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The Bushveld Complex was emplaced and cooled in less than one million years – results of zirconology, and geotectonic implications

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ABSTRACT

The Rustenburg Layered Suite (RLS) of the Bushveld Complex (BC) represents Earth's oldest large igneous province (>370 000 km^3), and contains the world's largest reserves of platinum-group elements, chromium and vanadium. However, its mode of formation, the exact timing and nature of magma emplacement, solidification and sub-solidus cooling history remain a matter of debate. High precision U–Pb dates, backed by petrological observations reveal that zircon throughout the RLS crystallised within 1.02 ± 0.63 Ma from highly fractionated intercumulus melts at temperatures between 940° and 670 °C. Zircon in quenched Marginal Zone rocks crystallised at 2055.91 ± 0.26 Ma, and slightly later at 2054.89 ± 0.37 Ma in cumulus rocks in the centre of the RLS. This timing is in agreement with field observations and the results of thermal modelling, which require rapid accumulation of magma at a flux rate of >5 km^3/yr over less than 100 ka, followed by crystallisation and cooling to below 700 °C within 950 ka. This short period of melt accumulation with an extreme flux rate, leading to a large volume of magma stalled within the upper crust, is suggested to result from active magma pumping, triggered by stress field change within the subcontinental lithospheric mantle (SCLM) at 2.056 Ga. This change was caused by rebounding of the SCLM after elimination of its lowest, eclogite-rich part during a mantle plume up-welling event.

1. Introduction

The RLS is the mafic component of the Bushveld Complex (BC; Fig. 1) and the largest layered intrusion on Earth, hosting giant reserves of platinum-group elements, vanadium, chromium and nickel (Eales and Cawthorn, 1996). The mafic and ultramafic cumulate rocks are 7500 to 9000 m thick, extend over an area of ca. 65 000 km^2, and have an estimated volume of 370 000–600 000 km^3 (Eales and Cawthorn, 1996; Cawthorn and Walraven, 1998). Mass balance constraints for compatible and incompatible elements like chromium, zirconium and potassium point to an additional volume of 400 000 km^3 of mafic magma, which might have been extracted during magma chamber accretion (Cawthorn and Walraven, 1998), either as volcanic eruptions or possibly an additional high-level intrusion now completely eroded.

Previous age determinations of BC rocks scatter over more than 10 million yr (Fig. 2). Uranium-lead ages obtained from zircon, baddeleyite and titanite by ID-TIMS (isotope dilution thermal ionisation mass spectrometry) and CA-ID-TIMS (chemical abrasion ID-TIMS) are commonly older and more precise (2058.9 ± 0.8 Ma to 2054.4 ± 1.3 Ma; Buick et al., 2001; Scoates and Friedman, 2008; Olsson et al., 2011) than Re–Os, Pt–Os and Ar–Ar ages. The latter comprise whole-rock isochron and mineral data which scatter between 2044 ± 3 Ma and 1995 ± 50 Ma (Schoenberg et al., 1999; Nomade et al., 2004; Reisberg et al., 2011; Coggon et al., 2012). Some U–Pb zircon ages obtained by SHRIMP (Sensitive High Resolution Ion Microprobe) also reveal a high degree of scatter and overlap with the CA-ID-TIMS and Ar–Ar data (Yudovskaya et al., 2013). The most precise U–Pb ages to date suggest a crystallisation time interval for BC rocks of 3–5 million yr. This timescale, however, is much longer in duration than the 75 ka previously required by thermo-mechanical modelling for the emplacement of the RLS (Cawthorn and Walraven, 1998) and the 500 ka required for BC emplacement and cooling below 580 °C (Cawthorn and Webb, 2013). This discrepancy raises questions about the reliability of published ages, and/or the validity of the thermal and paleomagnetic models (see discussions in Cawthorn and Webb, 2013). The apparent 3–5 Ma time-span for magma accretion may be partly biased by different procedures in different U–Pb laborato-

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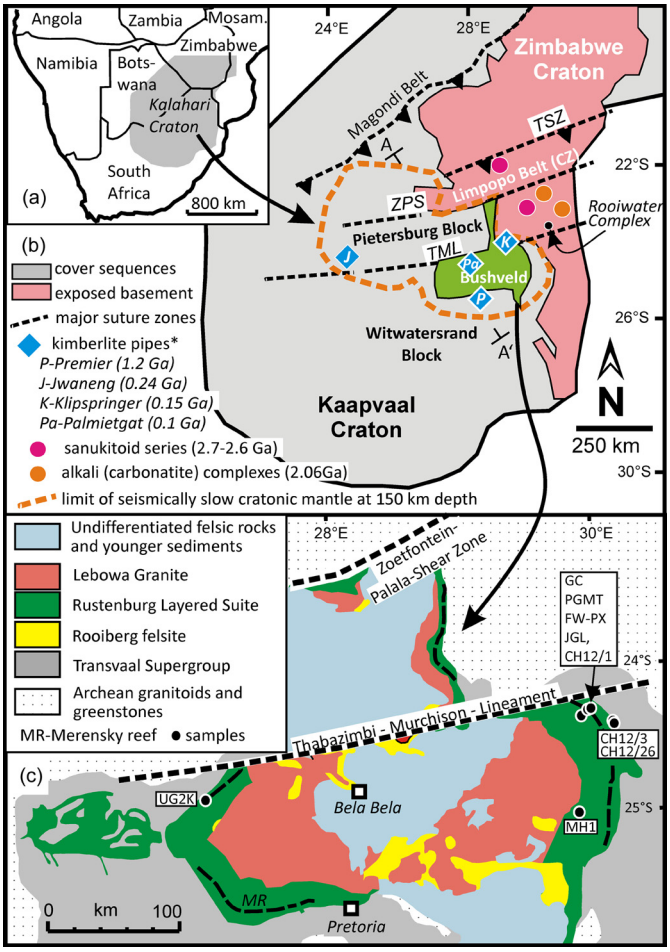

Fig. 1. Geological overview of the Kalahari Craton. (a) Position of the Kalahari Craton in southern Africa. (b) Main units and important terrane boundaries (suture zones) of the Kalahari Craton, and position of the Bushveld Complex. Also shown is the region of seismically-slow cratonic mantle at 150 km depth (James et al., 2001), and of diamond-bearing kimberlites (with age of emplacement). The profile A–A′ corresponds to Fig. 8. TSZ – Triangle shear zone; ZPS – Zoetfontein–Palala shear zone; TML – Thabazimbi–Murchison-Lineament. (c) Main units of the Bushveld Complex and surroundings with sample localities.

ries and through the use of different minerals and isotopic systems. Furthermore, additional uncertainty arises from data interpretation with respect to the timing of magma chamber accretion, cooling, and post-magmatic alteration.

In order to provide new and robust constraints on the timing of BC emplacement process and cooling, we present in this study a comprehensive and internally consistent dataset of high-precision U–Pb ages obtained by state-of-the-art CA-ID-TIMS from a large number of zircon grains ($n = 81$) extracted from nine mafic rocks, with different cooling histories (from the contact chill to cumulus rocks) of different units throughout the RLS, and characterised by raster electron imaging and trace element analyses. The age data and timing of events derived from it are subsequently compared with results of thermal modelling for BC accretion and cooling, and are used to confine a model for BC emplacement.

2. Geological setting of the Bushveld Complex

The BC intruded the central part of the Kalahari Craton at approximately 2.06 Ga, in an area where the craton is dissected by several crustal-scale shear zones, and where the underlying SCLM is characterised by low P-wave velocities at 150 km depth (James et al., 2001) – (Fig. 1a). The prominent suture zones (the Thabazimbi–Murchison Lineament, the Zoetfontein–Palala Shear Zone, and the Triangle Shear Zone) are suggested to have formed during successive amalgamation events of different terranes (Witwatersrand Block, Pietersburg Block, Limpopo Belt Central Zone and Zimbabwe Craton) between 2.97 and 2.65 Ga (for details see Zeh et al., 2009, 2013; Laurent et al., 2014; Zirakparvar et al., 2014) – (Fig. 1b).

The RLS intruded sedimentary rocks of the Transvaal Supergroup at a relatively shallow crustal level of <12 km (<0.4 GPa), as is indicated by andalusite-bearing metamorphic rocks underlying the RLS, and is capped by the Rooiberg volcanic suite, the Rashoop granophyres and the ca. 4000 m thick Lebowa Granite. Based on characteristic rock-types, the RLS is subdivided into five major stratigraphic successions, which from bottom to top are the Marginal, Lower, Critical, Main and Upper Zones (Eales and Cawthorn, 1996). The cumulate rocks of these zones formed without any significant hiatus during sequential accretion of the magma chamber (Cawthorn and Walraven, 1998), initially from a siliceous Mg-rich magma (Mg-andesite), called the B1-magma that gave rise to the Marginal, Lower and lower Critical Zones, followed by tholeiitic magmas (called the B2 and B3 magmas) that formed the upper Critical, Main and Upper Zones (Barnes et al., 2010; Wilson, 2012 and references therein). Both magma types reveal significant amounts of assimilation of ancient crustal material (between 20 and 40%), as is suggested by Sr, Nd, Hf, Os, and O isotopes (Kruger, 1994; Schoenberg et al., 1999; Maier et al., 2000; Harris et al., 2005; Reisberg et al., 2011; Zirakparvar et al., 2014). The assimilated material is suggested to have been derived from Kalahari Craton crust immediately prior to emplacement into the Transvaal Supergroup at ca. 2.06 Ga (e.g., Kruger, 1994; Maier et al., 2000; Harris et al., 2005; Reisberg et al., 2011), or from assimilation of ancient eclogites within the SCLM during the ascent of asthenospheric magma (Richardson and Shirey, 2008), or by a combination of both (Wilson, 2012).

3. Samples and analytical methods

Zircon grains from nine mafic rock samples from the RLS were dated by U–Pb techniques; eight from the eastern limb of the BC, and one from the western limb at Union mine (Fig. 1c), covering the Marginal, Lower Critical, Upper Critical, lowermost Main and Upper Zones (Table 1). Eight of the samples are coarse grained cumulus rocks of different composition comprising norite, pyroxenite, chromite-rich pyroxenite and magnetite-rich gabbro. One rock (sample CH12/3 from the Marginal Zone) represents a quenched micro-pyroxenite with elongated spinifex-like orthopyroxene crystals and was sampled close to the contact with Magaliesburg quartzite of the Pretoria Group in the eastern BC. Detailed petrographic descriptions, co-ordinates and microphotographs of all samples are given in the supplementary materials. All dated zircons were selected from heavy mineral concentrates derived from these rocks. In addition, some zircons were observed *in situ* in thin sections of samples CH12/3 and CH12/26 from the Marginal Zone, and UG2-1a and UG2-1b from the Upper Critical Zone, either by optical and/or by raster electron microscopy (Fig. 3, and Figs. S4, S5 in supplementary materials).

Bulk separated zircon grains were mounted in epoxy and ground and polished to expose the crystal cores. Internal zoning patterns were characterised by cathodoluminescence (CL) and back scattered electron (BSE) imaging using a Gatan miniCL detector coupled to a JEOL JSM 6490 raster electron microscope (Fig. 3). Mineral and melt inclusions were investigated by energy dispersive X-ray (EDX) analyses (JEOL JSM 6490), and by MicroRaman using a RENESHAW RM 1000, equipped with a green 500 nm laser, and a microscope with 50–100× objectives. Subsequently, zircon compositions (Ti, rare earth elements – REE, Th, U) were obtained using laser ablation-inductively coupled-sector field-mass spectrometry