



Plume-related diamond formation in reworked Archaean mantle: Sm–Nd age constraints from Voorspoed peridotitic and eclogitic diamonds (Kaatpvaal Craton)

Karen V. Smit^{1,2} · Michael U. Gress³ · Gareth R. Davies³ · Janne M. Koornneef³ · Ingrid L. Chinn⁴

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Abstract

Here we study silicate inclusion-bearing diamonds from the Voorspoed Group II kimberlite (or carbonate-rich olivine lamproite—CROL) in the central Kaapvaal Craton. Based on major and trace elements, along with Sm–Nd isotope characteristics, the *peridotitic* garnet and clinopyroxene inclusions define three compositional groups that are contemporaneous with lithospheric refertilisation and re-healing related to 2.79–2.68 Ga Ventersdorp-related plume magmatism across the central Kaapvaal craton. Three harzburgitic (G10) inclusions define an isochron of 2877 ± 249 Ma, with a low initial $\epsilon_{\text{Nd}} = -15 \pm 10$ that overlaps the oldest Kaapvaal enriched components as represented by crust in the 3.66–3.22 Ga Ancient Gneiss Complex. This finding suggests that harzburgitic diamond formation occurred in the oldest >3.2 Ga Kaapvaal lithospheric mantle. Five lherzolitic (G9) garnet and 11 Cr-diopside inclusions with $\text{La}_\text{N} > 1$ (where N refers to chondrite normalisation) and low $^{147}\text{Sm}/^{144}\text{Nd}$ (0.11–0.41), define a 2606 ± 95 Ma Sm–Nd isochron with an initial $\epsilon_{\text{Nd}} = -6.9 \pm 5.4$ that is consistent with diamond formation in enriched >3.0 Ga lithospheric mantle. Four lherzolitic (G9) garnet and five Cr-diopside inclusions with $\text{La}_\text{N} < 1$ and higher $^{147}\text{Sm}/^{144}\text{Nd}$ (0.45–1.51), define a 2560 ± 51 Ma Sm–Nd isochron with an initial $\epsilon_{\text{Nd}} = 9.8 \pm 7.8$. This initial ratio overlaps with depleted mantle indicating rapid re-healing of the lithospheric mantle after 2.79–2.68 Ga Ventersdorp-related plume magmatism. Sixteen *eclogitic* inclusions (10 garnets and six omphacites) define an isochron of 2196 ± 61 Ma, with initial $\epsilon_{\text{Nd}} = -9.3 \pm 3.9$. Growth of Voorspoed eclogitic diamonds is interpreted to be related to magmatism and failed rifting at the time of the 2.25–2.23 Ga Hekpoort LIP and associated magmatism across the Transvaal Basin. Low-pressure protoliths for the eclogite host rocks are supported by the presence of omphacite that is not stable as a high-pressure liquidus phase, along with Eu anomalies in the majority of eclogitic inclusions. The likely host rocks for eclogitic diamond formation are subduction-related eclogites in the lithospheric mantle that may be similar to those sampled nearby at Lace. The Voorspoed peridotitic and eclogitic diamonds document multiple episodes of melt infiltration and modification of older lithospheric mantle, and have allowed us to place diamond formation and preservation in the context of the long history of plume impingement on the Kaapvaal lithospheric mantle.

Keywords Kaapvaal Craton · Diamond formation ages · Sm–Nd isotopes · Lithospheric mantle · Voorspoed

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✉ Karen V. Smit
karen.smit@wits.ac.za

¹ School of Geosciences, University of the Witwatersrand, Braamfontein, Johannesburg 2001, South Africa

² Gemological Institute of America (GIA), 50 West 47th Street, New York City, NY 10036, USA

³ Vrije Universiteit, De Boelelaan 1100, 1081 Amsterdam, HZ, The Netherlands

⁴ De Beers Exploration, Private Bag X01, Southdale, Johannesburg 2135, South Africa

Introduction

A worldwide association between ancient cratons and diamond occurrences has long been known (Kennedy 1964; Clifford 1966; Gurney and Switzer 1973; Boyd and Gurney 1986). Even though early work recognised the association of diamonds with ancient cratons of at least 1.5 Ga age (Kennedy 1964; Clifford 1966), more commonly ‘craton’ is used to refer to ancient portions of Earth’s crust that have been stable since 2.5 Ga. It is becoming evident that much of the cratonic lithospheric mantle has experienced significant

reworking during the Proterozoic and Phanerozoic. Instead of crustal age, an updated definition of 'craton' uses thickness of the stabilising lithospheric mantle below continental crust, visualised through fast seismic shear wave speeds in global seismic velocity models. In this updated definition, cratons are regions of the Earth's continental crust that are underlain by 150–200 km of lithospheric mantle providing long-term stability since at least 1 Ga (Pearson et al. 2021). Using this definition, around 63% of exposed continental crust and 18% of Earth's surface is considered as cratonic areas that are older than 1 Ga.

The Kaapvaal Craton is the first region where diamonds were discovered in their primary kimberlite/CROL host rocks, and due to significant diamond mining, is one of the best studied regions of Archaean basement rocks worldwide. Despite the longevity of its lithospheric mantle and crust since the Archaean—consistent with the updated Pearson et al. (2021) definition for a craton—the Kaapvaal Craton has been impacted by several Archaean and Proterozoic plume-related large igneous provinces (LIPs) that generated large amounts of magma ($>0.1 \text{ M km}^3$) over short time intervals. These include three Ventersdorp LIP events between 2791 and 2683 Ma, the Hekpoort at 2247–2224 Ma, the Bushveld at 2056–2054 Ma, and the Umkondo at 1112–1106 Ma (see review by Ashwal 2021).

The thermal impact of these LIPs on the Kaapvaal lithospheric mantle and its diamond budget is not yet well understood. Diamonds have formed through nearly all of Earth's history, in episodes that can often be linked to regional tectonics (see review by Smit et al. 2022). Studying diamonds and their inclusions can lead to an improved understanding of how tectonic processes affected the cratonic lithospheric mantle and the thermal conditions required for diamond formation, along with their long-term preservation or destruction.

Here we study inclusion-bearing diamonds from the Voorspoed Group II kimberlite (also known as carbonate-rich olivine lamproites—CROLs; Kjarsgaard et al. 2022) in the central Kaapvaal Craton. The Voorspoed CROL erupted at 132 Ma through a region where the Archaean lavas of the Ventersdorp LIPs and their thermal impact have been extensively studied in surface exposures, deep crustal boreholes, and lower crustal xenoliths from kimberlites (see review by Khumalo et al. 2024). The inclusions in the Voorspoed diamonds allow us to evaluate the composition of the lithospheric mantle at the time of diamond formation. By determining Sm–Nd isotope compositions of the garnet and clinopyroxene inclusions we can obtain diamond formation ages and place diamond formation and preservation in the context of the long history of plume impingement on the Kaapvaal lithospheric mantle.

Geological background

The Kaapvaal Craton amalgamated during collision of the western Kimberley Block and the eastern Witwatersrand–Swaziland Blocks, with the Colesberg Magnetic Lineament suggested to be the collisional suture. In this proposed tectonic scenario, the Witwatersrand Basin formed as a forearc sedimentary basin, and the Kraaipan and Amalia granite–greenstone belts as magmatic arc complexes. This collisional model for the Kaapvaal Craton was first suggested based on the differing ages and tectonic fabrics of the granite–greenstone belts on either side of the Colesberg Lineament, the 3.01–2.7 Ga Amalia and Kraaipan belts trend N–S, whereas the 3.66–3.2 Ga Barberton, Pietersburg, Murchison and Giyani belts on the eastern blocks trend NE–SW (Corner et al. 1990; de Wit et al. 1992; Poujol et al. 2002). Based on lower crustal ages, Schmitz et al. (2004) proposed that the subduction of oceanic crust and collision of the western Kimberley Block with the eastern Witwatersrand–Swaziland Blocks occurred between 2.93 and 2.88 Ga. In seismic sections, the magnetic lineament does not correspond with any suture in the lower crust and mantle, and de Wit and Tinker (2004) suggest that the Colesberg Lineament may instead relate to magnetite-rich lithologies in the upper crust. Regardless, the Kimberley Block has a distinctive origin and evolutionary history relative to the eastern Witwatersrand–Swaziland Blocks (Fig. 1).

Kimberley Block

The oldest crust and mantle rocks from the Kimberley Block are around 3.3–3.2 Ga. In the crust, granitic–gneiss xenoliths from Bultfontein (Kimberley) have zircon cores with 3.25 Ga Pb–Pb ages (Drennan et al. 1990). From the mantle, two Bellsbank kyanite-bearing eclogites have extremely unradiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ that yield minimum model ages of 3.2–3.0 Ga (Shu et al. 2016). Similarly, the oldest Re–Os T_{RD} model ages from peridotites in the Kimberley Block show that the lithospheric mantle is at least 3.1–3.0 Ga (Fig. 2; Rehfeldt et al. 2008). Garnet inclusions in Finsch and Bultfontein diamonds have $^{87}\text{Sr}/^{86}\text{Sr}$ ratios that intersect with the mantle Sr isotope evolution curve at around 3.2 Ga (Richardson et al. 1984). These 'Sr model ages' are the oldest peridotitic diamond ages for the Kimberley Block, and aside from a young peridotitic population at Koffiefontein (Pearson et al. 1998a), all other reported diamonds dated so far have eclogitic inclusions and formed after 3 Ga (Smit et al. 2022).

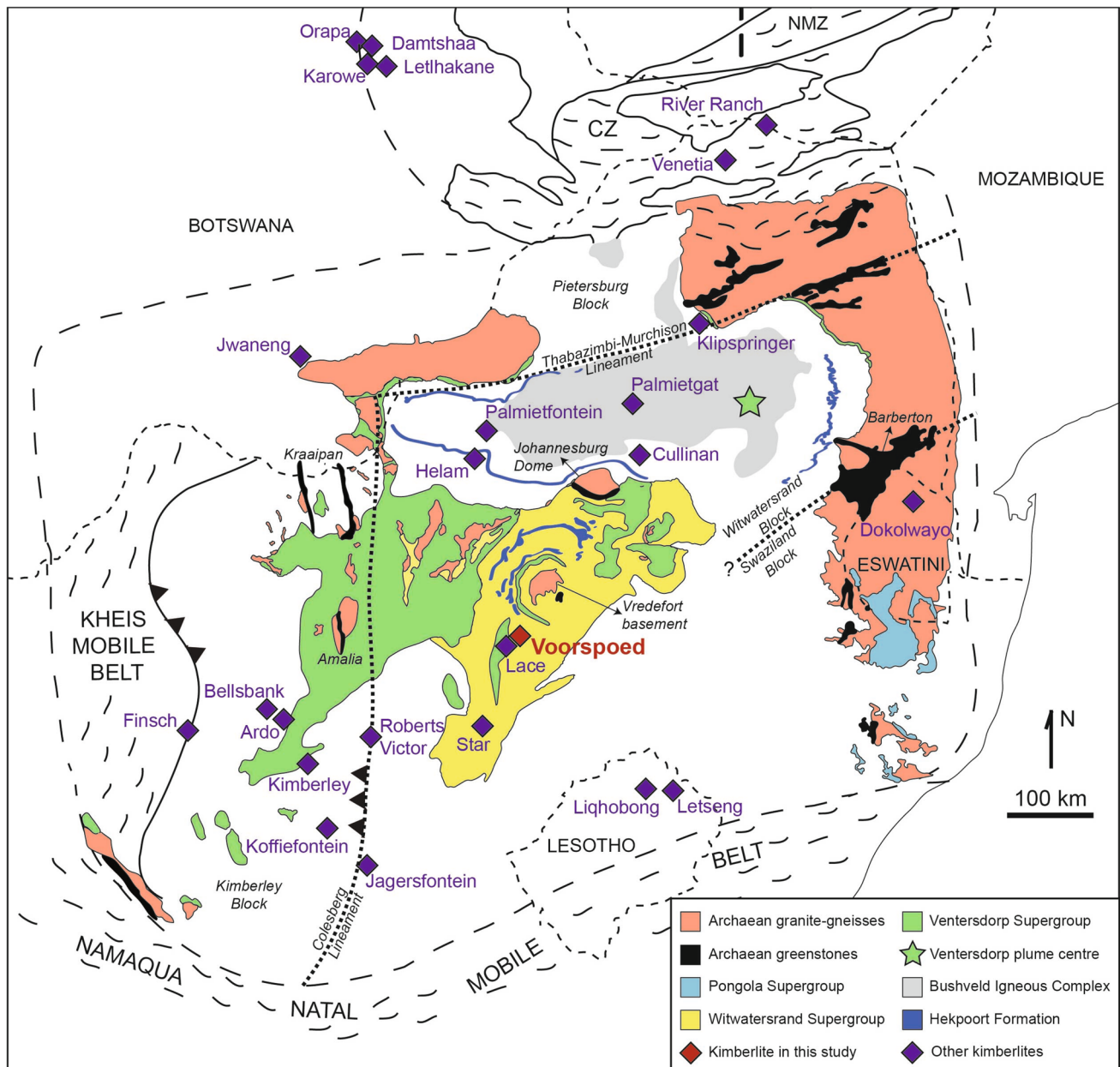


Fig. 1 Simplified geological map of the Kaapvaal Craton, with locations of selected kimberlites and CROLs, modified after Schmitz et al. (2004). Extent of the Hekpoort formation was taken from Lenhardt et al. (2020). Boundaries of the Kaapvaal with the Kheis and Namaqua-Natal Belts, and the position of the Coolsberg Lineament derived from the aeromagnetic maps published by the Council for Geoscience. Kim-

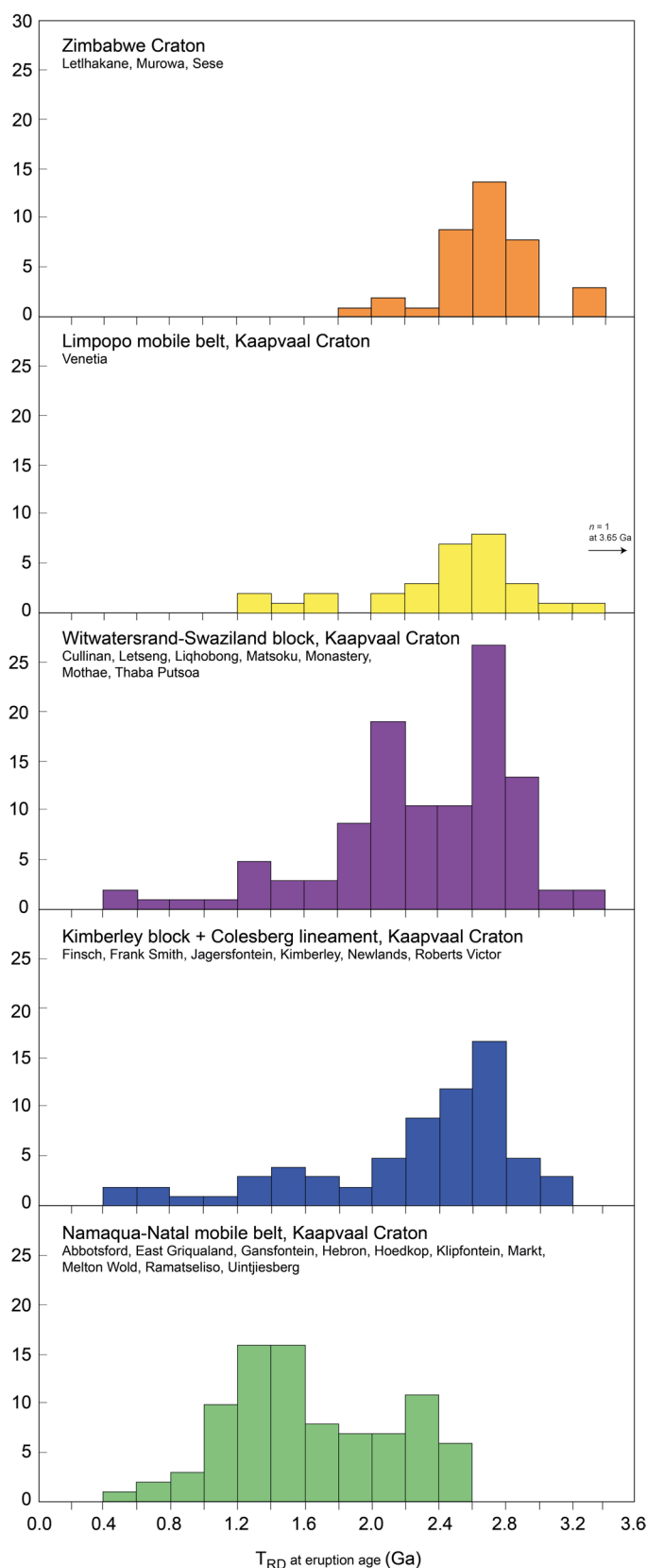
berlite/CROL localities determined from open pits on Google Earth. Voorspoed kimberlites (red symbol). The Coolsberg Lineament is suggested to represent the ~2.9 Ga collisional suture between western Kimberley Block and eastern Witwatersrand-Swaziland Block (de Wit et al. 1992; Schmitz et al. 2004)

Witwatersrand-Swaziland Blocks

The crust in the Witwatersrand-Swaziland Blocks has an older Palaeoarchaean heritage compared to the Kimberley Block. In the eastern Kaapvaal, the 3.54–3.2 Ga Barberton granite-greenstone belt and the 3.66–3.2 Ga Ancient Gneiss Complex are the oldest continental crust in Africa (see review in Kröner et al. 2019). Crustal accretion took

place around 3.2 Ga (de Wit et al. 1992; Lowe 1994), and although the tectonic mechanisms are still debated (Moyen et al. 2006; Kranendonk 2011), there is (undated) subduction-related eclogite in the mantle below the Ancient Gneiss Complex (xenocrysts and mineral inclusions at Dokolwayo; Daniels 1991; Letete et al. 2024). In the central Kaapvaal Craton, Archaean crust is exposed in the Vredefort basement complex (Gibson 2019) and the Johannesburg Dome

Fig. 2 Compilation of peridotite rhenium-depletion (T_{RD} ages) that give minimum ages for the lithospheric mantle in different regions of the Kaapvaal-Zimbabwe craton. The oldest peridotites in the Witwatersrand-Swaziland Blocks with T_{RD} ages between 3.3 and 3.0 Ga are from Lihobong and Premier/Cullinan (Pearson et al. 1995; Zhang et al. 2022). Both the Kimberley Block and the Witwatersrand-Swaziland Blocks have modes between 2.8 and 2.6 Ga, likely reflecting plume-related and/or asthenospheric material that re-healed the lithospheric mantle due to 2.79–2.68 Ga Ventersdorp plume magmatism (Gumsley et al. 2020; Khumalo et al. 2024). The other mode in the Witwatersrand-Swaziland Blocks is at 2.2–2.0 Ga that is dominated by Premier/Cullinan xenoliths and likely represents the influence of the Bushveld Igneous Complex at 2.06–2.05 Ga (Scoates and Friedman 2008; Zeh et al. 2015) and potentially also the Hekpoort LIP at 2.25–2.23 Ga (Burger and Coertze 1973; Cornell et al. 1996; Schröder et al. 2016). Data sources for peridotite ages: Walker et al. (1989), Pearson et al. (1995), Carlson et al. (1999), Menzies et al. (1999), Meisel et al. (2001), Irvine et al. (2001), Irvine (2001), Pearson et al. (2002), Pearson et al. (2004), Griffin et al. (2004), Carlson and Moore (2004), Becker et al. (2006), Rehfeldt et al. (2008), Janney et al. (2010), Maier et al. (2012), van der Meer et al. (2017) Zhang et al. (2022)



(Anhaeusser 2019). Vredefort basement gneisses formed between 3.5 and 3.3 Ga (Hart et al. 1981, 1990; Flowers et al. 2003; Armstrong et al. 2006), with peridotites from drill core also yielding 3.5–3.3 Ga Re–Os T_{RD} ages (Tredoux et al. 1999). Granitoids of the Johannesburg Dome range between 3.34 and 2.95 Ga (Poujol and Anhaeusser 2001).

The oldest lithospheric mantle reported from beneath the Witwatersrand–Swaziland Blocks is represented by five peridotites from Lihobong and Premier/Cullinan that have 3.3–3.0 Ga Re–Os T_{RD} model ages (Fig. 2; Pearson et al. 1995; Zhang et al. 2022). Additionally, there are zircon inclusions in Lace eclogitic diamonds with 3.2 ± 0.4 Ga Hf model ages interpreted as the age of the eclogitic protoliths (Karaevangelou et al. 2022). Roberts Victor kimberlite intruded in the region of the Colesberg Lineament, although it is not clear which lithospheric block the kimberlite sampled at depth. Peridotitic garnet xenocrysts from Roberts Victor give Lu–Hf isochron ages of 3266 ± 150 Ma (with initial $\varepsilon_{Hf} = 17.6 \pm 3.6$) and 2947 ± 58 Ma (with initial $\varepsilon_{Hf} = 2.7 \pm 1.4$), appearing to give ages for both initial lithospheric mantle formation and metasomatic modification of the lithosphere at the time of continental collision (Shu et al. 2013). The oldest diamonds dated from the Witwatersrand–Swaziland Blocks are Cullinan peridotitic diamonds that give a ‘Sr model age’ around 3.0 Ga (Richardson et al. 1993). The only other Archaean diamonds in the Witwatersrand–Swaziland Blocks are the 2.55 ± 0.15 Ga Klipspringer eclogitic diamonds (Westerlund et al. 2004) and the diamonds hosted in the 2.9–2.8 Ga Central Rand Group of the Witwatersrand Basin (Williams 1932; Gittus 1963; Raal and Robinson 1980).

Archaean–Proterozoic large igneous provinces (LIPs) in the Kaapvaal

Despite its lithospheric longevity, the Kaapvaal Craton hosts several LIPs that represent large amounts of magma over short time intervals during the Archaean and Proterozoic. The **Ventersdorp Supergroup** is comprised of multiple LIPs related to repeated plume impingement and a period of rifting and crustal extension: the Klipriviersberg Group with ages between 2791 and 2779 Ma, the Platberg Group between 2754 and 2709 Ma, and the Allanridge/Pniel Group between 2709 and 2683 Ma (Gumsley et al. 2020; Khumalo et al. 2024). Based on mapping of several dyke swarms of similar age, the plume impingement site is proposed to have occurred in the eastern Transvaal Basin, beneath the present-day eastern Bushveld (Olsson et al. 2011; Humbert et al. 2019). In addition to the surface manifestation of the Ventersdorp LIP (Fig. 1), the widespread thermal impact of Ventersdorp magmatism is recognised in both the Kaapvaal crust and lithospheric mantle (Dawson and Smith 1987; Dawson

et al. 1997; Moser and Hart 1998; Schmitz and Bowring 2003; Lazarov et al. 2009; Branchetti et al. 2021; Shu et al. 2024). The Ventersdorp events also correspond to the time of major reactivation of the Thabazimbi–Murchison Lineament—the northern boundary of the Witwatersrand Block with the Pietersburg Block—that has been traced down to mantle depths from seismic anisotropy studies (Vinnik et al. 1995; Good and de Wit 1997; Silver et al. 2001).

The 2.25–2.23 Ga **Hekpoort formation** (age data from Burger and Coertze 1973; Cornell et al. 1996; Schröder et al. 2016) is a recently recognised LIP, and consists of 300–830 m thick basaltic lava flows and volcanoclastic detritus over a 100 000 km² area in the Transvaal Basin of the Witwatersrand Block (Fig. 1; Humbert et al. 2018; Lenhardt et al. 2020). A plume impingement site for Hekpoort has not yet been proposed. The Hekpoort formation is distinct from the similarly-aged Ongeluk formation in Griqualand–West (Kimberley Block), where magmatism occurred at 2.43 Ga (Gumsley et al. 2016, 2017). The Hekpoort magmas have subduction-like trace element signatures and formed through partial melting of eclogite-bearing lithospheric mantle or lithosphere containing subduction-related metasomes (Myers et al. 1987; Harmer and von Gruenewaldt 1991).

Due to its economic importance as a source for platinum-group metals, the **Bushveld Igneous Complex** is extremely well-studied (e.g., Hatton 1995; Cawthorn and Walraven 1998; Schoenberg et al. 1999; Mungall et al. 2016; Roelofse and Ashwal 2012; Hayes et al. 2018; Magalhães et al. 2018). The Bushveld was emplaced around 2.06 Ga, with ages ranging from 2054 Ma (Scoates and Friedman 2008) to 2056–2055 Ma (zircon U–Pb; Zeh et al. 2015). The plume impingement site is proposed to be directly beneath the Bushveld, though melt sources have been suggested to be either the lithospheric mantle or the sub-lithospheric convecting mantle (Richardson and Shirey 2008; Zirakparvar et al. 2019; Ashwal 2021). Zirakparvar et al. (2019) proposed that melting of cumulates underplated during the 2.79–2.68 Ga plume-related Ventersdorp magmatism could have produced the observed Hf isotope compositions of the Rustenburg Layered Suite in the Bushveld. 1930 ± 40 Ma lherzolitic diamonds from the Cullinan mine (Richardson et al. 1993) formed within 100 My of the Bushveld and likely represent plume-related heating in the lithospheric mantle and melt mobilisation in peridotite. The initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of 0.5100 (ε_{Nd} of -2.49 at 1.93 Ga) indicates that the diamonds grew in 2.2–2.0 Ga lherzolite protoliths which could similarly represent lithospheric mantle that had been refertilised by Bushveld-related melts (Richardson et al. 1993).

Umkondo plume magmatism occurred between 1.112 and 1.106 Ga (Hanson et al. 2004, 2006). The plume

impingement site is suggested to be in present-day Botswana and large volumes of magmatism affected vast regions ($>2 \text{ M km}^3$) across the Kaapvaal and Zimbabwe Cratons (Ashwal 2021).

Voorspoed carbonate-rich olivine lamproite (CROL)

Voorspoed is part of the Kroonstad cluster of CROLs that erupted at $131.8 \pm 0.6 \text{ Ma}$ (Ar–Ar; Phillips et al. 1998) into the Witwatersrand Block. The only other economic intrusion in the Kroonstad cluster is Lace, where diamond-bearing kyanite eclogite xenoliths were reported (Aulbach et al. 2016). Lace diamonds contain both peridotitic and eclogitic mineral inclusions, and eclogitic diamonds include zircon inclusions with $3.2 \pm 0.4 \text{ Ga}$ Hf T_{CHUR} model ages providing the age of the eclogitic protoliths (Karaevangelou et al. 2022). Pressure and temperature calculations for mineral inclusions in diamonds and xenocrysts from Lace and Voorspoed, show that at 132 Ma the lithospheric mantle had a geotherm that is typical for worldwide cratonic lithosphere, corresponding to $38\text{--}40 \text{ mW/m}^2$ surface heat flow with a thickness around 220 km (Nimis et al. 2020; Karaevangelou et al. 2022). Along the geotherm determined from clinopyroxene xenocrysts, Voorspoed diamonds are stable at depths greater than 120 km (Nimis et al. 2020). However, based on geothermobarometry of mineral inclusions, Voorspoed diamonds have a formation window of $170 \pm 20 \text{ km}$, which is narrower than the depth interval of garnet and clinopyroxene xenocrysts (Nimis et al. 2020). Fibrous diamonds from Voorspoed contain silicic-carbonatitic, saline and high-Mg carbonatitic fluid inclusions, which along with distinct nitrogen aggregation characteristics for each compositional group likely reflect multiple fibrous diamond-forming events (Kempe et al. 2021, 2025).

Samples and analytical techniques

A suite of monocrystalline gem-quality Voorspoed diamonds were laser cut and polished using at Titanium laser system from OGI Systems Ltd., followed by conventional polishing on a diamond-embedded wheel at the Gemological Institute of America (GIA) in New Jersey. Diamonds were laser cut along the (110) orientation to prepare double-sided plates that contained mineral inclusions. Fourier Transform Infrared (FTIR) spectroscopy was conducted at GIA in New York. Diamonds were mounted along the side of glass slides with double-sided tape, and absorption spectra were measured using a Nicolet iN10 infrared microscope operating in transmission mode. The detector was cooled by liquid nitrogen and the sample stage continuously purged with dry air.

FTIR spectra were collected over the mid-infrared range ($5000\text{--}675 \text{ cm}^{-1}$), with a resolution of 1 cm^{-1} and a square aperture between 50 and 100 μm . Background spectra of 256 scans were recorded over three minutes prior to each analytical session and every hour during analyses. Background spectra were automatically subtracted from the diamond spectra to correct for non-sample contributions. Infrared maps for each diamond were compiled by recording spectra at $100\text{--}200 \mu\text{m}$ intervals, with each map containing between 1000 and 4000 spectra. Nitrogen concentration was calculated from absorption coefficients at 1282 cm^{-1} : $[\text{NA}] = 16.5 \times \mu\text{A}$ (Boyd et al. 1994) and $[\text{NB}] = 79.4 \times \mu\text{B}$ (Boyd et al. 1995), using DiaMap software for automated spectral deconvolution to handle the large amount of data generated (Howell et al. 2012b).

Following FTIR mapping and CL imaging, diamond plates were carefully broken in a steel cracker, and mineral inclusions picked out under magnification. We followed the procedures established for isotopic dating of single silicate inclusions at Vrije Universiteit in Amsterdam, and our methods are essentially those described in Timmerman et al. (2017) and Koornneef et al. (2017).

Major elements

Whole unpolished silicate inclusions were analysed for their major element composition using Jeol JXA-8800 M and Jeol JXA-8350F electron probe microanalysers at Utrecht Universiteit following the method of Timmerman et al. (2015). Flat, level crystal faces were targeted for analyses. Beam conditions during operation were 15 kV, 25 nA, and 1 μm beam size, with peak dwell time of 30 s and background dwell time of 15 s. Mineral standards used during analyses were chromite (Cr), corundum (Al), diopside (Si, Ca), fayalite (Fe), ilmenite (Ti), jadeite (Na), NiO (Ni), olivine (Mg), orthoclase (K), and tephroite (Mn).

Chemistry

After microprobe analyses, the inclusions were washed in ethanol, deionised, and Milli-Q water to remove the carbon coating prior to spiking and digesting the inclusions for column chromatography. Inclusions were spiked with a ^{84}Sr spike, ^{87}Rb spike and a $^{149}\text{Sm}\text{--}^{150}\text{Nd}$ mixed spike. In order to estimate of how much isotopic spike to add to each inclusion, approximate Nd concentrations were estimated based on the paragenesis of the inclusions and comparison to previously-analysed inclusions. Samples were dissolved in concentrated HF-HNO₃ on a hotplate at $140 \text{ }^\circ\text{C}$ for a minimum of three days. Chemical separation of the dissolved matrix was performed in a miniaturised downstream column procedure where the Sr-columns (0.07 mL

Fig. 3 Major element compositions of peridotitic and eclogitic garnet inclusions in Voorspoed diamonds. For comparison the compositions of Voorspoed inclusions studied by Viljoen et al. (2018) are also plotted in black and white symbols. Fields for harzburgitic (G10), lherzolitic (G9), eclogitic (G3) and pyroxenitic (G4) in (a) as defined by Grütter et al. (2004)

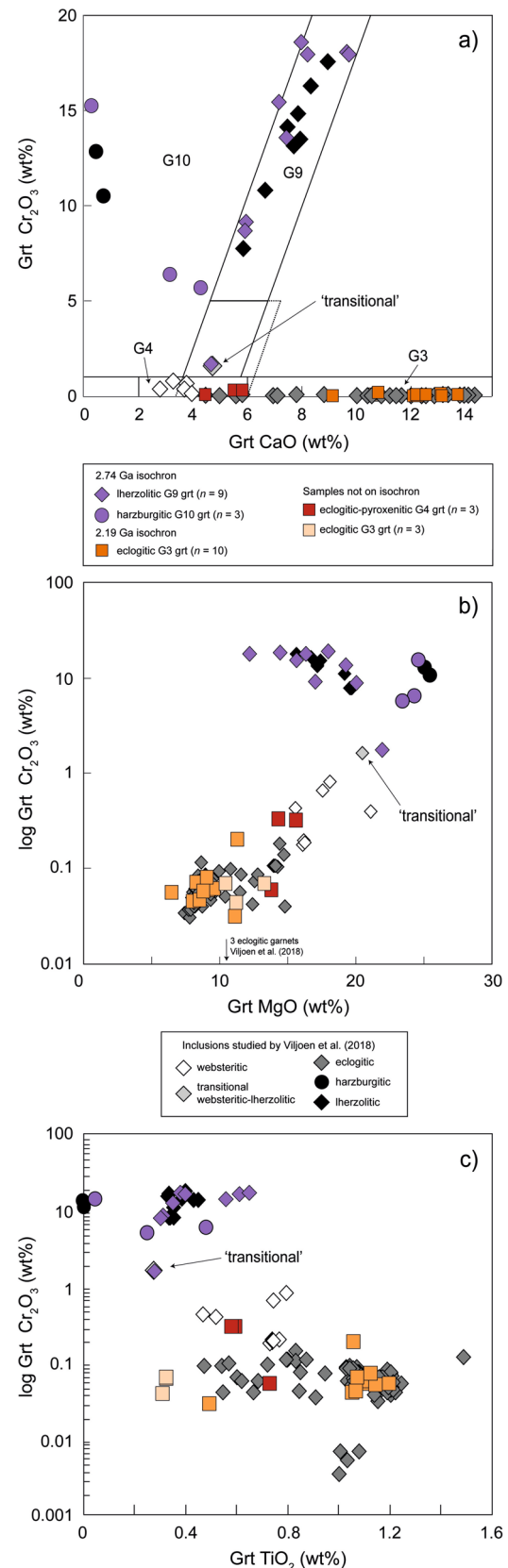
Eichrom Sr resin) were placed above the TRU columns (0.23 mL Eichrom TRU resin), followed by miniaturised endurable quartz-columns for Rb separation (0.16 mL Bio-Rad AG50 $\times$ 8 200–400 mesh) and miniaturised LN-resin (Eichrom 50–100 μ m; 0.74 mL) columns for Sm–Nd separation. For details, see Koornneef et al. (2017).

Trace elements

Following chromatography, all matrix fractions for each inclusion were merged and dried down for trace element analyses by inductively coupled plasma mass spectrometry (ICP-MS) on a Thermo X-Series II. Changes in instrument sensitivity over time were monitored using BHVO-2 ($\sim 30\,000\times$ diluted), which was analysed after every sample (modified after Eggins et al. 1997). After interference correction, elemental concentrations of the matrix cuts were calculated using a two-point calibration of blank and BHVO-2 (10 241 $\times$ diluted). Subsequently, the matrix cuts were further yield-corrected using the average of four to five aliquots (with different dilution factors similar to the samples) of the ~ 1 mg BHVO-2 that was previously processed together with the samples on the columns. Only data above the limit of quantification (LOQ) are reported.

Isotopic compositions

Samarium, Nd, Rb and Sr isotope compositions were measured by thermal ionisation mass spectrometry (TIMS) on a Thermo Scientific Triton Plus fitted with 10^{13} Ohm amplifiers on four Faraday cups. Reproducibility was assessed by measuring standards with different concentrations: $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.710300 ± 0.000121 ($n=5$; NBS987 0.2 ng) and 0.710255 ± 0.000025 ($n=8$; NBS987 200 ng); $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.511315 ± 0.000052 ($n=8$; CIGO 0.1 ng), 0.512104 ± 0.000052 ($n=9$; JNdi 200 ng); $^{149}\text{Sm}/^{152}\text{Sm} = 0.516829 \pm 0.000021$ (2SD; $n=5$). Samarium–Nd analyses were corrected for total procedural blanks of Sm = 0.04 pg ($n=8$) and Nd = 0.06 pg ($n=8$); with $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.511856 ± 0.00009 measured by Timmerman et al. (2017). Rubidium–Sr analyses were corrected for total procedural blanks of Rb = 0.36 pg ($n=7$) and Sr = 13.68 pg ($n=6$); with $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.711123 ± 0.00005 measured by Timmerman et al. (2017). Samarium–Nd isochron regressions were calculated using the online version of IsoPlotR (Vermeesch 2018).



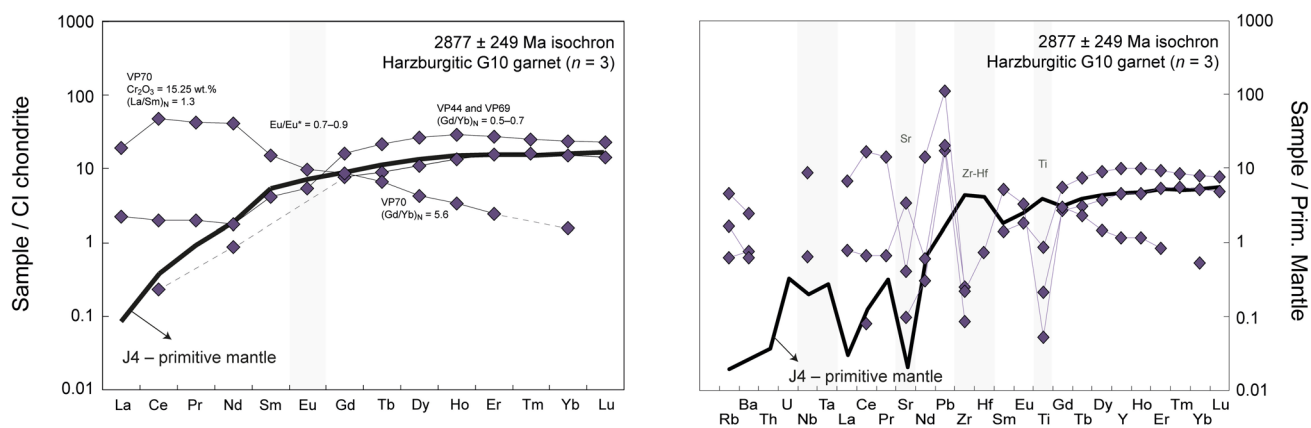


Fig. 4 Chondrite-normalised REE patterns and primitive-mantle-normalised extended trace element patterns for harzburgitic G10 garnet inclusions. J4 refers to garnet and clinopyroxene from the J4 Jagers-

fontein peridotite xenolith with a primitive mantle composition (Stachel et al. 2022a). Chondrite and primitive mantle normalising values from Sun and McDonough (1989)

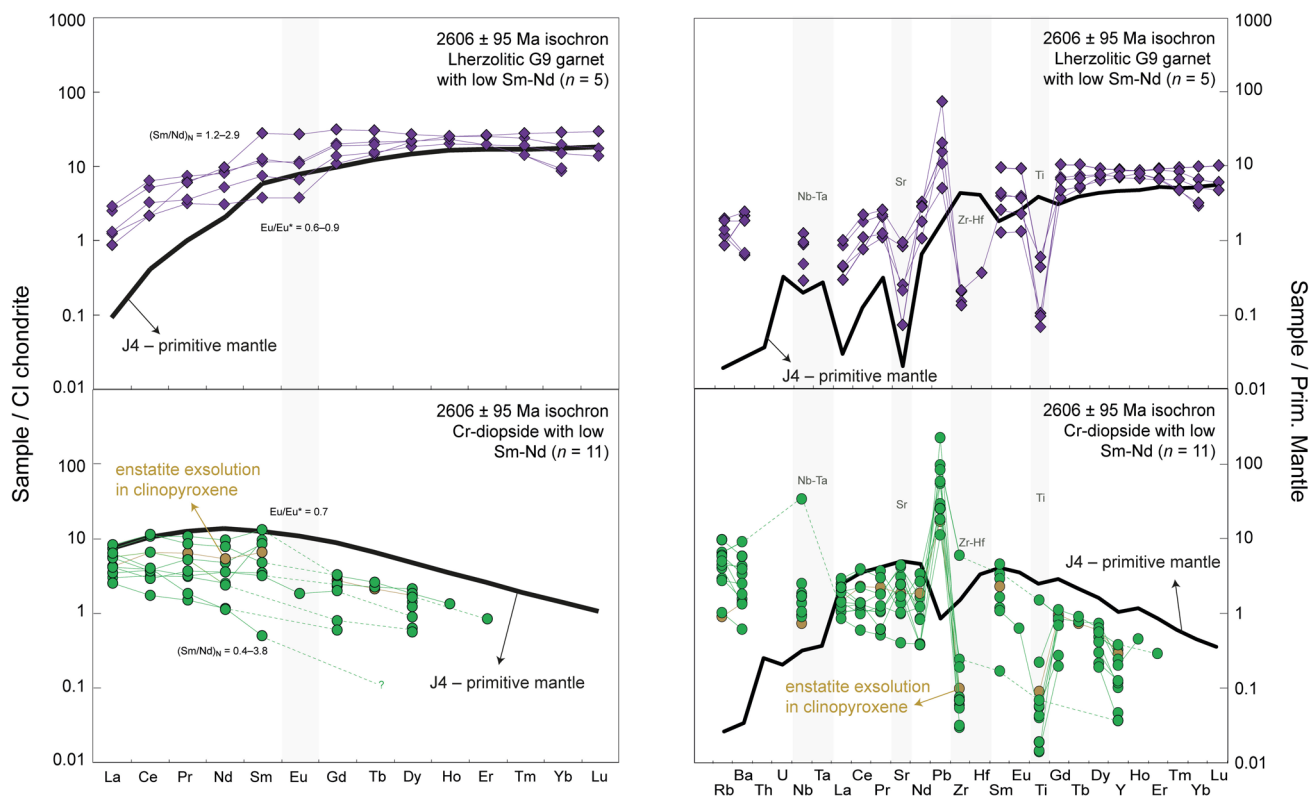


Fig. 5 Chondrite-normalised REE patterns and primitive-mantle-normalised extended trace element patterns for lherzolitic G9 garnet and Cr-diopside inclusions that have $La_N > 1$ and low $^{147}Sm/^{144}Nd = 0.11–0.41$. J4 refers to garnet and clinopyroxene from the J4 Jagersfontein

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Results

Inclusions major and trace element chemistry

Peridotitic—group 1

Twelve purple-pink garnets have sub-calcic to calcic pyrope compositions that are classified according to 'G-number' classification, following Grütter et al. 2004 (Fig. 3a). Three of these garnets are harzburgitic (G10), with $Mg\# = 76.2–90.4$ and $Cr\# = 17.2–43.7$ (Table S1). Two of the harzburgitic garnets have depleted LREE_N compositions with $(La/Sm)_N < 0.55$, relatively flat MREE–HREE_N and $(Gd/$

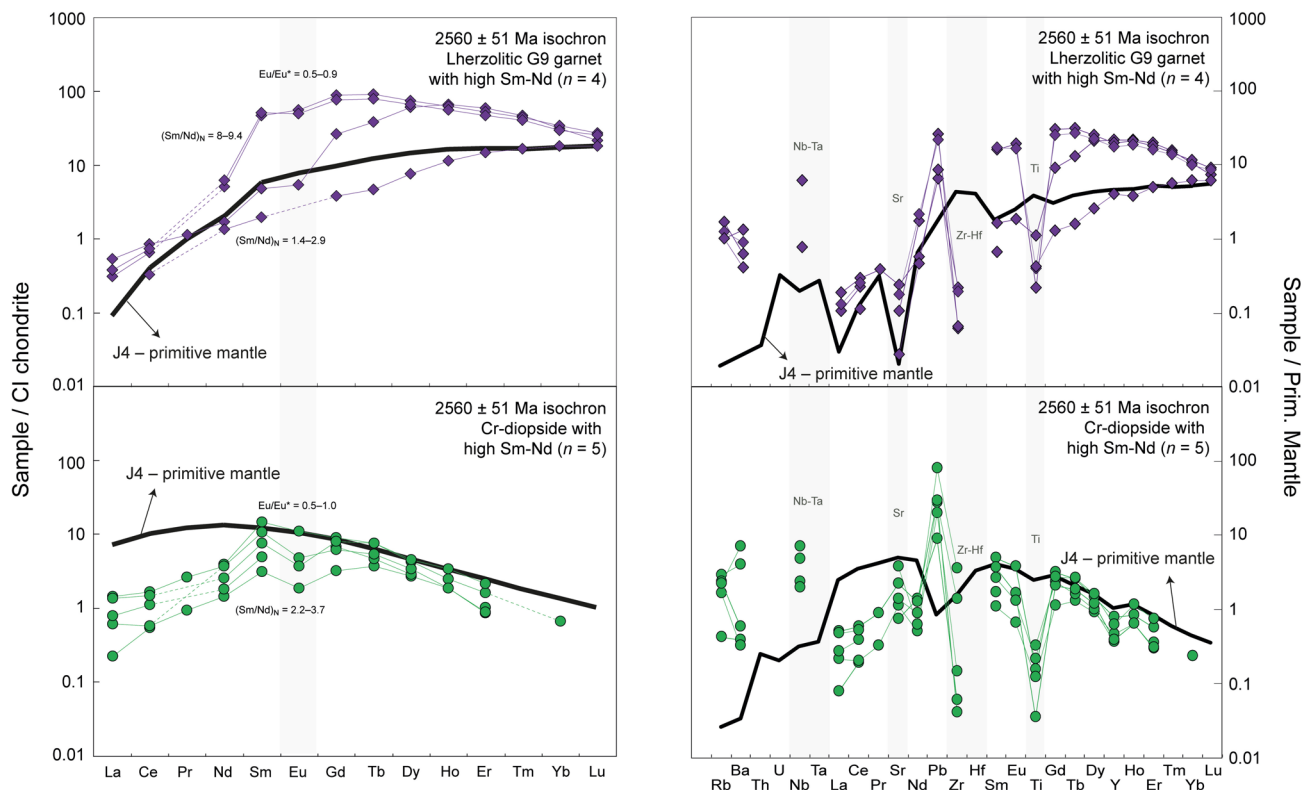


Fig. 6 Chondrite-normalised REE patterns and primitive-mantle-normalised extended trace element patterns for lherzolitic G9 garnet and Cr-diopside inclusions that have $La_N < 1$ and high $^{147}Sm/^{144}Nd = 0.45$ – 1.51 . J4 refers to garnet and clinopyroxene from the J4 Jagersfontein

$Yb_N = 0.5$ – 0.7 where REE_N refers to normalisation to CI chondrite abundances (Sun and McDonough 1989) (Fig. 4). One harzburgitic garnet (with Cr_2O_3 of 15.24 wt.%) is enriched in LREE, with $(La/Sm)_N = 1.3$ and depleted in HREE with $(Gd/Yb)_N = 5.6$. Small negative Eu anomalies are observed in two harzburgitic (G10) garnets, with $Eu/Eu^* = 0.7$ – 0.9 (Fig. 4). Europium and Sm were not determined on the most depleted harzburgitic garnet.

Nine garnets are lherzolitic (G9), with $Mg\# = 70.4$ – 83.7 and $Cr\# = 5.0$ – 61.9 . One of the lherzolitic (G9) garnets has low Cr_2O_3 of 1.73 wt.%, that corresponds to the “transitional websteritic-lherzolitic” Voorspoed inclusion assemblage described by Viljoen et al. (2018) (Fig. 3b, c). The nine lherzolitic garnets display REE_N patterns that are depleted in LREE to variable extents. Based on LREE abundances and $^{147}Sm/^{144}Nd$ ratios, the lherzolitic garnets can be divided into two categories: five garnets with $La_N > 1$ and lower $^{147}Sm/^{144}Nd = 0.3$ – 0.4 (Fig. 5) and four garnets with $La_N < 1$ and higher $^{147}Sm/^{144}Nd = 0.8$ – 1.5 (Fig. 6). Both subgroups have variable MREE-HREE_N with $(Gd/Yb)_N = 0.6$ – 2.6 , and negative Eu anomalies ($Eu/Eu^* = 0.5$ – 0.9) are observed. Three garnets in the higher $^{147}Sm/^{144}Nd$ subgroup have convex upwards MREE-HREE_N patterns (Fig. 6). On plots

peridotite xenolith with a primitive mantle composition (Stachel et al. 2022a). Chondrite and primitive mantle normalising values from Sun and McDonough (1989)

that use the Y-Zr and Ti contents of garnets to distinguish depleted from metasomatised garnets, Voorspoed garnets all have relatively low Zr contents and high Y and Ti contents (Fig. 7; Griffin and Ryan 1995).

Sixteen bright green peridotitic clinopyroxenes classify as Cr-diopside. They are easily distinguished from omphacitic pale green clinopyroxene that occurs in eclogite, where omphacite has $Na/(Na + Ca) > 0.2$. Cr-diopsides in Voorspoed diamonds studied here have $Na/(Na + Ca) = 0.03$ – 0.19 , and $Cr\#$ between 30 and 80 (Fig. 8). In one Cr-diopside (VP46B) where orthopyroxene exsolution was observed (similar to the exsolution described in Viljoen et al. 2018), we also targeted the orthopyroxene for major element analyses (Table S1).

Similar to the lherzolitic (G9) garnets described above, the Cr-diopsides can also be subdivided into two categories based on LREE abundances and Sm–Nd ratios: 11 Cr-diopsides with $La_N = 0.2$ – 1.4 and lower $^{147}Sm/^{144}Nd = 0.11$ – 0.16 (Fig. 5) and five Cr-diopsides with $La_N = 3$ – 8.3 and higher $^{147}Sm/^{144}Nd = 0.45$ – 0.56 (Fig. 6). Both groups of Cr-diopsides are depleted in MREE and HREE, where the higher $^{147}Sm/^{144}Nd$ group has $(Gd/Er)_N = 3.7$ – 6.9 , and the lower

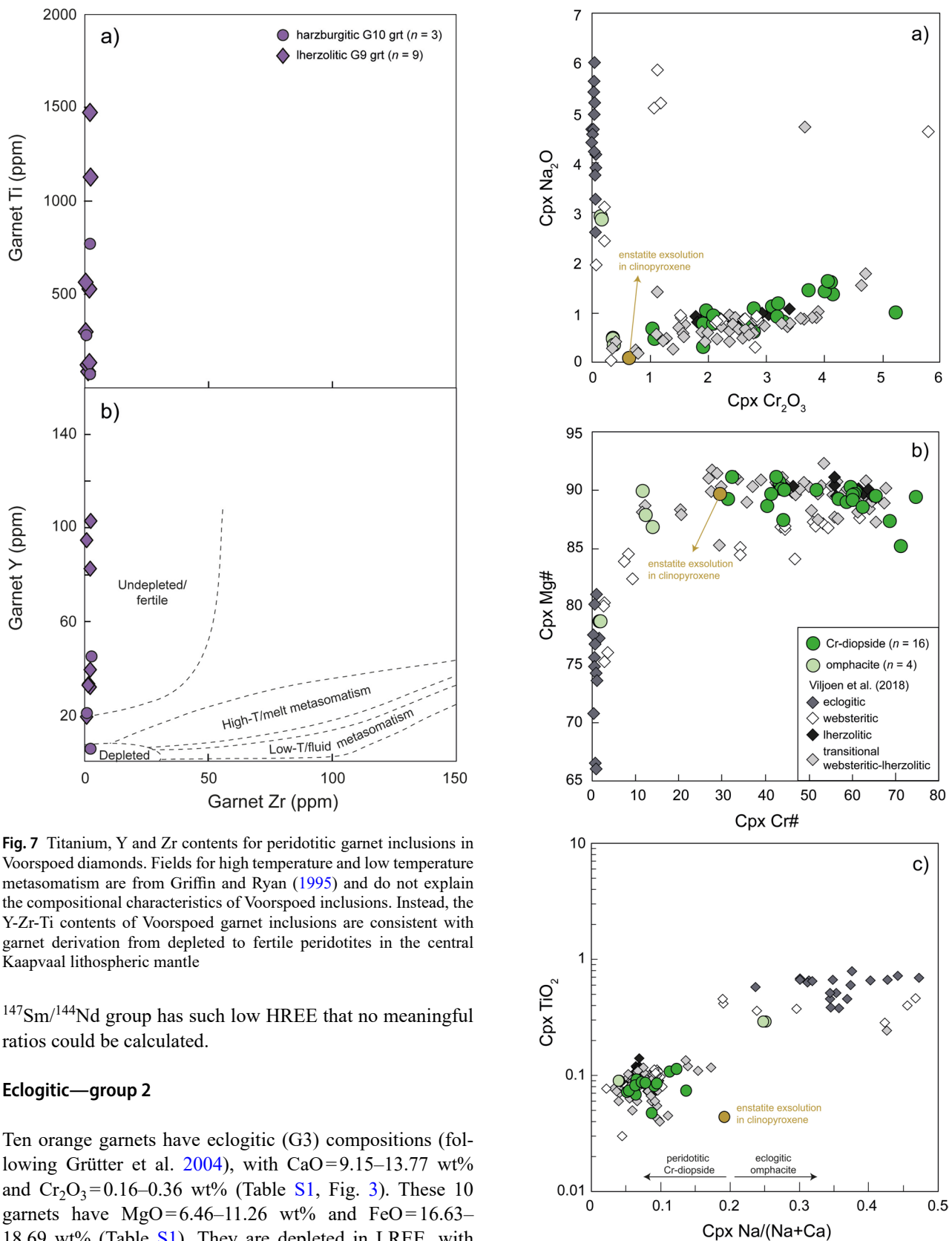


Fig. 7 Titanium, Y and Zr contents for peridotitic garnet inclusions in Voorspoed diamonds. Fields for high temperature and low temperature metasomatism are from Griffin and Ryan (1995) and do not explain the compositional characteristics of Voorspoed inclusions. Instead, the Y-Zr-Ti contents of Voorspoed garnet inclusions are consistent with garnet derivation from depleted to fertile peridotites in the central Kaapvaal lithospheric mantle

$^{147}\text{Sm}/^{144}\text{Nd}$ group has such low HREE that no meaningful ratios could be calculated.

Eclogitic—group 2

Ten orange garnets have eclogitic (G3) compositions (following Grütter et al. 2004), with $\text{CaO}=9.15\text{--}13.77\text{ wt}\%$ and $\text{Cr}_2\text{O}_3=0.16\text{--}0.36\text{ wt}\%$ (Table S1, Fig. 3). These 10 garnets have $\text{MgO}=6.46\text{--}11.26\text{ wt}\%$ and $\text{FeO}=16.63\text{--}18.69\text{ wt}\%$ (Table S1). They are depleted in LREE, with $(\text{La}/\text{Sm})_{\text{N}}=0.01\text{--}0.33$, and are moderately enriched in MREE over HREE, with $(\text{Gd}/\text{Yb})_{\text{N}}=1.14\text{--}14.60$. These

Fig. 8 Na-Mg-Cr-Ti compositions of clinopyroxene inclusions in Voorspoed diamonds, compared to the compositions of Voorspoed inclusions studied by Viljoen et al. (2018). Eclogitic omphacite is distinguished from peridotitic Cr-diopside by $\text{Na}/(\text{Na}+\text{Ca}) > 0.2$. Although there are six omphacitic clinopyroxenes from two diamonds (VP35, VP38) on the 2196 ± 61 Ma eclogitic isochron (Fig. 12), two inclusions from VP35 do not have major element compositions due to lack of flat surfaces for EPMA analyses (Table S1). Symbols are the same in all three panels, with the legend provided in b)

garnets have variable negative to positive Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.5\text{--}1.7$; Fig. 9).

Two pale green clinopyroxenes from VP38 have $\text{Na}/(\text{Na}+\text{Ca}) = 0.25$, indicating that they are omphacitic. In VP35, two pale green clinopyroxenes have lower $\text{Na}/(\text{Na}+\text{Ca}) = 0.03\text{--}0.04$ and $\text{Mg\#} = 86.9\text{--}89.9$ that overlap with peridotitic clinopyroxene suggesting they are pyroxenitic (Fig. 8 and Table S1). Although there are six eclogitic clinopyroxenes from two diamonds (VP35, VP38) on the same Sm–Nd isochron (see below), two inclusions from VP35 do not have major element compositions due to lack of flat surfaces for EPMA analyses (Table S1). The two omphacitic clinopyroxenes from VP38 are LREE-enriched, up to $100 \times$ chondrite, with $(\text{La}/\text{Sm})_{\text{N}} = 2.38\text{--}3.14$ (Fig. 9). One of these omphacites has a small positive Eu anomaly of 1.23, whereas the other omphacite did not contain measurable Eu (Table S1). The three omphacites from VP35 have LREE around $1 \times$ chondrite, and are moderately enriched in the MREE, with $(\text{La}/\text{Sm})_{\text{N}} = 0.20\text{--}0.62$ (Fig. 9). These omphacites did not contain measurable Eu (Table S1).

Eclogitic—group 3

A group of six orange-red eclogitic-pyroxenitic (G3–G4) garnets are classified based on their LREE-depleted character, with $(\text{Ce}/\text{Sm})_{\text{N}} = 0.08\text{--}1.11$ (Fig. 9). Unlike the Group 2 eclogitic (G3) garnet inclusions, these six eclogitic-pyroxenitic garnets are not enriched in MREE over HREE, and have $(\text{Gd}/\text{Yb})_{\text{N}} = 0.65\text{--}1.81$. The G4 garnets have negative Eu anomalies, with $\text{Eu}/\text{Eu}^* = 0.73\text{--}0.78$, whereas the Eu anomalies in the G3 garnets are negligible ($\text{Eu}/\text{Eu}^* = 0.96\text{--}1.06$). One eclogitic-pyroxenitic G4 garnet has a relatively flat $(\text{HREE})_{\text{N}}$ pattern, whereas the other five garnets are depleted in HREE relative to MREE (Fig. 9). The three G4 garnets have compositions with CaO between 4.49 and 5.84 wt% and Cr_2O_3 between 0.06 and 0.32 wt% (Fig. 3). These three G4 garnets have $\text{MgO} = 13.76\text{--}15.59$ wt% and $\text{FeO} = 16.34\text{--}20.05$ wt% (Table S1). The other three garnets have G3 eclogitic compositions, with CaO between 10.64 and 10.85 wt% and Cr_2O_3 between 0.04 and 0.07 wt% (Fig. 3). The G3 garnets have $\text{MgO} = 10.46\text{--}13.26$ wt% and $\text{FeO} = 15.93\text{--}16.60$ wt% (Table S1).

Sm–Nd isochron relationships of inclusions

Peridotitic group 1—2.9–2.6 Ga isochrones

All twenty-eight Group 1 peridotitic inclusions (12 peridotitic garnets and 16 Cr-diopside clinopyroxenes) define an isochron of 2745 ± 26 Ma, with MSWD of 6.7 (Fig. 10a). This isochron has an initial $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.50854 ± 0.00006 ($\epsilon_{\text{Nd}} = -10.6 \pm 1.9$). However on closer inspection, the peridotitic inclusions can be separated into different isochrons based on major/trace element compositions with ages between 2.9 and 2.6 Ga, and lower MSWDs closer to 1.

Three harzburgitic G10 inclusions (in three different diamonds – VP44, VP69, VP70) define an isochron of 2877 ± 249 Ma, with initial $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.50815 ± 0.00016 ($\epsilon_{\text{Nd}} = -15 \pm 10$), and MSWD of 1.2 (Fig. 10b). The two compositional subgroups of lherzolitic G9 garnet and Cr-diopside inclusions with distinct La_{N} contents and $^{147}\text{Sm}/^{144}\text{Nd}$ (Fig. 5 and 6) give younger ages closer to ~ 2.6 Ga. The low $^{147}\text{Sm}/^{144}\text{Nd}$ compositional group defines an isochron of 2606 ± 95 Ma, with initial $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.50891 ± 0.00015 ($\epsilon_{\text{Nd}} = -6.9 \pm 5.4$), and MSWD of 0.87 (Fig. 10c). The high $^{147}\text{Sm}/^{144}\text{Nd}$ compositional group defines an isochron of 2560 ± 51 Ma, with initial $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.50982 ± 0.00033 ($\epsilon_{\text{Nd}} = 9.8 \pm 7.8$), and MSWD of 0.92 (Fig. 10d).

Three diamonds had multiple inclusions of lherzolitic (G9) garnet and Cr-diopsides that provided the opportunity to calculate isochron ages for single diamonds (Fig. 11):

- (i) VP02 has one lherzolitic garnet and two Cr-diopsides (all in the low $^{147}\text{Sm}/^{144}\text{Nd}$ group defined above) that define an isochron of 2585 ± 144 Ma, with MSWD of 0.019 and initial $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.50893 ± 0.00018 ($\epsilon_{\text{Nd}} = -7.2 \pm 7.0$) (Fig. 11a).
- (ii) VP46 has two lherzolitic garnets and three Cr-diopsides (all in the low $^{147}\text{Sm}/^{144}\text{Nd}$ group defined above) that define an isochron of 2673 ± 198 Ma, with MSWD of 0.46 and initial $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.50893 ± 0.00042 ($\epsilon_{\text{Nd}} = -4.8 \pm 13.3$) (Fig. 11b).
- (iii) VP03 has three lherzolitic garnets and two Cr-diopsides (all in the high $^{147}\text{Sm}/^{144}\text{Nd}$ group defined above) that define an isochron of 2561 ± 64 Ma, with MSWD of 1.9 and initial $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.50980 ± 0.00048 ($\epsilon_{\text{Nd}} = 9.4 \pm 11.1$) (Fig. 11c).

Eclogitic group 2—2.2 Ga isochron

Sixteen eclogitic inclusions (10 garnets and six omphacitic clinopyroxenes) define an isochron of 2196 ± 61 Ma, with initial $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.50932 ± 0.00012 ($\epsilon_{\text{Nd}} = -9.3 \pm 3.9$) and MSWD of 0.96 (Fig. 12). This isochron is defined by several diamonds with multiple inclusions: VP18 has two

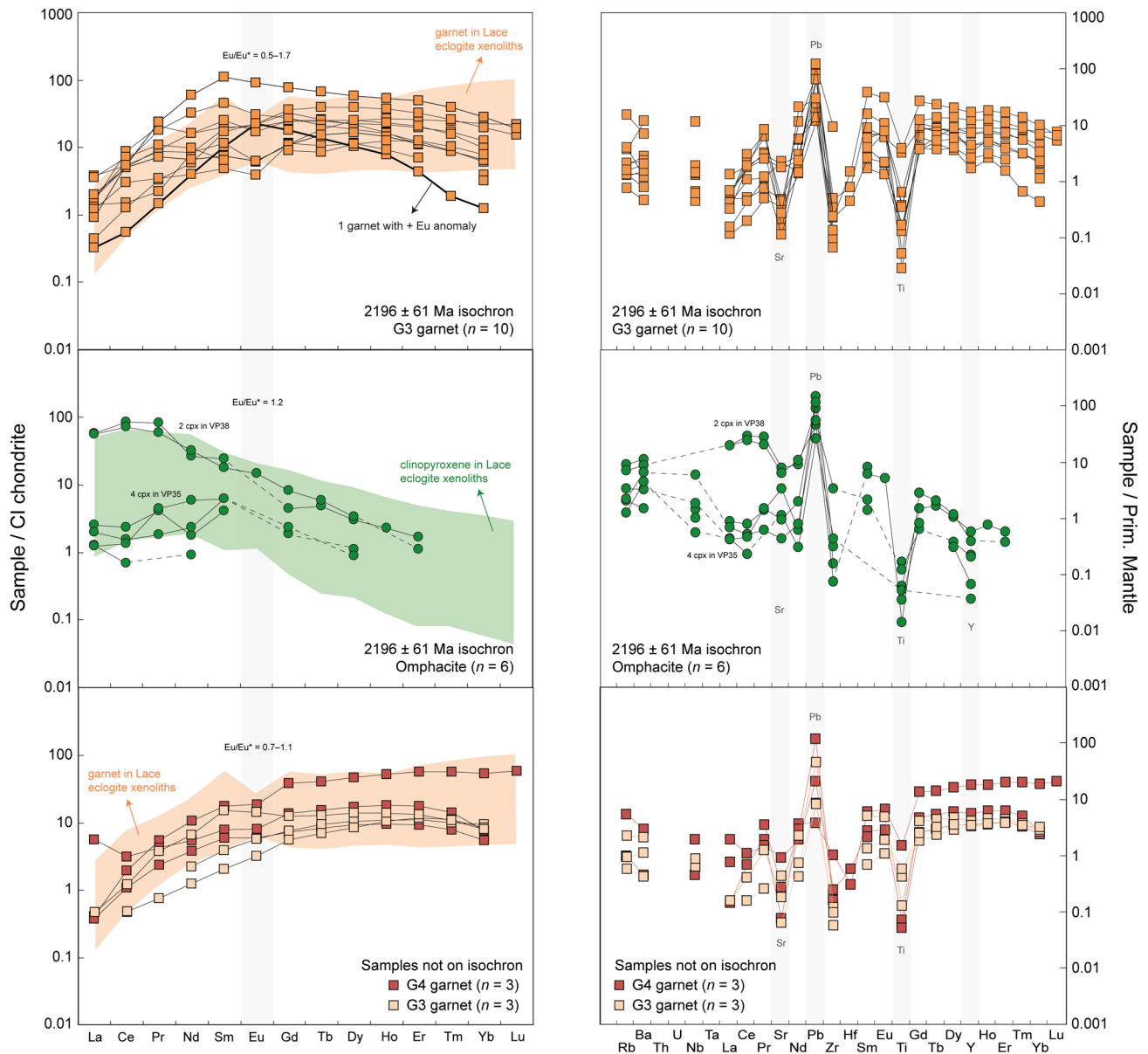


Fig. 9 Chondrite-normalised REE patterns and primitive-mantle-normalised extended trace element patterns for eclogitic garnet and clinopyroxene inclusions that form the 2196 ± 61 Ma Sm–Nd isochron.

garnet inclusions, VP19 has three garnet inclusions, VP21 has two garnet inclusions, VP35 has four clinopyroxene inclusions, VP38 has two clinopyroxene inclusions. Unfortunately, none of these diamonds contained both garnet and clinopyroxene and consequently the spread in Sm/Nd ratios between different inclusions was not large enough to define meaningful single diamond isochrons.

Compositions for garnet and clinopyroxene from Lacey eclogite xenoliths from Aulbach and Viljoen (2015). Chondrite and primitive mantle normalising values from Sun and McDonough (1989)

Eclogitic group 3—no age relationships

Six eclogitic inclusions with different trace element characteristics (three G4 pyroxenitic garnets and three G3 eclogitic garnets) have Sm–Nd isotope compositions that plot off the main 2.2 Ga eclogitic isochron (Fig. 12). These six inclusions do not provide strong age constraints other than to be consistent with formation during the Archaean or Proterozoic based on Sm–Nd model ages (Table S1).

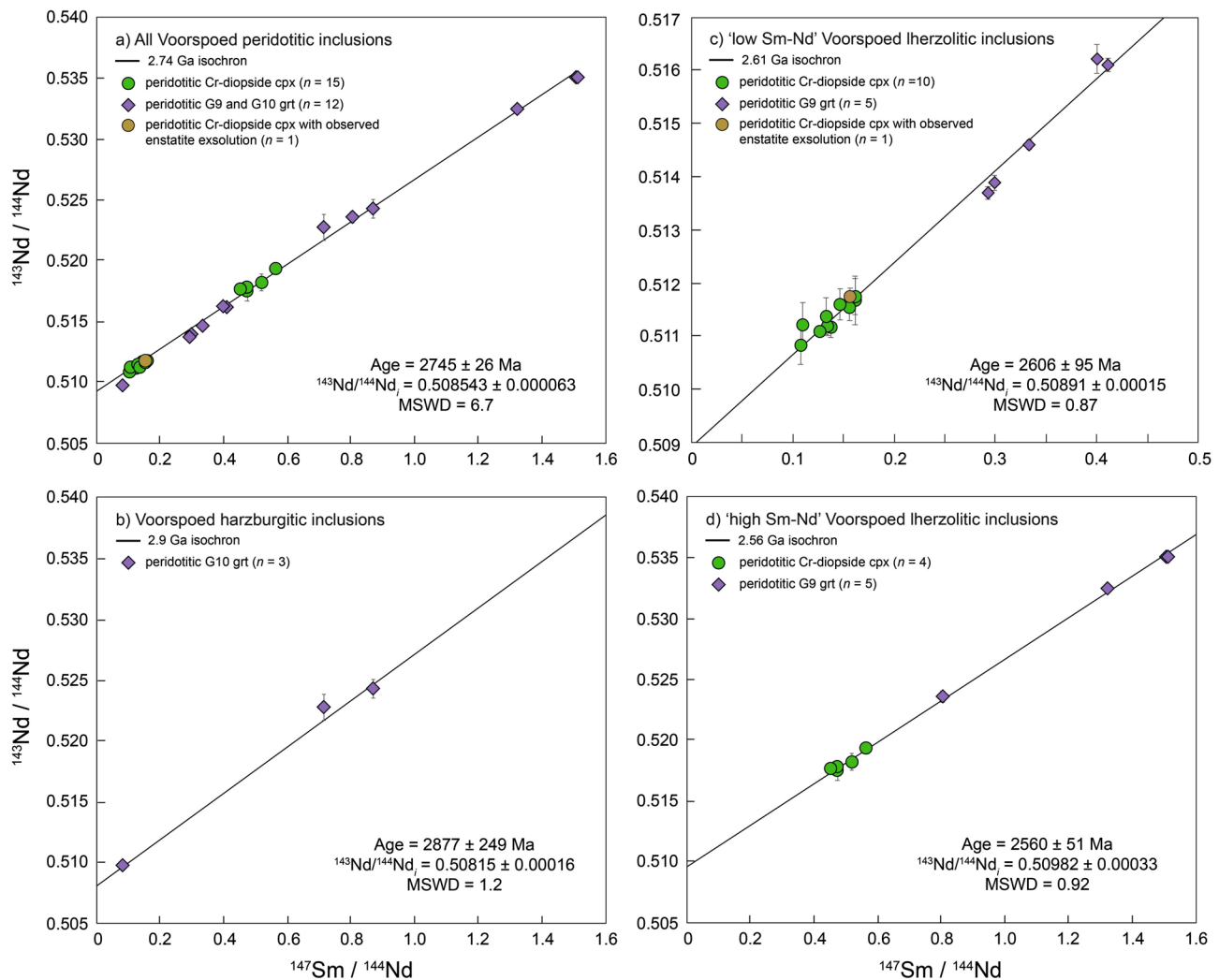


Fig. 10 **a** 28 peridotitic garnets and Cr-diopsides define a Sm–Nd isochron of 2745 ± 26 Ma, with MSWD of 6.7. This isochron represents an average age from the three isochron regressions determined from different major-trace element groupings in panels **b** to **d**. **b** Three harzburgitic G10 garnets define a Sm–Nd isochron of 2877 ± 249 Ma with an initial $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.50815 ± 0.00016 . **c** Five lherzolitic G9 garnet and 11 Cr-diopside inclusions with $\text{La}_N > 1$ and low $^{147}\text{Sm}/^{144}\text{Nd}$

(0.11–0.41), define a 2606 ± 95 Ma Sm–Nd isochron with an initial $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.50891 ± 0.00015 . **d** Four lherzolitic G9 garnet and five Cr-diopside inclusions with $\text{La}_N < 1$ and high $^{147}\text{Sm}/^{144}\text{Nd}$ (0.45–1.51), define a 2560 ± 51 Ma Sm–Nd isochron with an initial $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.50982 ± 0.00033 . Isochron regressions calculated with the online version of IsoplotR (Vermeesch 2018)

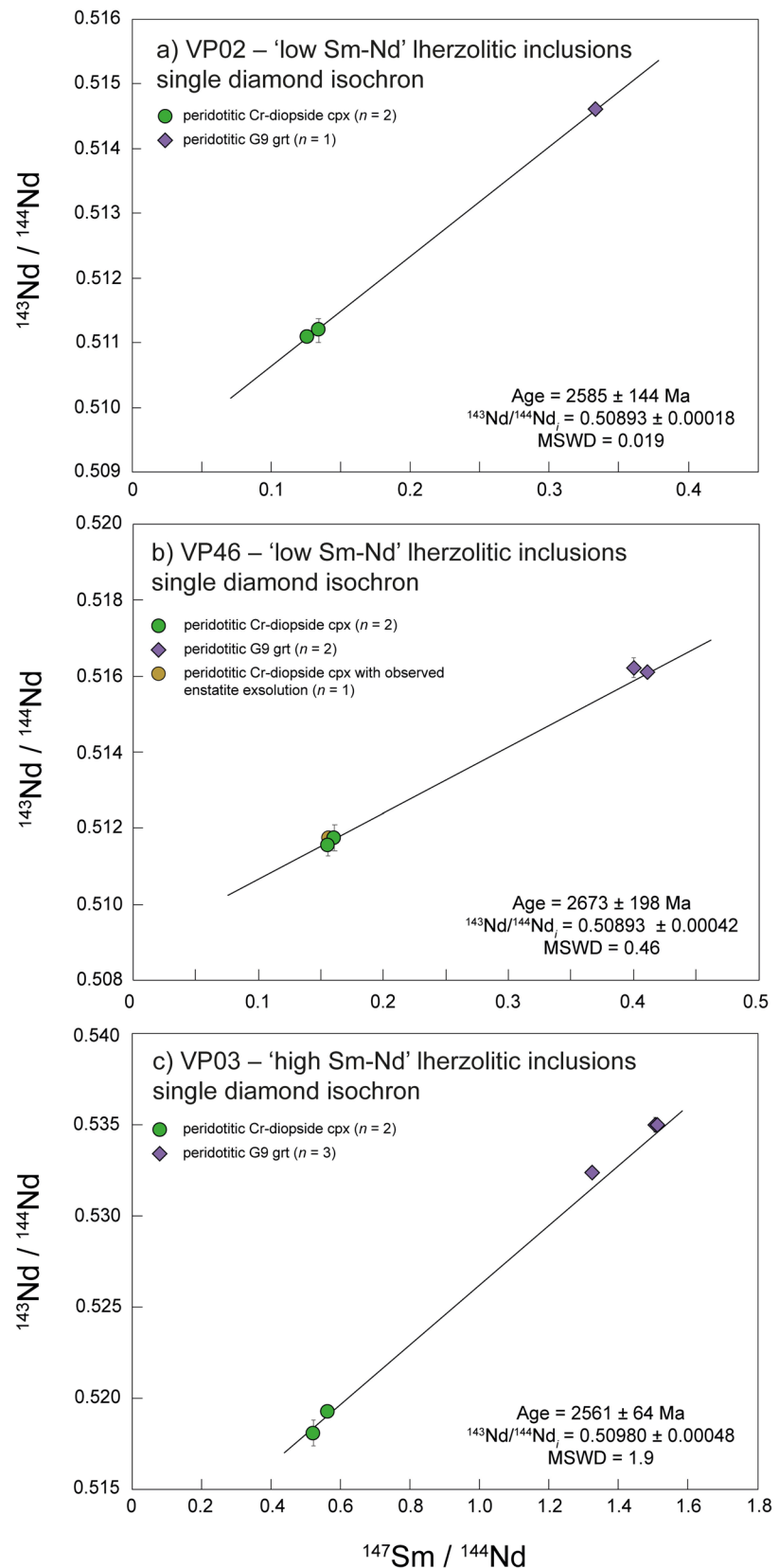
Nitrogen content and aggregation state of the diamonds

Nitrogen is the most common substitutional impurity in diamonds. For most geological studies of natural diamonds the conversion of C centres (N_S) to A centres (N_2) and ultimately B centres (V_1N_4) is interpreted as dependent on time and temperature, allowing time-integrated mantle residence temperatures to be calculated for given mantle residence times (Taylor et al. 1990). For each diamond plate mapped with 100 s of FTIR spectra, median values for %B aggregation and nitrogen content were calculated using BoxPlotR (Spitzer et al. 2014; Table S2).

Peridotitic—2.9–2.6 Ga isochrones

Median nitrogen contents for twenty Voorspoed diamonds with peridotitic garnet and clinopyroxene inclusions that plot on the 2.9–2.6 Ga Sm–Nd isochrons range between 18 and 116 at. ppm. All diamonds contain the majority of nitrogen as fully aggregated B centres, apart from one diamond (VP55) that contains 91% of nitrogen as B centres (Table S2). Isotherms were calculated for a mantle residence time of 2.6 billion years, given Voorspoed CROL eruption at 132 Ma (Phillips et al. 1998). Voorspoed peridotitic diamonds all record unusually high temperatures > 1250 °C in the lithospheric mantle (Fig. 13).

Fig. 11 Three diamonds had multiple inclusions of peridotitic garnet and Cr-diopside clinopyroxene that provided the opportunity to calculate isochron ages for single diamonds. **a** and **b** VP02 and VP46 contain three and five low $^{147}\text{Sm}/^{144}\text{Nd}$ inclusions, respectively, and the single diamond ages of 2585 ± 144 Ma and 2673 ± 198 Ma, overlaps with the low $^{147}\text{Sm}/^{144}\text{Nd}$ isochron regression of 2606 ± 95 Ma in Fig. 10c. **c** VP03 contains five inclusions with high $^{147}\text{Sm}/^{144}\text{Nd}$, and yields a single diamond age of 2561 ± 64 Ma that overlaps with the high $^{147}\text{Sm}/^{144}\text{Nd}$ isochron regression of 2560 ± 51 Ma in Fig. 10d. Isochron regressions calculated with the online version of IsoplotR (Vermeesch 2018)



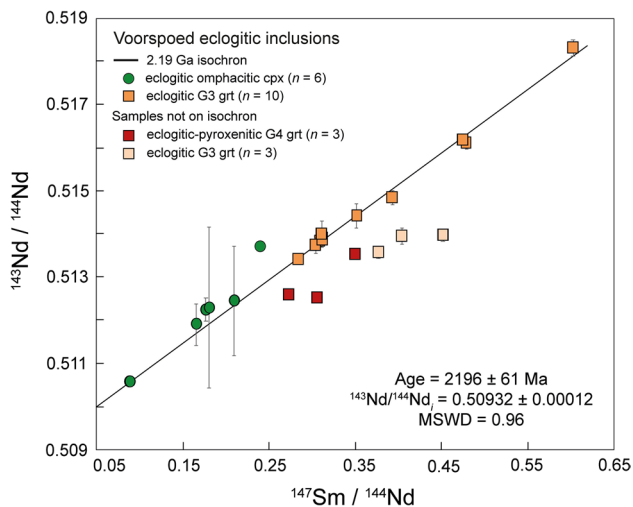


Fig. 12 Sixteen eclogitic inclusions (10 garnets and six omphacites) define an isochron of 2196 ± 61 Ma, with initial $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.50932 ± 0.00012 and MSWD of 0.96. This isochron is defined by several diamonds with multiple inclusions, unfortunately, none of these diamonds contained both garnet and clinopyroxene and consequently the spread in Sm/Nd ratios between different inclusions was not large enough to define meaningful single diamond isochrons. Isochron regression calculated with the online version of IsoplotR (Vermeesch 2018)

Eclogitic—2.2 Ga isochron

Median nitrogen contents for the six Voorspoed diamonds (one diamond cut into two plates) that contain eclogitic garnet and clinopyroxene inclusions on the 2.2 Ga Sm–Nd isochron range between 23 and 671 at. ppm, with 58–100%

of nitrogen as fully aggregated B centres (Table S2). Isotherms were calculated for a mantle residence time of 2.06 billion years. Voorspoed eclogitic diamonds yielded mantle residence temperatures between 1100 °C and > 1300 °C (Fig. 13).

Eclogitic—no age relationships

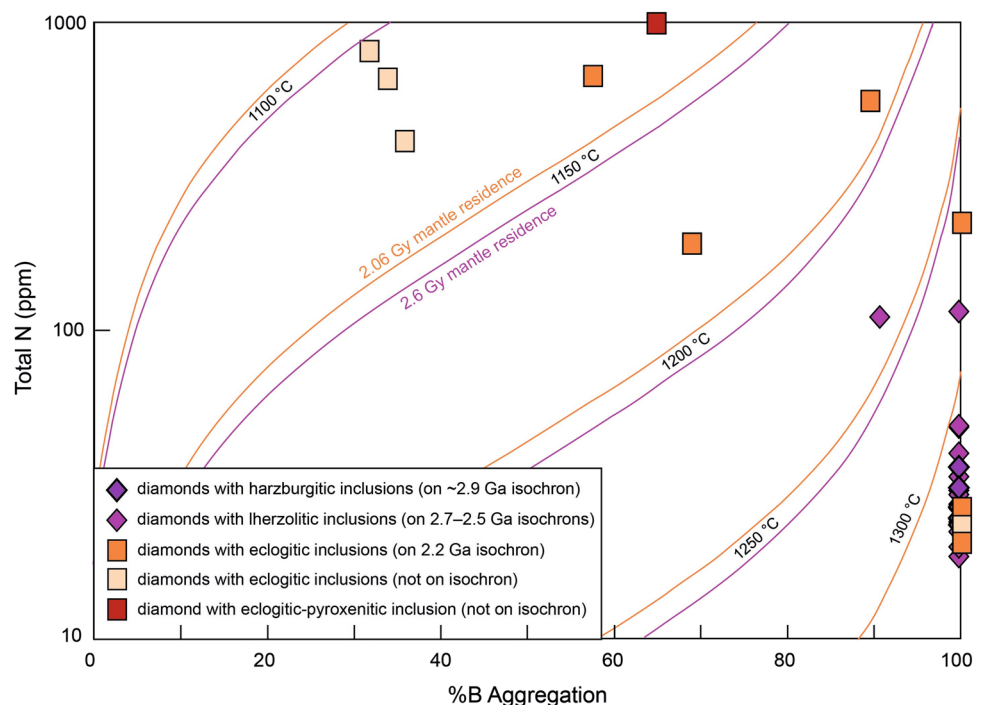
The five Voorspoed diamonds that contain eclogitic garnet and clinopyroxene inclusions that either have no measured Sm–Nd isotope compositions, or have Sm–Nd isotope compositions that do not plot on the 2.2 Ga eclogitic Sm–Nd isochron have median nitrogen contents that range between 414 and 998 at. ppm, with 32–100% of nitrogen as fully aggregated B centres (Table S2). Although ages were not determined for these diamonds, they are also plotted alongside isotherms that were calculated for a mantle residence time of 2.06 billion years. If a similar mantle residence time as the dated diamonds is assumed, these undated Voorspoed eclogitic diamonds yielded mantle residence temperatures between 1100 °C and > 1300 °C (Fig. 13).

Discussion

High temperature Voorspoed peridotitic and eclogitic diamond formation

The abundance of fully aggregated nitrogen in the 2.9–2.6 Ga peridotitic diamonds (Table S2; Fig. 13) indicates that

Fig. 13 Nitrogen content plotted against the percentage of B aggregation. Median values are plotted for 20 diamonds that have peridotitic inclusions on the 2.9–2.6 Ga Sm–Nd isochrons, and diamonds that have eclogitic inclusions on the 2196 ± 61 Ma Sm–Nd isochron. Isotherms were calculated for a mantle residence time of 2.6 billion years (peridotitic diamonds) and 2.06 billion years (eclogitic diamonds), with Voorspoed CROL eruption at 132 Ma (Phillips et al. 1998). Voorspoed harzburgitic and lherzolitic diamonds all resided at high temperatures > 1250 °C in the lithospheric mantle. Voorspoed eclogitic diamonds resided at temperatures between 1100 °C and > 1300 °C in the lithospheric mantle. FTIR data are reported in Table S2



the diamonds resided at anomalously high time-integrated temperatures in the lithospheric mantle (1250–1300 °C). Similarly, the ~2.2 Ga eclogitic diamonds also have a high abundance of fully aggregated nitrogen (Table S2; Fig. 13). Five eclogitic diamonds contain fully aggregated nitrogen in B centres, indicating high-temperatures of formation and storage close to 1300 °C. Three eclogitic diamonds have between 32 and 90% nitrogen occurring as B centres, indicating storage at lower temperatures between 1100 and 1200 °C. The calculated nitrogen-aggregation temperatures for our suite of Voorspoed diamonds are consistent with a previous study that reported two temperature groupings: one population between 1100 and 1150 °C and another more abundant population between 1200 and 1300 °C (Viljoen et al. 2018).

High-temperature origins for Voorspoed diamonds are also supported by compositions of mineral inclusions, with the following lines of evidence discussed in Viljoen et al. (2018): (1) Websteritic and 'transitional' websteritic-lherzolitic mineral inclusions indicate mantle source rocks that likely formed through melt infiltration into mantle peridotite; (2) Orthopyroxene ($\pm\text{SiO}_2 \pm \text{TiO}_2$) exsolution lamellae in clinopyroxene likely formed from higher-temperature monomineralic pyroxene during cooling; (3) Clinopyroxene-orthopyroxene intergrowths yield temperatures between 1100 and 1350 °C, and if reconstituted to a monomineralic pyroxene yield temperatures between 1238 and 1416 °C. The reconstituted temperatures represent the conditions at the time of diamond formation, with later exsolution once the lithosphere had cooled after diamond formation; (4) Elevated nitrogen aggregation states of the diamonds compared to the average for world-wide diamonds, may indicate diamond crystallisation during thermal pulses in the lithospheric mantle.

Voorspoed harzburgitic diamond formation and age of the oldest lithospheric mantle in the Witwatersrand-Swaziland blocks

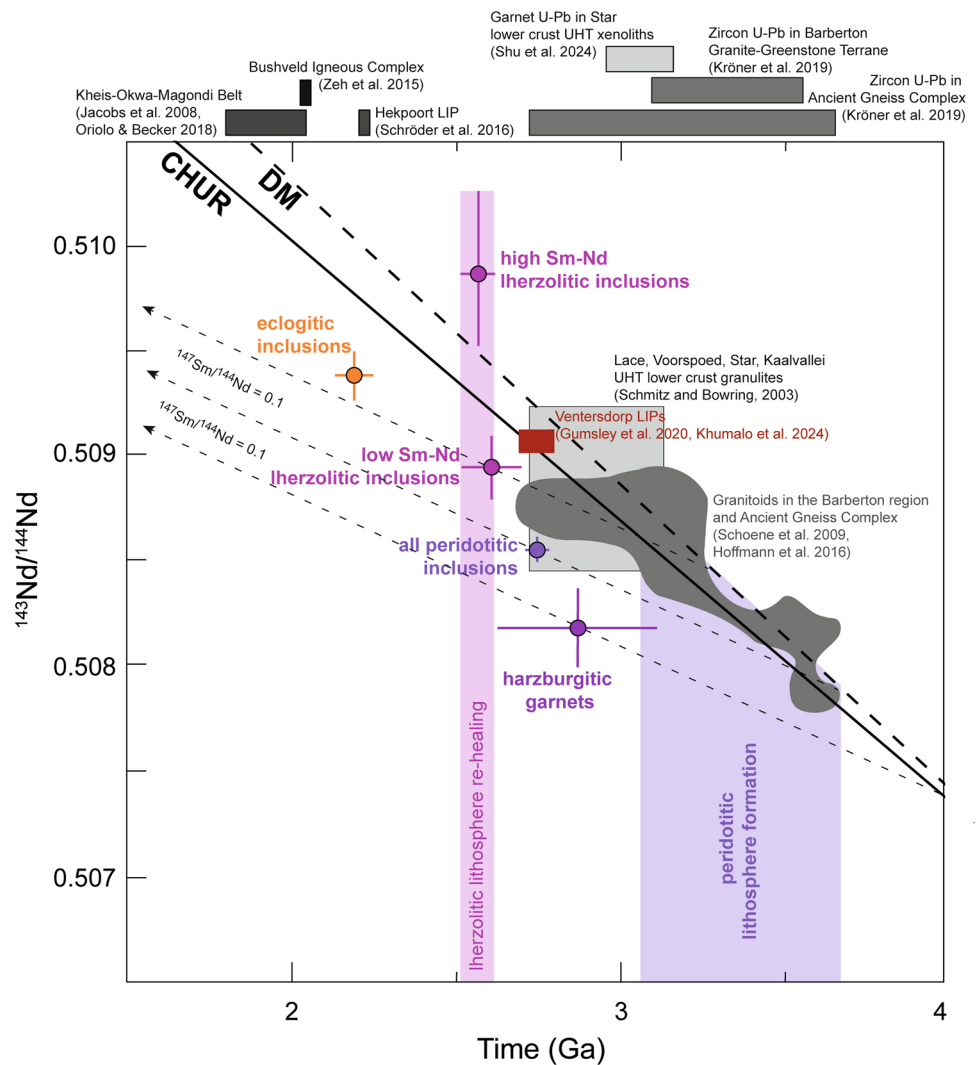
Three harzburgitic G10 inclusions (in three different diamonds—VP44, VP69, VP70) define an isochron of 2877 ± 249 Ma, with initial ϵ_{Nd} of -14.9 ± 9.5 (Fig. 10b). Due to the large uncertainty on this isochron, the age overlaps both with the time of early 3.66–3.2 Ga crust formation in the Witwatersrand-Swaziland Blocks (Barberton region and Ancient Gneiss Complex, Schoene et al. 2009; Hoffmann et al. 2016; Kröner et al. 2019), and plume-related magmatism of the Ventersdorp LIPs between 2.79 and 2.68 Ga (Gumsley et al. 2020; Khumalo et al. 2024). Formation and storage of harzburgitic diamonds related to high-temperature plume magmatism rather than during early craton formation events, is however supported by the high storage

temperatures of 1250–1300 °C (Fig. 13) that are higher than the average temperatures for peridotitic diamond formation (1130 °C, Stachel and Luth 2015; Nimis 2022).

The low initial $^{143}\text{Nd}/^{144}\text{Nd}$ of the harzburgitic isochron demonstrates that these diamonds formed in cratonic lithospheric mantle that is isotopically-enriched compared to the asthenospheric mantle. However, unlike the compositions seen in worldwide harzburgitic diamond inclusions and xenoliths (Stachel et al. 2022a), the Voorspoed harzburgitic garnet inclusions do not exhibit sinusoidal REE_N patterns (Fig. 4). One harzburgitic G10 garnet is LREE-enriched (Fig. 4), although it has the most depleted Y–Ti–Zr contents (Fig. 7). The other two harzburgitic garnets have REE_N patterns and Y–Ti–Zr contents typical of refertilised lithologies (Fig. 4, 7). These characteristics demonstrate that although depleted harzburgitic major element compositions were locally preserved as diamond inclusions in the Voorspoed lithospheric mantle, any depleted trace element compositions have been substantially overprinted. This overprinting could be due to the following scenarios: (1) Melts temporally related to UHT metamorphism between 3.14 and 2.93 Ga may have been responsible for metasomatism in the 3.2–3.0 Ga peridotite protoliths resulting in the observed fertile trace element compositions. The 3.14–2.93 Ga ages for UHT metamorphism in the central Kaapvaal are recorded by garnets in lower crustal xenoliths from nearby Star (Shu et al. 2024), and may be associated with widespread granitic magmatism related to intracratonic terrane accretion between the Witwatersrand and Swaziland Blocks (e.g., de Wit et al. 1992; Schoene et al. 2008), and/or to granitic-basaltic magmatism of the 2.99–2.96 Ga Dominion-Nzuse Igneous Province in the central and eastern Kaapvaal (Paprika et al. 2021); (2) Given the temporal overlap of Voorspoed diamond formation with the 2.79–2.68 Ga Ventersdorp plume-related LIPs and Ventersdorp-aged UHT metamorphism in the lower crust (Schmitz and Bowring 2003; Shu et al. 2024), it is plausible that the Ventersdorp plume(s) could be the cause of the melt refertilisation and high temperatures seen in the harzburgitic protoliths of the Voorspoed inclusions.

Assuming a low $^{147}\text{Sm}/^{144}\text{Nd}$ of <0.1 , the low initial $^{143}\text{Nd}/^{144}\text{Nd}$ of the harzburgitic isochron provides additional constraints on the age of the lithospheric mantle below the Witwatersrand-Swaziland Blocks. When extrapolated back to CHUR and DM, the initial $^{143}\text{Nd}/^{144}\text{Nd}$ yields minimum age constraints for the harzburgitic host rocks between 3.5 and 3.6 Ga (Fig. 14). These Paleo- to Mesoproterozoic peridotites in the Voorspoed lithospheric mantle may be the complementary reservoir to early crust formed in the Witwatersrand-Swaziland Blocks, such as the 3.66–3.2 Ga TTGs in the Ancient Gneiss Complex and Barberton regions (Schoene et al. 2009; Hoffmann et al. 2016; Kröner

Fig. 14 Initial $^{143}\text{Nd}/^{144}\text{Nd}$ from the peridotitic and eclogitic diamond isochrons given in Fig. 10, compared to the evolution of depleted (DM, Reiners et al. 2018) and chondritic (CHUR, Bouvier et al. 2008) mantle reservoirs. The initial ratio from the 2877 ± 249 Ma harzburgitic isochron yields $\epsilon_{\text{Nd}} = -14.9 \pm 9.5$ that correlates with the oldest Kaapvaal enriched components as represented by crust in the 3.66–3.22 Ga Ancient Gneiss Complex (Schoene et al. 2009; Hoffmann et al. 2016; Kröner et al. 2019). This is consistent with harzburgitic diamond formation in the oldest Kaapvaal lithospheric mantle. The initial ratio from the 2606 ± 95 Ma low Sm–Nd Iherzolitic isochron yields $\epsilon_{\text{Nd}} = -6.9 \pm 5.4$, that if assuming a $^{147}\text{Sm}/^{144}\text{Nd}$ ratio of 0.1 is consistent with diamond formation in enriched > 3.0 Ga lithospheric mantle. The initial ratio from the 2560 ± 51 Ma high Sm–Nd Iherzolitic isochron yields $\epsilon_{\text{Nd}} = 9.8 \pm 7.8$, overlapping with depleted mantle indicating rapid re-healing of the lithospheric mantle after 2.79–2.68 Ga Ventersdorp-related plume magmatism



et al. 2019), the 3.5–3.3 Ga gneisses and ultramafic rocks exposed in the Vredefort Dome (Hart et al. 1981, 1990; Tredoux et al. 1999; Flowers et al. 2003; Armstrong et al. 2006) and the 3.34–2.95 Ga granitoids in the Johannesburg Dome (Poujol and Anhaeusser 2001).

These Paleo-to Mesoarchaeon age constraints for the oldest Voorspoed lithospheric mantle are also consistent with other lithospheric age constraints in the Witwatersrand-Swaziland Blocks: peridotites with 3.3–3.0 Ga T_{RD} (minimum) ages from Lihobong ($n=2$) and Premier/Cullinan ($n=3$) (Pearson et al. 1995; Zhang et al. 2022), and a 3 Ga 'Sr model age' for peridotitic diamond formation at Cullinan (Richardson et al. 1993). Near the Colesberg Lineament, peridotitic garnet xenocrysts from Roberts Victor give Lu–Hf isochron ages of 3266 ± 150 Ma (with an initial $\epsilon_{\text{Hf}} = 17.6 \pm 3.6$, Shu et al. 2013). In the lower crust, UHT granulite xenoliths sampled at Voorspoed, Lace, Kaalvallei and Star, have 3.4–3.0 Ga Nd model ages (relative to DM; Schmitz and Bowring 2003). These lower crustal xenoliths

were interpreted as Mesoarchaeon metasedimentary protoliths that were metamorphosed during Ventersdorp magmatism at 2.7 Ga, a scenario comparable in its timing to the multi-stage and metasomatic origin of the harzburgitic G10 diamonds.

Voorspoed Iherzolitic diamond formation

There are two compositional groups of Iherzolitic G9 garnet and Cr-diopside inclusions, each with distinct La_N contents (Figs. 5, 6), $^{147}\text{Sm}/^{144}\text{Nd}$ ratios, and isochron ages (Fig. 10c, d). The low $^{147}\text{Sm}/^{144}\text{Nd}$ Iherzolitic inclusions define an isochron of 2606 ± 95 Ma, that temporally overlaps with the youngest Ventersdorp event, the 2709–2683 Ma Allanridge LIP (Gumsley et al. 2020; Khumalo et al. 2024). This isochron has a low initial ϵ_{Nd} of -6.9 ± 5.4 , indicating that diamond formation occurred in isotopically-enriched Iherzolite host rocks typical of the cratonic lithospheric mantle, and that plume melts were not directly responsible for diamond

formation. Assuming a low $^{147}\text{Sm}/^{144}\text{Nd}$ of 0.1, the initial $^{143}\text{Nd}/^{144}\text{Nd}$ yields age constraints for the low $^{147}\text{Sm}/^{144}\text{Nd}$ lherzolitic host rocks of at least 3.0 Ga (Fig. 14), when extrapolated back to CHUR. This overlaps with granitoids in the Barberton granite-greenstone terrane and Ancient Gneiss Complex that represent Neoarchaean craton formation and growth in the Witwatersrand-Swaziland Blocks (Schoene et al. 2009). For the inclusions from the 2606 ± 95 Ma diamonds that formed in these Mesoarchaean host rocks, melt refertilisation likely relates to 2.79–2.68 Ga Ventersdorp plume magmatism (Gumsley et al. 2020; Khumalo et al. 2024).

The high $^{147}\text{Sm}/^{144}\text{Nd}$ lherzolitic inclusions define an isochron of 2560 ± 51 Ma (Fig. 10d), that formed after the impact of the 2791–2683 Ma Ventersdorp LIPs (Gumsley et al. 2020; Khumalo et al. 2024) had dissipated. Unlike the low $^{147}\text{Sm}/^{144}\text{Nd}$ isochron, the high $^{147}\text{Sm}/^{144}\text{Nd}$ isochron is defined by an initial ϵ_{Nd} of 9.8 ± 7.8 that overlaps with the depleted mantle. Rather than forming in isotopically-enriched host rocks typical of the cratonic lithospheric mantle, the high initial ratio supports a model where the 2560 ± 51 Ma diamonds formed in a lithospheric mantle that had formed due to underplating of plume-related and/or asthenospheric material that re-healed the lithospheric mantle after the end of Ventersdorp plume magmatism.

Similar to the Voorspoed harzburgitic garnet inclusions, the Voorspoed lherzolitic garnet inclusions do not display sinusoidal REE_N patterns that are typical for global lherzolitic diamond inclusions (Figs. 5, 6; Stachel et al. 2022a). Instead, the lherzolitic garnet inclusions display REE_N patterns similar to those normally expected in lherzolite xenoliths (Stachel et al. 2022a). As discussed above for the harzburgitic garnets, any depleted trace element compositions in the Voorspoed lithospheric mantle have been substantially overprinted.

Thermal impact of Ventersdorp magmatism on the Kaapvaal lithospheric mantle

In addition to the high-temperature Voorspoed peridotitic diamonds (> 1250 °C, Fig. 13), the widespread thermal impact of Ventersdorp magmatism is recognised in both the Kaapvaal crust and lithospheric mantle. Lower crustal granulite xenoliths sampled at Voorspoed, Lace, Star and Kaalvallei have ultra-high temperature (UHT) metasedimentary assemblages of quartz $\pm$ sapphirine $\pm$ garnet $\pm$ sillimanite $\pm$ orthopyroxene (Dawson and Smith 1987; Dawson et al. 1997; Schmitz and Bowring 2003; Shu et al. 2024). Uranium-Pb isotope systematics indicate that the majority of metamorphic zircons in these UHT xenoliths crystallised between 2.74 and 2.66 Ga (Schmitz and Bowring 2003; Shu et al. 2024), although U-Pb dating of garnets in these

same xenoliths indicates UHT metamorphism between 3.14 and 2.93 Ga associated with granitic and basaltic magmatism across the Witwatersrand-Swaziland Blocks (Shu et al. 2024). The Lace CROL also sampled mafic granulites with zircons that intersect concordia at 2682 ± 7 Ma (Moser and Hart 1998). These ages were interpreted as evidence for Ventersdorp magmatic underplating of mafic magmas into the lower crust.

At the Klipspringer CROL, that intruded along the Thabazimbi-Murchison Lineament on the boundary of the Pietersburg and Witwatersrand Blocks at 148 Ma, eclogitic diamonds also formed in pre-existing lithologies in lithospheric mantle that was heated and (partially)-melted during the 2.79–2.68 Ga Ventersdorp LIPs (Westerlund et al. 2004). Five eclogitic sulphide inclusions plot along a 2554 ± 150 Ma Re-Os isochron regression (Westerlund et al. 2004), which is within uncertainty of the Platberg and Allanridge/Pniel Groups of the Ventersdorp (Gumsley et al. 2020; Khumalo et al. 2024). The elevated initial $^{187}\text{Os}/^{188}\text{Os}$ of 0.187 ± 0.046 from the Klipspringer eclogitic isochron requires evolution in a high Re/Os protolith, such as Archaean sulphide-bearing eclogite in the Kaapvaal lithospheric mantle. Ventersdorp magmatism heated the lithosphere, caused (partial) melting of sulphide-bearing eclogite, loss of Re and lowering of the Re/Os ratio along with homogenisation of the Re-Os isotopes resulting in isochronous Re-Os isotopic relationships between the pre-existing sulphides (Westerlund and Gurney 2004; Westerlund et al. 2004). Data from worldwide silicate and sulphide inclusions support the reworking of peridotite and eclogite in the lithospheric mantle during diamond formation, with pre-existing mineral phases recrystallising in equilibrium with the diamond-forming melt/fluid (Harris et al. 2022; Smit et al. 2022).

A compilation of Kaapvaal peridotite Re-Os T_{RD} ages shows that both the western and eastern blocks have prominent modes between 2.8 and 2.6 Ga (Fig. 2). These ages are observed in peridotites from Lesotho, Cullinan and Monastery, showing the widespread impact of 2.79–2.68 Ga plume impingement across the Kaapvaal lithospheric mantle (Gumsley et al. 2020; Khumalo et al. 2024). Furthermore, garnets from Kimberley peridotite xenoliths define a Lu-Hf isochron age of 2702 ± 64 Ma (with an initial ϵ_{Hf} = 44, Branchetti et al. 2021), and Finsch peridotitic garnet xenocrysts give a Lu-Hf isochron age of 2621 ± 110 Ma (with an initial ϵ_{Hf} = 27.5, Lazarov et al. 2009; Shu et al. 2013). Although these isochrons most probably reflect mixing of mantle components they demonstrate a major metasomatic event at ~ 2.7 Ga. At Lace, peridotitic garnet xenocrysts fall along an imprecise Lu-Hf isochron age of 3.2 ± 0.5 Ga (with an initial ϵ_{Hf} = 16, Shu et al. 2013). While this age for Lace garnets appears to overlap with the Ventersdorp LIP, the analytical uncertainties on the age yield a range from 3.7 to

2.5 Ga and could equally represent residues of melt extraction to form the earliest crust in the Kaapvaal Craton, at a similar time to crust formation in the 3.66–3.2 Ga Ancient Gneiss Complex.

In addition to triggering diamond formation, Ventersdorp magmatism may also have been the cause of the melt re-equilibration recorded by the harzburgitic and lherzolitic protoliths of the Voorspoed diamond inclusions (see discussion above). This conclusion is consistent with the expected variable impact of LIPs at lithospheric scale, causing heterogeneous thermal perturbations and melt metasomatism across the Kaapvaal lithospheric mantle and its diamond budget. Other LIP-related diamond inclusions from the Kaapvaal are not characterised by the same level of trace element enrichment as the Voorspoed peridotitic inclusions. Premier/Cullinan lherzolitic diamonds formed at 1930 Ma shortly after the Bushveld LIP at ~2.06 Ga, yet at that time the Premier lithospheric mantle still preserved melt-depleted peridotitic domains with sinusoidal REE patterns (Richardson et al. 1993). Similarly, the Proterozoic harzburgitic diamond suite from Venetia (in the Limpopo Mobile Belt) formed by melt-dominated metasomatism related to the 1.1 Ga Umkondo LIP have sinusoidal REE patterns indicative of metasomatism of a harzburgitic mantle (Koornneef et al. 2017). Additionally, 3.3–3.2 Ga harzburgite xenoliths are preserved at Premier despite the clear evidence of extensive re-healing of the lithosphere immediately after the Bushveld LIP event (Pearson et al. 1995; Zhang et al. 2022). Because the Bushveld LIP did not destroy either of the older diamond populations at Voorspoed or the Archaean diamonds at Venetia (Koornneef et al. 2017), we suggest that the Bushveld had a localised imprint on the lithospheric mantle. The impact of the Bushveld on the lithospheric mantle may only have been towards the west and north-west of the Bushveld since ~2 Ga Re-Os ages are observed in Jwaneng and Orapa diamonds (Davies et al. 2017; 2024), but are not observed in the Kimberley xenoliths in the southwestern Kaapvaal (Branchetti et al. 2021).

For Voorspoed 2.9–2.6 Ga peridotitic diamonds, the widespread thermal reactivation in the crust and metasomatism plus melting in lithospheric mantle still needs to be reconciled with approximately coeval diamond formation and the preservation of thick lithospheric mantle. Review of diamond formation and inclusion compositions above implies that the impact of the Ventersdorp LIPs was heterogeneous across the base of the central Kaapvaal lithospheric mantle. In some areas there may be only localised heating by Ventersdorp LIPs. In other areas, where older lithosphere may have been partially destroyed (e.g., the lithospheric mantle in which the harzburgitic diamonds grew), the lithospheric mantle may have re-healed and new lithospheric mantle formed due to underplating of plume-related and/or

asthenospheric material after the effects of the Ventersdorp LIPs had dissipated. This model was proposed by Moser and Hart (1998) for mafic granulites at Lace, and is similar to the model proposed for re-healing of the Premier/Cullinan lithosphere after Bushveld plume magmatism (Zhang et al. 2022). In the case of the 2560 ± 51 Ma Voorspoed diamonds, this re-healing must have occurred within 120 My after the youngest 2.68 Ga Allanridge/Pniel plume impact, such that the high $^{147}\text{Sm}/^{144}\text{Nd}$ lherzolitic diamonds could form in new lithospheric mantle that had formed after the end of Ventersdorp plume magmatism (Fig. 14).

2.2 Ga eclogitic diamond formation at Voorspoed

A Sm–Nd isochron age for 16 eclogitic garnet and clinopyroxene inclusions from Voorspoed indicates diamond formation at 2196 ± 61 Ma (Fig. 12). There are no other documented diamond formation events in the Kaapvaal lithospheric mantle at this time (see Kaapvaal diamond age compilation in Smit et al. 2022). Temporally, the closest subduction event that affected the Kaapvaal Craton and could have introduced diamond-forming fluids/melts into the lithospheric mantle is the Kheis-Okwa-Magondi orogenic event along the western cratonic margin between 2.03 and 1.75 Ga (Jacobs et al. 2008; Oriolo and Becker 2018), which was suggested to disrupt/shutdown 2.06–2.05 Ga Bushveld plume magmatism (Zhang et al. 2022). However, this subduction and collision event is too young to overlap with 2196 ± 61 Ma eclogitic diamond formation. Instead, growth of Voorspoed eclogitic diamonds correlates temporally with magmatism and failed rifting at the time of the 2.25–2.23 Ga Hekpoort LIP and related magmatism across the Transvaal Basin (Burger and Coertze 1973; Cornell et al. 1996; Lenhardt et al. 2012, 2020; Schröder et al. 2016; Humbert et al. 2018). Formation and storage of eclogitic diamonds related to high-temperature plume magmatism rather than any subduction events, is further supported by high time-integrated temperatures close to 1300 °C (Fig. 13) that are significantly higher than the typical temperatures for worldwide eclogitic diamond formation (1100 °C, Nimis 2022; Stachel et al. 2022a).

Composition of the eclogitic protoliths—subduction signatures

The major element compositions of the eclogitic inclusions in our suite overlap with the Voorspoed eclogitic inclusions studied by Viljoen et al. (2018) (Fig. 3). At first glance the eclogitic garnet inclusions have trace element compositions very similar to global eclogitic inclusions, with characteristic depletion in LREE_N and flat MREE – HREE_N (see Fig. 34 in Stachel et al. 2022a). However, the garnets in the

2196±61 Ma eclogitic diamonds are moderately enriched in MREE_N over HREE_N with $(\text{Gd/Yb})_N = 1.14\text{--}14.60$ (Fig. 9a). We cannot constrain whether this MREE enrichment occurred in the eclogite host rocks prior to diamond formation, or whether this is a signature of the diamond-forming fluid.

The relatively low initial ratio of the 2196±61 Ma diamond inclusion isochron ($\epsilon_{Nd} = -9.3 \pm 3.9$) requires storage of the protolith for at least 0.5 Ga prior to diamond formation (Fig. 14). It is plausible that the eclogite host rocks for these diamonds could be the higher pressure equivalents of the 2.7 Ga Lace granulitic mafic xenoliths that formed during Ventersdorp magmatic underplating (Moser and Hart 1998). However, with igneous origins at high pressure, liquid clinopyroxenes are expected to be predominantly Ca-Tschermaks (experimental compositions of Eggins 1992). Therefore, the presence of jadeitic clinopyroxene (omphacite) as inclusions in Voorspoed diamonds does not support a higher pressure origin for the eclogite host rocks, but rather indicates that the eclogites formed through the metamorphic conversion of low-pressure oceanic crust. Low-pressure protoliths for the eclogite host rocks are additionally supported by the presence of Eu anomalies in the majority of eclogitic inclusions. Of the inclusions on the 2196±61 Ma isochron, seven garnets have negative Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.5\text{--}0.9$), one garnet has a positive $\text{Eu}/\text{Eu}^* = 1.7$, and one omphacite has a positive Eu anomaly of 1.23 (Fig. 9). The presence of Eu anomalies in the eclogitic inclusions require the accumulation and fractionation of plagioclase. Because plagioclase converts to spinel at pressures higher than 0.6–0.8 GPa (e.g., Borghini et al. 2010), the presence of Eu anomalies strongly supports plagioclase-bearing oceanic crustal protoliths for the high-pressure eclogite host rocks (see reviews by Jacob 2004; Stachel et al. 2022a; Aulbach and Smart 2023).

The likely host rocks for eclogitic diamond formation are subduction-related eclogites in the lithospheric mantle that may be similar to those sampled at nearby Lace (Aulbach and Viljoen 2015). These Lace eclogites have clear subduction signatures, with Pb–Pb ages > 2.5 Ga (Aulbach and Viljoen 2015), and single-stage Holmes–Houtermans ages of 2.84 and 2.90 Ga (Aulbach et al. 2019). The Lace eclogites are synchronous with 2.9 Ga eclogites and 2.9 Ga eclogitic diamond growth that formed due to amalgamation of the Kimberley and Witwatersrand–Swaziland Blocks along the Colesberg Lineament (Richardson et al. 2001; Shirey et al. 2001; Schmitz et al. 2004). Because we have no age data for the eclogite host rocks, we cannot rule out the presence of even older eclogites in the Voorspoed lithospheric mantle, potentially related to Mesoarchaean lithospheric mantle formation in the Witwatersrand–Swaziland Blocks (e.g.,

Schoene et al. 2009; Hoffmann et al. 2016; Kröner et al. 2019).

Thermal impact of Hekpoort magmatism on the Kaapvaal lithospheric mantle

A compilation of Kaapvaal peridotite Re–Os T_{RD} model ages shows that there is a clear mode between 2.2 and 2.0 Ga (Fig. 2). This mode is dominated by Premier/Cullinan xenoliths and likely predominantly represents the influence of the Bushveld Igneous Complex at 2.06–2.05 Ga (Scoates and Friedman 2008; Zeh et al. 2015). However there are also peridotites from Lesotho and Monastery in the 2.2–2.0 Ga age distribution demonstrating that the lithospheric mantle across a larger region of Witwatersrand–Swaziland Block was impacted at this time. Considering that 2.25–2.23 Ga Hekpoort magmatism is widely recognised across the Transvaal Basin (Fig. 1), the 2.2–2.0 Ga peridotite age mode may plausibly reflect a combined effect of both Bushveld and Hekpoort LIPs on heating and melting the lithospheric mantle.

A limitation of our age compilation is that it contains some sampling bias, because there are no peridotite xenoliths from Lace, Star, Voorspoed and Kaalvallei represented. Given that the impact of the Hekpoort LIP is reflected as diamond formation in the Voorspoed lithospheric mantle, it may be that if peridotites from these localities are analysed for their Re–Os T_{RD} model ages, the impact of the Hekpoort LIP would be clearer. However, we note that there are no recognised ultra-high temperature metamorphic events recognised in the lower crust at the time of Hekpoort magmatism, unlike the widespread impact of 2.79–2.68 Ga Ventersdorp magmatism across the central Kaapvaal lower crust (Dawson and Smith 1987; Dawson et al. 1997; Schmitz and Bowring 2003; Shu et al. 2024).

The apparent limited impact of the Hekpoort LIP on the Kaapvaal lithospheric mantle and lower crust is consistent with the preservation of the older 2.9–2.6 Ga peridotitic diamonds at Voorspoed, despite Hekpoort magmatism impacting the same lithospheric mantle section. Although the plume impingement site for Hekpoort magmatism has not yet been identified, the Voorspoed lithospheric mantle is away from the main centre of basaltic magmatism and failed rifting in the Transvaal Basin (Eriksson et al. 2001, 2006; Lenhardt et al. 2012, 2020) and it is plausible that the ~2.2 Ga Voorspoed eclogitic diamonds formed due to the percolation of low-degree melts and fluids away from the plume centre. The available peridotite Re–Os T_{RD} model age distribution, the preservation of Ventersdorp-aged UHT lower crustal xenoliths, and the preservation of Ventersdorp-aged diamonds in the lithospheric mantle, demonstrates that the thermal impact of Hekpoort magmatism on the

Kaapvaal lithospheric mantle may not have been as significant or widespread as that of the Ventersdorp magmatism and hence insufficient to overprint the earlier Ventersdorp thermal impact.

Conclusions

We analysed garnet and clinopyroxene inclusions in diamonds from Voorspoed in the central Kaapvaal Craton to constrain diamond formation ages. Based on major elements, trace elements and the Sm–Nd isotopic compositions, we can constrain a minimum of four diamond formation events in the harzburgitic, lherzolitic and eclogitic parageneses.

Harzburgitic and lherzolitic diamonds formed in association with lithospheric refertilisation due to the 2.79–2.68 Ga Ventersdorp plumes impacting the Kaapvaal lithosphere, along with lithospheric re-healing after the plumes had dissipated.

The oldest harzburgitic diamonds formed at 2877 ± 249 Ma, where the isochron regression has a low initial ϵ_{Nd} that, if assuming a $^{147}\text{Sm}/^{144}\text{Nd}$ isotope ratio of < 0.1 would be similar to the oldest enriched components in the eastern Kaapvaal as represented by the Ancient Gneiss Complex and the Barberton Greenstone Belt.

The first population of lherzolitic diamonds formed at 2606 ± 95 Ma in enriched lithospheric mantle. A second population of lherzolitic diamonds formed at 2560 ± 51 Ma, after the major modification of the lithosphere and the thermal effects of the Ventersdorp plumes had dissipated. The initial ratio from the 2560 ± 51 Ma isochron overlaps with depleted mantle and requires that the modified lithospheric mantle underwent rapid re-healing and cooling to allow diamond stability.

Eclogitic diamonds formed in subduction-related eclogites, due to 2.25–2.23 Ga Hekpoort plume magmatism and refertilisation in the Kaapvaal lithospheric mantle. Diamond formation due to high-temperature plume magmatism rather than subduction processes is supported by high time-integrated temperatures close to 1300 °C.

Our study of inclusion-bearing diamonds from Voorspoed in the central Kaapvaal Craton, allows for better understanding of the variable impact of LIPs on the global lithospheric mantle and its diamond budget. Even though the Kaapvaal Craton preserves its Archaean heritage it has been continually reworked and metasomatised during episodes of subduction, terrane collision and plume magmatism. The Kaapvaal experienced repeated plume impingement (Ashwal 2021), yet thick lithospheric mantle and multiple generations of diamonds are preserved (Smit et al. 2022). In particular, the Voorspoed peridotitic and eclogitic diamonds document multiple episodes of melt infiltration and modification of

older lithospheric mantle. It is notable that the Voorspoed diamond population contains (one of) the largest proportion of high temperature lithospheric diamonds, an observation that warrants further study to fully understand the exact tectono-magmatic implications, although the impact of several plumes on the lithosphere appears to be a major controlling influence.

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References

- Anhaeusser CR (2019) Palaeo- Meso- and neoarchaeoan granite-greenstone basement geology and related rocks of the Central and Western Kaapvaal Craton, South Africa. In: Kröner A, Hofmann A (eds) The Archaean geology of the Kaapvaal Craton, Southern Africa. Regional Geology Reviews. Springer Nature, Cham, pp 55–81

- Armstrong RA, Lana C, Reimold WU, et al (2006) SHRIMP zircon age constraints on Mesoarchean crustal development in the Vredefort dome, central Kaapvaal craton, South Africa. In: Reimold WU, Gibson RL (eds) Processes on the early Earth. Geological Society of America, Special Paper, p 233–253
- Ashwal LD (2021) Sub-lithospheric mantle sources for overlapping southern African large igneous provinces. *S Afr J Geol* 124(2):421–442
- Aulbach S, Smart KA (2023) Petrogenesis and geodynamic significance of xenolithic eclogites. *Annu Rev Earth Planet Sci* 51:521–549
- Aulbach S, Viljoen KS (2015) Eclogite xenoliths from the Lace kimberlite, Kaapvaal craton: From convecting mantle source to palaeo-ocean floor and back. *Earth Planet Sci Lett* 431:274–286
- Aulbach S, Gerdes A, Viljoen KS (2016) Formation of diamondiferous kyanite–eclogite in a subduction mélange. *Geochim Cosmochim Acta* 179:156–176
- Aulbach S, Höfer HE, Gerdes A (2019) High-Mg and low-Mg mantle eclogites from Koidu (West African craton) linked by Neoproterozoic ultramafic melt metasomatism of subducted Archaean plateau-like oceanic crust. *J Petrol*. <https://doi.org/10.1093/ptrology/egz011>
- Becker H, Horan MF, Walker RJ et al (2006) Highly siderophile element composition of the Earth's primitive upper mantle: constraints from new data on peridotite massifs and xenoliths. *Geochim Cosmochim Acta* 70:4528–4550
- Borghini G, Fumagalli P, Rampone E (2010) The stability of plagioclase in the upper mantle: subsolidus experiments on fertile and depleted lherzolite. *J Petrol* 51:229–254
- Bouvier A, Vervoort JD, Patchett PJ (2008) The Lu–Hf and Sm–Nd isotopic composition of CHUR: constraints from unequilibrated chondrites and implications for the bulk composition of terrestrial planets. *Earth Planet Sci Lett* 273:48–57
- Boyd FR, Gurney JJ (1986) Diamonds and the African lithosphere. *Science* 232:472–477
- Boyd SR, Kiflawi I, Woods GS (1994) The relationship between infrared absorption and the A defect concentration in diamond. *Philos Mag B* 69(6):1149–1153
- Boyd SR, Kiflawi I, Woods GS (1995) Infrared absorption by the B nitrogen aggregate in diamond. *Philos Mag B* 72(3):351–361
- Branchetti M, Zepper JCO, Peters STJ et al (2021) Multi-stage garnet formation and destruction in Kimberley harzburgitic xenoliths, South Africa. *Lithos* 390–391:106119
- Burger AJ, Coertze FJ (1973) Radiometric age determinations on rocks from southern Africa up to the end of 1971. *Geol Surv S Afr Bull* 58:1–46
- Carlson RW, Pearson DG, Boyd FR, et al (1999) Re–Os systematics of lithosphere peridotites: Implications for lithosphere formation and preservation. In: Gurney J, Gurney J, Pascoe M, et al (eds) Proceedings of the 7th International Kimberlite Conference, Cape Town, 1998, vol 1. Red Roof Design, p 99–108
- Carlson RW, Moore RO (2004) Age of the Eastern Kaapvaal mantle: re–Os isotope data for peridotite xenoliths from the Monastery mine. *S Afr J Geol* 107:81–90
- Cawthorn RG, Walraven F (1998) Emplacement and crystallization time for the Bushveld Complex. *J Petrol* 39:1669–1687
- Clifford TN (1966) Tectono-metallogenic units and metallogenic provinces of Africa. *Earth Planet Sci Lett* 1:421–434
- Cornell DH, Schutte SS, Eglington BL (1996) The ongeluk basaltic andesite formation in Griqualand West, South Africa: submarine alteration in a 2222 Ma proterozoic sea. *Precamb Res* 79:101–123
- Corner B, Durrheim RJ, Nicolaysen LO (1990) Relationships between the Vredefort structure and the Witwatersrand basin within the tectonic framework of the Kaapvaal craton as interpreted from regional gravity and aeromagnetic data. *Tectonophysics* 171:49–61
- Daniels LRM (1991) Diamonds and related minerals from the Dokolwayo kimberlite, Kingdom of Swaziland. PhD thesis, University of Cape Town
- Davies GR, van der Meer M, Borst A, Davidheiser B, Meulemans T, de Jong S, Nooitgedacht CS, de Heij C (2017) The genesis and evolution of subcontinental lithospheric mantle beneath Botswana and N. South Africa. *Int Kimberlite Conf Extend Abst*. <https://doi.org/10.29173/ikc3883>
- Davies GR, Visser RA, Branchetti M, Zepper JC, Gress MU, Pals AS, Pearson DG, Reisberg L, Koornneef JM, Preston R, Chinn IL (2024) Large scale rejuvenation of lithospheric mantle beneath Jwaneng, Botswana: implication for diamond growth and destruction. *Int Kimberlite Conf Extend Abst*. <https://doi.org/10.29173/ikc4058>
- Dawson JB, Smith JV (1987) Reduced sapphirine granulite xenoliths from the Lace kimberlite, South Africa: implications for the deep structure of the Kaapvaal Craton. *Contrib Mineral Petrol* 95:376–383
- Dawson JB, Harley SL, Rudnick RL et al (1997) Equilibration and reaction in Archaean quartz–sapphirine granulite xenoliths from the Lace kimberlite pipe, South Africa. *J Metamorph Geol* 15:253–266
- de Wit MJ, Tinker J (2004) Crustal structures across the central Kaapvaal Craton from deep-seismic reflection data. *S Afr J Geol* 107(1/2):185–206
- de Wit MJ, Roering C, Hart RJ et al (1992) Formation of an Archaean continent. *Nature* 357:553–562
- Drennan GR, Robb LJ, Meyer FM, et al (1990) The nature of the Archaean basement in the hinterland of the Witwatersrand Basin: II. A crustal profile west of the Welkom Goldfield and comparisons with the Vredefort crustal profile. *South African Journal of Geology* 93(1):41–53
- Eggins SM (1992) Petrogenesis of Hawaiian tholeiites: 1. Phase equilibria constraints. *Contrib Mineral Petrol* 110:387–397
- Eggins SM, Woodhead JD, Kinsley LPJ et al (1997) A simple method for the precise determination of 40 trace elements in geological samples by ICPMS using enriched isotope internal standardisation. *Chem Geol* 134:311–326
- Eriksson PG, Altermann W, Catuneanu O et al (2001) Major influences on the evolution of the 2.67–2.1 Ga Transvaal basin, Kaapvaal Craton. *Sedim Geol* 141–142:205–231
- Eriksson PG, Altermann W, Hartzel FJ (2006) The Transvaal Supergroup and its precursors. In: Johnson MR, Anhaeusser CR, Thomas RJ (eds) The Geology of South Africa. Geological Society of South Africa, Council for Geoscience, p 237–260
- Flowers RM, Moser DE, Hart RJ (2003) Evolution of the amphibolite–granulite facies transition exposed by the Vredefort impact structure, Kaapvaal craton, South Africa. *S Afr J Geol* 111:455–470
- Gibson RL (2019) The Mesoarchaean basement complex of the Vredefort Dome—a mid-crustal section through the central Kaapvaal Craton exposed by impact. In: Kröner A, Hofmann A (eds) The Archaean geology of the Kaapvaal Craton, Southern Africa. Springer Nature, Cham, pp 109–132
- Gittus JH (1963) Metallurgy of the rarer metals-8. Uranium. Butterworths, London
- Good N, de Wit MJ (1997) The thabazimbi–murchison lineament of the Kaapvaal craton, South Africa: 2700 Ma of episodic deformation. *J Geol Soc London* 154:93–97
- Griffin WL, Ryan CG (1995) Trace elements in indicator minerals: area selection and target evaluation in diamond exploration. *J Geochem Explor* 53:311–337
- Griffin WL, Graham S, O'Reilly SY et al (2004) Lithosphere evolution beneath the Kaapvaal Craton: Re–Os systematics of sulfides in mantle-derived peridotites. *Chem Geol* 208(1–4):89–118

- Grütter HS, Gurney JJ, Menzies AH, et al (2004) An updated classification scheme for mantle-derived garnet, for use by diamond explorers. *Lithos* 77 - Proceedings of the 8th International Kimberlite Conference. pp. 841–857
- Gumsley A, Rådman J, Söderland U et al (2016) U-Pb baddeleyite geochronology and geochemistry of the White Mfolozi Dyke Swarm: unravelling the complexities of 2.70–2.66 Ga dyke swarms across the eastern Kaapvaal Craton, South Africa. *GFF* 138(1):115–132
- Gumsley AP, Chamberlain KR, Bleeker W et al (2017) Timing and tempo of the great oxidation event. *Proc Natl Acad Sci USA* 114:1811–1816
- Gumsley A, Stamsnijder J, Larsson E et al (2020) Neoarchean large igneous provinces on the Kaapvaal Craton in southern Africa redefine the formation of the Ventersdorp Supergroup and its temporal equivalents. *GSA Bull* 132(9/10):1829–1844
- Gurney JJ, Switzer GS (1973) The discovery of garnets closely related to diamonds in the Finsch Pipe, South Africa. *Contrib Mineral Petrol* 39:103–116
- Hanson RE, Crowley JL, Bowring SA et al (2004) Coeval large-scale magmatism in the Kalahari and Laurentian cratons during Rodinia assembly. *Science* 304:1126–1129
- Hanson RE, Harmer RW, Blenkinsop TG et al (2006) Mesoproterozoic intraplate magmatism in the Kalahari Craton: a review. *J Afr Earth Sci* 46:141–1687
- Harmer RE, von Gruenewaldt G (1991) A review of magmatism associated with the Transvaal Basin – implications for its tectonic setting. *S Afr J Geol* 94:104–122
- Harris JW, Smit KV, Fedortchouk Y et al (2022) Morphology of monocrystalline diamond and its inclusions. *Rev Mineral Geochem* 88:119–166
- Hart RJ, Nicolaysen LO, Gales NH (1981) Radioelement concentrations in the deep profile through Precambrian basement of the Vredefort structure. *J Geophys Res* 86:10639–10652
- Hart RJ, Andreoli MAG, Tredoux M et al (1990) Geochemistry across an exposed section of Archaean crust at Vredefort: with implications for mid-crustal discontinuities. *Chem Geol* 82:21–50
- Hatton CJ (1995) Mantle plume origin for the Bushveld and Ventersdorp magmatic provinces. *J Afr Earth Sci* 21:571–577
- Hayes B, Bybee GM, Mawela M et al (2018) Residual melt extraction and out-of-sequence differentiation in the Bushveld Complex, South Africa. *J Petrol* 59(12):2413–2434
- Hoffmann JE, Kröner A, Hegner E et al (2016) Source composition, fractional crystallization and magma mixing processes in the 3.48–3.43 Ga Tsawela tonalite suite (Ancient Gneiss Complex, Swaziland) – implications for Palaeoarchaean geodynamics. *Precambrian Res* 276:43–66
- Howell D, O'Neill CJ, Grant KJ et al (2012) micro-FTIR mapping: distribution of impurities in different types of diamond growth. *Diamond Relat Mater* 29:29–36
- Humbert F, de Kock MO, Altermann W et al (2018) Petrology physical volcanology and geochemistry of a Palaeoproterozoic large igneous province: the Hekpoort Formation in the southern Transvaal sub-basin (Kaapvaal Craton). *Precambrian Res* 315:232–256
- Humbert F, de Kock M, Lenhardt N et al (2019) Neoarchaean to early Palaeoproterozoic within-plate volcanism of the Kaapvaal Craton: comparing the Ventersdorp supergroup and the Ongeluk and Hekpoort formations (Transvaal Supergroup). In: Kröner A, Hofmann A (eds) *The Archaean geology of the Kaapvaal Craton, Southern Africa. Regional geology reviews*. Springer Nature, Cham, pp 277–302
- Irvine GJ, Pearson DG, Carlson RW (2001) Lithospheric mantle evolution in the Kaapvaal craton: a Re-Os isotope study of peridotite xenoliths from Lesotho kimberlites. *Geophys Res Lett* 28:2505–2508
- Irvine GJ (2001) Time constraints on the formation of lithospheric mantle beneath cratons: a Re-Os isotope and platinum group element study of peridotite xenoliths from northern Canada and Lesotho. PhD thesis, Durham University
- Jacob DE (2004) Nature and origin of eclogite xenoliths from kimberlites. *Lithos* 77:295–316
- Jacobs J, Pisarevsky S, Thomas RJ et al (2008) The Kalahari Craton during the assembly and dispersal of Rodinia. *Precambrian Res* 160(1–2):142–158
- Janney PE, Shirey SB, Carlson RW et al (2010) Age, composition and thermal characteristics of South African off-craton mantle lithosphere: evidence for a multi-stage history. *J Petrol* 51(9):1849–1890
- Karaevangelou M, Kopylova MG, Luo Y et al (2022) Mineral inclusions in Lace diamonds and the mantle beneath the Kroonstad kimberlite cluster in South Africa. *Contrib Mineral Petrol* 177:20
- Kempe Y, Weiss Y, Chinn IL, Navon O (2021) Multiple metasomatic diamond-forming events in a cooling lithosphere beneath Voorspoed. *South Africa Lithos* 398–399:106285
- Kempe Y, Koornneef JM, Davies GR, Tirosh O, Chinn IL, Weiss Y (2025) Trace element and Sr-Nd-Pb isotope compositions of diamond-forming fluids in Voorspoed diamonds. *Mineral Petrol*. <https://doi.org/10.1007/s00710-025-00940-2>
- Kennedy W (1964) The structural differentiation of Africa in the Pan-African (± 500 my) tectonic episode. University of Leeds, Research Institute of African Geology, Annual Report on Scientific Results pp 48–49
- Khumalo KB, Ashwal LD, Hayes B et al (2024) Neoarchean lavas of the Ventersdorp Large Igneous Province, South Africa: Sr-Nd-Hf isotopic and trace element evidence for a long-lived plume beneath a stationary African continent. *Earth Sci Rev* 252(104752):1258
- Kjarsgaard BA, de Wit M, Heaman LM, Pearson DG, Stiefenhofer J, Januszczak N, Shirey SB (2022) A review of the geology of global diamond mines and deposits. *Rev Mineral Geochem* 88(1):1–117
- Koornneef JM, Gress MU, Chinn IL et al (2017) Archaean and Proterozoic diamond growth from contrasting styles of large-scale magmatism. *Nat Commun* 8:648
- Kranendonk MJV (2011) Cool greenstone drips and the role of partial convective overturn in Barberton greenstone belt evolution. *J Afr Earth Sci* 60:346–352
- Kröner A, Hoffmann JE, Wong JM et al (2019) Archaean crystalline rocks of the Eastern Kaapvaal Craton. In: Kröner A, Hofmann A (eds) *The Archaean geology of the Kaapvaal Craton, Southern Africa. Regional geology reviews*. Springer Nature, Cham, pp 1–32
- Lazarov M, Brey GP, Weyer S (2009) Time steps in the depletion and enrichment in the Kaapvaal craton as recorded by subcalcic garnets from Finsch (SA). *Earth Planet Sci Lett* 279:1–10
- Lenhardt N, Eriksson PG, Catuneanu O et al (2012) Nature of and controls on volcanism in the c. 2.32–2.06 Ga Pretoria Group, Transvaal Supergroup, Kaapvaal Craton, South Africa. *Precambrian Res* 214–215:106–123
- Lenhardt N, Altermann W, Humbert F et al (2020) Lithostratigraphy of the Palaeoproterozoic Hekpoort Formation (Pretoria Group, Transvaal Supergroup), South Africa. *S Afr J Geol* 123(4):655–668
- Letete K, Smit KV, Burness S (2024) Age and origin of the lithospheric mantle below the Ancient Gneiss Complex, Eswatini. *Int Kimber Conf Extend Abst*. <https://doi.org/10.29173/ikc4149>
- Lowe DR (1994) Accretionary history of the Archean Barberton greenstone belt (3.55–3.22 Ga), southern Africa. *Geology* 22:1099–1102
- Magalhães N, Penniston-Dorland S, Farquhar J et al (2018) Variable sulfur isotope composition of sulfides provide evidence for multiple sources of contamination in the Rustenburg Layered Suite, Bushveld Complex. *Earth Planet Sci Lett* 492:163–173

- Maier WD, Peltonen P, McDonald I et al (2012) The concentration of platinum-group elements and gold in southern African and Karelian kimberlite-hosted mantle xenoliths: Implications for the noble metal content of the Earth's mantle. *Chem Geol* 302–303:119–135
- Meisel T, Walker RJ, Irving AJ et al (2001) Osmium isotopic compositions of mantle xenoliths: a global perspective. *Geochim Cosmochim Acta* 65(8):1311–1323
- Menzies AH, Shirey SB, Carlson RW, et al (1999) Re-Os systematics of Newlands peridotite xenoliths: implications for diamond and lithosphere formation. In: Gurney JJ, Gurney JL, Pascoe MD, et al (eds) *Proceedings of the 7th International Kimberlite Conference*. Red Roof Design, Cape Town, p 566–583
- Moser DE, Hart RJ (1998) Neoproterozoic and Paleoproterozoic re-activation of the crust-mantle transition beneath the central Kaapvaal craton, Lace kimberlite. *Extend Abst Int Kimberl Conf* 7:609–611
- Moyen JF, Stevens G, Kisters A (2006) Record of mid-Archaean subduction from metamorphism in the Barberton terrain, South Africa. *Nature* 442:559–562
- Mungall JE, Kamo SL, McQuade S (2016) U-Pb geochronology documents out-of-sequence emplacement of ultramafic layers in the Bushveld Igneous Complex of South Africa. *Nat Commun* 7:13385
- Myers RE, Cawthorn RG, McCarthy TS et al (1987) Fundamental uniformity in the trace element patterns of the volcanics of the Kaapvaal craton from 3000 to 2100 Ma: evidence for the lithospheric origin of these continental tholeiites. *Geol Soc South Africa* 33:315–326
- Nimis P (2022) Pressure and temperature data for diamonds. *Rev Mineral Geochem* 88:533–566
- Nimis P, Preston R, Peritt SH et al (2020) Diamond's depth distribution systematics. *Lithos* 376–377:105729
- Olsson JR, Söderlund U, Hamilton MA et al (2011) A late Archean radiating dyke swarm as possible clue to the origin of the Bushveld Complex. *Nat Geosci* 4:865–869
- Oriolo S, Becker T (2018) The Kalahari Craton, Southern Africa: from archaean crustal evolution to Gondwana Amalgamation. *Geology of Southwest Gondwana*. Regional geology reviews. Springer Nature, Cham, pp 133–159
- Paprika D, Hofmann A, Agangi A et al (2021) Age of the Dominion-Nsuze Igneous Province, the first intracratonic igneous province of the Kaapvaal Craton. *Precamb Res* 363:106335
- Pearson DG, Carlson RW, Shirey SB et al (1995) Stabilisation of Archaean lithospheric mantle: a Re-Os isotope study of peridotite xenoliths from the Kaapvaal Craton. *Earth Planet Sci Lett* 134(3–4):341–357
- Pearson DG, Shirey SB, Harris JW et al (1998) Sulphide inclusions in diamonds from the Koffiefontein kimberlite, S Africa: constraints on diamond ages and mantle Re-Os systematics. *Earth Planet Sci Lett* 160:311–326
- Pearson DG, Irvine GJ, Ionov DA et al (2004) Re-Os isotope systematics and platinum group element fractionation during mantle melt extraction: a study of massif and xenolith peridotite suites. *Chem Geol* 208:29–59
- Pearson DG, Scott JM, Liu J et al (2021) Deep continental roots and cratons. *Nature* 596:199–210
- Pearson DG, Irvine GJ, Carlson RW, et al (2002) The development of lithospheric keels beneath the earliest continents: time constraints using PGE and Re-Os isotope systematics. In: Fowler CMR, Ebinger CJ, Hawkesworth CJ (eds) *The Early Earth: Physical, Chemical and Biological Development*, vol 199. The Geological Society of London, Special Publications, p 65–90
- Phillips D, Machin KJ, Kiviets GB et al (1998) A petrographic and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronological study of the Voorspoed Kimberlite, Africa; implications for the origin of Group II kimberlite magmatism. *S Afr J Geol* 101(4):299–306
- Poujol M, Anhaeusser CR (2001) The Johannesburg Dome, South Africa: new single zircon U-Pb isotopic evidence for early Archaean granite-greenstone development within the central Kaapvaal Craton. *Precambrian Res* 108:139–157
- Poujol M, Robb LJ, Anhaeusser CR et al (2002) Geochronological constraints on the evolution of the Kaapvaal craton, South Africa. *Econ Geol Res Inst Inf Circ* 360:12
- Raal FA, Robinson DN (1980) Green for rarity. *Nuclear Active* 23:5–8
- Rehfeldt T, Foley SF, Jacob DE et al (2008) Contrasting types of metasomatism in dunite, wehrlite and websterite xenoliths from Kimberley, South Africa. *Geochim Cosmochim Acta* 72:5722–5756
- Reiners PW, Carlson RW, Renne PR et al (2018) Geochronology and thermochronology. AGU, Wiley
- Richardson SH, Shirey SB (2008) Continental mantle signature of Bushveld magmas and coeval diamonds. *Nature* 453:910–913
- Richardson SH, Gurney JJ, Erlank AJ et al (1984) Origin of diamonds in old enriched mantle. *Nature* 310:198–202
- Richardson SH, Harris JW, Gurney JJ (1993) Three generations of diamond from old continental mantle. *Nature* 366:256–258
- Richardson SH, Shirey SB, Harris JW et al (2001) Archean subduction recorded by Re-Os isotopes in eclogitic sulfide inclusions in Kimberley diamonds. *Earth Planet Sci Lett* 191:257–266
- Roelofse F, Ashwal LD (2012) The lower main zone in the northern limb of the Bushveld Complex – >1.3 km thick sequence of intruded and variably contaminated crystal mushes. *J Petrol* 53(7):1449–1476
- Schmitz MD, Bowring SA (2003) Ultrahigh-temperature metamorphism in the lower crust during Neoproterozoic Ventersdorp rifting and magmatism, Kaapvaal Craton, southern Africa. *GSA Bull* 115(5):533–548
- Schmitz MD, Bowring SA, de Wit MJ et al (2004) Subduction and terrane collisions stabilize the western Kaapvaal craton tectosphere 2.9 billion years ago. *Earth Planet Sci Lett* 222:363–376
- Schoenberg R, Kruger FJ, Nägler TF et al (1999) PGE enrichment in chromitite layers and the Merensky Reef of the western Bushveld Complex; a Re-Os and Rb-Sr isotope study. *Earth Planet Sci Lett* 172:49–64
- Schoene B, de Wit M, Bowring SA (2008) Mesoproterozoic assembly and stabilization of the eastern Kaapvaal craton: a structural-thermochronological perspective. *Tectonics* 27:1–27
- Schoene B, Dudas FOL, Bowring SA et al (2009) Sm-Nd isotopic mapping of lithospheric growth and stabilization in the eastern Kaapvaal craton. *Terra Nova* 21:219–228
- Schröder S, Beukes NJ, Armstrong RA (2016) Detrital zircon constraints on the tectonostratigraphy of the Paleoproterozoic Pretoria Group, South Africa. *Precamb Res* 278:362–393
- Scoates JS, Friedman RM (2008) Precise age of the platinumiferous Merensky Reef, Bushveld Complex, South Africa, by the U-Pb zircon chemical abrasion ID-TIMS technique. *Econ Geol* 103(3):465–471
- Shirey SB, Carlson RW, Richardson SH et al (2001) Archean emplacement of eclogitic components into the lithospheric mantle during formation of the Kaapvaal Craton. *Geophys Res Lett* 28(13):2509–2512
- Shu Q, Brey GP, Gerdes A et al (2013) Geochronological and geochemical constraints on the formation and evolution of the mantle underneath the Kaapvaal craton: Lu-Hf and Sm-Nd systematics of subcalcic garnets from highly depleted peridotites. *Geochim Cosmochim Acta* 113:1–20
- Shu Q, Brey GP, Höfer HE et al (2016) Kyanite/corundum eclogites from the Kaapvaal Craton: subducted troctolites and layered gabbros from the mid- to early Archean. *Contrib Miner Petrol* 171:11
- Shu Q, Beranoaguirre A, Albert R et al (2024) Multi-stage ultrahigh temperature metamorphism in the lower crust of the Kaapvaal craton by U-Pb ages of garnet. *Contrib Mineral Petrol* 179:49

- Silver PG, Gao SS, Liu KH (2001) Mantle deformation beneath southern Africa. *Geophys Res Lett* 28:2493–2496
- Smit KV, Timmerman S, Aulbach S et al (2022) Geochronology of diamonds. *Rev Mineral Geochem* 88:567–636
- Spitzer M, Wildenhain J, Rappsilber J, Tyers M (2014) Boxplotr: a web tool for generation of box plots. *Nat Methods* 11:121–122
- Stachel T, Luth RW (2015) Diamond formation - where, when and how? *Lithos* 220–223:200–220
- Stachel T, Aulbach S, Harris JW (2022) Mineral inclusions in lithospheric diamonds. *Rev Mineral Geochem* 88:307–392
- Sun SS, McDonough WF (1989) Chemical and isotopic systematics of oceanic basalts: implications for mantle compositions and processes. In: Saunders AD, Norry MJ (eds) *Magmatism in the ocean basins*. Geological Society, London, pp 313–345
- Taylor WR, Jaques AL, Ridd M (1990) Nitrogen-defect aggregation characteristics of some Australasian diamonds: time-temperature constraints on the source regions of pipe and alluvial diamonds. *Am Mineral* 75:1290–1310
- Timmerman S, Matveev S, Gress MU et al (2015) A methodology for wavelength dispersive electron probe microanalysis of unpolished silicate minerals. *J Geochem Explor* 159:243–251
- Timmerman S, Koornneef JM, Chinn IL et al (2017) Dated eclogitic diamond growth zones reveal variable recycling of crustal carbon through time. *Earth Planet Sci Lett* 463:178–188
- Tredoux M, Hart RJ, Carlson RW et al (1999) Ultramafic rocks at the center of the Vredefort structure: further evidence for the crust-on-edge model. *Geology* 27:923–926
- van der Meer QHA, Klaver M, Reisberg L et al (2017) Preservation of an Archaean whole rock Re-Os isochron for the Venetia lithospheric mantle: evidence for rapid crustal recycling and lithosphere stabilisation at 3.3 Ga. *Geochim Cosmochim Acta* 216:242–263
- Vermeesch P (2018) IsoplotR: a free and open toolbox for geochronology. *Geosci Front* 9:1479–1493
- Viljoen KS, Perriett SH, Chinn IL (2018) An unusual suite of eclogitic, websteritic and transitional websteritic-lherzolitic diamonds from the Voorspoed Kimberlite in South Africa: mineral inclusions and infrared characteristics. *Lithos* 320–321:416–434
- Vinnik LP, Green RWE, Nicolaysen LO (1995) Recent deformations on the deep continental roots in Southern Africa. *Nature* 375:50–52
- Walker R, Carlson R, Shirey S et al (1989) Os, Sr, Nd, and Pb isotope systematics of southern African peridotite xenoliths and implications for the chemical evolution of the subcontinental mantle. *Geochim Cosmochim Acta* 53:1583–1595
- Westerlund KJ, Gurney JJ (2004) Silicate and oxide inclusion characteristics and infra-red absorption analysis of diamonds from the Klipspringer kimberlites, South Africa. *S Afr J Geol* 107:131–146
- Westerlund KJ, Gurney JJ, Carlson RW et al (2004) A metasomatic origin for late Archean eclogitic diamonds: implications from internal morphology of diamonds and Re-Os and S isotope characteristics of their sulfide inclusions from the late Jurassic Klipspringer kimberlites. *S Afr J Geol* 107:119–130
- Williams AF (1932) *The genesis of the Diamond II*. Ernest Benn Ltd., London
- Zeh A, Ovtcharova M, Wilson AH et al (2015) The bushveld complex was emplaced and cooled in less than one million years—results of zirconology, and geotectonic implications. *Earth Planet Sci Lett* 418:103–114
- Zhang Q, Morel MLA, Liu J et al (2022) Re-healing cratonic mantle lithosphere after the world's largest igneous intrusion: constraints from peridotites erupted by the Premier kimberlite, South Africa. *Earth Planet Sci Lett* 598:117838
- Zirakparvar NA, Mathez EA, Rajesh HM et al (2019) Lu-Hf isotope evidence of a deep mantle plume source for the 2.06 Ga Bushveld Large Igneous Province. *Lithos* 348–349:105168
- Zwaan F, Schreurs G (2023) Analog models of lithospheric-scale rifting monitored in an X-ray CT scanner. *Tectonics* 42:e2022TC007291

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