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Petrographic, geochemical and SHRIMP U–Pb titanite age characterization of the Thabazimbi mafic sills: Extended time frame and a unifying petrogenetic model for the Bushveld Large Igneous Province

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A B S T R A C T

Mafic sills occur within and in the vicinity of the Thabazimbi iron ore deposit, near the northern edge of the western limb of the Bushveld Complex. The sills are hosted in the 2.46 Ga Penge Iron Formation of the Transvaal Supergroup. The gabbroic sills have a primary mineral assemblage of clinopyroxene, plagioclase, accessory Fe–Ti oxides and titanite, with augites in places having been replaced by amphibole and/or biotite. K-feldspar veins crisscross through some of the more altered sill samples. Both primary and secondary titanite occurs in the sills, with the primary titanite rich in Fe (Fe/Al ∼0.65–0.88) and secondary titanite rich in Al (Fe/Al ∼0.17–0.47). SHRIMP U–Pb characterization of titanites separated from one of the sills (titanite Fe/Al in this sill ∼1) indicate an emplacement age of 2046.6 ± 3.4 Ma.

In terms of whole-rock Mg#, the Thabazimbi sills fall into groups – a low Mg# (∼44–55) group and a high Mg# (∼63–76) group. The high Mg# sills are basaltic-andesitic and calc-alkaline, while the low Mg# sills are basaltic and tholeiitic. The highest Mg# samples with the lowest Fe_2O_{3tot}/MgO ratio have the highest Cr and Ni contents, representing the closest to parental magma composition. The continuous trends between the high and low Mg# groups and relatively higher abundances of highly incompatible elements in the high Mg# group likely indicate differences in the degree of partial melting. The petrogenetic characteristics of Thabazimbi sills involving contribution from the sub-continental lithospheric mantle (SCLM) and later crustal contamination have clear similarities with those of basaltic rocks from large igneous provinces (LIPs) like the Karoo and Paraná.

Using a compilation of available geochronological and geochemical data, we extent the approach using geochemical characteristics to the different rock units of the Bushveld Complex *proper* and syn-Bushveld rock types occurring within the Kaapvaal Craton and forming part of the Bushveld LIP. The recognition of low-Ti and high-Ti grouping among different units from different age brackets suggest that the Bushveld LIP likely consisted of three main pulses – ∼2.061–2.060 Ga, ∼2.059–2.054 Ga and ∼2.046–2.042 Ga – with the second pulse which produced the Bushveld Complex *proper* lasting the longest. A possible unifying model involving melting of the metasomatized SCLM beneath the Kaapvaal Craton by an asthenosphere-derived magma and later contamination by crustal material, with rocks of the high-Ti group derived deeper, as smaller degree partial melts than rocks of the low-Ti group is presented.

1. Introduction

While the better preserved large igneous provinces (LIPs) of Mesozoic and Cenozoic age are dominated by volcanic components (flood basalts) (Coffin and Eldholm, 1994), due to erosion and tectonism Precambrian LIPs typically consists of volcanic remnants, dyke swarms, sills, layered mafic to ultramafic intrusions and associated felsic magmatism (Bryan and Ernst, 2008). For example, the ∼1.27 Ga Mackenzie LIP in northern Canada includes the giant Mackenzie dyke swarm, the Coppermine River flood basalts and the Muskox mafic to ultramafic layered intrusion, which becomes progressively more silicic toward the top, with a prominent sheet of granophyres capping the intrusion (Irvine, 1980; Dostal et al., 1983; LeCheminant and Heaman, 1989; Baragar et al., 1996). As many of the Precambrian LIPs are only partially preserved, with unknown thickness being lost to erosion, the delineation of the original extent of these LIPs largely depends on the delineation and characterization of similar aged magmatic units of smaller size

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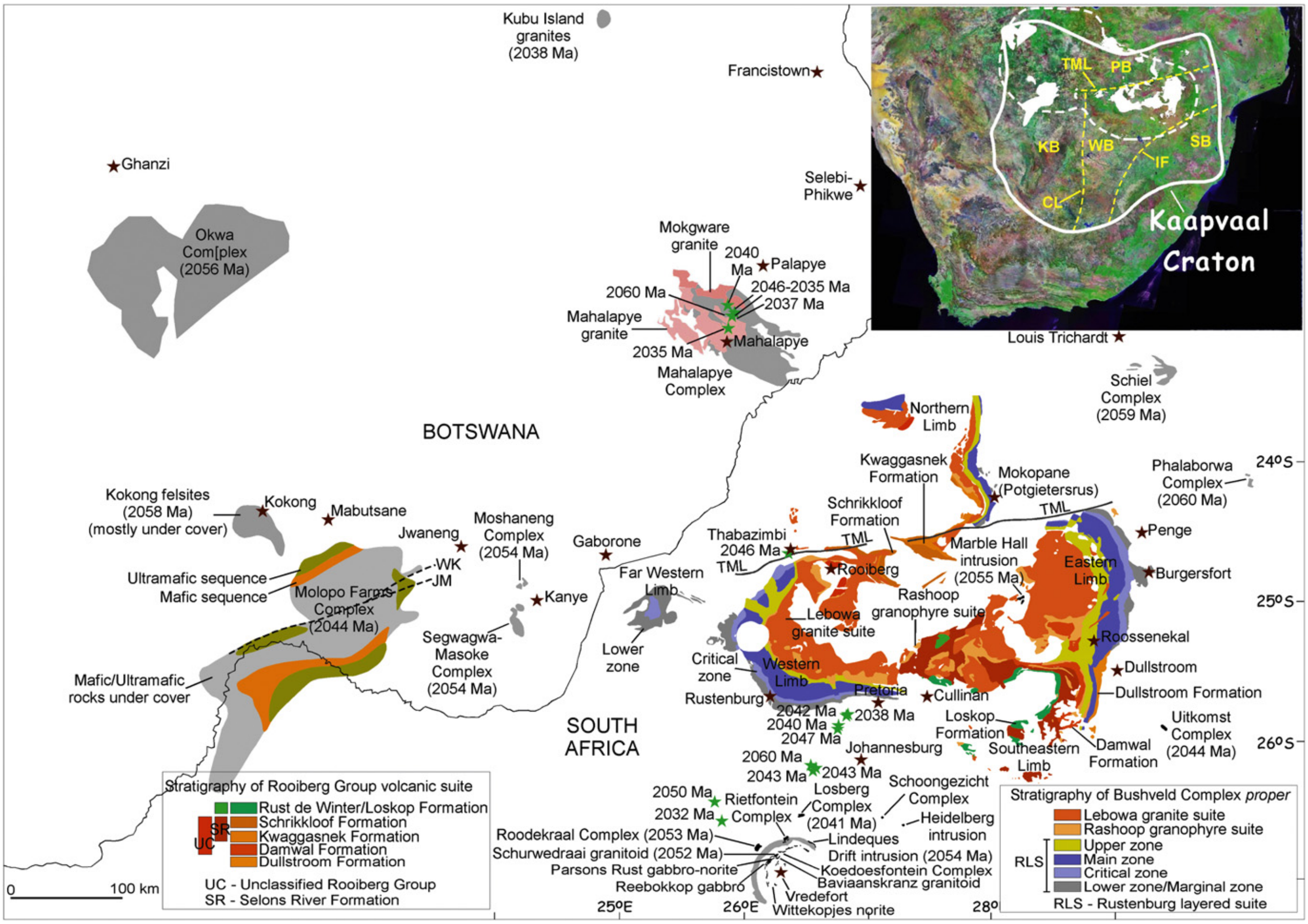

Fig. 1. Generalized geological map of the different units that form part of the Bushveld large igneous province [map modified from the 1:1,000,000 geology map of South Africa, including information from Bisschoff (1972), Key and Ayres (2000), Reichhardt (1994), Coetzee et al. (2006), De Waal et al. (2006), Mapeo and Wingate (2009), and Walker et al. (2010)]. Only the presently exposed (and preserved) remnants of the different units are shown. The original extent is far wider. Available ages of individual units other than the Bushveld Complex *proper* and Rooiberg Group volcanic suite are indicated. The green stars indicate approximate location where ages were obtained by Alexandre et al. (2006) and Rasmussen et al. (2007) to the south and south-west of the Bushveld Complex *proper*, Zeh et al. (2007, 2009) and Millonig et al. (2010) from the Mahalapye Complex, and this study from Thabazimbi. See Appendix 3 for details of the ages mentioned. See Appendix 2 for details of the different units. Inset is a TM742 (as RGB) compilation for southern Africa showing the location of Bushveld large igneous province with respect to the Kaapvaal Craton. The dotted line in the inset surrounds the region of seismically slow cratonic mantle at 150 km depth resulting from the Bushveld magmatism (James et al., 2001; James and Fouch, 2002). The concept here is that in the seismic tomographic image of upper mantle beneath the Kaapvaal Craton (James et al., 2001), the relatively low Vp beneath Bushveld largely reflect the progressive refertilisation of the Archean root during the passage of large volumes of magma through the lithosphere related with the Bushveld magmatism (James and Fouch, 2002); areas of high Vp map out the distribution of relatively less metasomatised Archean SCLM. The different blocks [Kimberley block (KB), Witwatersrand block (WB), Pietersburg block (PB) and Swaziland block (SB)] of the Kaapvaal Craton and the known suture zones [Colesberg lineament (CL), Thabazimbi-Murchinson lineament (TML) and Inyoka fault (IF)] between them are also shown in the inset. The shear zones [shown by dotted lines; E-NE-trending Jwaneng-Makopong (JM) and NE-trending Werda-Kgare (WK) shear zones; also known as the Dikgomodikae Lineament; Chatupa, 1995] separating the Molopo Farms Complex may continue into the Thabazimbi-Murchinson lineament (TML) (Reichhardt, 1994). But Walker et al. (2010) points out that any westward projection of the TML into Botswana would lie to the north of the Molopo Farms Complex.

or aerial extent that are thought to have originally belonged to a LIP-scale event [the LIP 'fragments' of Ernst (2007)]. Whole-rock geochemical characterization of similar aged LIP 'fragments' can aid the purpose. For example, the recognition of low- and high-Ti grouping is a well-documented geochemical characteristic of basaltic rocks in better-preserved younger continental LIPs such as the Ethiopian plateau, Paraná, Etendeka, Ferrar, Karoo, Siberian traps and Emeishan (Cox et al., 1967; Hornig, 1993; Fodor, 1987; Lightfoot et al., 1993; Gibson et al., 1996; Peate, 1997; Pik et al., 1998; Xu et al., 2001; Ewart et al., 2004; Jourdan et al., 2007). One can look for similar low- and high-Ti grouping in rocks that make up the LIP 'fragments' in a Precambrian LIP.

With the world's largest layered ultramafic-mafic intrusion (Bushveld Complex), associated with basalt-rhyolite volcanics, granite and granophyre rocks, in the center and widely distributed coeval magmatic rocks in the Kaapvaal Craton, the ~2.06 Ga Bushveld large igneous province is an LIP in the Precambrian (James and Fouch, 2002; Hanson, 2003; Ernst and Bell, 2010). Ultramafic to mafic sills which underlie the Bushveld Complex layered intrusion and intrusive into the country rock sediments have attracted a number of studies trying to estimate the composition of the magmas that formed the layered ultramafic and mafic sequence (Cawthorn et al., 1981; Sharpe, 1981; Davies and Tredoux, 1985; Harmer and Sharpe, 1985; Sharpe and Hulbert, 1985; Barnes et al., 2010). Here we present the results of a petrographic, mineral chemical, geochemical and SHRIMP U–Pb titanite age characterization of syn-Bushveld mafic sills in the Thabazimbi area, near the northwestern edge of the Bushveld Complex. The ensuing petrogenetic characterization of these sills incorporates two important components of the prevailing model for the Bushveld Complex – the presence of a sub-continental lithospheric mantle component and significant amounts of crustal contamination. With the slightly younger age of the Thabazimbi sills supporting an extended time frame for the Bushveld LIP, a compilation of available geochemical data of all the Bushveld Complex and syn-Bushveld rocks within the Kaapvaal Craton is carried out to evaluate whether they preserve