservoirs have been found in the BC.

The presence of clinopyroxene-rich parapyroxenite in the FAZ has been interpreted to represent a recrystallization of originally igneous cumulates in the presence of a Ca-rich fluid originating from crustal sediments of carbonatic composition (Grobler et al., 2019). During this process, trace elements from crustal material must also have been introduced into the Bushveld cumulates. Scandium does not appear to have been introduced from the crust, nor is this likely, since Sc tends to be strongly associated with igneous processes (Williams-Jones and Vasyukova, 2018; Wang et al., 2021).

Figure 6 illustrates the ranges of Sc for different zones of the BC, as found in this study and taken from literary sources. Sc values overlap for the Main Zone of both the northern and western limbs. Values of Sc for the Flatreef reef portions, the FCU, and the Critical Zone of the eastern limb in this study largely fit within the same parameters, with Sc generally increasing with the amount of clinopyroxene. There also appears to be a steep trend of Sc enrichment in a few samples including silicate and chromitite samples from the Critical Zone as well as the Flatreef pegmatoidal pyroxenite, two FAZ samples, and a few Main Zone samples. A possible explanation for this ‘trend’ is that these samples were trapped between other layers (for example, silicate inclusions in chromitite layers) and thus Sc could not concentrate as efficiently into the clinopyroxene fraction.

Most of the FAZ samples analysed in this study plot along a gentle trend of Sc enrichment with increasing clinopyroxene (see Figure 6). The deficiency in Sc for the FAZ, as discussed above can clearly be seen in this graph.

Certainly, the values of Sc that we have found in the BC for this study do not appear to be economic, even if Sc were to be exploited as a by-product. With improving recovery through enhanced leaching processes and increasing demand for Sc leading to rising prices, this could conceivably change. The Southern African mining industry thrives on innovation; selenium and tellurium, two other metals associated with growing technologies, are now being produced from copper refinery anode slimes in Ndola, Zambia (Dworzanowski, 2019). Even the low grades of Sc found in this study can be of economic interest, especially considering that the Sc ‘missing’ from the FAZ may be concentrated elsewhere.

**Concluding remarks**

The values of Sc in the Bushveld Complex strongly correlate with the presence of clinopyroxene and do not differ significantly from Sc concentrations for typical mafic-ultramafic rocks, even in the lithologies of the northern limb, which are significantly contaminated with crustal material. The pyroxenites of the Critical Zone from the eastern limb and the Flatreef of the northern limb from this study contain approximately 40 ppm Sc, whereas the Merensky pyroxenite of the eastern and western limbs contains about 22 ppm Sc on average. The difference is most likely due to the increasing cpx to opx ratio, which corresponds with higher cpx concentrations in the CZ and the Flatreef lithologies.

**Acknowledgments**

The authors wish to thank the staff of Ivanplats in Mokopane, particularly Mr Fabian Fredericks, for their kind co-operation in obtaining sample material and previous assays for this study, as well as assistance in understanding the lithologies of the Flatreef. This research was entirely supported by post-doctoral funding from the University of the Free State.
Geological setting and concentration of scandium


