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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

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A R T I C L E I N F O

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A B S T R A C T

We review the properties of the Neoarchean Ventersdorp Supergroup and provide new trace element concentrations and the first combined Sr-Nd-Hf isotopic compositions for the mafic magmatic products. These sequences contain the remnants of some of the world's oldest Large Igneous Provinces (total preserved volume = 0.659 × 10^6 km^3). Ventersdorp rocks have been divided into three major units, separated by prominent unconformities: the basal Klipriviersberg Group (~2.78 Ga), the medial Platberg Group (2.72 Ga) and the upper Pniel Sequence (2.68 Ga). The base of the Klipriviersberg Group is the Westonaria Formation, composed almost entirely of picrites (12–18 wt% MgO) and komatiites (>18 wt% MgO). All other formations of the Klipriviersberg Group contain mainly basaltic (<12 wt% MgO, 45–57 wt% SiO_2) and andesitic rocks (57–63 wt% SiO_2). The Platberg Group is composed of bimodal mafic lavas (Goedgenoeg and Rietgat Formations) and crustally derived dacites and rhyolites (Makwassie Formation); we did not study the crustally derived sequences. The Pniel Sequence contains basaltic lavas in the Allanridge Formation (<7.8 wt% MgO). Strontium isotopes have been modified by extensive low-grade hydrothermal alteration processes and cannot be used to make inferences about magmatic processes. Initial ε_{Nd} and ε_{Hf} values are highest for Westonaria picrites and komatiites (maximum $\varepsilon_{Nd} = +2.16$; $\varepsilon_{Hf} = +3.60$), and match Neoarchean depleted, asthenospheric mantle, implying derivation from large degree partial melting in a plume head. Klipriviersberg basaltic-komatiitic lavas have the largest volume (0.145 × 10^6 km^3), qualifying this as a Large Igneous Province in its own right; Platberg and Allanridge basalts and basaltic andesites have unradiogenic ε_{Nd} and ε_{Hf} ($\varepsilon_{Nd} = -2.45$ to -4.01; $\varepsilon_{Hf} = -2.73$ to -10.12), and lower volumes (Platberg = 0.022 × 10^6 km^3; Allanridge = 0.042 × 10^6 km^3), too small to represent LIPs. Although Westonaria picrites and komatiites were likely sourced from the hot, central portions of a flattened plume head, the other magmatic Formations in the Ventersdorp Supergroup may have been derived from cooler, compositionally different, marginal parts of the plume head, or possibly the plume tail. The three Ventersdorp magmatic components can be interpreted in terms of a single, long-lasting plume, with the spatial overlap having been caused by a stationary African plate over a time interval of >100 million years. Trace element ratios and isotopic compositions suggest that fractional crystallization and crustal assimilation were minor to absent in Ventersdorp basaltic magmas. Negative Nb—Ta anomalies are present in all magmatic rocks except those of the Westonaria Formation, suggesting that the lithospheric mantle component bears a subduction signature; this component probably represents deeply subducted oceanic lithosphere that was entrained in the deep mantle by an ascending plume. Volume and compositional relations preclude derivation of the basaltic lavas from subcontinental lithospheric mantle or small, enriched domains in the SCLM. Zn/Fe relations can be interpreted in terms of heterogeneous sub-lithospheric mantle sources, with Klipriviersberg Group lavas having been derived dominantly from peridotitic sources, whereas Platberg and Allanridge mafic lavas were derived from a source richer in pyroxenitic components. Our new Nd isotopic data coupled with lithostratigraphic differences indicate that correlations between the Ventersdorp (South Africa) and the coeval (2.77–2.71 Ga) Fortescue (Australia) sequences are more complex than is currently understood, possibly reflecting differences in basin structure and

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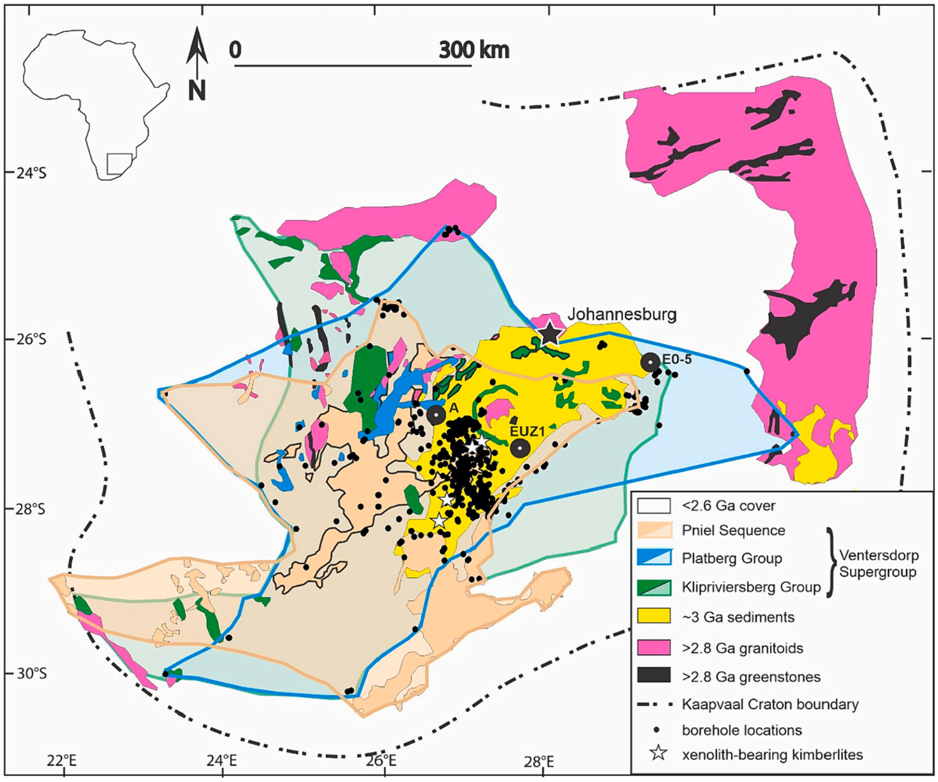

Fig. 1. Pre-Transvaal Archean surface and subsurface geology of southern Africa showing areal extent of mafic magmatic rocks of the Klipriviersberg, Platberg (Rietgat Formation) and Pniel (Allanridge Formation) Groups of the Ventersdorp Supergroup constrained by surface exposures (darker colors), borehole locations (black dots, $n = 602$, Supplementary Table 1) and xenoliths in kimberlites, including Voorspoed, Lace, Kaalvallei and Star (white stars, Schmitz and Bowring, 2003). Larger dotted black circles show the locations of boreholes E0–5 and EUZ1, from which our samples were taken; all other sampled boreholes are located within the dotted black circle labelled "A" (see Supplementary Table 3). Thick green, blue and orange lines delineate the areal extents of the Klipriviersberg and Platberg Groups and the Pniel Sequence, respectively. Older ~3 Ga sediments include the Witwatersrand, Dominion and Pongola Supergroups outlined for ease of reference. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

evolution. More data are needed to constrain the Vaalbara hypothesis, which postulates that the Kaapvaal and Pilbara Cratons were adjoined in the late Archean.

1. Introduction

Large Igneous Provinces (LIPs) are defined as enormous volumes (> 0.1×10^6 km^2; > 0.1×10^6 km^3) of intraplate magmatism emplaced or erupted in a short period of geological time (mostly <10 million years) (Ernst, 2014; Ernst and Youbi, 2017). They are represented as continental flood basalts (e.g., Karoo, Deccan), mafic-ultramafic layered intrusions (e.g., Bushveld Complex), oceanic flood basalts (e.g., Ontong-Java Plateau), sill complexes (e.g., Midland Valley, Scotland) and dyke swarms (e.g., Mackenzie swarm, Canada) (see review by Ernst, 2014). LIP magmatism has been attributed to mantle plumes with the melting of either the asthenospheric mantle (Crow and Condie, 1988; Hatton, 1995; White, 1997; Eriksson et al., 2002; Campbell, 2005, 2007; Ashwal, 2021; Hayes et al., 2024) or the subcontinental lithospheric mantle (SCLM) (Hawkesworth et al., 1984; Marsh et al., 1992; Jourdan et al., 2009; Humbert et al., 2019), or both, with or without crustal contamination. The lavas in the Neoarchean Ventersdorp Supergroup of South Africa are some of the oldest continental flood basalt province(s) in the world and were erupted onto the Kaapvaal Craton of southern Africa (Van der Westhuizen et al., 1991; White, 1997; Marsh et al., 1992; Stamsnijder, 2017; Gumsley et al., 2020). The Ventersdorp lavas provide an excellent natural laboratory to study the mantle sources and magmatic evolution of an Archean continental flood basalt province and provide important insights into early Earth geodynamics.

Although the Ventersdorp lavas have been extensively studied from surface exposures and over 600 deep boreholes (Fig. 1; Winter, 1976; Burke et al., 1985; Crow and Condie, 1988; Myers et al., 1990; Armstrong et al., 1991; Van der Westhuizen et al., 1991, Van der Westhuizen et al., 2006; Hatton, 1995, White, 1997; de Kock et al., 2009, 2012; Cornell et al., 2017; Stamsnijder, 2017; Meintjes and van der Westhuizen, 2018a, 2018b; Gumsley et al., 2020), their mantle sources, spatial distribution, and duration still need better characterization. In particular, isotopic data are notably limited.

The Ventersdorp lavas have previously been regarded as a single magmatic province (e.g., Armstrong et al., 1991). However, recent high-precision geochronology studies were able to discern at least two temporally disparate magmatic provinces within the Ventersdorp Supergroup, separated by some 80 million years (Stamsnijder, 2017; Gumsley et al., 2020): the 2.79–2.78 Ga Klipriviersberg LIP and the 2.71–2.68 Ga Allanridge LIP (Gumsley et al., 2020). However, the genetic relationships between these entities are not well understood. There is also the intervening Platberg "event", which consists of bimodal lavas, whose relations to the Klipriviersberg and Allanridge mafic magma sequences are also not clear-cut. We assess and propose a model for the origin and evolution of these sequences.

This subdivision into 3 distinct magmatic components increases our interest in the Ventersdorp Supergroup, highlighting the importance of acquiring new isotopic data. Therefore, in this study, we present 96 new

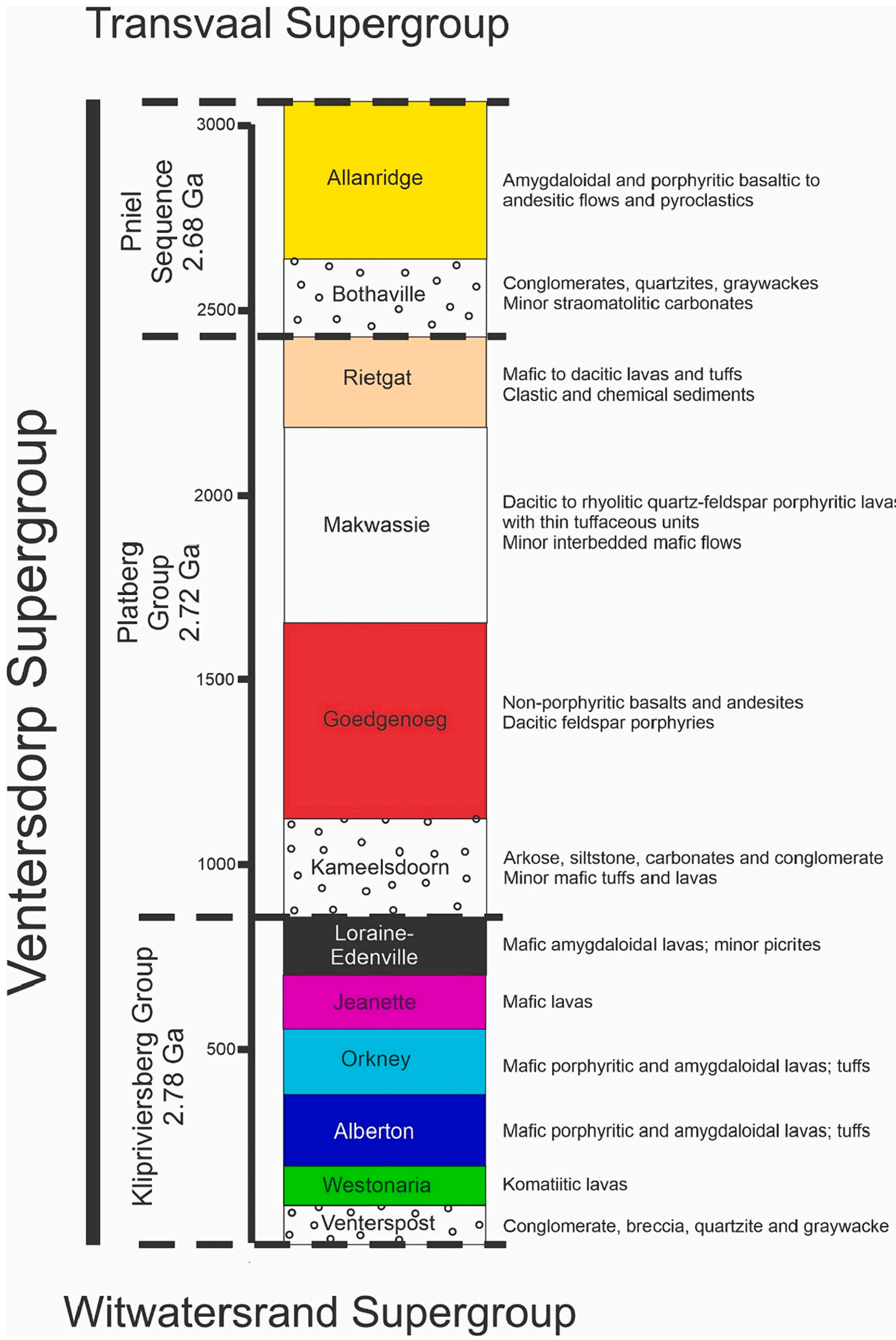

Fig. 2. General lithostratigraphic column of the Ventersdorp Supergroup, showing its Groups and Formations, with typical lithologies that are characteristic of the units. Units are scaled (in meters) as to their average thicknesses. Colour coding for magmatic rocks is as per that used in the geochemical plots. Prominent unconformities are shown as thick dashed lines.

trace element analyses and 61 new high-precision Sr-Nd-Hf isotope measurements for the Ventersdorp lavas. These data represent the first combined Sr—Nd and the first Hf isotope analyses for Ventersdorp magmatic rocks.

We use the new data to constrain the magma sources, petrogenesis and plume longevity, and we discuss the possible effects of crustal contamination during their transport through the crust. Furthermore, the data are used to test the proposed genetic connection of the volcano-sedimentary succession of the Ventersdorp Supergroup on the Kaapvaal Craton and the Fortescue Group (2.77 to 2.71 Ga) on the Pilbara Craton in Australia and the existence of an Archean supercraton, called Vaalbara (e.g., de Kock et al., 2012).

2. Properties of the Ventersdorp LIP

The Neoarchean Ventersdorp Supergroup is a volcano-sedimentary sequence (approx. avg. = 2930 m thick), extending over an areal extent of 225,000 km^2 on the Kaapvaal Craton (Fig. 1; Crow and Condie, 1988; Van der Westhuizen et al., 2006; de Kock et al., 2012; Cornell et al., 2017; Altermann and Lenhardt, 2012; Meintjes and van der Westhuizen, 2018a, 2018b). The basal lavas unconformably overlie the auriferous clastic sedimentary rocks of the >2.79 Ga Witwatersrand

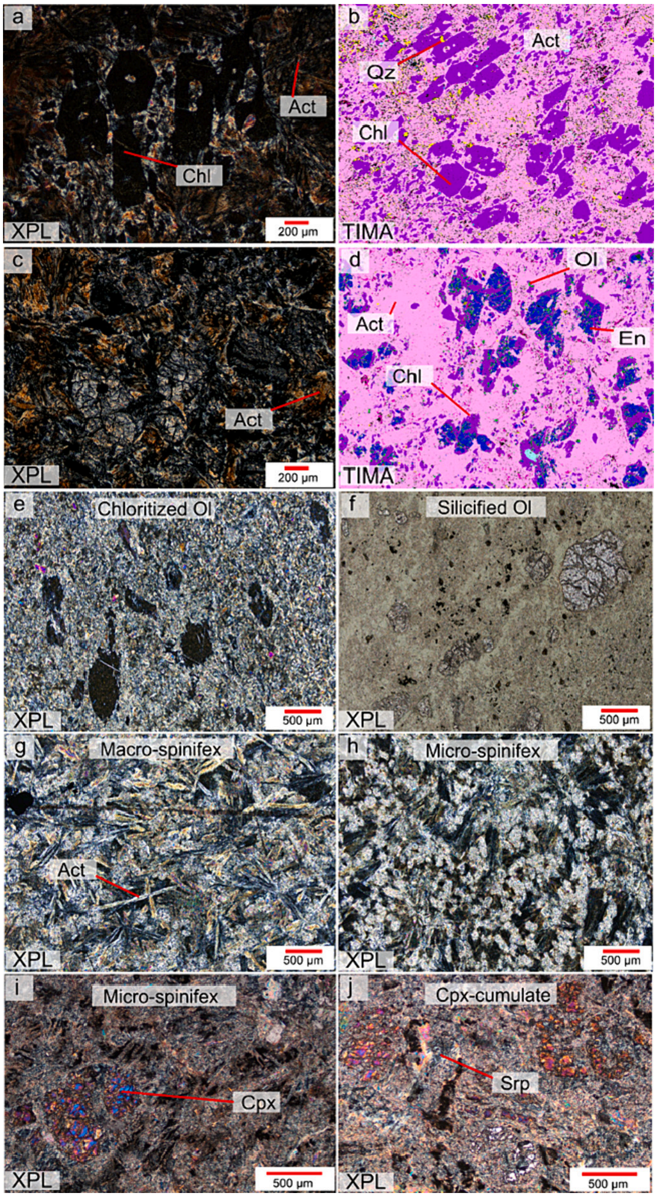

Fig. 3. Petrographic sections through the komatiite flow of the Westonaria Formation showing a well-developed flow fabric. a) and b) show the glomerocrysts of pseudomorphed olivine that have been chloritized and hosted in an actinolite matrix. (c and d) show the cumulate composed of partially chloritized pyroxene. (e and f) show the porphyritic texture with chloritized and silicified phenocrysts, previously olivine. (g and h) show spinifex textures that vary in the sizes of the needles. (i) shows clinopyroxene phenocrysts set in micro-spinifex, and (j) shows cumulus clinopyroxene crystals in the pyroxene cumulate zone. Act = actinolite, Chl = chlorite, En = enstatite, Ol = olivine, Qz = quartz, Cpx = clinopyroxene, and Srp = serpentine. (a) Sample R502, (b) R502, (c) R503, (d) R503, (e) R506, (f) R507, (g) R508, (h) R509, (i) R510, (j) R511.

Supergroup (Gumsley et al., 2020), and the uppermost rocks are unconformably overlain by the <2.6 Ga Transvaal Supergroup. Units of the Ventersdorp Supergroup show enormous thickness variations and are divided into the basal Klipriviersberg Group, medial Platberg Group and the upper Pniel Sequence (Fig. 2; Winter, 1976; Van der Westhuizen et al., 1991). The Klipriviersberg Group is divided into 6 Formations: the basal clastic sedimentary Venterspost Formation, which is overlain by 5 volcanic Formations distinguished on the basis of lithologies, textures and structures: Westonaria (avg. thickness ~ 100 m), Alberton (avg. = 510 m thick), Orkney (avg. = 460 m thick), Jeanette (avg. = 370 m thick) and Loraine-Edenville (avg. = 400 m thick) (Myers et al., 1989). The Westonaria Formation consists of well-preserved, fine-grained komatiites, basaltic komatiites and picrites, some with spinifex textures (Khumalo, 2023). The 4 overlying Formations consist of basalts and basaltic andesites and are distinguished on the basis of colour, grain size, and the presence or absence of phenocrysts, amygdales, variolites, spherulites and flow-top breccia (Wyatt, 1976; Reddy and Germs, 1994; Van der Westhuizen et al., 1991; Van der Westhuizen et al., 2006).

The Platberg Group unconformably overlies the Klipriviersberg Group and is divided into 2 sedimentary and 2 volcanic Formations (Fig. 2). The basal Kameeldoorns Formation consists of arkose, siltstone, carbonates and conglomerates, with minor mafic tuffs and lavas (Crow and Condie, 1988; Grobler et al., 1989; Van der Westhuizen et al., 1991). The Goedgenoeg Formation consists of basal non-porphyritic basalts and andesite, overlain by dacitic feldspar porphyries. The Goedgenoeg Formation conformably overlies the Kameeldoorns Formation through a gradational contact formed by interbedding of lavas and sediments (Van der Westhuizen et al., 2006). The Makwassie Formation consists of dacitic to rhyolitic porphyritic lavas (quartz/feldspar phenocrysts) with thin tuffaceous units and minor interbedded mafic lava flows (Van der Westhuizen et al., 1991; Van der Westhuizen et al., 2006; Meintjes and van der Westhuizen, 2018a, 2018b). The uppermost Formation of the Platberg Group, the Rietgat Formation, consists of clastic and chemical sediments, and mafic-to-dacitic lavas and tuffs. The lavas are porphyritic (mostly plagioclase phenocrysts up to 3 mm) and are characterized by intergranular textures (Winter, 1976; Van der Westhuizen et al., 1991). The volcanic rocks have amygdaloidal flow tops and sedimentary rocks include siltstones, arkosic sandstones, gritstones and stromatolitic cherty limestones (Van der Westhuizen et al., 1991; Eriksson et al., 2002).

The Pniel Sequence unconformably overlies the Platberg Group and consists of the Bothaville Formation, with conglomerates, quartzites, graywackes and minor stromatolitic carbonates (Winter, 1976; Crow and Condie, 1988; Van der Westhuizen et al., 1991). This is conformably overlain by the Allanridge Formation, which is dominated by fine- to medium-grained amygdaloidal and porphyritic basaltic and andesitic flows and pyroclastics (Crow and Condie, 1988; Eriksson et al., 2002; Van der Westhuizen et al., 2006; Altermann and Lenhardt, 2012). The basaltic lavas are similar to those of the middle Klipriviersberg Group, both chemically and petrographically (Schneiderhan et al., 2011), and have been linked on the basis of ages, geochemistry and paleomagnetism to the ~2.65 Ga east-to southeast-trending Rykoppies dyke swarm located in the Archean basement in the eastern Kaapvaal Craton (Olsson et al., 2010; Klausen et al., 2010; Altermann and Lenhardt, 2012).

Constraining the thicknesses and volumes of the entire Ventersdorp Supergroup and of its individual units is important for understanding the origin of the magmas in terms of craton geodynamics and LIP evolution. However, erosion, sedimentary cover, thickness variations and tectonic duplication of units compromise precise thickness and volume estimates. Fortunately, the determination of thicknesses and areal extents is aided by the existence of kimberlites that have brought to the surface lower to middle crustal Ventersdorp rocks as xenoliths (Schmitz and Bowring, 2003) and most importantly, numerous deep drillcores (Crow and Condie, 1988; Myers et al., 1990; Linton et al., 1994; McCarthy et al., 2018). These cited studies make use of only a handful of boreholes; however, one of us (P.G.M.) has had access to over 1300 company boreholes (drilled for exploration for the underlying gold-bearing Witwatersrand Supergroup), of which 602 boreholes intersected Ventersdorp lithologies. Averages and maximum thicknesses of the Ventersdorp units based on core logs of these boreholes are reported here (Fig. 1; Supplementary Table 1). From bottom to top these are (Fig. 2): Venterspost Formation (avg. thickness = 100 m), Westonaria (avg. = 100 m), Alberton (avg. = 188 m), Orkney (avg. = 177 m), Jeannette (avg. = 137 m), Loraine-Edenville (avg. = 148 m), combined Klipriviersberg (avg. = 750 m, max. = 2529 m), Kameelsdoorn (avg. = 250 m, max. = 2102 m), Goedgenoeg (avg. = 500 m, max. = 2558 m), Makwassie (avg. = 500 m, max. = 3063 m), Rietgat (avg. = 230 m, max.

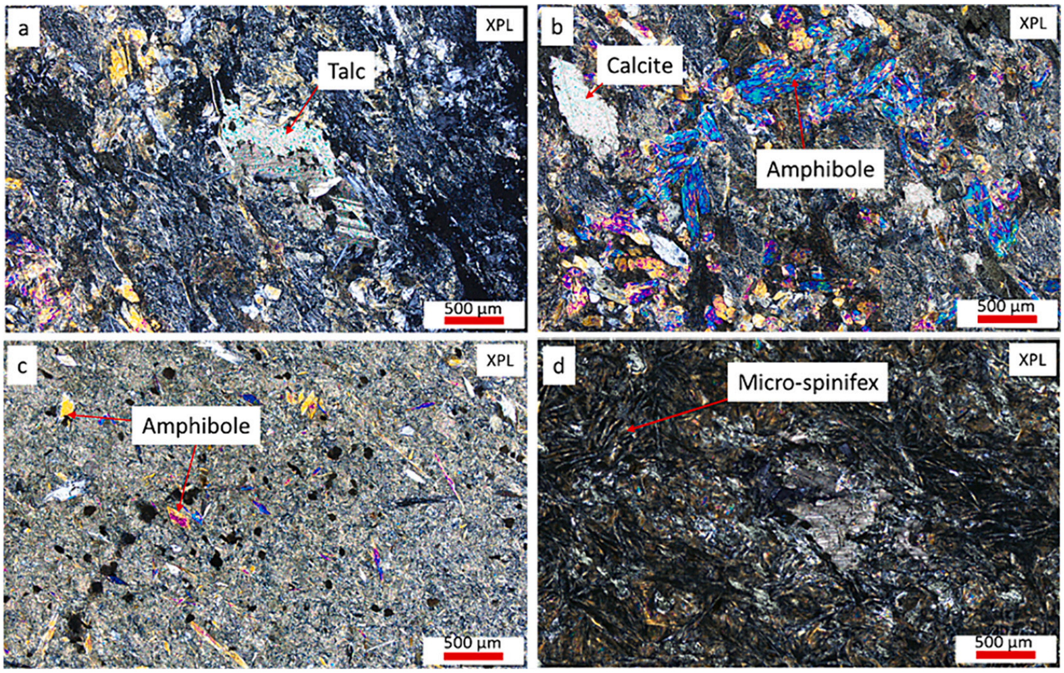

Fig. 4. Photomicrographs of samples that show severe alteration and metamorphism. (a- c) Metamorphic minerals in the samples are well crystallized (euhedral and coarse grained). (d) Altered micro-spinifex texture showing coarse calcite and talc grains. (a) Sample R360, (b) R360, (c) R434, (d) R359.

= 1390 m), Bothaville (avg. = 200 m, max. = 1177 m), and Allanridge (avg. = 400 m, max. = 1210 m). These thickness estimates should be considered as minimum values, given the incomplete coverage of boreholes throughout the Kaapvaal Craton and the fact that many boreholes were not drilled completely through the Ventersdorp stratigraphy (Supplementary Table 1). The Ventersdorp Supergroup may be substantially larger than the estimates given here. There are also significant spatial variations in thickness that are poorly constrained.

Based on the locations of boreholes and their lithologies intersected (Supplementary Table 1), and on the maps given in Schmitz and Bowring (2003), Myers et al. (1990), Linton et al. (1994), Eriksson et al. (2002) and McCarthy et al. (2018), the entire Ventersdorp Supergroup can be estimated to have an areal extent of ~225,000 km^2 (Fig. 1), and with an average thickness of 2.93 km, this yields a volume of ~0.659 × 10^6 km^3. However, what is of interest to us are the volumes of the magmatic products, especially the mantle-derived ones. Basaltic and komatiitic lavas of the Klipriviersberg Group are present over an area of ~193,000 km^2 (Fig. 1) and have a total average thickness of 750 m, yielding a volume of 0.145 × 10^6 km^3, which is sufficient to be considered a Large Igneous Province in its own right (> 0.1 × 10^6 km^2; > 0.1 × 10^6 km^3; Ernst, 2014). Units of the Platberg Group are present in no less than 25 individual graben and half-graben structures with NE-SW orientation (Meintjes, 1998; Eriksson et al., 2002), over an area of ~113,000 km^2 (Fig. 1; McCarthy et al., 2018). Graben structures containing Ventersdorp lithologies have also been identified in seismic reflection profiles (Tinker et al., 2002). It is unlikely, however, that the individual graben are contiguous below younger cover. Assuming that these graben structures are similar in size, shape and volume to the Ireton Graben, characterized by Stanistreet and McCarthy (1990) using surface exposures and drillcores to be ~1200 km^2, this gives an approximate (minimum) areal extent of the Platberg Group of ~30,000 km^2. Using the average thicknesses mentioned above, the volumes of the constituent basaltic magmatic products can be constrained as follows: Goedgenoeg (0.015 × 10^6 km^3) and Rietgat (0.007 × 10^6 km^3), collectively = 0.022 × 10^6 km^3, below the threshold to qualify this as a LIP. Basaltic lavas of the Pniel Sequence are present in the Allanridge Formation, with an areal extent of 106,000 km^2 (Fig. 1) and a thickness of ~400 m, yielding a volume of 0.042 × 10^6 km^3, also too small for a LIP. Again, it must be stressed that these volume estimates are minima. The implications of these volumes and ages are discussed below.

An important property of Ventersdorp Supergroup rocks is the secondary effects of hydrothermal alteration, which may have affected element mobility and isotopic resetting. The presence of actinolite, epidote, chlorite, talc, titanite, calcite, ankerite, pumpellyite and quartz indicates prehnite-pumpellyite to lower greenschist metamorphic conditions (Van der Westhuizen et al., 1991; Van der Westhuizen et al., 2006). The presence of calcite- and quartz-rich veins in the samples indicates that there was both carbonatisation and silicification. Carbonic fluids may have been derived from carbonate-rich rocks of the overlying Transvaal Supergroup (Khumalo, 2023). All primary olivine in Ventersdorp rocks has been replaced by chlorite, and commonly contains calcite-filled fractures; clear pseudomorphs of primary olivine crystal shapes are abundant, however, as discussed below. Preserved primary phases in the basaltic lavas include clinopyroxene and plagioclase. Duane et al. (2004) dated a craton-wide metamorphic event at ~2.0 Ga that might have resulted in greenschist facies metamorphism and hydrothermal alteration. The alteration possibly contributed to the formation of the Pb—Zn deposits in the Allanridge Formation with the hydrothermal fluids sourcing these metals from the quartz porphyries of the Makwassie Formation (Whitelaw, 1998; Duane et al., 2004).

The Ventersdorp Supergroup has been considered as a single magmatic event for over a century (Stow and Jones, 1874; Hatch, 1903), and this was initially corroborated by U—Pb zircon SHRIMP ages of 2714 ± 8 Ma for amygdaloidal and porphyritic lavas of the Klipriviersberg Alberton Formation and 2709 ± 4 Ma for quartz feldspar porphyries from the Platberg Makwassie Formation (Armstrong et al., 1991). However, more recent dating using ID-TIMS, LA-ICPMS and SHRIMP on zircon and baddeleyite indicates that Klipriviersberg Group rocks are ~2.78 Ga and the Platberg Group rocks are ~2.72 Ga (Poujol et al., 2005; de Kock et al., 2012; Cornell et al., 2017; Stamsnijder, 2017; Gumsley et al., 2020). Individual dates are provided in Supplementary Table 2. The Allanridge Formation of the Pniel Sequence has been linked to basaltic sills with baddeleyite ages between 2659 ± 13 and 2701 ± 11 Ma (average 2.68 Ga) (Olsson et al., 2010, 2011). The new dates suggest that the Platberg Group is some 60 m.y. and the Pniel Sequence as much as 100 m.y. younger than the Klipriviersberg Group. This has

Fig. 5. Full thin section photomicrograph showing a porphyritic basalt with elongate, subhedral plagioclase phenocrysts that are hosted in a fine-grained to medium-grained ($\leq$0.5 mm) groundmass of plagioclase microphenocrysts. The plagioclase phenocrysts display a preferred orientation, and the groundmass microphenocrysts are randomly orientated. There are large quartz-epidote-filled amygdales and smaller quartz amygdales (shown in red box). Allanridge Formation sample R038.

important implications for understanding the petrogenesis of the Ventersdorp Supergroup, the deposition of the Witwatersrand and Transvaal Supergroups, as well as for the evolution of the Kaapvaal Craton.

3. Methods

In this study a total of 96 samples were analysed for trace elements and 61 for Sr-Nd-Hf isotopes. These are the first combined Sr—Nd and the first Hf isotope analyses for Ventersdorp magmatic rocks. All samples were obtained from drillcore material characterized in Myers (1990) in which major elements concentrations can be found. Our samples come from eleven different boreholes, whose locations can be seen in Fig. 1. GPS locations of the boreholes are given in Supplementary Tables 1 and 3.

Trace element concentrations (Supplementary Table 3) were determined using a Thermo Scientific iCAP RQ ICP-MS at the Earth Laboratory at the University of the Witwatersrand. In brief, 50 mg of sample powder was digested in Ultra High Purity 2:1 HF:HNO_3 and placed on a hotplate at 100 °C in order to evaporate, and subsequently taken up in HF:HNO_3, capped and placed on the hotplate at 70 °C for 72 h. The sample solutions were diluted to 50 ml with 5% HNO_3 for measurement by ICP-MS (inductively coupled mass spectrometry). Internal Standards and Certified Reference Materials were monitored throughout the analyses (Khumalo, 2023). Methodology can be found in Khumalo (2023).

The samples were prepared for chemical purification of Lu, Hf, Rb, Sr, Sm and Nd and isotopic analyses in the Wits Isotope Geosciences Laboratory (WIGL) in the School of Geosciences (University of the Witwatersrand). Isotopic results are given in Supplementary Table 4. The sample powders were spiked with mixed ^{176}Lu—^{180}Hf, ^{149}Sm—^{150}Nd and ^{87}Rb—^{86}Sr tracers and dissolved in HF-HNO_3 in PFA beakers on the hotplate at 110 °C for 5 days. After sample digestion, the chemical purification of the elements was obtained by a 3-stage chromatography method set up and calibrated in the WIGL and detailed in Bourdeau et al. (2022).

All isotopic measurements were performed in low resolution mode on a Nu Instruments Plasma II MC-ICP-MS (Nu Instrument, Wrexham) housed at Spectrum (University of Johannesburg). Overall during the sessions, JMC-475 (^{176}Hf/^{177}Hf = 0.28216; Weis et al., 2007) yielded an average ^{176}Hf/^{177}Hf of 0.282141 ± 0.000060 (2σ: n = 90), JNdi (^{143}Nd/^{144}Nd = 0.512115; Tanaka et al., 2000) yielded an average ^{143}Nd/^{144}Nd of 0.512116 ± 0.000013 (2σ: n = 107) and SRM 987 (^{87}Sr/^{86}Sr = 0.710244, Jochum et al., 2007) yielded an average ^{87}Sr/^{86}Sr of 0.710247 ± 0.000017 (2σ: n = 150). Tabulations of analyses of standards and reference materials are given in Supplementary Table 4.

4. Results

4.1. Petrography

The samples show marked variation in phenocryst content and the extent of alteration (Figs. 3 and 4). There is evidence in some of the boreholes for the presence of multiple, composite komatiite flows in the Westonaria Formation, with cumulate, porphyritic and spinifex zones all preserved (Fig. 3). No primary olivine is preserved. Pseudomorphed olivine (Fig. 3a) and fresh pyroxene phenocrysts are the dominant phases in the cumulate zones and porphyritic zones. Some of the porphyritic samples are characterized by glomerocrysts that locally contain aligned, euhedral olivine pseudomorphs (chloritized) and which are hosted in a fine-grained matrix of secondary actinolite (Figs. 3 a-d, 4 b, c). The cumulate zones are well developed, and they vary in their crystal content (up to 90% modal abundance). Fig. 3 shows cumulate (c and d) and phenocryst-rich zones (a and b) composed of chloritized orthopyroxene that appears to have replaced olivine. Some pseudomorphed olivine phenocrysts show resorbed, and amoeboid, textures (Fig. 3 a, b). These phenocrysts are hosted in an actinolite-rich matrix, and they display a preferred orientation (Fig. 3 a, b). There are also clinopyroxene-rich cumulate zones (Fig. 3 i-j). Serpentinization is apparent in the cumulate zones (Fig. 3j). Locally there are silicified (pseudomorphed) olivine phenocrysts crosscut by calcite-filled fractures, and which are hosted in an actinolite- and chlorite-rich matrix (Fig. 3f). Randomly oriented needles of spinifex are also present (Fig. 3 g, h) in which the elongated grains are secondary actinolite needles. The coarse spinifex texture grades into a microspinifex zone with microphenocryst pseudomorphs (Fig. 3 g, h). Coarse clinopyroxene phenocrysts are set in the microspinifex zone (Fig. 3 i, j) and which grades into a clinopyroxene-rich cumulate. Calcite-, quartz- and chlorite-rich veins are observed in some sections. Secondary titanite, talc, epidote, and ankerite are also present in all samples. Some samples contain well preserved plagioclase phenocrysts and groundmass microlites (Fig. 5). Further petrographic details may be found in Bowen (1984) and Crozier (2001).

4.2. Major and trace element geochemistry

We have compiled a comprehensive database of nearly 2400 Ventersdorp magmatic rocks (available upon request from Lewis.Ashwal@wits.ac.za or Ben.Hayes@wits.ac.za) from the following sources: Georoc database (https://georoc.eu/), published papers and unpublished post-graduate theses. Major elements are plotted on a Total Alkalies vs Silica diagram in Fig. 6. Secondary hydrothermal

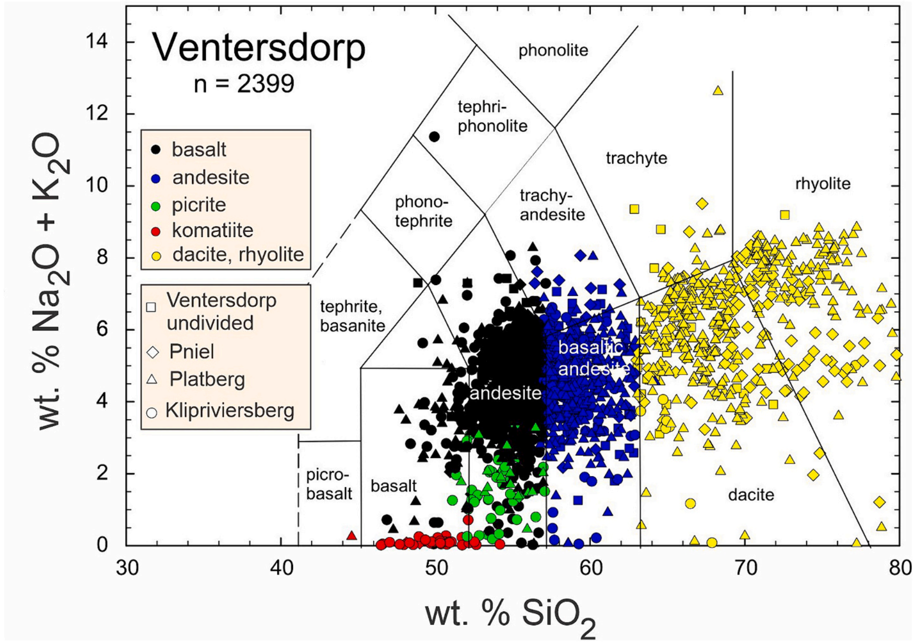

Fig. 6. Total Alkalies vs Silica (TAS) diagram showing a compilation of 2399 whole-rock major element analyses for all magmatic rocks of the Ventersdorp Supergroup South Africa. Database available upon request from Lewis.Ashwal@wits.ac.za or Ben.Hayes@wits.ac.za. Data sources are given in the text. Lithologies are defined as basalt (45–53 wt% SiO_2, <12 wt% MgO), andesite (53–57 wt% SiO_2), basaltic andesite (57–63 wt% SiO_2), picrite (12–18 wt% MgO), komatiite (>18 wt% MgO) dacite and rhyolite (>63 wt% SiO_2).

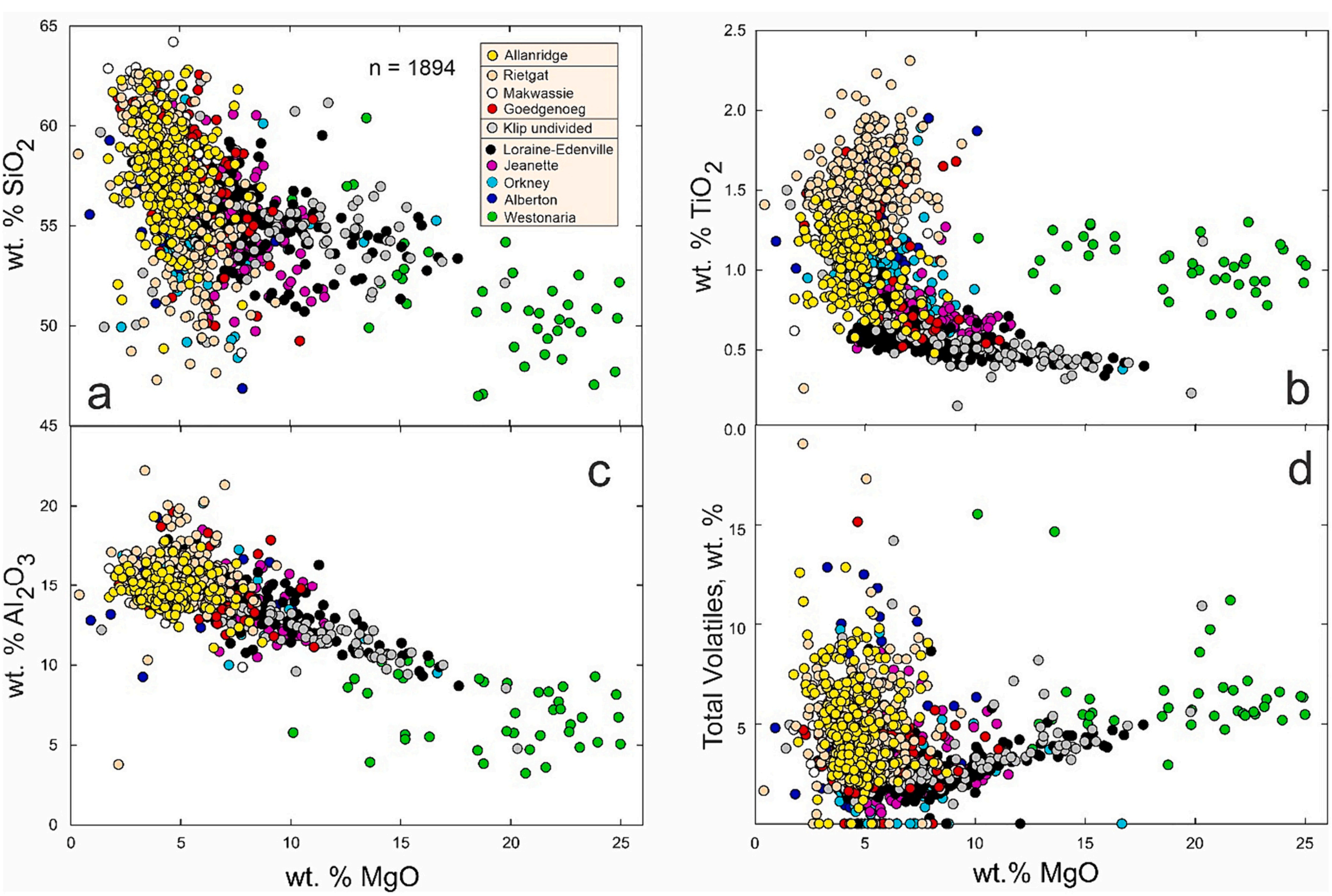

Fig. 7. Plots of wt% MgO vs wt% SiO_2 (a), wt% TiO_2 (b), wt% Al_2O_3 (c) and Total Volatiles (d) for Ventersdorp lavas (felsic rocks such as rhyolite and dacite are omitted).

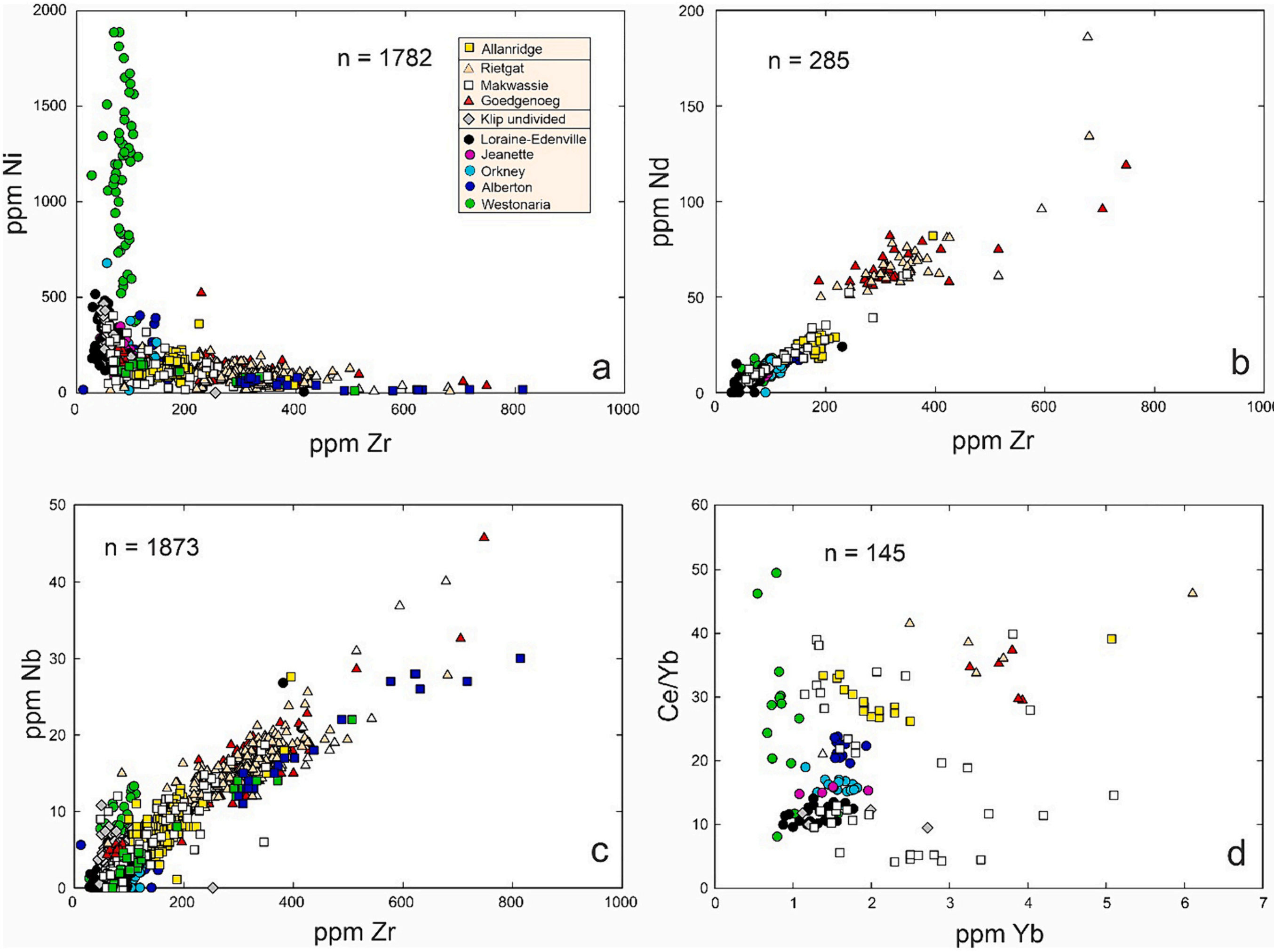

Fig. 8. Plots of Zr vs Ni (a) Nd (b), Nb (c) and Yb vs Ce/Yb for Ventersdorp lavas (felsic rocks such as rhyolite and dacite are omitted). REE data are available for only a relatively small number of samples, explaining fewer data points compared to other diagrams.

silicification has very likely shifted many basalts into the fields of basaltic andesite and andesite. The most primitive rocks are the komatiites and picrites of the Westonaria Formation, with MgO = 7.46–24.99 wt% (average = 18.12 ± 7.01 wt%, n = 40) (Fig. 4). Komatiites of the Westonaria Formation have higher TiO_2 (0.72–1.30 wt %, Fig. 7b) than most komatiites globally, which have $TiO_2 < 1$ wt%. The immediately overlying lavas of the Alberton Formation are more evolved, but become progressively more primitive (higher MgO, Mg#, Ni and lower incompatible element concentrations) stratigraphically upwards through the Orkney, Jeanette and Loraine-Edenville Formations (Figs. 7, 8, see also Fig. 15), which contain minor picritic lavas, but there are no Loraine-Edenville komatiites (Crow and Condie, 1988; Van der Westhuizen et al., 2006). A shallow negative array is apparent for the Loraine-Edenville Formations on the plots of MgO vs TiO_2 and Al_2O_3 (Figs. 7 b, c), and this corresponds to a positive array for Total Volatiles vs MgO (Fig. 7d), suggesting that these correlations are controlled by secondary hydrothermal alteration. Total Volatiles (H_2O, CO_2 and LOI) can reach up to nearly 20 wt% (Fig. 7d), and this results from secondary minerals in fractures and vesicles, the replacement of olivine by chlorite and calcite, and the presence of other low-grade metamorphic replacement minerals.

Trace elements are given in Supplementary Table 3 and are shown in a series of plots in Figs. 8, 9 and 10. Westonaria komatiites and picrites show a large range in Ni concentration (371–1887 ppm) at constant Zr, whereas all the other Formations have constant and low Ni concentrations at variable Zr (Fig. 8a). On a plot of Nd vs Zr (Fig. 8b), Klipriviersberg and Allanridge lavas form clusters at low Nd and Zr, and individual clusters form short linear arrays up to 200 ppm Zr and 30 ppm Nd for Klipriviersberg. The Goedgenoeg and Rietgat Formations plot as a more diffuse but parallel array at higher Nd. The array for the Makwassie lavas extends over the entire range of data, from low to high Nd and Zr. Other incompatible elements, such as Nb, plot in a single, diffuse array (Fig. 8c). Westonaria picrites and komatiites show variable Ce/Yb at constant Yb (Fig. 8d), indicating fanning of the LREE at approximately constant HREE (see also Fig. 9). Also, in terms of Ce/Yb and Yb, the Alberton, Orkney, Jeanette, Lorraine-Edenville and Goedgenoeg Formations show individual clusters, but Makwassie, Rietgat and Allanridge lavas show very wide scattering.

The Ventersdorp lavas display LREE enrichment patterns with weak Eu anomalies (Fig. 9). The lavas show greater variation in LREE than HREE (Fig. 9). The concentration of incompatible elements decreases up section from the Alberton Formation to the Loraine-Edenville Formation, consistent with the increase in primitiveness stratigraphically upward, as discussed above. The Westonaria Formation overlaps with the rest of the Klipriviersberg lavas. The Klipriviersberg lavas display a flattening of the HREE patterns from the Alberton Formation towards the Loraine-Edenville Formations, except for the Westonaria Formation, which displays variation in the HREE patterns ($Gd/Yb_{(N)}$: 2.13–3.05) overlapping with the rest of the Klipriviersberg lavas ($Gd/Yb_{(N)}$: 1.17–2.60: Fig. 9). The Platberg Group lavas (Fig, 9c) plot at higher

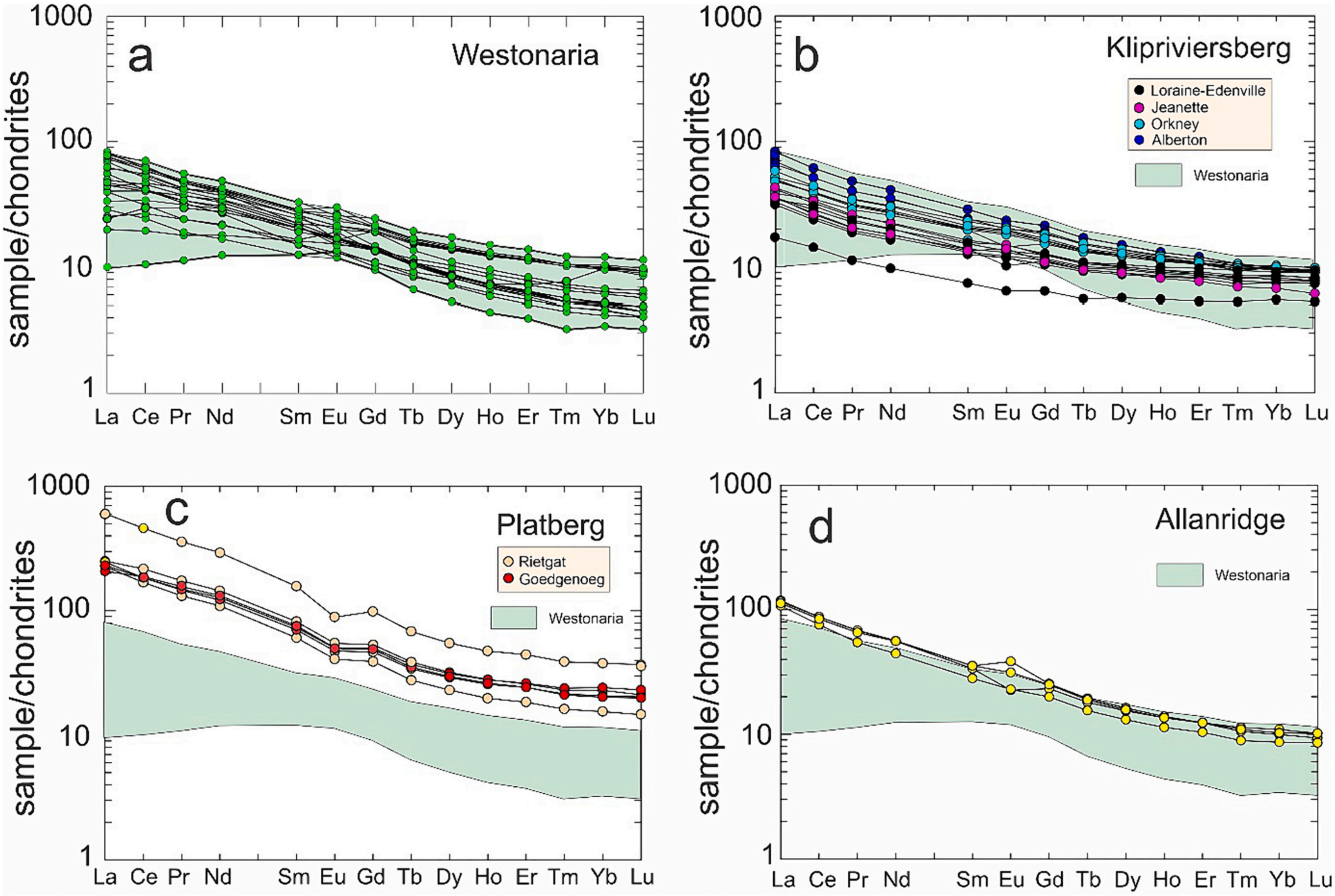

Fig. 9. Chondrite-normalised rare earth elements (REE) diagrams of Ventersdorp lavas. The lavas show L/HREE enrichment. The Westonaria lavas are shown as the green background for comparison with other units. The normalisation values are from McDonough and Sun (1995).

values of enrichment relative to chondrites (above 100× chondrites for the LREE and 20× chondrites for the HREE), parallel to the Klipriviersberg Group samples (Fig. 9b). The Goedgenoeg and Rietgat lavas of the Platberg Group display greater LREE enrichment compared to the Klipriviersberg lavas. The Allanridge lavas of the Pniel Sequence are parallel to both the Klipriviersberg and Platberg Groups (Fig. 9c and d).

Multi-element diagrams normalised using primitive mantle values (McDonough and Sun, 1995) are shown in Fig. 10. Westonaria picrites and komatiites tend to have the lowest concentrations of incompatible elements relative to all overlying formations. Mobile elements like Rb, Ba and possibly K also tend to be relatively low in these lavas. The Alberton Formation, immediately overlying Westonaria rocks has the highest values of incompatible elements of the Klipriviersberg Group (Fig. 10b see also Fig. 15), which seem to progressively decrease stratigraphically upward through the Orkney, Jeanette and Loraine-Edenvale Formations. Goedgenoeg and Rietgat lavas (Fig. 10c) have the highest incompatible concentrations and trace element patterns of the Allanridge basalts and andesites (Fig. 10d) resemble those of the upper units of the Klipriviersberg Group. Negative Ti anomalies are present in all our samples; those of highest magnitude occur in Platberg lavas. Negative Sr anomalies are present in Westonaria and Platberg lavas; small positive Sr anomalies are present in other Klipriviersberg samples (Fig. 10b) and Allanridge samples tend to have no Sr anomalies. Prominent negative Nb—Ta anomalies occur in all Ventersdorp lavas except those of the Westonaria Formation; Klipriviersberg rocks stratigraphically above the Westonaria Formation have the highest magnitude Nb—Ta anomalies (Fig. 10b). Platberg samples are also relatively depleted in U and Th (Fig. 10c),

4.3. Isotope geochemistry

High-precision Sr-Nd-Hf isotope data can be found in Supplementary Table 4 and are plotted in Fig. 11. Initial Sr ratios show much wider variation (0.693936–0.716536, Figs. 11a, c) compared to initial Nd or Hf (expressed as ε_{Nd} or ε_{Hf}); this is explicable in terms of secondary hydrothermal alteration processes, as discussed below. Sr isotopes, therefore, cannot be used to make inferences about magmatic processes. The initial ε_{Nd} values calculated at 2.78 Ga for the Klipriviersberg lavas range from −1.85 to +2.12, with the Westonaria picrites and komatiites having the highest ε_{Nd} values and most depleted isotopic compositions (Figs. 11a, b, c, d). The Platberg lavas have ε_{Nd} (calculated at 2.72 Ga) ranging from −4.00 to −2.55, and Allanridge lavas have ε_{Nd} (calculated at 2.68 Ga) ranging from −3.74 to −2.45. Initial ε_{Hf} values for the Klipriviersberg lavas range from −15.31 to +3.88 and correlate positively with ε_{Nd}, forming a diffuse array corresponding to a Neoarchean mantle array (Fig. 11b). Klipriviersberg lavas have the most depleted Nd—Hf isotopic signatures, and Platberg and Allanridge samples cluster at more enriched ε_{Nd} and ε_{Hf} values (ε_{Hf} = −10.30 to −2.53). The temporal evolution of Nd isotopic compositions is shown in Fig. 11d. Klipriviersberg lavas have a wide range of ε_{Nd} but the highest values match Neoarchean depleted mantle. Platberg and Allanridge have distinctly lower ε_{Nd}, corresponding either to continental crust or enriched mantle.

5. Discussion

5.1. Secondary processes

The ~2.7 Ga Ventersdorp Supergroup lavas show evidence of

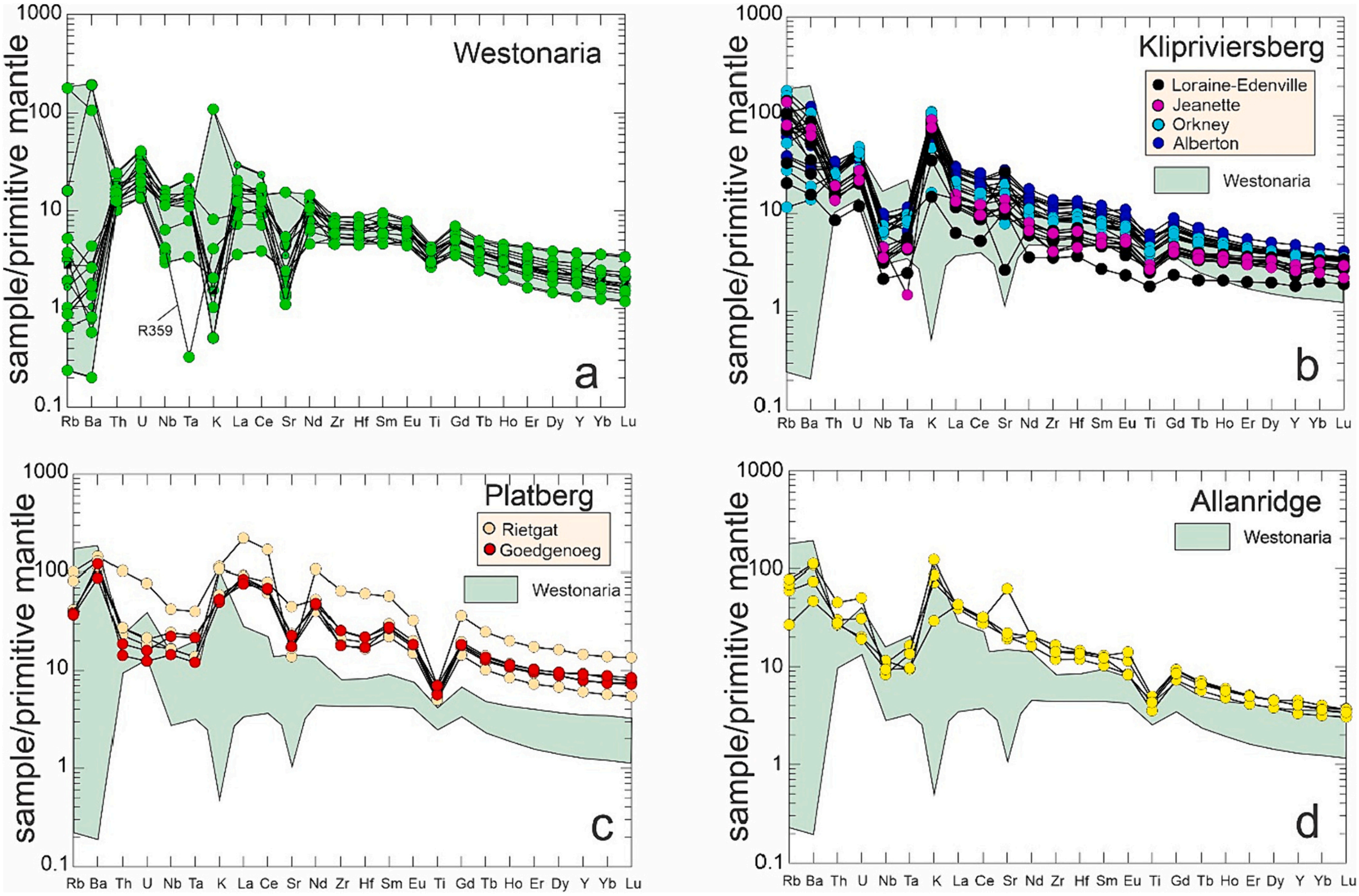

Fig. 10. Multi-element diagram of the Ventersdorp Supergroup lavas normalised to the primitive mantle composition. Shaded green fields represent Westonaria lavas for comparison (excludes data for sample R359, which shows abnormally low Ta). Negative Nb—Ta anomalies are present in all but Westonaria samples. The normalisation values are from McDonough and Sun (1995)

multiple secondary processes, possibly caused by younger events such as the 2.6–2.7 Ga Limpopo orogeny (Van Reenen et al., 2019) and/or the 2.0 Ga Kaapvaal Craton-wide metamorphic event documented by Duane et al. (2004). The effects of alteration and metamorphism on the isotopic compositions of the Ventersdorp lavas are investigated before we use these data to constrain the magma source(s).

The wide range of Initial $^{87}Sr/^{86}Sr$ isotopic compositions of the Klipriviersberg Group lavas suggests that there has been disturbance of the Rb—Sr isotope system, possibly by hydrothermal fluids that percolated through the lavas, and which may have caused the loss and/or gain of radiogenic Sr and/or Rb. Evidence of hydrothermal fluids having passed through the lavas include calcite-chlorite and chlorite-quartz veins, epidote-quartz amygdales (Fig. 5) and replacement of primary magmatic minerals by a variety of secondary phases. The addition of Rb due to its high mobility lowered initial $^{87}Sr/^{86}Sr$ below ~0.700 (Fig. 12a). The loss of Rb resulted in the higher initial $^{87}Sr/^{86}Sr$ of the Westonaria lavas. Loss of Rb, as well as of Ba and K in Westonaria samples is also evident on the multi-element diagrams (Fig. 10); these rocks suffered higher element mobility largely because they originally contained more olivine, all of which has been replaced by secondary minerals. Carbonic (CO_2-rich) fluids and silicic fluids that exploited the rift- and graben-faults of the Ventersdorp basin may have altered the lavas, and the carbonic fluids might have formed REE complexes, as they have the ability to mobilize the REE (Lahaye et al., 1995). Therefore, the effect of element mobility by the fluids on the bulk isotope systems should be considered when interpreting the Sm—Nd and Lu—Hf isotopic compositions in terms of the compositions of mantle sources.

Khumalo (2023) proposed that carbonates in the overlying 2.5–2.3 Ga Transvaal Supergroup were the potential source for the carbonic fluids. Duane et al. (2004) determined that a 2.0 Ga craton-wide metamorphic event (thermal and hydrothermal) metamorphosed and altered the Ventersdorp Supergroup lavas. The alteration possibly contributed to the formation of the Pb—Zn deposits in the Allanridge Formation with the hydrothermal fluids sourcing these metals from the Makwassie Quartz Porphyry (Whitelaw, 1998; Duane et al., 2004). The presence of actinolite, epidote, pumpellyite and quartz in the Klipriviersberg Group basalts indicates prehnite-pumpellyite to lower greenschist facies metamorphic conditions. The different isotopic compositions between the stratigraphic units of the Ventersdorp Supergroup indicate small-scale modification of the Sm—Nd and Lu—Hf isotopic systems as opposed to a large-scale modification that would have homogenized the isotopic compositions. Therefore, it is assumed that any disturbance in the isotopic systems happened at a small scale and that samples still possess isotopic compositions that allow constraints to be placed on the magmatic petrogenesis of the Ventersdorp Supergroup. This certainly applies to the Sm—Nd and the Lu—Hf systems, as the conditions (<400 °C) of the greenschist facies metamorphism would only significantly affect the Rb—Sr system (Scherer et al., 2000). Khumalo (2023) showed that the Sm—Nd system was less disturbed compared to the Rb—Sr system, and that the Lu—Hf system remained robust in the komatiitic Westonaria lavas. This is seen in the wide range in the initial $^{87}Sr/^{86}Sr$ compositions and the relatively narrow range of ε_{Nd} and ε_{Hf} values of the Ventersdorp lavas (Fig. 11b, c). Mobility of Rb is illustrated in Fig. 12a, as samples with Initial Sr (t) <0.700 have experienced Rb gain whereas those with values >0.715 have experienced Rb loss. The disturbance of the Rb—Sr isotope system was more enhanced in the Westonaria lavas than in the other Formations because of the former presence of abundant olivine. The plot of $^{176}Lu/^{177}Hf$ versus $\varepsilon_{Hf\ (t)}$ better

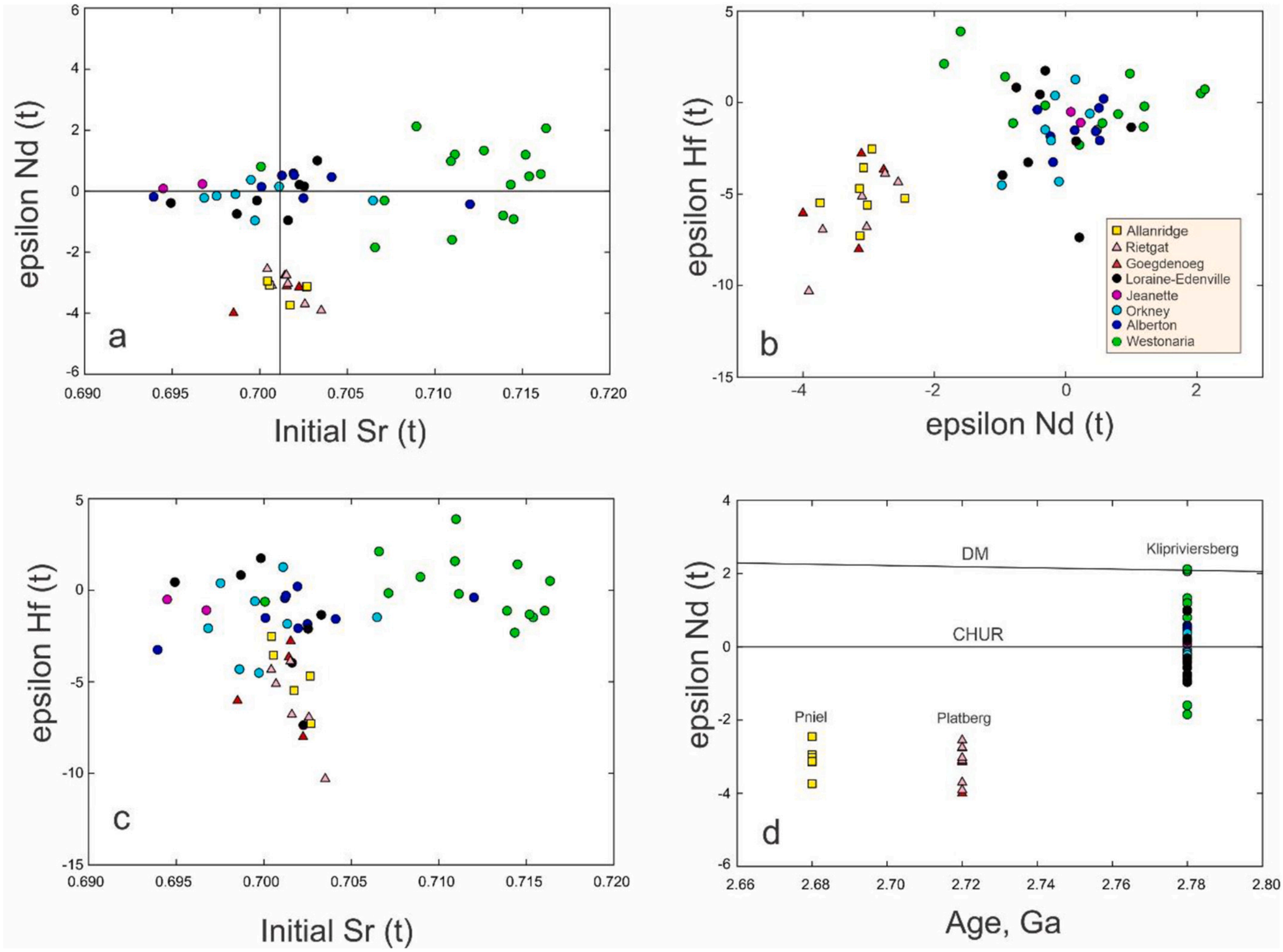

Fig. 11. Radiogenic isotopic compositions of Ventersdorp mafic lavas at time of formation. Plots are: ε_{Nd} vs Initial Sr ratio (a), ε_{Hf} vs ε_{Nd} (b), ε_{Hf} vs Initial Sr ratio (c) and ε_{Nd} vs age (d). Decay constants used for calculations are from Steiger and Jäger (1977), Begemann et al. (2001) and Söderlund et al. (2004). Bulk Earth values at 2.75 Ga in (a) (black lines) are from DePaolo and Wasserburg (1976): Initial Sr = 0.7012; ε_{Nd} = 0). CHUR parameters used to calculate epsilon values are from Wasserburg et al. (1981) and Bouvier et al. (2008). Depleted mantle (DM) evolution in (d) is taken from DePaolo (1981). CHUR = chondritic uniform reservoir.

discriminates the Formations, indicating that the alteration effect on the HREE and Lu—Hf isotope system was minimal (Fig. 12b). This testifies to the reliability of the isotopes used in our work and the effectiveness of using the three isotope systems with different strengths against alteration and metamorphism (Lu-Hf > Sm-Nd > Rb-Sr). Despite the secondary processes discussed in this section, the effects of alteration and metamorphism were not significant upon isotopic compositions except for the Rb—Sr isotopic system; the Lu—Hf and Sm—Nd isotopic systems are robust and can be used to infer the mantle sources of the lavas in the Ventersdorp Supergroup.

5.2. How many LIPs?

The Ventersdorp lavas have been considered as a single LIP (e.g., Armstrong et al., 1991), but new geochronology reveals that as much as 100 m.y. may have elapsed between the bottom and top of the stratigraphic package, far too long for a single LIP, which by definition has eruption intervals of <5–10 m.y. (Ernst, 2014). Could it be that the Klipriviersberg Group (2.78 Ga, 0.142 × 10^6 km^3), Platberg Group (2.72 Ga, 0.022 × 10^6 km^3) and Allanridge Formations (2.68 Ga, 0.042 × 10^6 km^3) can be considered as 3 separate LIPs? This would be consistent with the wide range of ages between them and the fact that they are separated by prominent unconformities. This brings to mind the 4 largest spatially overlapping LIPs of southern African: Ventersdorp (broadly 2.7 Ga), Bushveld (2.06 Ga), Umkondo (1.11 Ga) and Karoo (0.18 Ga), although these were emplaced over a much larger time interval of over 2.5 b.y. (Ashwal, 2021), far too long for a single plume. However, if we accept the qualifying criteria for LIPs in terms of areal extent (>0.1 × 10^6 km^2) and volume of mafic magmatic products (>0.1 × 10^6 km^3) (Coffin and Eldholm, 1994; Ernst, 2014), then both the Klipriviersberg Group and Allanridge Formation could be considered as LIPs based on areal extent, but based on volume, only the Klipriviersberg Group would qualify.

Another possibility is that the 3 components of the Ventersdorp Supergroup represent the magmatic products of a *single* plume, with the spatial overlap having been caused by a stationary African continent over a time interval of ~100 m.y. (from 2.78 to 2.68 Ga). In the present Earth, the longest-duration active hot spots, albeit below moving plates, are the Tristan plume, with a well-defined magmatic province as old as 132 Ma (Paraná-Etendeka LIP, Gomes and Vasconcelos, 2021) and the Great Meteor (New England) hotspot, with initial plume products at 125 Ma (Monteregian Hills, Quebec, Kinney et al., 2020). A single hot spot origin below a stationary African plate for the 3 Ventersdorp mafic magmatic groups would be consistent with the initial large-volume magmatic products of the Klipriviersberg Group having been derived from the hot, central portions of the plume head, and the subsequent, lower-volume Platberg and Allanridge lavas having been derived from the narrower plume tail, or, more likely, from the annular or donut-

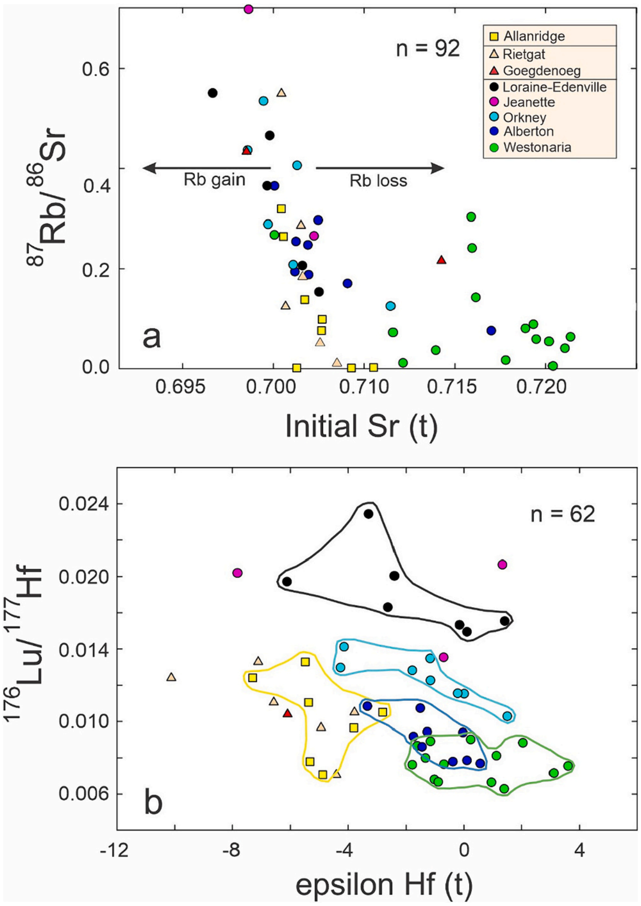

Fig. 12. (a) ^{87}Rb/^{86}Sr vs Initial Sr (t) shows the effect of the hydrothermal alteration on the Sr isotope compositions. The addition of Rb in the lavas resulted in lower initial isotope ratios and the loss of Rb resulted in higher ratios. (b) ^{176}Lu/^{177}Hf vs ε_{Hf} (t) plot effectively discriminates between the Formations, showing the minimal effect of alteration on the Hf isotopic composition. The alteration did not homogenise the isotopic compositions of the lavas.

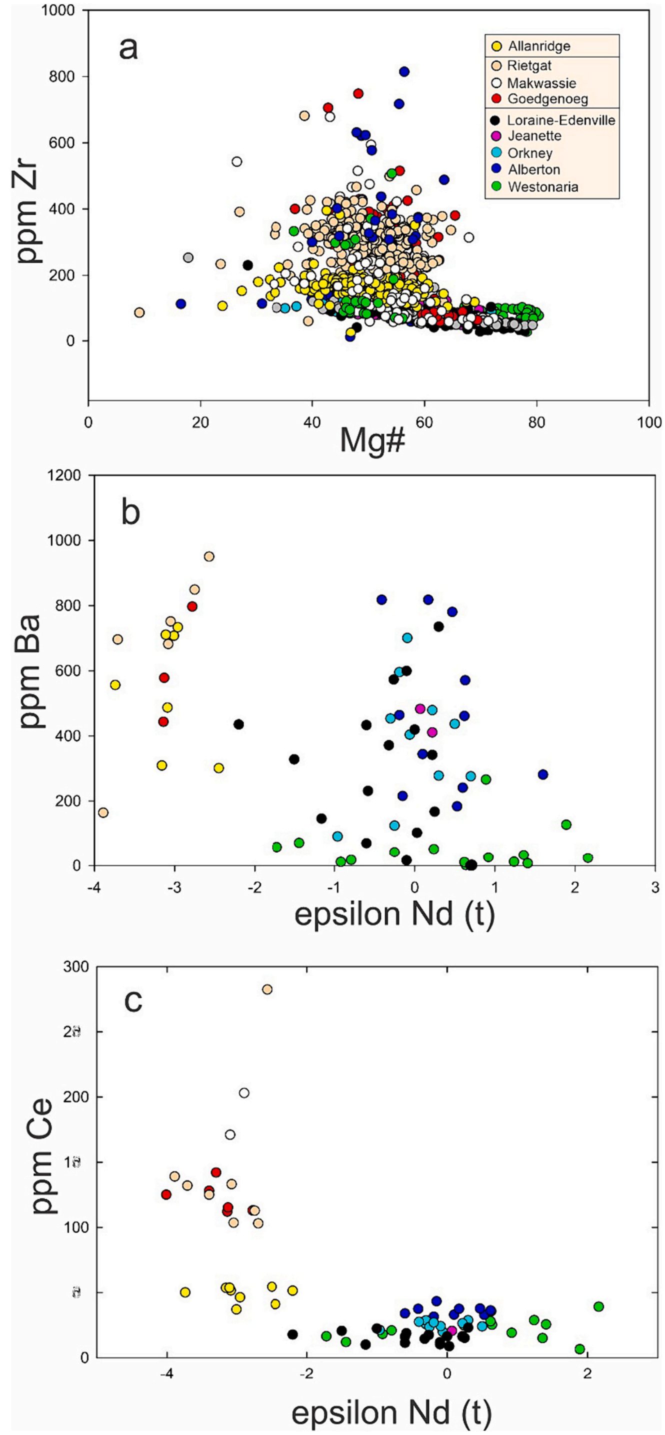

Fig. 13. Plots of ppm Zr vs Mg# (a), ppm Ba vs ε_{Nd} (b) and ppm Ce vs ε_{Nd} (c) for mafic lavas of the Ventersdorp Supergroup.

shaped marginal parts of the plume head, formed by entrainment of asthenospheric material during plume ascent (Campbell and Griffiths, 1990) (Fig. 15). Additional high-precision age dates for Ventersdorp lavas would be most welcome to further evaluate these possibilities.

5.3. Magmatic processes

In this section, we consider the magmatic processes responsible for the wide variations in chemical and isotopic compositions of Ventersdorp lavas. Fractional crystallization of the Ventersdorp magmas, such as might have taken place in subvolcanic or deep crustal magma chambers, would be expected to show negative correlations between incompatible element concentrations and well-known indices of fractionation such as Mg#; this is clearly not the case (Fig. 13a). Crystal fractionation alone should show variable major and trace element concentrations, at constant values of initial isotopic ratios, which is also not apparent (Fig. 13b). Assimilation of continental crust components should produce negative arrays on plots of compatible vs incompatible elements (e.g., Fig. 8a) and on plots of isotopic compositions vs incompatible elements (e.g., Fig. 13c); such arrays are not apparent. For similar reasons, combined assimilation–fractional crystallization (AFC) processes were not operative in Ventersdorp magmas; most importantly, there are no arrays on isotope-isotope plots like ε_{Nd} vs initial Sr (Fig. 11b) or ε_{Nd} vs ε_{Hf} (Fig. 11c). Variations in the degree of partial melting of one or more mantle sources should result in constant isotopic compositions at variable incompatible element concentrations, which is not the case (e.g., Fig. 13b), although Westonaria picrites and komatiites surely represent larger degrees of partial melting than the basaltic rocks in all the other Formations. What our data do imply for Ventersdorp magmatic rocks is a derivation from multiple mantle sources, as we discuss below.

5.4. Mantle source(s)

The geochemical arrays in the Ventersdorp dataset allow us to

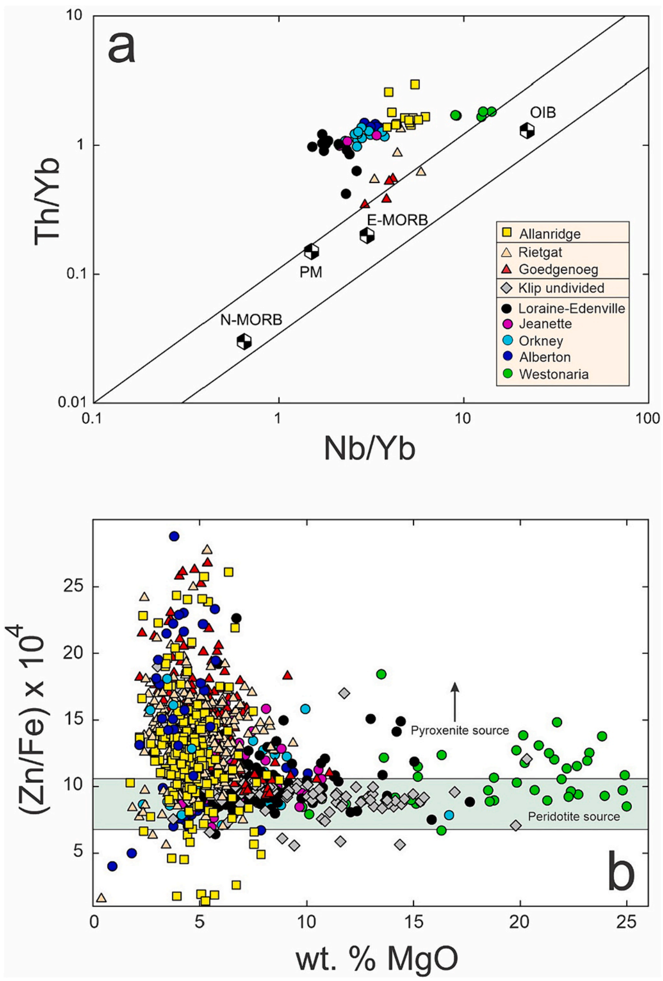

Fig. 14. (a) Plot of Th/Yb vs Nb/Yb for mafic Ventersdorp lavas relative to the mantle array of Pearce (2008), shown as solid lines. N-MORB = Normal MORB; *E*-MORB = Enriched-MORB; PM = Primitive Mantle; OIB = Ocean Island Basalt. (b) Plot of (Zn/Fe) x 10^4 vs MgO showing how peridotite and pyroxenite mantle sources can be distinguished (after Le Roux et al., 2010). Average Zn/Fe (x 10^4) of ~8.5 ± 2 for mantle peridotites is illustrated as a green bar in (b)

provide constraints on two, perhaps three mantle sources. That the data plot as linear arrays rather than tight clusters suggests that mixing of sources, or of partial melts of sources was operative. One source was highly depleted, as constrained by Westonaria picrites and komatiites, with maximum $\varepsilon_{Nd} = +2.12$, $\varepsilon_{Hf} = +3.88$ (Figs. 11 a, b), Th/Yb = 1.8 and Nb/Yb = 14.2 (Fig. 14a). This resembles the average OIB source and may be taken to represent the asthenospheric or plume component (Fig. 14a).

The positive array above the mantle array on the plot of Th/Yb vs Nb/Yb (Fig. 14a) that includes all of Klipriviersberg as well as Allanridge lavas suggests mixing of the depleted asthenospheric source with a possibly lithospheric source with low Th/Yb and Nb/Yb, which may plot at the position of the Loraine-Edenville lavas, or on an extension of the array, towards lower Th/Yb and Nb/Yb. We prefer the latter possibility because a source matching the composition of Loraine-Edenville lavas would imply the wholescale melting of that source. Cogent arguments based on volume-composition considerations against such melting events were presented by Ashwal (2021) for southern African LIPs. Alternatively, the lithospheric source may represent small, enriched domains in the SCLM, as suggested for the small-volume, high-Ti suite of magmatic products in the 0.182 Ga Karoo LIP (Ashwal, 2021), but we consider this as unlikely because Allanridge volumes are too large to consider the small, enriched mantle domains as possible sources. Isotopic compositions of Allanridge and Platberg mafic lavas are similar (Fig. 11), implying a common mantle source, although Th/Yb are lower in Platberg samples (Fig. 14a), possibly reflecting secondary Th loss from Goedgenoeg and Rietgat lavas.

The negative Nb—Ta anomalies for all Klipriviersberg rocks except those of the Westonaria Formation (Fig. 10a) imply the involvement of a source component that bears a subduction signature for the younger lavas. This would be consistent with the picrites and komatiites of the Westonaria Formation having been derived from large-degree partial melting of an asthenospheric source in the plume head, followed by variable smaller-degree partial melting for the younger Formations of subduction-modified lithosphere present in the marginal parts of plume heads (or tails) due to entrainment of subducted lithosphere into the deep mantle (Koppers et al., 2021). Another alternative is a heterogeneous plume with compositionally distinct materials that occur as domains or "streaks" (e.g., Gibson et al., 2000). This is illustrated in Fig. 15, which shows all Ventersdorp units, scaled in terms of volume, and colour-coded as per their mantle sources, either from the central hotter parts of a deep mantle plume, or from subduction-modified mantle in plume margins or tails, or both. We argue that SCLM, or enriched domains in SCLM, are not viable sources for Ventersdorp mantle-derived magmatic rocks based on volume arguments presented in Ashwal (2021). Dacites and rhyolites of the Goedgenoeg and Makwassie Formations were generated by partial melting in the continental crust due to heating by ascending mafic magmas (Meintjes and van der Westhuizen, 2018a).

Le Roux et al. (2010) have shown how Zn/Fe can be used to distinguish peridotitic from pyroxenitic mantle sources for mafic magmatic rocks. Because mantle peridotites have average Zn/Fe (x 10^4) of ~8.5 ± 2 (illustrated as a green bar in Fig. 14b), and because olivine and orthopyroxene have partition coefficients for Zn/Fe that approach 1, then the Zn/Fe of partial melting products of peridotite should not change much from their source materials. But Zn/Fe mineral/melt partition coefficients for garnet and clinopyroxene are distinctly <1, such that melts derived from pyroxenitic or eclogitic sources would have high Zn/Fe, depending on the garnet/pyroxene ratio. On this basis, Klipriviersberg lavas show derivation dominantly from peridotitic sources, whereas Platberg and Allanridge lavas show a higher proportion of pyroxenitic sources.

5.5. *Implications for the Vaalbara supercraton*

Based on lithostratigraphy, geochemistry, geochronology and paleomagnetism, the Ventersdorp volcano-sedimentary succession on the Kaapvaal Craton has been correlated with similar successions on the Pilbara Craton of Australia (Trendall, 1968; Button, 1979; Nelson et al., 1992; Cheney, 1996a, 1996b; Grobler et al., 1989; Wingate, 1998, 1999; Blake et al., 2004; de Kock et al., 2012). The 2.77–2.71 Ga Fortescue Group on the Pilbara Craton has similar rock types and some geochemical similarities to the Ventersdorp Supergroup, which have been used to argue for a Neoarchean supercraton called Vaalbara, implying that the Kaapvaal and Pilbara Cratons were once adjoined. Furthermore, the Transvaal Supergroup overlying the Ventersdorp Supergroup on the Kaapvaal Craton has also been correlated with the Hammersley Group on the Pilbara Craton (e.g., Cheney, 1996a, 1996b), and the quartz porphyries of the Kylena and Maddina basalts (2724–2721 Ma) on the Pilbara Craton might be related to the Platberg Group quartz porphyries based on their ages (e.g., Stamsnijder, 2017). However, our new Nd isotopic data call into question these correlations between South African and Australian cratonic entities (Fig. 16). Note that Sr isotopes can be shown to have been modified by secondary processes and Hf isotopic data have not yet been measured in Fortescue rocks. The volcanics of the Mt. Roe, Hardley, Bamboo Creek, Kylena and Maddina Formations of the Fortescue Group (Fig. 16) have similar ε_{Nd} values throughout the whole stratigraphy ($\varepsilon_{Nd} = -4.8$ to $+1.9$, Nelson et al., 1992; Mole et al., 2018) and are similar to those of the Platberg

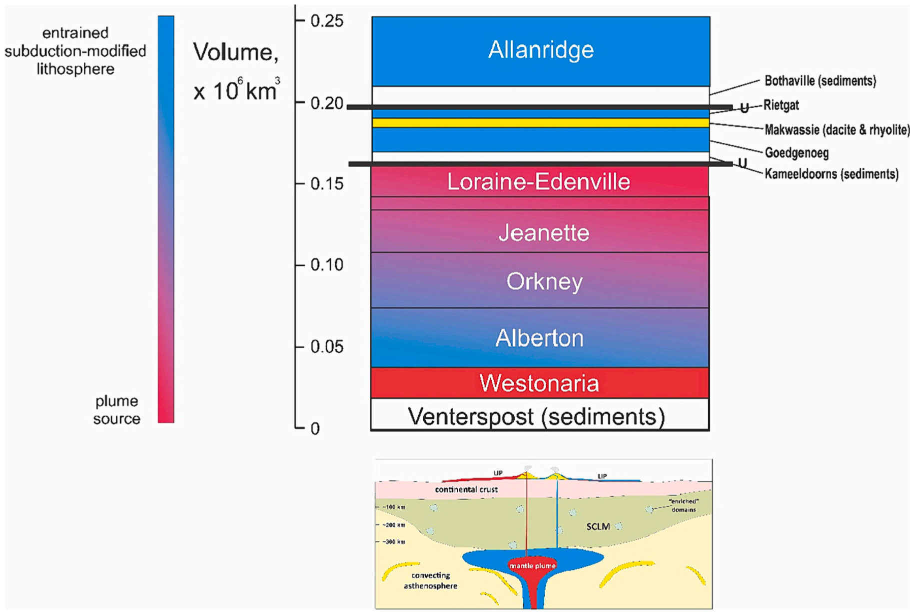

Fig. 15. Lower panel shows a schematic cross section through continental lithosphere and upper asthenosphere with possible mantle source regions for Ventersdorp mafic magmatic rocks. These include (1) the sub-continental mantle lithosphere (SCLM, green), (2) small, enriched domains in the SCLM (light blue), (3) convecting asthenosphere (yellow with darker yellow indicating convection) and (4) a rising deep mantle plume (shades of red and darker blue indicating possible compositional and temperature heterogeneity). Modified from Ashwal (2021). Upper panel show Ventersdorp stratigraphy calibrated in terms of average Formation volumes. Major unconformities are shown as thick black lines labelled "U". We suggest that the volume/compositional relations of Ventersdorp mafic magmas preclude mantle sources in the lithosphere or enriched domains in the lithosphere. Instead, the large volumes of magmas in the Klipriviersberg Group, as well as the presence of early komatiites/picrites argue for derivation from melting in the hot, central parts of a plume head (red in upper panel) flattened upon impingement at the SCLM. Evolved rocks in the Alberton – Jeanette Formations represent derivation from variable amounts of subduction-modified lithosphere (darker blue in upper panel) entrained from deep mantle by ascending plumes, before a return to the involvement of hot, centrally located mantle in the central parts of the plume head. Mafic lavas of the Goedgenoeg, Rietgat and Allanridge Formations were derived largely from subduction-modified asthenospheric (dark blue) or lithospheric (light blue) mantle. Rhyolites and dacites of the Makwassie Formation were derived by partial melting of continental crust.

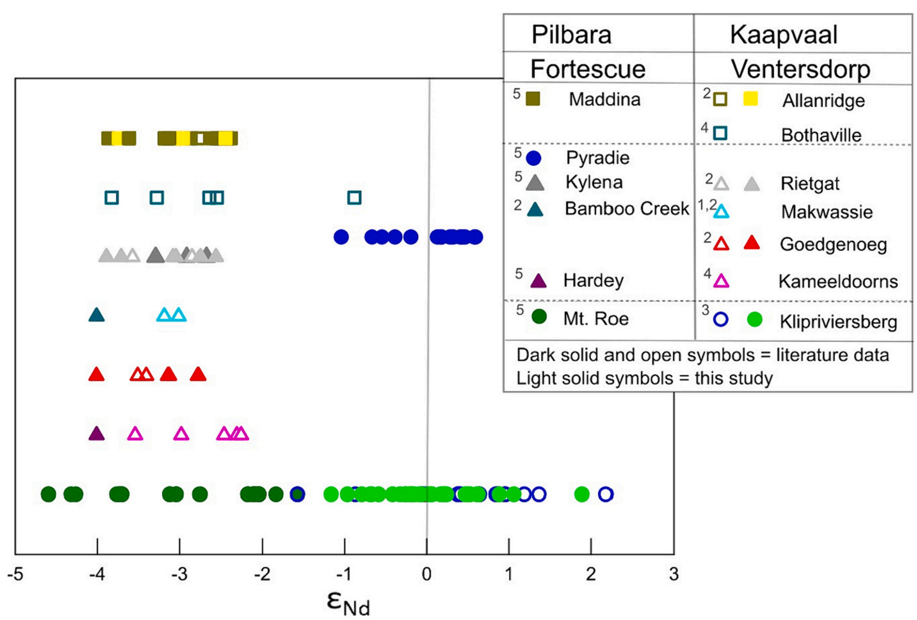

Fig. 16. Nd isotopic compositions of the Ventersdorp lavas and Fortescue lavas as well as of the correlative lavas on the Kaapvaal craton. The plot shows that the Klipriviersberg Group and the proposed equivalent, the Mount Roe, on the Pilbara craton possess different Nd isotopic signatures. However, the rest of both sequences have similar isotopic signatures except for the Pyradie komatiites. Note that Pyradie and Kylena lavas differ slightly in age. Data sources: 1) Van der Westhuizen et al. (1991), 2) Nelson et al. (1992), 3) Marsh et al. (1992), 4) Schneiderhan et al. (2011) and 5) Mole et al. (2018).

and Allanridge units ($\varepsilon_{Nd} = -4.01$ to -2.45) but are significantly lower than those of the Klipriviersberg Group ($\varepsilon_{Nd} = -1.72$ to $+2.16$) (Fig. 16). Komatiitic rocks of the Pyradie Formation ($\varepsilon_{Nd} = -1.1$ to $+0.5$, Mole et al., 2018) do resemble Westonaria picrites and komatiites but occur much higher in the Fortescue stratigraphy rather than occupying a basal level, as in the Ventersdorp stratigraphy. These similarities and differences in lithostratigraphy and isotopic compositions may reflect differences in basin architecture and structural evolution. More work, such as additional isotopic compositions for Fortescue rocks and additional geochronology for both sequences is needed to further constrain the viability of the Vaalbara hypothesis.

6. Summary

The Neoarchean Ventersdorp Supergroup represents one of the oldest volcano-sedimentary successions on Earth and has well-preserved mafic lavas that can be subdivided into 3 separate magmatic events: the Klipriviersberg LIP, the Platberg magmatic event, and the Allanridge event. We present new trace element and Sr-Nd-Hf isotope data for the Ventersdorp mafic lavas to better constrain their mantle sources and petrogenetic evolution, and to test the possible connection between the Kaapvaal and Pilbara cratons in the so-called "Vaalbara" supercontinent. The processes responsible for the chemical and isotopic diversity of Ventersdorp mafic lavas were dominated by partial melting of heterogeneous mantle sources. Fractional crystallization and crustal assimilation processes were minor to absent. Picrites and komatiites of the basal Westonaria Formation were produced at ~2.78 Ga by large degree partial melting of a peridotitic depleted sublithospheric mantle source, likely in a hot plume head, as it impinged upon and flattened beneath the subcontinental lithospheric mantle of the Kaapvaal Craton. Relatively evolved basalts of the overlying Alberton Formation formed by smaller degrees of partial melting, possibly sourced in the pyroxenitic or eclogitic, lower temperature, outer regions of a temperature- and compositionally zoned mantle plume. These external regions may represent deeply subducted oceanic lithosphere that was entrained by an ascending plume and that imparted negative Nb and Ta anomalies to the derivative magmas. Progressively more primitive lavas are found stratigraphically upwards, in the Orkney, Jeanette and Loraine-Edenville Formations (Fig. 15), recording successively larger involvement of depleted sublithospheric mantle, while still maintaining a subduction-modified signature. Uplift and erosion must have taken place before the eruption of basaltic lavas of the Platberg Group at ~2.72 Ga. Volume estimates for mafic lavas of the Platberg Group and Allanridge Formations suggest that they represent products of melting in outer portions or the tail of the plume. Dacites and rhyolites of the Platberg Group were generated by partial melting in the continental crust due to heating by ascending mafic magmas. Another interval of uplift and erosion took place between the eruption of Rietgat lavas and the sedimentation of Bothaville rocks and eruption of Allanridge basalts at ~2.68 Ga. Our new Nd isotopic data coupled with lithostratigraphic differences indicate that correlations between the Ventersdorp (South Africa) and Fortescue (Australia) sequences are more complex than is currently understood, reflecting differences in basin structure and evolution; more data are needed to constrain the Vaalbara hypothesis.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.earscirev.2024.104752.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availabilityAll new geochemical and isotopic data for this paper are given in Supplementary Tables 3 and 4. In addition, we have compiled a comprehensive database of nearly 2400 Ventersdorp magmatic rocks (available upon request from Lewis.Ashwal@wits.ac.za or Ben.Hayes@wits.ac.za) from the following sources: Georoc database (https://georoc.eu/), published papers and unpublished post-graduate theses. Information for the 602 boreholes used to determine minimum areal extents of Ventersdorp units, including generalized stratigraphic logs is given in Supplementary Table 1.

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