The Precambrian Mafic Magmatic Record, Including Large Igneous Provinces of the Kalahari Craton and Its Constituents: A Paleogeographic Review

M. O. de Kock, A. P. Gumsley, M. B. Klausen, U. Söderlund and C. Djeutchou

Abstract The study of Precambrian dyke swarms, sill provinces and large igneous provinces on the Kalahari craton in southern Africa has expanded greatly since the pioneering work initiated almost four decades ago. The main contributors to this progress have been a large number of precise U–Pb crystallization ages of mafic rocks, published in a number of recent papers. This information is compiled here into a series of maps that provide a nearly 3 billion year intraplate magmatic record of the Kalahari craton and its earlier constituents, the proto-Kalahari, Kaapvaal and Zimbabwe cratons. We also review their possible paleogeographic relations to other cratons or supercontinents. This review provides a more accessible overview of individual magmatic events, and mostly includes precise U–Pb ages of mafic dykes and sills, some of which can be linked to stratigraphically well-constrained volcanic rocks. The extrusion ages of these volcanic units are also starting to be refined by, among others, in situ dating of baddeleyite. Some mafic dyke swarms, previously characterized entirely on similarity in dyke trends within a swarm, are found to be temporally composite and sometimes consist of up to three different generations. Other mafic dyke swarms, with different trends, can now be linked to protracted volcanic events like the stratigraphically well preserved Mesoarchean Nsuze Group (Pongola Supergroup) and Neoarchean Ventersdorp Supergroup. Following upon these Archean events, shorter-lived Proterozoic large igneous provinces also intrude the Transvaal Supergroup, Olifantshoek Supergroup and Umkondo Group,

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and include the world's largest layered intrusion, the Bushveld Complex. Longer-lived late Paleoproterozoic magmatic events are also preserved as mafic intrusions and lava units within the Waterberg and Soutpansberg groups as well as the granitic basement. Many gaps in our knowledge of the Precambrian mafic record of the Kalahari craton remain, but further multi-disciplinary studies combining the latest advances in U–Pb geochronology and both paleomagnetism and geochemistry will help solve the Precambrian paleogeographic puzzle.

1 Introduction

The recognition of intraplate igneous events, and especially large igneous provinces (LIPs), has increased dramatically in recent years and offer key temporal and spatial constraints for creating paleogeographic reconstructions back into Precambrian time. Such studies rely mainly on mafic volcanic rocks and their feeder systems, which are preserved in Precambrian terranes as regional mafic sill provinces and dyke swarms, as well as mafic-ultramafic layered intrusions.

Dyke swarms are defined as groups of dykes of similar age that may form linear, radiating or arcuate arrays (Ernst et al. 1995). It is important to note that dyke swarms of different ages—yet without other apparent petrographical or compositional differences—may have overlapping patterns that can only be separated on the basis of precise age constraints. The adjective "giant" can be added if swarms are longer than 300 km (Ernst et al. 1995). However, some smaller individual dyke swarm fragments may be part of "giant" swarms, when properly restored (or chronologically matched) together with other craton fragments (e.g., Bleeker and Ernst 2006). For this reason we avoid using the adjective "giant" in this contribution. Sill provinces are less rigorously defined into lesser and greater types and are herein simply regarded as any collection of coeval sills that share a similar stratigraphic host unit, and is confined within a certain geographical extent.

Numerous mafic dyke swarms and sill provinces cross-cut the Precambrian terranes of southern Africa, and many of these intrusions are only recently constrained as syn-magmatic with volcanic units preserved within remnants of supracrustal volcano-sedimentary successions. Many of these magmatic events form integral parts of recognized LIPs; whereas other events have not yet been linked to a specific LIP. However, apart from some pioneering regional studies (e.g., McElhinny and Opdyke 1964; Jones and McElhinny 1966; Hunter and Reid 1987; Wilson et al. 1987; Uken and Watkeys 1997), the Precambrian dyke swarms and sill provinces across southern Africa received little scientific attention before the early part of the twenty-first century. McElhinny and Opdyke (1964) were the first to show that there were two major Proterozoic sill provinces on the Zimbabwe craton of distinctly different ages, based on paleomagnetic signatures. The follow up work of Jones and McElhinny (1966) is one of the first examples of the use of paleomagnetism for correlating isolated occurrences of mafic units over large distances. Hunter and Reid (1987) and Wilson et al. (1987) began to characterize and group mafic dykes across southern Africa into different swarms. The identification of these swarms was primarily based on observable trends, degrees of deformation and metamorphism, and lithology. Ages were mostly based upon cross-cutting relationships, paleomagnetism and a limited number of K–Ar mineral and whole-rock as well as Rb–Sr whole-rock ages. Some swarms were tentatively linked to igneous units with better temporal constraints, including volcanic units, sills, and even larger layered intrusions. Uken and Watkeys (1997) advanced these early observations by interpreting the dyke swarm trends in terms of prominent structural lineaments, associating them more specifically with continental 'rifts' during the extrusion and deposition of various known volcano-clastic successions in the supracrustal record. With an increased development of analytical techniques employed for U–Pb geochronology, both on igneous zircon, and especially baddeleyite crystals (Krogh 1973; Heaman and LeCheminant 1993), and improved separation techniques for these minerals (Söderlund and Johansson 2002), the study of mafic dykes and sills in southern Africa has increased substantially; sometimes with far-reaching implications. In this review, we aim to highlight these recent advances in our knowledge of mafic magmatism across southern Africa and through Precambrian times, and thereby try to simplify what may otherwise be regarded as a complex spatial and temporal array of mainly subalkaline mafic lavas, sills, dykes and larger intrusions. In addition, some attention is given to relatively low-volume kimberlites, carbonatites and other alkaline igneous complexes, as these may also represent intraplate mafic magmatism that can be part of LIPs (e.g., Ernst 2014); albeit, often representing magmas derived through much lower degrees of partial mantle melting. Brief mention is also made of felsic igneous units that form part of some identified LIP or magmatic event. This review, however, focuses primarily on the precise U–Pb dates obtained directly from mafic units in recent years. Dates discussed in this contribution are U–Pb dates obtained during recent years, derived directly from igneous zircons and baddeleyites within mafic intrusions unless stated otherwise. It is acknowledged that this review could be complimented by an existing rich geochronological database based on several other isotopic systems, techniques and minerals from a range of other rock types, including igneous ages of granitic rocks and tuffaceous units, as well as detrital zircon studies of sedimentary cover successions that can be associated with a mafic magmatic event. A complete discussion of such a larger database is, however, beyond the scope of this contribution. Where no robust age data is available directly from a mafic unit, we do speculate about possible age assignments based on other isotopic systems (e.g., Rb–Sr or noble gas constraints).

The ultimate goal of this focused review is strictly to provide an updated overview of Precambrian mafic magmatic events across southern Africa, and thereby possibly group or subdivide these into lesser or greater events of shorter or longer durations. This naturally provide some new constraints on the architecture, modes of emplacement and magma petrogenesis within paleogeographic reconstructions that may ultimately shed more light on tectonic settings. We only make superficial reference to the geochemistry and petrology of these mafic magmatic events, however, unless composition may be used to further distinguish between different, yet spatially and structurally overlapping events. Instead, we aim to identify questions that remain to be resolved on (1) the paleogeographic and magmatic barcode record of southern Africa's Precambrian crustal blocks, back through time, (2) how these events were emplaced, and (3) which of these events classify as LIPs.

2 Crustal Architecture of Southern Africa

The Kalahari craton of southern Africa (originally defined by Clifford 1970) is a mosaic of crustal terranes of varying age. It is principally made up of a composite Archean core, which consists of the Kaapvaal and Zimbabwe cratons joined along the Limpopo Metamorphic Complex (Fig. 1). Along the western margin of this Archean Kaapvaal-Zimbabwe core there are progressively younger Paleoproterozoic accreted terranes and fold-and-thrust belts (i.e., the Kheis orogen, Magondi orogen, Okwa terrane, and Rehoboth terrane), which collectively make up the so-called proto-Kalahari craton. The proto-Kalahari craton is in turn surrounded by an accreted Mesoproterozoic rim, inclusing the Namaqua-Natal orogen, and the Konkiep and Choma Kaloma terranes. We in this context follow the definition of Hartnady et al. (1985), in which the Kalahari craton is constituted by the proto-Kalahari craton and its Mesoproterozoic rim. In addition, paleomagnetic data indicates that the Kaapvaal craton was likely contiguous with the Archean Grunehogna terrane, and associated Mesoproterozoic Maud orogen, of East Antarctica, at least during Mesoproterozoic to Phanerozoic times (e.g., Jones et al. 2003). Grunehogna, as well as the Mesoproterozoic basement of the Falkland Islands, and the Mesoproterozoic Haag Nunatak are therefore also considered a part of the Kalahari craton, but separated from their southern African counterparts during and since the break-up of Gondwana (Jacobs et al. 2008). Much of the focus of this review is on the Archean-Paleoproterozoic proto-Kalahari craton, however, and this is not intentional, but rather a combined artifact of preservation, outcrop, and accessibility of the involved terranes. Much of the western and southern margins of the Kalahari craton is, for example, covered by younger Phanerozoic (mainly Karoo Supergroup) rock successions and unconsolidated Quaternary (mainly Kalahari Group) sands, respectively; whereas, much older host rocks are remarkably well exposed within the Kaapvaal and Zimbabwe craton cores.

The Kaapvaal craton of South Africa, Botswana and Swaziland (Fig. 1) can be subdivided into separate structural domains that generally young towards the north and west (e.g., De Wit et al. 1992; Eglington and Armstrong 2004). The southeastern Swaziland block includes the oldest recorded basement rocks of the Kaapvaal craton, which probably merged with the Witwatersrand block along the Barberton greenstone belt. The 3.3–2.8 Ga Pietersburg block constitutes the northern part of the Kaapvaal craton, north of the prominent Thabazimbi-Murchison lineament (TML; Laurent et al. 2013). The east- to northeast trending and 3.6–2.8 Ga old basement structures of the Swaziland, Witwatersrand, and Pietersburg blocks are truncated by more north-trending structures of the 3.0 Ga Kimberley block in the west (De Wit et al. 1992; Tinker et al. 2002; Eglington and Armstrong 2004). Granitoid emplacement between 2.93 and 2.88 Ga places a minimum age constraint on this amalgamation

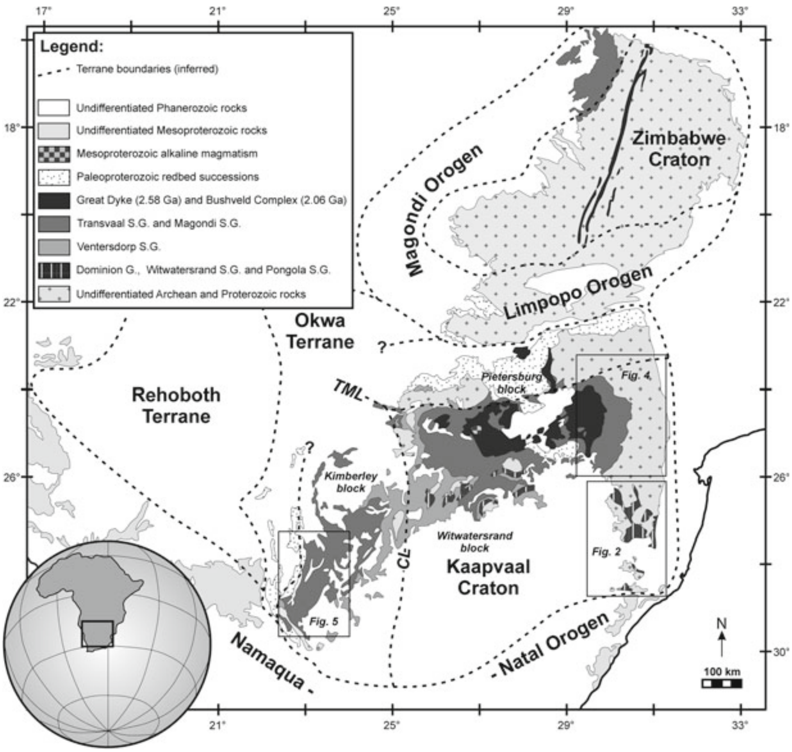

Fig. 1 Generalized Precambrian geology of the Kalahari craton of southern Africa after Hammerbeck and Allcock (1985) The Kalahari craton is made up of the Kaapvaal and Zimbabwe cratons with the intervening Limpopo Metamorphic Complex (LMC), as well as younger Proterozoic terranes and orogens to the west (e.g., the Rehoboth terrane). The Witwatersrand, Kimberley and Pietersburg blocks constitute the Kaapvaal craton, and these blocks are separated by the prominent Colesberg and Thabazimbi-Murchison lineaments (i.e., the CL and TML)

along the Colesberg lineament (CL; Mapeo et al. 2004a; Schmitz et al. 2004). Final stabilization of the Kaapvaal craton occurred with the intrusion of late-stage granites at about 2.7 Ga (Eglington and Armstrong 2004). The Zimbabwe craton borders the northern margin of the Kaapvaal craton (Fig. 1) along an intervening LMC, which is a polymetamorphic belt that experienced high-grade metamorphism between 2.7 and 2.6 Ga, and again at approximately 2.0 Ga (e.g., Kramers and Mouri 2011). The second episode of metamorphism and deformation is thought by some (e.g., Schaller et al. 1999; Söderlund et al. 2010) to represent the transpressive docking of the Zimbabwe and Kaapvaal cratons to form the Archean-Paleoproterozoic nucleus of the proto-Kalahari craton. Hanson et al. (2011b) have even argued for a final docking after 1.88 Ga. However, the idea that the LMC is mainly the product of continent-

continent collision between 2.7 and 2.6 Ga (e.g., Roering et al. 1992; Kramers et al. 2011) is the more widely accepted interpretation at present.

The Zimbabwe craton, which occurs mostly in Zimbabwe (Fig. 1), probably formed during two episodes of crustal growth between 3.8 and 3.2 Ga, with a voluminous and protracted third episode occurring between 3.0 and 2.6 Ga representing its final cratonization (Wilson et al. 1995). The 2.0 Ga Magondi orogen wraps around the western margin of the Zimbabwe craton, and separates it from the Rehoboth terrane further to the west in Botswana (Treloar 1988; Majaule et al. 2001; McCourt et al. 2001). The ca. 1.78 Ga Rehoboth terrane is a geophysically distinct but otherwise poorly exposed entity (Jacobs et al. 2008).

The Kheis orogen (Fig. 1) along the western margin of the Kaapvaal craton records post 1.9 Ga accretion of the Rehoboth terrane and crustal shortening (Moen 1999), during the amalgamation of parts of the proto-Kalahari craton into the Nuna/Columbia supercontinent. The Kheis orogen has been correlated with the Magondi orogen (Master 1991), but these two orogens are structurally separated by a poorly exposed, but geophysically distinct Paleoproterozoic Okwa terrane (Fig. 1). Farther to the southwest of the Rehoboth terrane the 2.0–1.7 Ga Richtersveld terrane was an allochtonous microcontinent that accreted along a late Mesoproterozoic Namaqua-Natal orogeny, around the southern half of the proto-Kalahari craton (Jacobs et al. 2008). This crustal growth is discussed in detail by Jacobs et al. (2008), and it records the proto-Kalahari craton's involvement in the assembly and ultimate amalgamation of the Rodinia Supercontinent. Between 1.2 and 1.0 Ga, syn-orogenic volcano-sedimentary successions were deposited along these active northwestern (e.g., Hanson et al. 2006), southern and eastern margins of the proto-Kalahari craton, culminating in continent-continent or continent-island arc collisions, which formed the Namaqua-Natal orogen that can be traced via the Falkland Islands, Haag nunatak and Maud orogen in paleogeographic reconstructions of Gondwanaland (Robb et al. 1999; Thomas et al. 2000; Jacobs et al. 2008).

3 Catalogue of (Mostly Mafic) Intraplate Magmatic Events

The Precambrian mafic dyke swarm and sill province record of the exposed eastern Kaapvaal craton and that of the exposed Zimbabwe craton are more apparent than the record of the more poorly exposed central and western Kaapvaal craton, as well as the remainder of the proto-Kalahari craton. The latter largely due to Archean to Paleoproterozoic volcano-sedimentary cover successions across the central and western Kaapvaal craton, as well as younger Phanerozoic Karoo Supergroup and post-Karoo cover (including the Quaternary sands of the Kalahari desert) across other parts. Geophysical constraints, scarce outcrops and drill core intersections provide most of the record for these more peripheral parts of the Kalahari craton outside of its Archean-Proterozoic crustal core. The Zimbabwe craton is essentially stripped of its supracrustal cover successions, making darker mafic dykes and sills more prominently exposed against the paler granitic basement.

Mafic dykes have only been sporadically mapped throughout southern Africa in the past, and traditionally been subdivided into more pristine "dolerite dykes" or metamorphosed "diabase dykes", tentatively assigning these to the Jurassic Karoo LIP or older (Precambrian) magmatic events, respectively. We use the more neutral, but less specific term "mafic" in this review's coverage of the Precambrian intrusions.

Since the latter half of the twentieth century, a large number of geochronological studies have improved upon our understanding of the different mafic dyke swarms and sill provinces across southern Africa. As an introduction to a systematic catalogue of mafic magmatic events presented here, it can be stated that the first major mafic igneous event following cratonic stabilization of the Zimbabwe craton was the intrusion of the Great Dyke and its satellites at 2.58–2.57 Ga (e.g., Wingate 2000). On the Kaapvaal craton, the oldest well-dated major mafic igneous event following initial cratonization formed the 2.99–2.98 Ga Usushwana Complex and associated 2.98–2.97 Ga Badplaas mafic dyke swarm (Olsson et al. 2010; Gumsley et al. 2015). Only from ca. 1.88 Ga onwards does the Kaapvaal and Zimbabwe cratons share igneous rocks derived from common magmatic events (Söderlund et al. 2010), like the Umkondo and Karoo LIPs (e.g., Erlank 1984; Hanson et al. 2004a) and coeval Waterberg-hosted and Mashonaland sill provinces (e.g., Hanson et al. 2011b). In the following, we review our current understanding of mafic magmatic events that formed within apparently more coherent episodes of the (1) Mesoarchean, (2) Neoarchean, (3) late Neoarchean to early Paleoproterozoic, (4) the middle Paleoproterozoic Bushveld Complex, (5) late Paleoproterozoic, (6) early Mesoproterozoic, (8) the late Mesoproterozoic Umkondo LIP, and, finally, (9) the Neoproterozoic.

3.1 Mesoarchean Mafic Magmatism Within the Witwatersrand-Pongola Basins

Following initial 3.1 Ga stabilization of the Witwatersrand block a bimodal volcanic pile of basalts and rhyolites of the Dominion Group (Marsh et al. 1989; Armstrong et al. 1991) erupted across its central part. The Dominion Group has been shown to be geochemically and stratigraphically similar to another bimodal volcanic pile within the south-eastern Swaziland block, known as the Nsuze Group of the Pongola Supergroup (e.g., Cole 1994; Gold 2006; Fig. 2). This is supported by the proposed stratigraphic correlation of the Pongola's Mozaan Group and the Witwatersrand Supergroup unconformably overlying the Dominion Group (Beukes and Cairncross 1991). However, the Nsuze Group has been dated to between 2985 and 2968 Ma (Hegner et al. 1994; Nhleko 2003; Mukasa et al. 2013), which is significantly younger than the available 3074 ± 6 Ma age for the Dominion Group (Armstrong et al. 1991). Even though the Witwatersrand Supergroup is predominantly sedimentary, its upper successions host the basaltic-andesitic Crown and Bird Member lavas (Fig. 2) that are stratigraphically comparable with the Mozaan Group's Tobolsk Formation and

Gabela Formation lavas, and where an age of 2914 ± 8 Ma has been determined for the Crown Member (Armstrong et al. 1991).

Uken and Watkeys (1997) first noted that the Nsuze Group is broadly coeval to mafic dykes within a 80 km wide, >100 km long southeast-trending swarm across the southeastern Kaapvaal craton, called the Badplaas dyke swarm by Olsson et al. (2010). Many of the dykes within this swarm were presumed to be of Archean age (Hunter and Reid 1987) based on cross-cutting relations to ca. 3.1 Ga granitoid batholiths in the region of the Barberton Greenstone Belt. None of these dykes appear to intrude the Neoarchean to Paleoproterozoic Transvaal Supergroup and many terminate against the ca. 2.7 Ga Mbabane granitoid batholith (Layer et al. 1989). Geochronological studies show that the Badplaas dyke swarm consists of at least two sub-parallel dyke generations. The two generations have been dated at 2980 ± 1 Ma and 2967–2966 Ma (Olsson et al. 2010; Gumsley et al. 2015).

The two main dyke-like limbs of the Mesoarchean Usushwana Complex—crossing the border between South Africa and Swaziland—conspicuously follow the same southeast trend as the Badplaas dyke swarm (Fig. 2). The Complex is a layered intrusion composed of both gabbro (Piet Retief Suite) and granophyre (Hlelo Suite), which both reportedly formed at ca. 2860 Ma (Hunter and Reid 1987). Using the same ID-TIMS dating methodology, however, Gumsley et al. (2015) showed that the mafic Piet Retief Suite of the Usushwana Complex is broadly coeval with the older (2990–2978 Ma) Nsuze Group and the ca. 2980 Ma generation of the Badplaas dyke swarm. Thus, the Piet Retief Suite of the Usushwana Complex and southeast-trending mafic dykes were likely part of a protracted event, which, in turn, are coeval with, and likely fed the 2985–2977 Ma Nhlebela Formation (also known as the Pypklipberg Formation; Fig. 2) lavas of the lower Nsuze Group (Hegner et al. 1994; Nhleko 2003; Mukasa et al. 2013; Gumsley et al. 2015). The other overlapping younger generation of sub-parallel dykes likely fed the 2968–2966 Ma Agatha Formation lavas of the upper Nsuze Group (Fig. 2). Paleomagnetic studies on the ca. 2980 Ma and 2967–2966 Ma Badplaas dyke swarm also link the dykes to the Nsuze Group lavas (Lubnina et al. 2010; Maré and Fourie 2012). Klausen et al. (2010), furthermore, found that coeval dykes and lavas roughly share similar basaltic andesite compositions (with clac-alkaline affinities) and incompatible element signatures.

Mafic sills dated at 2874–2866 Ma by U–Pb on baddeleyite using ID-TIMS (Gumsley et al. 2013, 2015) intrude the Pongola Supergroup, south of Swaziland in South Africa. This includes the layered mafic-ultramafic 2866 ± 2 Ma Hlagothi Complex near the base of the Nsuze Group (Gumsley et al. 2013), as well as potentially the layered mafic-ultramafic Thole Suite. Mafic sills of this age generation are pervasive throughout the Mozaan Group (Fig. 2), and may be coeval with the mentioned Tobolsk and Gabela Formation lavas within in the upper Pongola Supergroup, as well as Crown and Bird Member lavas within the Witwatersrand Supergroup (Beukes and Cairncross 1991; Gumsley et al. 2013); all of which are of basaltic to more evolved andesitic or even dacitic compositions. The Hlelo Suite granophyres of the Usushwana Complex may also relate to the same 2.86 Ga event, although further U–Pb geochronology is needed to confirm its 2860 ± 26 Ma whole-rock Pb–Pb date by Walraven and Pape (1994). The dacitic to rhyolitic volcanic rocks and granophyre of

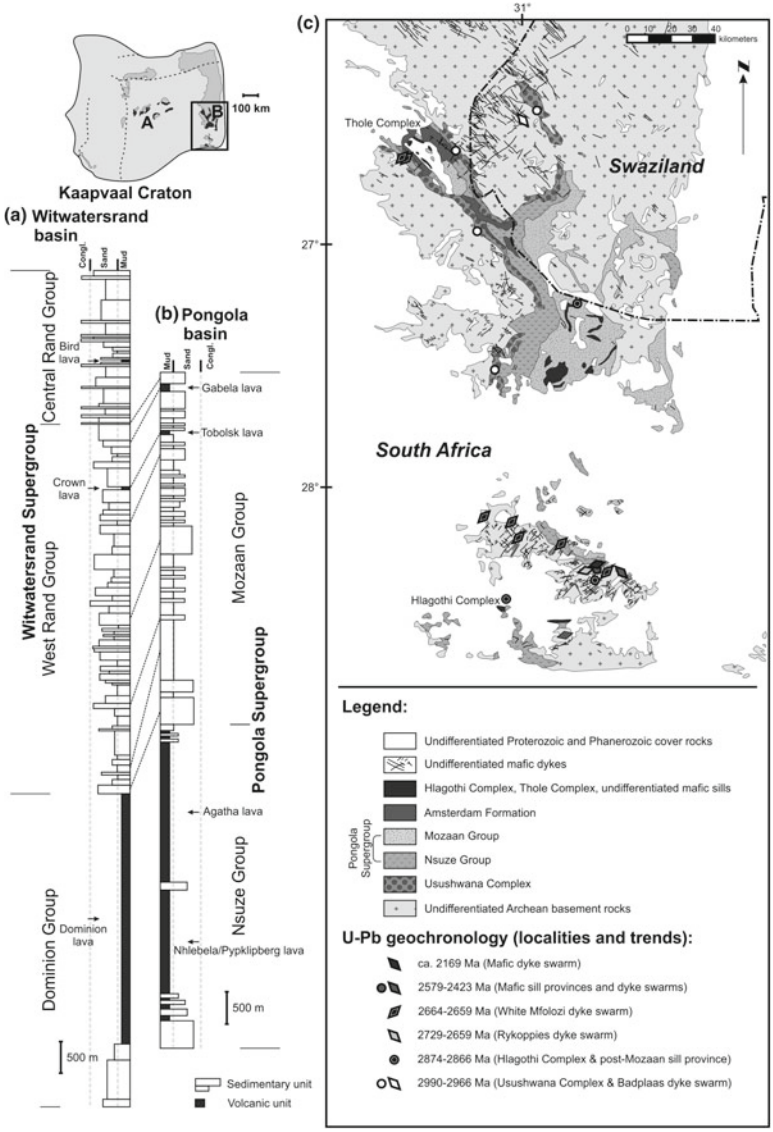

Fig. 2 Generalized lithological succession and correlation of the Witwatersrand basin (**a**) and the Pongola basin (**b**). **c** Geology and mafic dykes of the southeastern Kaapvaal craton. Unless stated otherwise, all maps in this and subsequent map figures are extracted from the Council of Geosciences' electronic 1:1,000,000 ArcGIS geology map of South Africa; whereas, dyke swarms, were digitized and added from a large number georeferenced 1:250,000 geological maps of the Republic of South Africa (Council of Geoscience). Geochronology symbols: diamonds = dated dyke and its trend; circles = dated sill, sheet, or plutonic body

the Amsterdam Formation, outcropping within the central parts of a major Pongola Supergroup (Gold 2006) syncline may also be related to this magmatic event, but have not yet been dated.

The Nsuze Group, as well as the Badplaas dyke swarm and Usushwana Complex is generally regarded as being emplaced within the oldest known continental rift (e.g., Burke et al. 1985). Many authors (Hunter and Reid 1987; Klausen et al. 2010; Gumsley et al. 2015) have tentatively suggested the involvement of a mantle plume for all three events (i.e., 2990–2978, 2968–2966 Ma, and the 2874–2866 Ma), typically centered at the southeastern end of the Badplaas dyke swarm and near the current margin of the Kaapvaal craton. However, there are few constraints on the tectonic setting for this rift, and even less conclusive evidence in support of any plume involvement. Coeval granites are associated with volcanism within the Nsuze Group, and include the 2973–2960 Ma Hlatikulu and 2981–2961 Ma Nhlangano plutons (Mukasa et al. 2013; Hofmann et al. 2015). However, these granitoids are difficult to relate to any orogenic event, and might rather reflect increased regional crustal anataxis during a period of anomalously high mantle melting (e.g., Hofmann et al. 2015).

3.2 Long-Lived Neoarchean Magmatism

After an apparent quiescence in mafic magmatism, crossing into the Neoarchean, volcanism resumed toward the central and northwestern parts of the Kaapvaal craton, as evidenced by the Ventersdorp Supergroup and associated groups and formations within related coeval sub-basins (Van der Westhuizen et al. 1991, 2006).

The oldest ages for compositionally bimodal volcanic rocks, associated with the Ventersdorp Supergroup, are determined for the Derdepoort Formation of northwestern South Africa as well as the bimodal volcanic rocks of the Lobatse Group and Kanye Formation, of Botswana all dated to approximately 2785–2781 Ma (Grobler and Walraven 1993; Moore et al. 1993; Walraven et al. 1996; Wingate 1998). An associated 2.78 Ga mafic dyke swarm has not yet been identified (Fig. 3), but these volcanic rocks are broadly coeval with both mafic and felsic plutons (e.g., the Modipe gabbro, Gabarone and Turfloop granites; Moore et al. 1993; Henderson et al. 2000; Denyszyn et al. 2013).

The Ventersdorp Supergroup conformably overlies the Witwatersrand Supergroup in the central part of the Kaapvaal craton (along the gold-rich and so-called Ventersdorp Contact Reef), but this contact becomes more unconformable towards the west. An up to 3 km-thick pile of flood basalts—overlying some basal conglomerate breccia and other clastic horizons interbedded by komatiitic lavas—dominate the Klipriviersberg Group of the lower Ventersdorp Supergroup. The Klipriviersberg Group is unconformably overlain by compositionally bimodal volcanic rocks and sedimentary successions of the Platberg Group, which, in turn is unconformably overlain by the clastic Bothaville Formation and overlying, predominantly basaltic andesite lavas of the Allanridge Formation (Van der Westhuizen et al. 1991). So-called proto-basinal

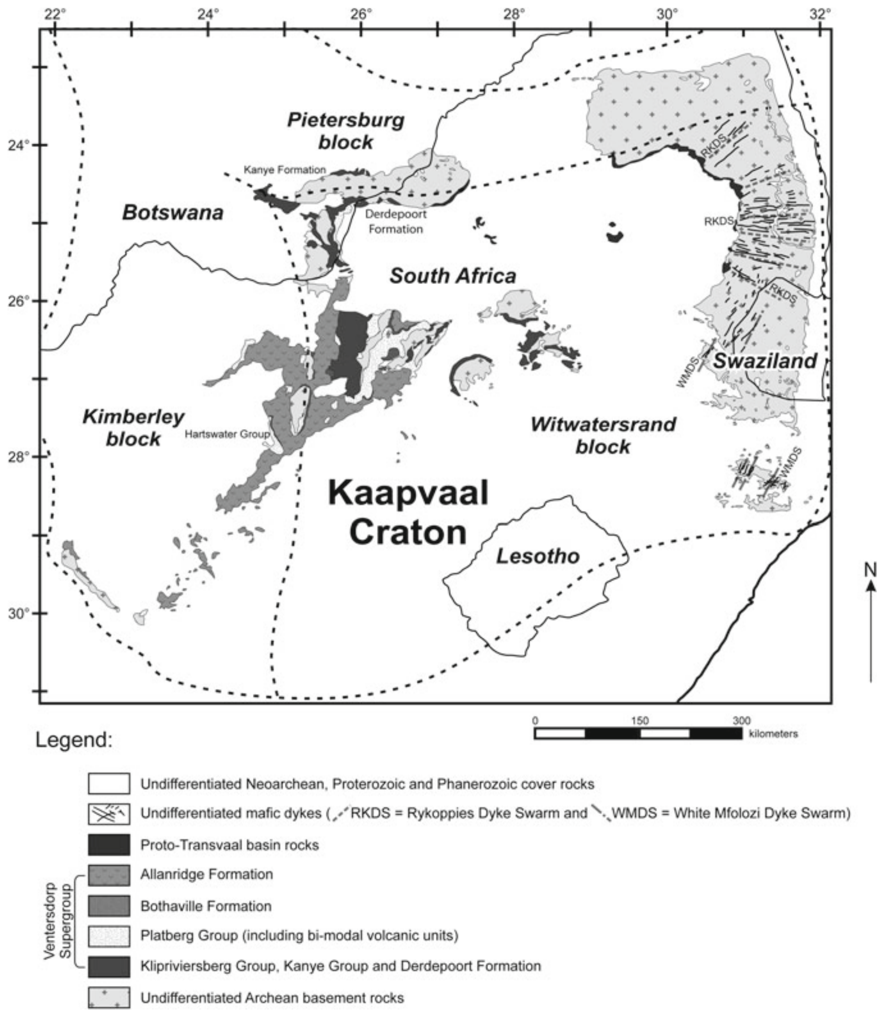

Fig. 3 Distribution of the Ventersdorp Supergroup and equivalent rock units on the Kaapvaal craton, as well as the prominent Neoarchean mafic dyke swarms of the eastern Kaapvaal craton (i.e., the radiating Rykoppies and the northeast-trending White Mfolozi swarms). Compiled as in Fig. 2

volcanic and sedimentary rocks (i.e., the Buffelsfontein Group, Godwan Formation and Wolkberg Group) were deposited unconformably on top of granite-greenstone basement, presumably during or after the Allanridge Formation lavas, forming the base of the Neoarchean-Paleoproterozoic Transvaal Supergroup, with the Buffelsfontein Group having been dated by Barton et al. (1995) to 2664 ± 1 Ma.

The Ventersdorp Supergroup and the proto-basinal rocks are generally thought to have been deposited within a relatively short time interval, between 2714 and 2664 Ma (Armstrong et al. 1991; Barton et al. 1995), but this has recently been questioned by older 2746 ± 9 Ma and 2720 ± 2 Ma ages for the Platberg Group (Cornell et al. 2018). These new ages, however, are in agreement with crystallization ages determined from Platberg Group correlatives such as the 2714 ± 3 Ma felsic Zoetlief Group (Walraven et al. 1991), the 2729 ± 3 Ma felsic Amalia Group (Poujol et al. 2005), the 2733–2724 Ma bimodal Hartswater Group (De Kock et al. 2012), and 2739 ± 39 Ma bimodal Sodium Group (Altermann and Lenhardt 2012)—see Fig. 3. These ages put a maximum age limit to the overlying Allanridge Formation (capping the Ventersdorp Supergroup), which has not yet been dated. Of greater implications, the Klipriviersberg Group must be older than the previously accepted 2714 Ma age by Armstrong et al. (1991). Wingate (1998) highlighted possible lead loss affecting the 2714 Ma date of Armstrong et al. (1991) and regarded it as a minimum age constraint for the Klipriviersberg Group. De Kock et al. (2012) suggested that the Klipriviersberg Group is perhaps better correlated with 2.78 Ga volcanic and magmatic units in the northwest of the craton, such as the 2782 ± 5 Ma Derdepoort Formation. It is interesting to note that Cornell et al. (2018) reports a 2781 ± 5 Ma date from a basaltic unit intersected in drill core near Kimberley that is usually assigned to the Platberg Group. This older sample more likely represents a correlative of the volcanics of the 2.78 Ga Derdepoort Formation and possibly the Klipriviersberg Group.

The development of the Platberg Group is broadly coeval with ca. 2.72 Ga felsic magmatism on the southeastern Kaapvaal craton (e.g., the Hlathikulu and Kwetta plutons; Mukasa et al. 2013). Although only observed in sub-outcrop mapping from mines and drill core, mafic dykes and sills have been documented within the Witwatersrand Supergroup, and have been geochemically linked to the overlying Klipriviersberg Group basalts in the central Kaapvaal craton (Meier et al. 2009). The age of the Allanridge Formation flood basalts remains unknown, but is bracketed by the extrusion of the 2720 ± 2 Ma quartz porphyries of the Platberg Group (Armstrong et al. 1991; Cornell et al. 2018) and the eruption of volcanic rocks preserved within the proto-basinal fill sequences at ca. 2664 Ma (Barton et al. 1995). The Ventersdorp Supergroup thus likely presents two pulses of continental flood basalt eruption at 2.78 and 2.70 Ga separated by a long intervening period of rift related bimodal volcanism and sedimentation.

Across the better exposed Archean granitoid-greenstone basement part of the Kaapvaal craton, a dominantly east-trending Rykoppies mafic dyke swarm radiates out eastward from beneath the Bushveld Complex and underlying Transvaal Supergroup (Olsson et al. 2010; Fig. 4). This dyke swarm was initially thought to be younger than the southeast-trending Badplaas dyke swarm, as several of the east-trending dykes cross-cut southeast-trending dykes (Hunter and Reid 1987; Uken and Watkeys 1997). Uken and Watkeys (1997) argued that these dykes are most likely of ca. 2.05 Ga Bushveld Complex age because they coincide conspicuously with the elongated outcrop of Bushveld's main eastern and western lobes and likely diverge into mafic sills within the Transvaal Supergroup. However, mafic dykes within this Rykoppies dyke swarm are now dated using ID-TIMS U–Pb on baddeleyite to between 2685 and 2683 Ma, and at 2662 ± 2 Ma (Olsson et al. 2010, 2011), consistent with the observation that these dykes do not intrude the Transvaal Supergroup. These often more andesitic dykes, with strong calc-alkaline affinities, commonly incorporate large quantities of partially digested country rock xenoliths (Klausen et al. 2010; Olsson et al. 2010) and have geochemical signatures that are best explained by the assimilation of large amounts of the tonalite-trondhjemite-granodiorite basement (Klausen et al. 2010; Gumsley et al. 2016). While Klausen et al. (2010) matched compositions of both Rykoppies dykes and Allanridge Formation lavas, geochemical signatures remain to be compared with more likely coeval proto-basinal volcanic rocks, for which there at present are no geochemical analysis including a significant number of trace elements.

Both to the north and south of the east-trending Rykoppies dyke swarm, broadly coeval dykes are found amongst a younger and the roughly parallel northeast-trending Black Hills dyke swarm (Sect. 3.6) and the southeast-trending Badplaas dyke swarm, respectively, which combine into a conspicuously radiating pattern (Olsson et al. 2010, 2011). However, this radiating swarm is found to be made up of two distinct generations, clustering between 2701–2692 Ma and 2662–2659 Ma, which both occur on either side of the Rykoppies dyke swarm (Olsson et al. 2010, 2011). Regardless, the radiating nature of these dyke swarms led Olsson et al. (2011) to propose a coeval mantle plume (after Hatton 1995) to coincide with the convergence center of this radiating dyke swarm, and thereby offering an alternate hypothesis for the much later emplacement of the Bushveld Complex, as discussed in Sect. 3.5.

The protracted, extensive and complex Ventersdorp magmatic event is further accentuated by a ca. 2729 Ma mafic dyke, trending east across the southeasternmost margin of the Kaapvaal craton (Larsson 2015) as indicated on Fig. 2. This dyke is likely related to Ventersdorp Supergroup volcanism (e.g., Hartswater Group), albeit located almost 500 km away (Fig. 2). A northeast-trending White Mfolozi dyke swarm also cuts across the southeastern part of the Kaapvaal craton, in the northern KwaZulu-Natal and southeastern Mpumalanga provinces, and has been dated using U–Pb on baddeleyite by ID-TIMS, producing a combined weighted mean age of 2662 ± 2 Ma for the entire swarm (Gumsley et al. 2016). This ca. 2662 Ma age is near-coeval with the youngest dykes of the 2701–2659 Ma radiating Rykoppies dyke swarm, as well as ca. 2664 Ma proto-basinal volcanic rocks of the Transvaal Supergroup (Barton et al. 1995). However, the White Mfolozi mafic dyke swarm not only cuts across the Rykoppies radiating dyke swarm, but is also made up of distinctly different plagioclase megacrystic dykes, with more depleted geochemical signatures (Klausen et al. 2010; Gumsley et al. 2016). It should in this context be mentioned that the radiating Rykoppies dyke swarm, overall, exhibits a significant correlation between geochemical signatures and the terrain they are hosted within (although, not exactly the same terrains as defined by Eglington and Armstrong 2004), rather than dyke ages or trends (Gumsley et al. 2016). This suggests yet undefined lithospheric control on magma compositions.

Finally, within the Central Zone of the LMC, the deformed mafic Causeway and Stockford dykes yielded emplacement ages of 2607 ± 4 Ma and 2604 ± 6 Ma, and younger metamorphic ages at ca. 2.0 Ga using zircon analyzed for U–Pb Sensitive High-Resolution Ion Microprobe or SHRIMP geochronology (Xie et al. 2017). Xie et al. (2017) suggested that the ca. 2605 Ma dykes intruded after an earlier continent-

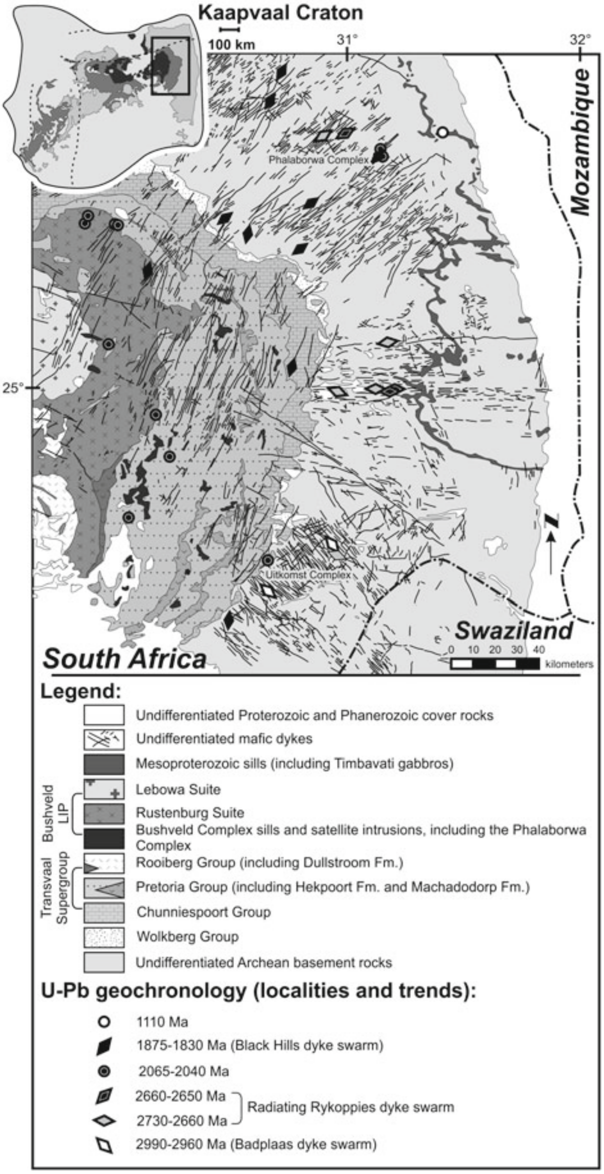

Fig. 4 Geological map emphasizing the distribution of mafic dykes across the eastern Kaapvaal craton. The affinity of undated northeast-trending dykes in the northwest of the mapped area and northwest-trending dykes to the north of the Badplaas dyke swarm remains to be confirmed. Compiled as in Fig. 2. Geochronology symbols: diamonds = dated dyke and its trend; circles = dated sill, sheet, or plutonic body

continent collision of the Zimbabwe and Kaapvaal cratons, during post-orogenic collapse and long before intracontinental transpressive deformation at 2.0 Ga.

3.3 Late Neoarchean to Early Paleoproterozoic Magmatic Events

Near the end of the Neoarchean, the Great Dyke of Zimbabwe is the first main mafic magmatic event following the stabilization of the Zimbabwe craton (Fig. 5). This 550 km-long, north to northeast-trending layered intrusion spans the entire craton (Wilson et al. 1987; Söderlund et al. 2010), and hosts world-class platinum-group element deposits. It was dated to 2574 ± 2 Ma using baddeleyite (Wingate 2000) and 2575 ± 1 Ma using zircon and rutile (Oberthür et al. 2002). Its sub-parallel East and Umvimeela satellite dykes have yielded near-coeval ages, with Söderlund et al. (2010) providing the first U–Pb ID-TIMS age on baddeleyite at 2575 ± 2 Ma for the Umvimeela dyke (Fig. 5).

U–Pb ID-TIMS baddeleyite ages of ca. 2580 Ma and ca. 2574 Ma are also reported for an east and a southeast-trending dyke, respectively, from the southeasternmost part of the Kaapvaal craton by Larsson (2015), which is broadly coeval with the Great Dyke and its satellite intrusions (Fig. 2). Granitoids of similar age have also been reported within the Vredefort Dome (Hart et al. 1999). However, these South African dykes and granitoids are located nearly 1500 km south of the Great Dyke of Zimbabwe, which, together with their very different compositions do not lend much support for any direct link between these events inside a coherent Kalahari craton at present.

Following upon the Great Dyke, the north to northeast-trending Sebanga mafic dykes constitute one of the most extensive swarms on the Zimbabwe craton (Fig. 5), being approximately 550 km wide and 350 km long (Wilson et al. 1987; Söderlund et al. 2010). These dykes were originally linked to the late Paleoproterozoic Mashonaland mafic sill province on the basis of similar paleomagnetic signatures (Jones et al. 1974). However, Söderlund et al. (2010) revealed much older ages within the swarm, spanning up to 100 Myr. The age of the most prominent Sebanga Poort dyke was determined by ID-TIMS on baddeleyite to 2408 ± 2 Ma (Söderlund et al. 2010), whereas the parallel-trending Crystal Springs dyke was dated to 2512 ± 2 Ma (Söderlund et al. 2010). In addition the Mtshingwe dyke, again of the same trend, was dated to 2470 ± 1 Ma (Söderlund et al. 2010). As no similar ages were at the time reported from the Kaapvaal craton, Söderlund et al. (2010) used this as further support for a later amalgamation of the Kaapvaal and Zimbabwe cratons along the ca. 2.0 Ga Central Zone of the LMC.

Unlike the Zimbabwe craton, and following upon the Ventersdorp Supergroup, proto-basinal volcanism and related intrusions, reviewed in Sect. 3.2, the Kaapvaal craton entered a period of relative magmatic quiescence until the eruption of the early Paleoproterozoic Ongeluk Formation basalts. The Kaapvaal craton preserves

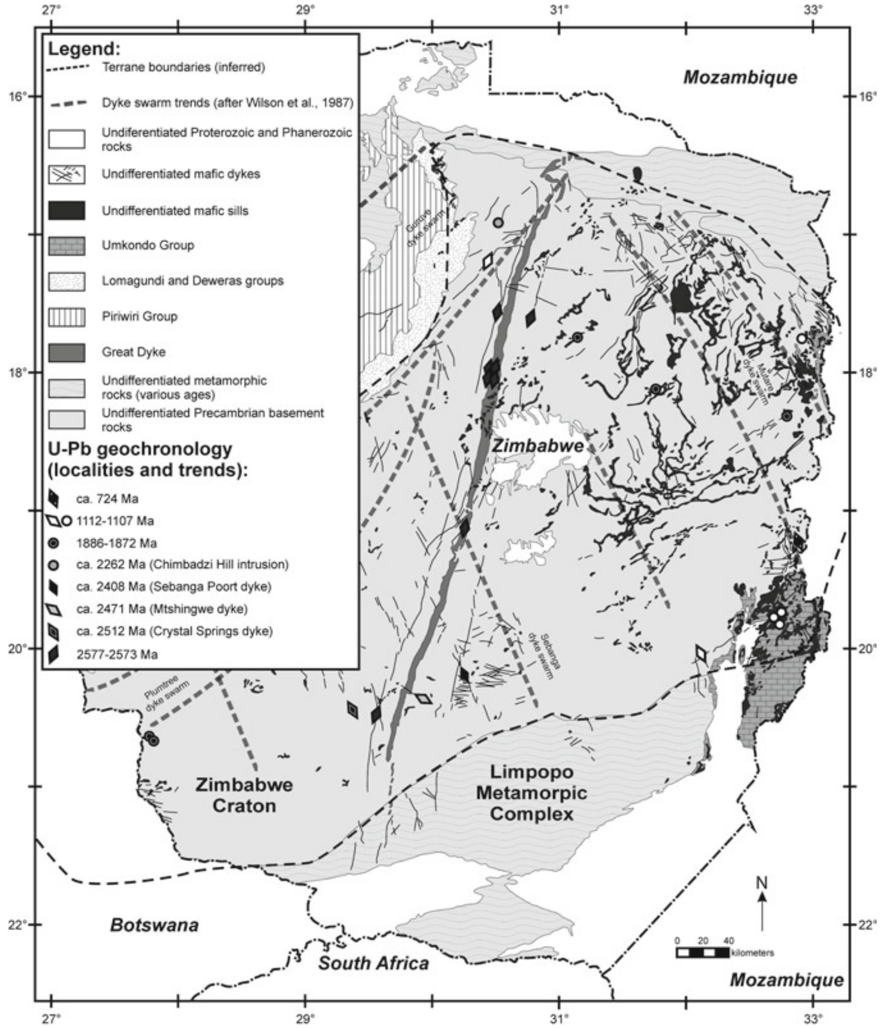

Fig. 5 The geology, including mafic dyke swarms and sills of the Zimbabwe, digitized from the 1:1,000,000 provisional geological map of Zimbabwe (1977) of the Zimbabwe Geological Survey. Note that although Botswana geology is not shown here, the Mashonaland sills extend across the border of Zimbabwe into Botswana. Geochronology symbols: diamonds = dated dyke and its trend; circles = dated sill, sheet, or plutonic body

a supracrustal record of being partly submerged during a major marine transgression, and records the deposition of shallower water carbonates and deeper water iron formations of the Transvaal Supergroup during the late Neoarchean (e.g., Eriksson et al. 2006). Subsequent uplift of the Kaapvaal craton, with accompanying glaciation, as testified by glacial diamictite of the Makganyene Formation of the Postmasburg Subgroup (Fig. 6), led to a deep erosional incision and a resulting unconformity across much of the craton as sea-levels fell. An exception is where the Makganyene Formation is preserved in the Griqualand-West sub-basin of the Transvaal Supergroup (e.g., Eriksson et al. 2006; Polteau et al. 2006). The 2426 ± 3 Ma Ongeluk Formation volcanic rocks erupted in close succession as sub-aqueous flood basalts on top of these diamictites (Cornell et al. 1996; Kampmann et al. 2015; Gumsley et al. 2017). These 2424 ± 24 Ma basalts (Gumsley et al. 2017) are coeval with the 2428–2426 Ma Westerberg sill province (Kampmann et al. 2015), and a 2423 ± 4 Ma north-trending mafic dyke along the western margin of the Kaapvaal craton (Gumsley et al. 2017; Fig. 6), where several other parallel dykes cluster (Fig. 6). The magmatic event also includes a ca. coeval 2423 Ma-old northeast dipping mafic sheet on the southeastern part of the Kaapvaal craton and almost 1000 km east of the Ongeluk Formation (Gumsley et al. 2017; Fig. 2). Finally, this recently discovered Ongeluk event on the Kaapvaal craton also falls within the protracted 2.51–2.41 Ga age-span of Zimbabwe's Sebanga dyke swarm, and thereby represents the first correlation of mafic magmatism on both cratons.

The Ongeluk Formation has previously been correlated stratigraphically with the compositionally similar Hekpoort Formation basaltic-andesites (Fig. 4), farther to the east within the main Transvaal sub-basin (e.g., Cornell et al. 1996; Eriksson et al. 2006). However, this correlation is now shown to be incorrect using the combined ID-TIMS and in situ secondary ion mass spectrometry (SIMS) age data on baddeleyite by Gumsley et al. (2017) and Kampmann et al. (2015) from the Ongeluk Formation and the Westerberg sill province. Detrital zircon population ages establish a likely minimum age of ≤2250–2240 Ma (Rasmussen et al. 2013; Schröder et al. 2016) for subaerial Hekpoort Formation volcanism, which also has a different paleomagnetic signature compared to the Ongeluk LIP (Evans et al. 1997; Gumsley et al. 2017; Humbert et al. 2017). Cornell et al. (1996) reported a Rb–Sr whole-rock age of ca. 2184 ± 76 Ma for the Hekpoort Formation, which is similar to a ca. 2168 Ma mafic dyke dated by Larsson (2015) using ID-TIMS on baddeleyite from the southeastern part of the Kaapvaal craton (Fig. 2). However, the large error bar on the Rb–Sr result and the possibility of open-system behavior in the Rb–Sr isotopic system does not presently allow a definite correlation between the two rock units.

Undated Bushy Bend Member andesitic lavas (Eriksson et al. 1994) underlie the Hekpoort Formation, but are of very limited extent, while higher up in the succession the undated volcanic rocks of the Machadodorp Member alkali basaltic and volcanoclastic rocks are more extensively exposed within the Transvaal Supergroup (cf., Fig. 4). Elsewhere in this volume, Wabo et al. (2019) report 2208–2276 Ma amphibole Ar–Ar ages for intrusions that east of the town of Mashising and close to the Transvaal-hosted Machadodorp Member. In Zimbabwe the Chimbadzi Hill intrusion yielded a U-Pb baddeleyite age of 2262 ± 2 Ma, but the extent of this Paleoporterozoic event is unkown as this is the only such reported age from that craton (Manyeruke et al. 2004).

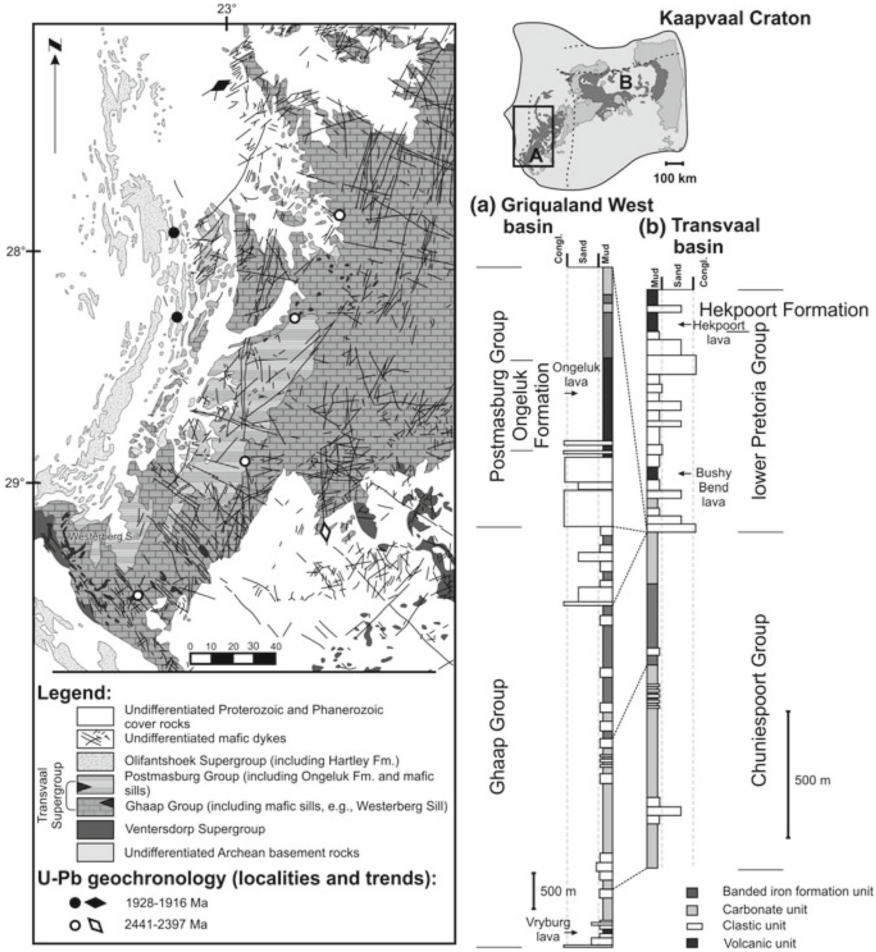

Fig. 6 Stratigraphic correlation between the **a** Griqualand West sub-basin and **b** the Transvaal sub-basin (after Gumsley et al. 2017). **c** Geology including mafic dyke swarms from the southwestern Kaapvaal craton. The affinity of southeast-trending dykes in the south of the mapped area, east-southeast-trending dykes in central and northern part of the mapped area, and north-northeast-trending dykes in the northern part of the mapped area remains to be determined. Compiled as in Fig. 2. Geochronology symbols: diamonds = dated dyke and its trend; circles = dated sill, sheet, or plutonic body

3.4 The Bushveld Complex and Associated Sills, Complexes and Volcanic Rocks

The Bushveld Complex was emplaced into the Kaapvaal craton closely following on from the intrusion of the alkaline and carbonatititic Phalaborwa Complex and Schiel Complex (Cawthorn et al. 2006; Fig. 4). The Phalaborwa Complex has U–Pb baddeleyite ages of ca. 2.06 Ga (e.g., Wu et al. 2011; and references therein). Walraven et al. (1992) report a Pb–Pb whole-rock errorchron date of 2059 ± 35 Ma for the Schiel Complex, but Barton et al. (1996) suggested that the complex is significantly youger. Barton et al. (1996) presented zircon dates for the Schiel Complex at 1853 ± 6 Ma and 2005 ± 7 Ma, the older population of dates being interpreted as xenocrystic. More recently Laurent and Zeh (2015) precisely dated zircon from rocks of Schiel Complex at 2054 ± 4 Ma and 2051 ± 6 Ma. The Phalaborwa Complex is broadly coeval with the ca. 2061 Ma bimodal volcanic Rooiberg Formation (Walraven 1997; Fig. 4), which partly underlies the most recognized part of the Bushveld Complex; namely, its layered ultramafic-mafic Rustenburg Layered Suite that hosts the world's largest deposits of platinum and chromium. The Bushveld Complex also incorporates the felsic Lebowa Suite (Cawthorn et al. 2006), many near-coeval satellite intrusions (e.g., De Waal et al. 2008), as well as numerous mafic sills mostly hosted in the Transvaal Supergroup (Cawthorn et al. 1981; Sharpe 1981, 1982). Cawthorn et al. (1981) identified these sills as having a pre-, syn-, or post-emplacement relationship with the Bushveld Complex based mostly on mineralogy and stratigraphic locations. The sills were geochemically characterized by Barnes et al. (2010); whereas, Wabo et al. (2015a) studied the sills geochemically and paleomagnetically, as well as presented two U–Pb ID-TIMS baddeleyite ages of ca. 2058 Ma (Fig. 4). These ages are broadly coeval with other satellite intrusions, including ca. 2058 Ma ages on both baddeleyites and zircons from the Uitkomst Complex (Wabo et al. 2015b; Maier et al. 2017); the ca. 2057 Ma Molopo Farms Complex (De Kock et al. 2016); and the ca. 2055 Ma Moshaneng Complex, Marble Hall diorite, Lindeques Drift intrusion and Roodekraal Complex (De Waal and Armstrong 2000; Mapeo et al. 2004b; De Waal et al. 2006; Fig. 7).

The Rustenburg Layered Suite is an up to 9 km thick layered sequence that arguably accumulated within an enormous lopolith (e.g., Cawthorn et al. 2006; Cole et al. 2014). Zeh et al. (2015) demonstrated with high-precision chemical abrasion ID-TIMS U–Pb zircon ages that the entire suite crystallized within less than 1 Myr from 2055.91 ± 0.26 Ma to 2054.89 ± 0.37 Ma. Additional high-precision U–Pb dating of zircons and baddeleyites support the rapid emplacement of the suite, where chromite layers may unexpectedly have been emplaced out-of-sequence within slightly older norites (Mungall et al. 2016). An older U–Pb ID-TIMS baddeleyite age of 2058 ± 2 Ma from the Marginal Zone of the Rustenburg Layered Suite (Olsson et al. 2010) does not possess equally high precision as those by Zeh et al. (2015) and Mungall et al. (2016). Although the Rustenburg Layered Suite formed very rapidly, Bushveld Complex magmatism likely continued with the emplacement of an overlying Lebowa Suite of granophyres and granites until ca. 2054 Ma (Walraven and Hattingh 1993; Van Tongeren et al. 2016).

The Bushveld Complex differs from other large mafic events on the Kaapvaal craton by apparently not having any associated regional dyke swarm, or any other type of exposed feeder, whereby one could explain the rapid mode of emplacement of such unusually large volumes of mafic magma (e.g., Olsson et al. 2011). An equally large, but currently hidden feeder, like the Great Dyke of Zimbabwe, could initially have fed marginal sills of the Bushveld Complex, which eventually coalesced into a

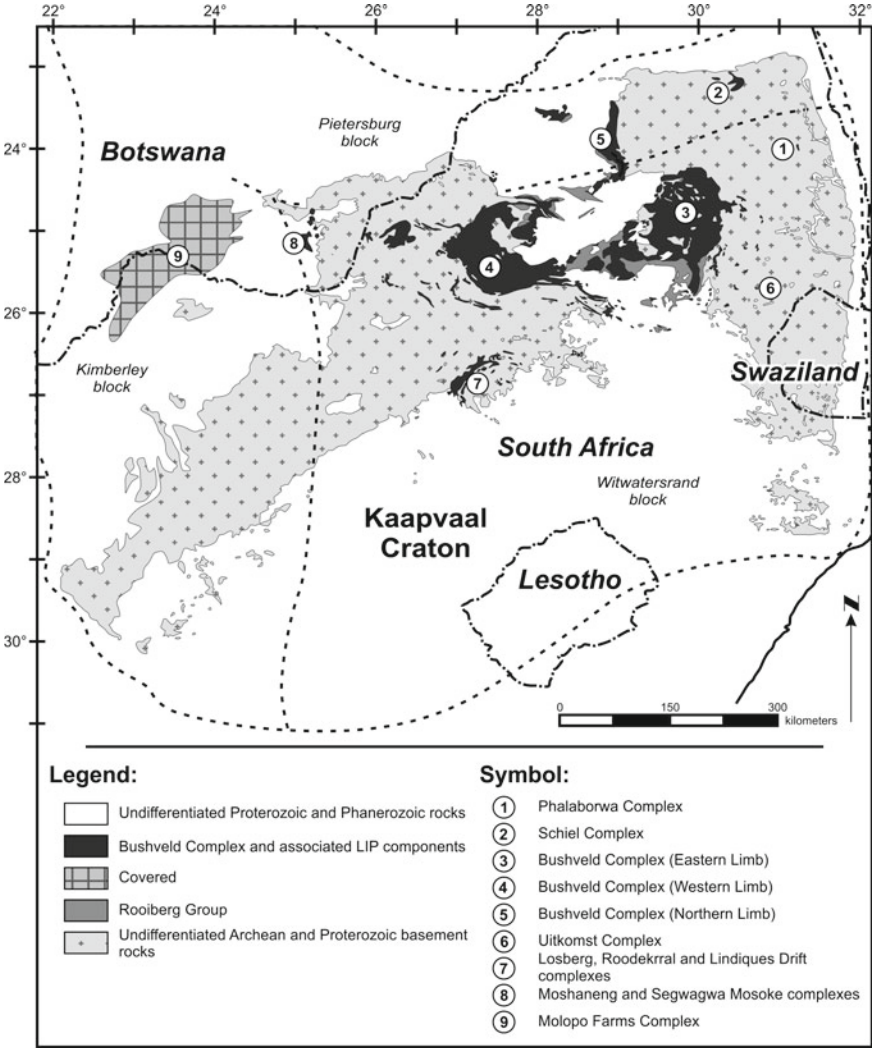

Fig. 7 Distribution of the Bushveld LIP across the Kaapvaal craton. Compiled as in Fig. 2

replenished large lopolith (e.g., Cawthorn et al. 2006), which ultimately crystallized into the Rustenburg Layered Suite. The most likely location of such a hypothetical feeder zone might be along the E–W trending TML (Clarke et al. 2009), which aligns sub-parallel to the LMC, and its Central Zone that is dominated by ages that conform to a major 2.05–2.03 Ga metamorphic event and subsequent dextral displacement between 2.03 and 1.9 Ga (Holzer et al. 1998).

3.5 Late Paleoproterozoic Events

Isolated remnants of volcanic rocks have been recognized within the extensive Paleoproterozoic red-bed successions on the Kaapvaal craton. SHRIMP zircon U–Pb dates indicate that the deposition of these red-bed successions spanned more than 200 Myr (Dorland et al. 2006; Geng et al. 2014). Minor quartz porphyry lavas near the bottom of the Waterberg Group immediately postdate the intrusion of the Bushveld Complex (Dorland et al. 2006). More prominent occurrences of younger volcanic rocks, including more mafic lavas, are preserved as the Hartley Formation, within the Olifantshoek Supergroup, and the Sibasa and Ngwanedzi formations, within the Soutpansberg Group.

The volcanic rocks within the Hartley Formation are compositionally bimodal basalts and rhyolites, which have been dated to 1916 ± 1 Ma using four different methods on a quartz porphyry flow unit (Cornell et al. 2016). A previous age of 1928 ± 4 Ma on the same quartz porphyry (Cornell et al. 1998) and a 1920 ± 4 Ma age on another quartz porphyry have also been reported (Alebouyeh Semami et al. 2016). An east-northeast-trending mafic dyke swarm, termed the Tsineng dyke swarm, was identified by Goldberg (2010) as stemming from a magmatic centre that was located outside the western margin of the Kaapvaal craton (Alebouyeh Semami et al. 2016; Figs. 6 and 8). As this up to 300 km long, and at least 100 km wide swarm appears to be truncated by the <1.9 Ga Kheis orogen, but cuts the Waterberg Group, Goldberg (2010) tentatively assigned it a ca. 1.9 Ga age. One mafic dyke of the Tsineng dyke swarm was dated to 1923 ± 6 Ma using ID-TIMS on baddeleyite (Alebouyeh Semami et al. 2016). Furthermore, broadly coeval mafic sills from Botswana (near Moshaneng) yield ages of ca. 1927 Ma (Hanson et al. 2004b). In addition, drill core samples from the buried Trompsburg Complex (Fig. 8)—a roughly circular and 50 km wide layered mafic intrusion beneath the Phanerozoic Karoo Supergroup sedimentary rocks in the southern part of the Kaapvaal craton—is dated to ca. 1915 Ma (Maier et al. 2003), and is thereby also a potential member of the same LIP.

Approximately 40 Myr later, the northeastern Kaapvaal craton was intruded by northeast-trending mafic dykes termed the Black Hills dyke swarm. Extensive dating by Olsson et al. (2016; 2011) has shown that dykes within this swarm are intermixed with the northeast-trending 2.66 Ga branch of the proposed radiating dyke swarm, described in Sect. 3.2 (Figs. 4 and 8). The ID-TIMS U–Pb baddeleyite ages of the Black Hills dyke swarm (sensu stricto) range from 1871 to 1839 Ma (Olsson et al. 2016), where age resolutions allow these authors to distinguish between an earlier and compositionally more primitive suite, and a later more evolved suite. Mafic sills further west within the Waterberg Group are geochemically indistinguishable from the Black Hill dyke swarm, and thereby extend the magmatic age range back to ca. 1886 Ma (Hanson et al. 2004b; Olsson et al. 2016; Fig. 8). Paleomagnetic data are available for many Black Hills dykes and post-Waterberg sills, and give consistent results that are supported by positive baked-contact tests from two dykes (Letts et al. 2005; De Kock et al. 2006; Letts et al. 2010; Lubnina et al. 2010; Maré and Fourie 2012). The post-Waterberg sills across the northeastern part the Kaapvaal

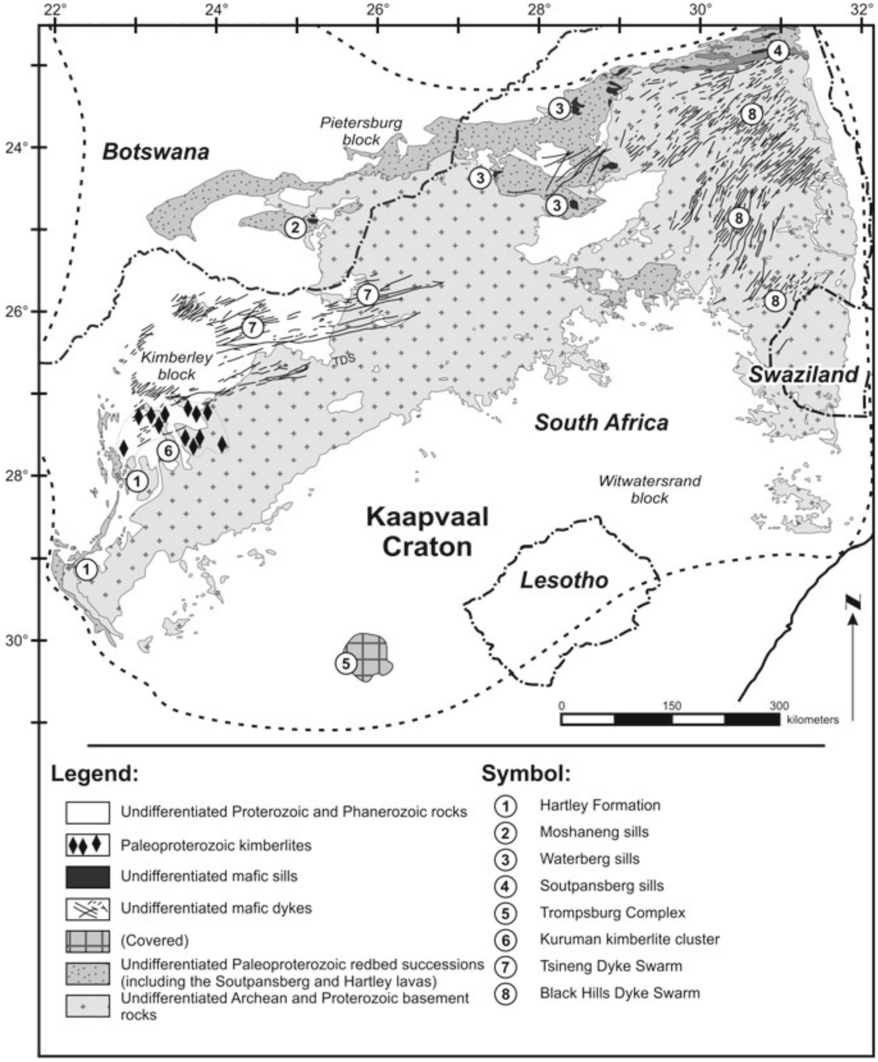

Fig. 8 Late Paleoproterozoic magmatic units on the Kaapvaal craton. These are the 1.93–1.92 Ga Hartley LIP (including the east-northeast-trending Tsineng dyke swarm, Trompsburg Complex, and Moshaneng sills), the 1.88–1.83 Ga Black Hills dyke swarm, post-Waterberg sills, and Soutpansberg Group volcanic units. Compiled as in Fig. 2

craton are furthermore broadly coeval with the Mashonaland sill province within the Zimbabwe craton (Wilson et al. 1987; Söderlund et al. 2010; Fig. 5), representing the first well-established magmatic barcode link between the Kaapvaal craton and the Zimbabwe craton. Based on significantly different paleomagnetic poles of the Mashonaland and Waterberg sill provinces, Hanson et al. (2011b) so suggested that these two sill provinces—and thereby their respective host cratons—must have been as much as 3000 km apart, before being brought closer together after their ca. 1.88 Ga emplacement.

The age of the Sibasa Formation of the Soutpansberg Group (Fig. 8) is constrained by 1830 ± 15 Ma and 1832 ± 9 Ma U–Pb SHRIMP dates by the youngest zircon grains from the formation's uppermost pyroclastic units, which were interpreted as depositional ages of its ash beds (Geng et al. 2014). The lavas of the Sibasa Formation may therefore be related to the younger phase of Black Hills dyke emplacement (Geng et al. 2014). The Ngwanedzi Formation of the Soutpansberg Group is located stratigraphically above the Sibasa Formation, but is not yet dated (Fig. 8). An age on this volcanic event could potentially extend the age range of the protracted 1888-1830 Ma magmatic event, represented by early post-Waterberg and Mashonaland sills, the Black Hills dyke swarm and late Sibasa volcanism, even further, and thereby making it difficult to view this as a classical short-lived LIP. Instead, Olsson et al. (2016) view this protracted magmatic event as emplaced within a continental back-arc setting, behind a parallel and convergent plate boundary along the northwestern margin of the proto-Kalahari craton.

The Soutpansberg Group is also cut by mafic intrusions, some of which have been assigned to the 1112–1108 Ma Umkondo LIP (Jones and McElhinny 1966; Hanson et al. 2004a). However, an older ca. 1.75 Ga phase of magmatism is suggested by a highly uncertain 1749 ± 104 Ma Rb–Sr whole rock age on one mafic sill (Barton 1979) as well as Paleoproterozoic paleopoles for other intrusions (Hanson et al. 2004b). These potentially older sills are here referred to as the Soutpansberg mafic sills to distinguish these from younger (ca. 1.11 Ga) Umkondo LIP sills and dykes (Sect. 3.8), as well as the ca. 1.88 Ga post-Waterberg mafic sills; the latter of which are too old to be hosted by the Soutpansberg Group. The Soutpansberg mafic sills have been suggested to coeval with the Ngwanedzi lavas in the upper Soutpansberg Group (Dorland et al. 2006). The Bathlaros Kimberlite, the oldest preserved kimberlite cluster on the Kaapvaal craton (Fig. 8), with U–Pb perovskite ages that range from 1830 to 1650 Ma (Donnelly et al. 2011, 2012), is broadly coeval, but spatially far removed from the Soutpansberg Group.

The Richterveld terrane, in the far southwestern corner of the proto-Kalahari craton (Fig. 9) incorporates 2.0–1.73 Ga volcanic and sedimentary rocks of the Orange River Group and coeval plutonic rocks of the Vioolsdrif Suite, which likely represents an island arc terrane that accreted onto the proto-Kalahari craton during the Mesoproterozoic Namaqua-Natal orogeny (Reid 1997; Jacobs et al. 2008).

3.6 Early Mesoproterozoic Magmatism

Several Mesoproterozoic alkaline intrusions, including carbonatites, are known from the interior of the Kaapvaal craton, the largest of which is the Pilanesberg Complex (see Hanson et al. 2006; Verwoerd 2006 for a more detailed overview; Fig. 9). These intrusions are mostly not well-dated, but the Pilanesberg Complex recently

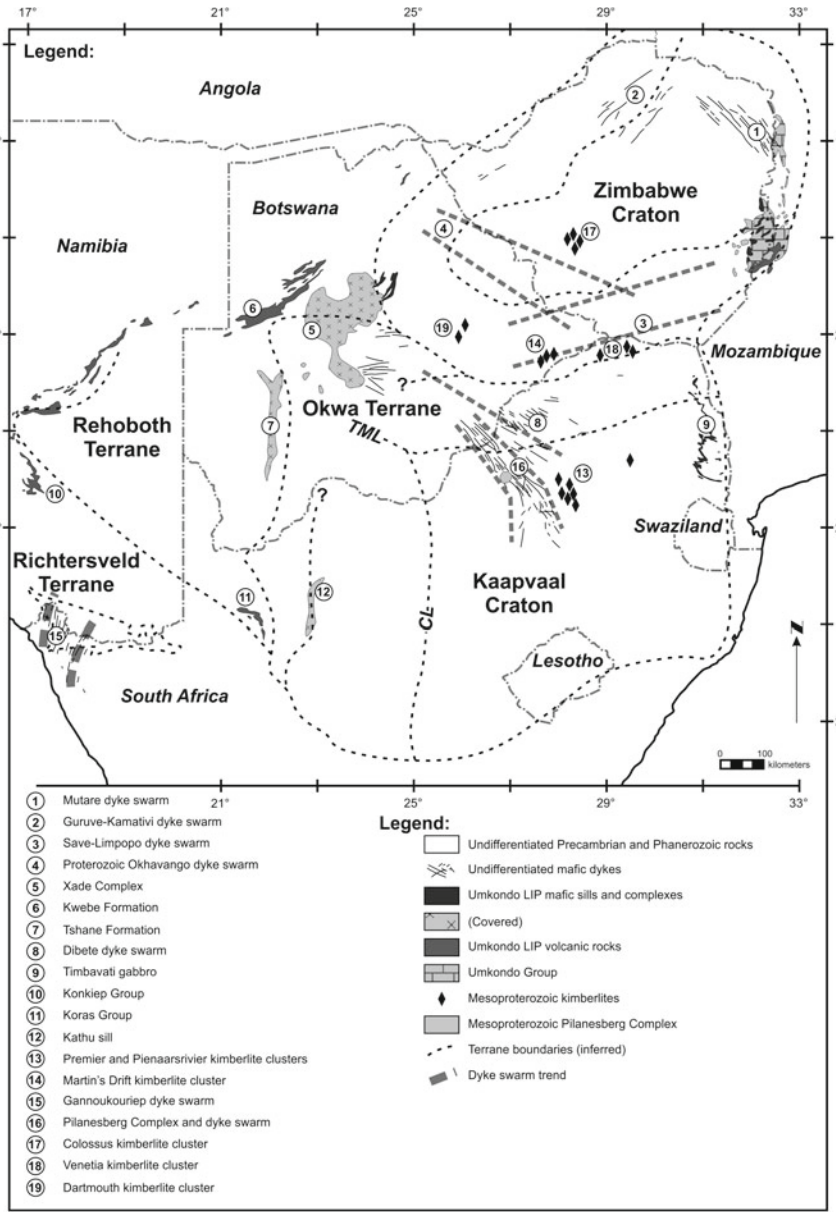

Fig. 9 Mesoproterozoic and Neoproterozoic magmatic units of the Kalahari craton. South African geology was compiled as in Fig. 2, while Botswana and Zimbabwe geology is from the 1: 1,000,000 geological maps of those respective countries

yielded a U–Pb age on titanite of 1395 +10/−11 Ma (Elburg and Cawthorn 2017).

Hanson et al. (2006) cited many well-constrained, but unpublished U–Pb zircon and titanite ages for several intrusions that range in age between 1397 and 1381 Ma. A reasonably well-constrained Rb–Sr age of ca. 1340 Ma was also reported by Harmer (1999) for the Spitskop Complex. Preliminary paleomagnetic constraints have also been reported for many of these intrusions, but paleomagnetic stability field tests are generally lacking (Gose et al. 2013). The Mesoproterozoic carbonatites and other alkaline magmatic intrusions of southern Africa appear to be spatially associated with old terrane boundaries and younger extensional faults (Friese et al. 1995). The Pilanesberg Complex is centered on a prominent, >400 km long, and south-southeast- to north-trending Pilanesberg dyke swarm (e.g., Hunter and Reid 1987). Paleomagnetic data and 1.3–1.1 Ga Rb–Sr and K–Ar ages on its many dykes suggest relatively prolonged magmatic activity, and several overlapping generations may be present within this swarm, consistent with the presence of both normal and reversely magnetized dykes (Gough and Hales 1956; Schreiner and Van Niekerk 1958; Van Niekerk 1962; McDougall 1963; Jones and McElhinny 1966; Emerman 1991). Jones and McElhinny (1966), furthermore, obtained a virtual geomagnetic pole for a ca. 1130 Ma dyke (K–Ar feldspar age; McDougall 1963) that differs significantly from other dykes in the swarm.

Numerous kimberlites on the Kaapvaal craton are also Mesoproterozoic, including the ca. 1150 Ma Premier cluster and ca. 1465 Ma Martin's Drift cluster (Wu et al. 2013; Griffin et al. 2014). The Martin's Drift cluster is associated with east-northeast-trending basement lineaments across the Kaapvaal craton, while the Premier cluster is associated with more north-trending lineaments (Jelsma et al. 2004).

3.7 The Umkondo Large Igneous Province

Apart from the Jurassic Karoo LIP, the most widespread magmatic event on the Kalahari craton is the ca. 1.11 Ga Umkondo LIP (Hanson et al. 2004a; Fig. 9). It was named after the extensive sills that intruded into the Umkondo Group, preserved on the eastern Zimbabwe craton along the Zimbabwe-Mozambique border (McElhinny and Opdyke 1964). The Umkondo Group was shown, on the basis of paleomagnetism and geochemistry, to host both a basaltic lava succession and coeval doleritic sills (McElhinny 1966; Munyanyiwa 1999). Since then, many mafic sills, as well as dykes across both the Zimbabwe and Kaapvaal cratons have been geochronologically and paleomagnetically linked into a remarkably this short-lived and extensive LIP event (Hanson et al. 1998; Wingate 2001; Hanson et al. 2004a; Gose et al. 2006; De Kock et al. 2014; Swanson-Hysell et al. 2015). Large subsurface Tshane, Xade and Tsetseng mafic intrusions in Botswana have also been linked to the Unkondo LIP (e.g., Hanson et al. 2006), where recent geophysical studies of the Xade Complex have dramatically increased its size to one of the largest such Mesoproterozoic mafic complexes in southern Africa (Corner et al. 2012). Intraplate 1.1 Ga volcanic rocks are also described from as far afield as the Rehoboth terrane further to the southwest (Becker et al. 2006; Miller 2008, 2012). Bimodal basaltic and rhyolitic volcanic rocks inside the northwestern Botswana rift (e.g., Key and Mapeo 1999), across the western edge of the Kalahari craton, known as the Kgwebe Formation, have also been geochronologically linked to the Umkondo LIP (Singletary et al. 2003). Granites of the same age have been revealed by geophysical data, drilling, and one poor outcrop in northwestern Botswana (Singletary et al. 2003). A small 1.1 Ga layered gabbroic to dioritic complex has also been identified within the Kwando Complex in Botswana (Singletary et al. 2003).

In Dronning Maud Land of East Antarctica the widespread 1.1 Ga Borgmassivet mafic and ultramafic intrusions of the Grunehogna terrane intrude strata of the Proterozoic Ritscherflya Supergroup as well as the Archean basement (Hanson et al. 2006). The Ritscherflya Supergroup is capped by basalts that are related to the Borgmassivet intrusions, and these are contiguous with the Umkondo Group of Zimbabwe and Mozambique in typical Gondwana reconstructions (Krynauw et al. 1991; Jones et al. 2003). Paleomagnetic data of the Borgmassivet intrusions and Ritscherflya basalts are indistinguishable from that of the Umkondo LIP (Jones et al. 2003; Gose et al. 2006; Swanson-Hysell et al. 2015).

Even before the Umkondo LIP was recognized, Wilson et al. (1987) observed that northeast-trending Guruve and Kamativi dyke swarms across Zimbabwe may on the basis of limited paleomagnetic and Rb–Sr isotopic data be coeval with the Umkondo dolerites and lavas in eastern Zimbabwe. A ca. 1.11 Ga age of some of the Guruve dykes was finally confirmed through U–Pb ID-TIMS baddeleyite age dating (De Kock et al. 2014). Other aeromagnetically pronounced dyke swarms, including the east-southeast-trending Dibete, northeast-trending Save-Limpopo and northwest-trending Okavango dyke swarms—intersecting each other across the central parts of the Kalahari craton—were all originally thought to be of Karoo age (Fig. 9). However, reconnaissance Ar–Ar age dating (Jourdan et al. 2004, 2006) revealed that these dyke swarms are made up of overlapping and apparently sub-parallel mafic dykes with both Karoo and Proterozoic ages; the latter of which were confirmed to be at least partly of Umkondo age (De Kock et al. 2014; Figs. 5 and 9). Due to the many different trending Umkondo dyke swarms, De Kock et al. (2014) also identified up to three magmatic centers for possible radiating swarms, all located along proposed passive margins that may have been conjugate to at least three other cratonic blocks, hosting coeval intrusions across a since dispersed Rodinia supercontinent. However, this proposed break-up scenario also occurred penecontemporaneous with widespread 1135–1050 Ma collisional orogenesis in many parts of the world, forming for example the Grenville orogen in Laurentia and the Namaqua-Natal orogen in southern Africa. The enigmatic tectonic regime of the relatively short-lived yet spatially extensive and voluminous Umkondo LIP event during a regional orogenic event is further accentuated by localized volcanic and sedimentary rock successions within the Koras and Konkiep groups, which both outcrop along the southwestern margin of the Kalahari craton. Here, bimodal basaltic and rhyolitic volcanic rocks of the Koras Group erupted between 1.17 and 1.09 Ga, within a post-orogenic rift that is superimposed on highly deformed metamorphic rocks in this part of the Namaqua-Natal orogen (Pettersson et al. 2007; Bailie et al. 2011; Kasbohm et al. 2016; Panzik et al. 2016), see Fig. 9. Miller (2012) introduced the Konkiep Group to include rocks previously assigned to the Sinclair Group (a term that is now discontinued) as well as other coeval units across the Rehoboth terrane. The Konkiep Group thereby includes a variety of arc-related and intraplate igneous rocks with ages between 1.38 to 1.11 Ga (Miller 2012; Cornell et al. 2015). The paleogeographic relations of the arc-related rocks to the proto-Kalahari craton is unclear, but Panzik et al. (2016) showed that the Konkiep terrane (previously the Sinclair terrane) had docked with the Kalahari craton by 1.1 Ga during the eruption of compositionally bimodal volcanic rocks of the Guperas Formation bimodal volcanic rocks and a post-Guperas dyke swarm. The paleomagnetic signature of the Guperas Formation, post-Guperas dykes and upper Koras Group are very similar to that of Umkondo LIP units, and can thereby be considered an extension of it (Kasbohm et al. 2016; Panzik et al. 2016).

3.8 Neoproterozoic Magmatic Events

The north to northeast-trending Gannakouriep dyke swarm, along the border between South Africa and Namibia, has been dated at 792–788 Ma, using more traditional U–Pb on ID-TIMS methods on both baddeleyite and zircon (Rioux et al. 2010). A slightly older preferred age of 795 ± 1 Ma was provided for one of its dykes, however, using U–Pb isotopic data on discretely digested zircons (Rioux et al. 2010). These mafic dykes intrude for over more than 300 km across several terrane boundaries within the Namaqua-Natal orogenic belt, as well as the Rehoboth terrane on the western limits of the Kalahari craton (Fig. 9). The dykes have been metamorphosed to between greenschist and amphibolite facies, and have until recently been only cursorily studied (e.g., Reid et al. 1991). The Gannakouriep dykes also cut across 890–880 Ma and 830–800 Ma granitic plutons (Frimmel et al. 2001; Miller 2008; Hanson Pers. comm.), and paleomagnetic results form both units are currently being prepared for publication (Bartholomew 2008; Hanson et al. 2011a). This magmatism is generally interpreted as heralding the breakup of Rodinia in the Kalahari craton's geological record (Frimmel et al. 2001) and are tentatively related to ca. 750 Ma bimodal volcanic rocks within the Rosh Pinah Formation, as para-autochtonous parts of the Gariep orogen farther to the west (Frimmel et al. 1996; Borg et al. 2003).

The arcuate Mutare dyke swarm trends north-northwest-trending mafic dyke swarm across the eastern Zimbabwe craton, near the border of Mozambique (Wilson et al. 1987; Ward et al. 2000), and is up to 300 km long and 100 km wide (Figs. 5 and 9). It was initially suspected to be of Umkondo-age (e.g., Hanson et al. 2006), until Mukwakwami (2005) obtained a 724 ± 4 Ma ID-TIMS U–Pb age on baddeleyites. Nevertheless, Mukwakwami (2005) thought the swarm may contain ca. 1.1 Ga parallel dykes, which could help explain the swarm's compositional heterogeneity (Ward et al. 2000).

As reviewed by Hanson (2003), there are many Neoproterozoic igneous rocks within other Pan-African orogenies that surround and may represent intraplate magmatism of the Kalahari craton. Along the northern margin of the Kalahri craton, ca. 750 Ma continental rift deposits are incorporated within the Neoproterozoic supracrustal successions of the Damara and Kaoko orogens, including extensive occurrences of tholeitic alkaline basalts within the Damara orogeny. Farther to the northeast, along in the Zambezi orogen in Zambia and Zimbabwe, there are numerous 870–730 Ma intraplate bimodal volcanic rocks and intraplate mafic and felsic intrusions. More detail and data on these occurrences are provided by Katongo et al. (2004), Johnson et al. (2005), and Johnson et al. (2007). Most of these Zambezi rocks are linked to the Congo craton by Johnson et al. (2007), but it could be debated whether some units formed along a northern rifted margin of the Kalahari craton.

A few Neoproterozoic Kimberlite occurrences from the Kalahari craton have also been U–Pb dated, using on groundmass perovskite (Griffin et al. 2014). This includes the 611 ± 5 Ma South African Dartmouth kimberlite (Griffin et al. 2014), the 572–522 Ma South African Venetia kimberlite cluster (Allsopp et al. 1995; Woodhead et al. 2009; Griffin et al. 2014), the 583 ± 64 Zimbabwean Beitbridge kimberlite (Griffin et al. 2014), and 541 ± 10 Ma Zimbabwean Colossus kimberlite cluster (Donnelly et al. 2012).

4 Discussion

4.1 A Precambrian Magmatic Barcode and Paleogeography of the Kalahari Craton

Figure 10 is a compilation of available precise U–Pb zircon and baddeleyite ages for the Precambrian mafic magmatic units, which intruded into the Kalahari craton and its constituents after stabilization (summarized in Table 1). This magmatic barcode represents a temporal fingerprint which can be compared with other Precambrian terranes globally (Bleeker and Ernst 2006), and where a sharing of at least two magmatic events can be used as a possible indication of paleogeographic continuity between the terranes. Many of the magmatic events identified in the barcode have paleomagnetic data, of variable quality, which constrain the paleolatitudinal drift of the Kaapvaal, Zimbabwe and subsequent Kalahari cratons (Fig. 11). Paleolatitudinal constraints are considered reliable if there is justifiable cause (e.g., rock magnetic investigation, field stability tests, etc.) to assign the rock age to the paleomagnetic constraint (Table 1; cases where any less reliable records are identified). In many cases, several Precambrian crustal blocks can be identified as optional nearest paleo-neighbors to the Kaapvaal, Zimbabwe or Kalahari cratons based on magmatic barcode matches, yet only in a few cases can specific paleogeographic reconstructions be proposed (Fig. 11).

From this data, the magmatic barcode of the Kaapvaal craton remains unique for Mesoarchean mafic magmatism associated with the Pongola Supergroup, Usushwana Complex and older components of the Badplaas dyke swarm, as well as the Hlagothi Complex. The Usushwana Complex has been compared paleomagnetically to the ca. 2.87 Ga Millindina Complex of the Pilbara craton of Western Australia, suggesting

Table 1 Summary of recognized magmatic events of the Kalahari craton with paleomagnetic constraints[a] listed where available

Event		Terrane	Age (Ma)	Unit	Number of units dated	Geochronology reference	Latitute	Longitude	dp	dm	Paleomagnetism reference
36	Colossos kimberlite cluster	Kalahari craton	**ca. 541**	Colossos kimberlite cluster	1	Donnelly et al. (2012)	No published data				
35	Venetia kimberlite cluster	Kalahari craton	**572–522**	Venetia kimberlite cluster	3	Allsopp et al. (1995), Woodhead et al. (2009), Griffin et al. (2014)	No published data				
34	Beitbridge kimberlite	Kalahari craton	**ca. 583**	Beitbridge kimberlite	1	Griffin et al. (2014)	No published data				
33	Dartmouth kimberlite	Kalahari craton	**ca. 611**	Dartmouth kimberlite	1	Griffin et al. (2014)	No published data				
32	Mutare dyke swarm	Kalahari craton	**ca. 724**	Mutare dyke swarm	1	Mukwakwami (2005)	No published data				
31	Rosh Pinah Formation	Kalahari craton	**ca. 750**	Rosh Pinah Formation	1	Frimmel et al. (1996)	No published data				
30	Gannakouriep dyke swarm	Kalahari craton	**795–788**	Gannakouriep dyke swarm	4	Rioux et al. (2010), Hanson et al. (2011a)	No published data				
29	Late Mesoproterozoic rifts (bimodal)	Kalahari craton	**1105–1092**	Upper Koras Group	5	Pettersson et al. (2007), Bailie et al. (2011)	**57**	**3**	**7**	**7**	Briden et al. (1979)

(continued)

Table 1 (continued)

Event		Terrane	Age (Ma)	Unit	Number of units dated	Geochronology reference	Latitute	Longitude	dp	dm	Paleomagnetism reference
				Konkiep Group	3	Panzik et al. (2016), Miller (2012), Cornell et al. (2015)	**69.8**	**4.1**	**7.4**	**7.4**	Panzik et al. (2016)
29	Umkondo LIP	Kalahari craton	**1107–1112**	Paleoproterozoic Okavango dyke swarm	2	De Kock et al. (2014)	**64**	**39**	**4**	**4**	Swanson-Hysell et al. (2015)
				Sill intruding the Kwando Complex	1	Singletary et al. (2003)					
				Xade Complex	1	Hanson et al. (2004a)					
				Umkondo Sills (Waterberg Group)	4	Hanson et al. (2004a)					
				Anna's Rust Complex	2	Hanson et al. (2004a)					
				Divuli Ranch dyke	1	De Kock et al. (2014)					
				Umkondo Sill Province	4	Hanson et al. (2004a), Wingate (2001)					

(continued)

Table 1 (continued)

Event		Terrane	Age (Ma)	Unit	Number of units dated	Geochronology reference	Latitute	Longitude	dp	dm	Paleomagnetism reference
				NE-trending intrusion (Botswana)	1	De Kock et al. (2014)					
				Dibete dyke swarm	1	De Kock et al. (2014)					
				Guruve dyke swarm	1	De Kock et al. (2014)					
				Timbavati gabbro	1	Hanson et al. (2004a)					
				Umkondo Sills (Palapye Group)	7	Hanson et al. (2004a)					
28	Late Mesoproterozoic rifts (bimodal)	Kalahari craton	**ca. 1172**	Lower Koras Group	2	Pettersson et al. (2007), Gutzmer et al. (2000)	*55*	*77*	*12.9*	*12.9*	Briden et al. (1979)
27	Premier kimberlite cluster	Kalahari craton	**ca. 1150**	Premier kimberlite	–	Wu et al. (2013)	**41**	**55**	**16**	**16**	Powell et al. (2001)
26	Pienaars River kimberlite cluster	Kalahari craton	**ca. 1332**	Pienaars River kimberlite	–	Jelsma et al (2004)	**−11.5**	**43.3**	**5.6**	**5.6**	Gose et al. (2013)
25	Martin's Drift kimberlite cluster	Kalahari craton	**ca. 1465**	Martin's Drift kimberlite	–	Griffin et al. (2014)	No published data				

(continued)

Table 1 (continued)

Event		Terrane	Age (Ma)	Unit	Number of units dated	Geochronology reference	Latitute	Longitude	dp	dm	Paleomagnetism reference
24	Pilanesberg Complex	Kalahari craton	**1397–1340**	Pilanesberg Complex	1	Elburg and Cawthorn (2017), Hanson et al. (2006), Harmer (1999)	**43.1**	**284.2**	**5.1**	**8.1**	Gose et al. (2013)
23	Kuruman kimberlite cluster	Kalahari craton	**1830–1650**	Bathlaros kimberlite	1	Donnelly et al. (2011; 2012)	**30**	**8.2**	**8.9**	**8.9**	Hargraves (1989)
22	Upper Soutpansberg lavas	Kalahari craton	**undated**	Ngwanedzi Formation	–	–	No published data				
21	Lower Soutpansberg lavas	Kalahari craton	**ca. 1830**	Sibasa Formation	2	Geng et al. (2014)	No published data				
21	Black Hills LIP	Kaapvaal craton	**1879–1839**	Black Hills dyke swarm	12	Olsson et al. (2016)	**10.1**	**18.1**	**7.9**	**7.9**	Letts et al. (2010)
				Post-Waterberg sills	3	Hanson et al. (2004b)	*8.6*	*15.4*	*17.3*	*17.3*	Hanson et al. (2004b); Recalculated by De Kock et al. (2006)
20	Mashonaland sill province	Zimbabwe craton	**1886–1872**	Mashonaland sills	5	Söderlund et al. (2010); Hanson et al. (2011b)	**6.5**	**338.5**	**5**	**5**	Hanson et al. (2011b)
19	Hartley LIP (bimodal)	Kaapvaal craton	**1928–1915**	Ttrompsburg Complex	1	Maier et al. (2003)	No published data				

(continued)

Table 1 (continued)

Event		Terrane	Age (Ma)	Unit	Number of units dated	Geochronology reference	Latitute	Longitude	dp	dm	Paleomagnetism reference
				Tsineng dyke swarm	1	Alebouyeh Semami et al. (2016)	**22.7**	**328.6**	**11.7**	**11.7**	Alebouyeh Semami et al. (2016)
				Moshaneng sill province	3	Hanson et al. (2004b)					
18	Bushveld LIP (bimodal)	Kaapvaal craton	**2058–2055**	Rustenburg Layered Suite	15	Zeh et al. (2015); Olsson et al. (2010); Mungall et al. (2016)	**19.2**	**30.8**	**5.8**	**5.8**	Letts et al. (2009)
				Molopo Farms Complex	1	De Kock et al. (2016)	No published data				
				Uitkomst Complex	2	Wabo et al. (2015a), Maier et al. (2017)	*28.7*	*58.5*	*6.2*	*9.4*	Wabo et al. (2015a)
				Moshaneng Complex	1	Mapeo et al. (2004b)	No published data				
				Marble Hall diorite	1	De Waal and Armstrong (2000)	No published data				
				Lindeques Drift intrusion	1	De Waal et al. (2006)	No published data				
				Roodekraal Complex	1	De Waal et al. (2006)	No published data				
				Bushveld Sill Province	2	Wabo et al. (2015a)	*13.1*	*44*	*14.1*	*14.1*	Wabo et al. (2015a)

(continued)

Table 1 (continued)

Event		Terrane	Age (Ma)	Unit	Number of units dated	Geochronology reference	Latitute	Longitude	dp	dm	Paleomagnetism reference
18	Phalaborwa Complex	Kaapvaal craton	**2062–2060**	Palaborwa Complex	numerous	Wu et al. (2011), Heaman and LeCheminant (1993), Reischmann (1995), French et al. (2008), Horn et al. (2000), Wingate (2000), Heaman (2009)	**27.7**	**35.8**	**6.6**	**6.6**	Letts et al. (2010)
18	Schiel Complex	Kaapvaal craton	**2054–2051**	Schiel Complex	2	Laurent and Zeh (2015)	No published data				
18	Rooiberg Group (bimodal)	Kaapvaal craton	**ca. 2061**	Rooiberg volcanics	1	Walraven (1997)	No published data				
17	Unnamed dyke	Kaapvaal craton	**ca. 2168**	Unnamed dyke	1	Larsson (2015)	No published data				
17	Machadodorp Member	Kaapvaal craton	**undated**	Machadodorp Member	–	–	No published data				
16	Hekpoort Formation	Kaapvaal craton	**ca. 2184**	Hekpoort Formation	1	Cornell et al. (1996)	*−44.1*	*40*	*9.9*	*10.4*	Humbert et al. (2017)
15	Chimbadzi Hills intrusion	Zimbabwe craton	**ca. 2262**	Chimbadzi Hills intrusion	1	Manyeruke et al. (2004)					
14	Sebanga Poort dyke swarm	Zimbabwe craton	**ca. 2408**	Sebanga Poort dyke	1	Söderlund et al. (2010)	*17.2*	*6.1*	*14.3*	*14.3*	Smirnov et al. (2013)
13	Ongeluk LIP	Kaapvaal craton	**2428–2423**	Gewonne dyke swarm	1	Gumsley et al. (2017)	**4.1**	**282.9**	**5.3**	**5.3**	Gumsley et al (2017)

(continued)

Table 1 (continued)

Event		Terrane	Age (Ma)	Unit	Number of units dated	Geochronology reference	Latitute	Longitude	dp	dm	Paleomagnetism reference
				Ongeluk volcanics	1	Gumsley et al. (2017)					
				Westerberg sill province	3	Gumsley et al. (2017), Kampmann et al (2015)					
12	Sebanga Poort dyke swarm	Zimbabwe craton	**ca. 2471**	Mtshingwe dyke	1	Söderlund et al. (2010)	No published data				
11	Sebanga Poort dyke swarm	Zimbabwe craton	**ca. 2512**	Crystal Springs dyke	1	Söderlund et al. (2010)	No published data				
10	Great Dyke and sattelites	Zimbabwe craton	**2577–2573**	Great Dyke and sattelites	5	Armstrong and Wilson (2000), Wingate (2000), Söderlund et al. (2010), Oberthür et al. (2002)	**23.6**	**57.4**	**8.9**	**8.9**	Smirnov et al. (2013)
9	Unnamed dykes	Kaapvaal craton	**2580–2574**	Unnamed dykes	2	Larsson (2015)	No published data				
8	Sand River dykes	LMC Central Zone	**2607–2602**	Stockford and Causeway dykes	2	Xie et al. (2017)	No published data				
7	White Mfolozi dyke swarm	Kaapvaal craton	**2664–2654**	White Mfolozi dyke swarm	7	Gumsley et al (2016)	No published data				
7	Proto-basinal volcanics	Kaapvaal craton	**ca. 2664**	Buffelsfontein Group	1	Barton et al (1995)	No published data				
7	Rykoppies dyke swarm	Kaapvaal craton	**2686–2659**	Rykoppies dyke swarm	5	Olsson et al (2010; 2011)	**−62.1**	**336**	**3.5**	**4.2**	Lubnina et al (2010)

(continued)

Table 1 (continued)

Event		Terrane	Age (Ma)	Unit	Number of units dated	Geochronology reference	Latitute	Longitude	dp	dm	Paleomagnetism reference
6	2.7 Ga Ventersdorp LIP (bimodal)	Kaapvaal craton	**2746–2709**	Makwassie Formation	1	Armstrong et al. (1991)	**−69.8**	**345.6**	**5.8**	**5.8**	De Kock et al. (2009)
				Makwassie Formation	1	Cornell et al. (2018)	**−69.8**	**345.6**	**5.8**	**5.8**	De Kock et al. (2009)
				Hartswater Group	2	De Kock et al. (2012)	No published data				
				Amalia Group	1	Poujol et al (2005)	No published data				
				Zoetlief Group	1	Walraven et al. (1991)	No published data				
				Goedgenoeg Formation	1	Cornell et al. (2018)	No published data				
				Unnamed dyke	1	Larsson (2015)	No published data				
				Klipriviersberg Group	1	Armstrong et al. (1991)	*−17.1*	*47.9*	*18.8*	*18.8*	Strik et al. (2007)
5	2.78 Ga Ventersdorp LIP (bimodal)	Kaapvaal craton	**2787–2781**	Derdepoort volcanics	1	Wingate (1998)	−39.6	4.7	17.5	17.5	Wingate (1998)
				Modipe gabbro	1	Denyszyn et al. (2013)	**−47.6**	**12.4**	**8.6**	**9.3**	Denyszyn et al (2013)
				Kanye Formation	3	Moore et al. (1993), Grobler and Walraven (1993)	No published data				

(continued)

Table 1 (continued)

Event		Terrane	Age (Ma)	Unit	Number of units dated	Geochronology reference	Latitute	Longitude	dp	dm	Paleomagnetism reference
				Lobatse Group	1	Walraven et al. (1996)	No published data				
				Unit previously assigned to the Goedgenoeg Formation	1	Cornell et al. (2018)	No published data				
4	Hlagothi Complex	Kaapvaal craton	**2874–2866**	Hlaghothi Complex (may include undated Thole Complex, and Post-Mozaan sills)	3	Gumsley et al. (2013); Gumsley et al. (2015)	*23.4*	*53.4*	*8.2*	*11.8*	Gumsley et al (2013)
3	Witwatersrand volcanics	Kaapvaal craton	**ca. 2914**	Crown Member	1	Armstrong et al. (1991)	No published data				
2	Mozaan volcanics	Kaapvaal craton	**ca. 2954**	Tobolsk Formation	1	Mukasa et al. (2013)	No published data				
1	Badplaas dyke swarm	Kaapvaal craton	**2980–2966**	Badplaas dyke swarm	3	Olsson et al. (2010); Gumsley et al. (2015)	**−63.6**	**285.4**	**2.3**	**4**	Lubnina et al (2010)
1	Nsuze volcanics	Kaapvaal craton	**2985–2968**	Nsuze volcanics	3	Mukasa et al. (2013); Hegner et al. (1994); Nhleko (2003)	**−67**	**285.6**	**5.3**	**9.2**	Lubnina et al (2010)
1	Usushwana Complex	Kaapvaal craton	**2990–2978**	Usushwana Complex	3	Gumsley et al. (2015)	*9.2*	*347*	*7.6*	*7.6*	Layer (1988)

[a]Paleomagnetic constraints in bold face are considered reliable, while those in regular italic face are either virtual geomagnetic poles or considered unreliable

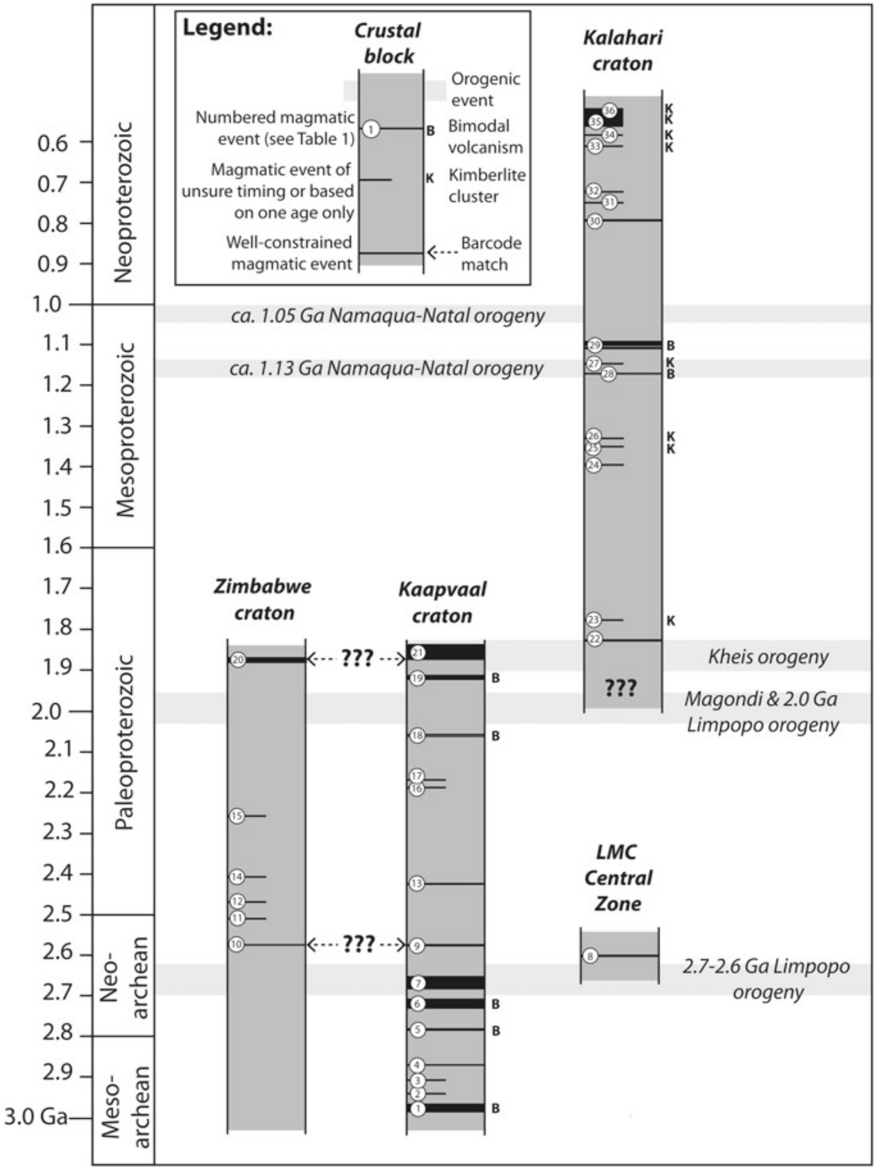

Fig. 10 Magmatic barcodes for the Kaapvaal and Zimbabwe cratons and the Central Zone of the LMC before 1.8 Ga, and a magmatic barcode for the Kalahari craton from 1.8 to 0.5 Ga

a proximity between the Kaapvaal and Pilbara cratons (Zegers et al. 1998), but a new 2.99–2.98 age from the Usushwana Complex invalidates such a paleomagnetic interpretation.

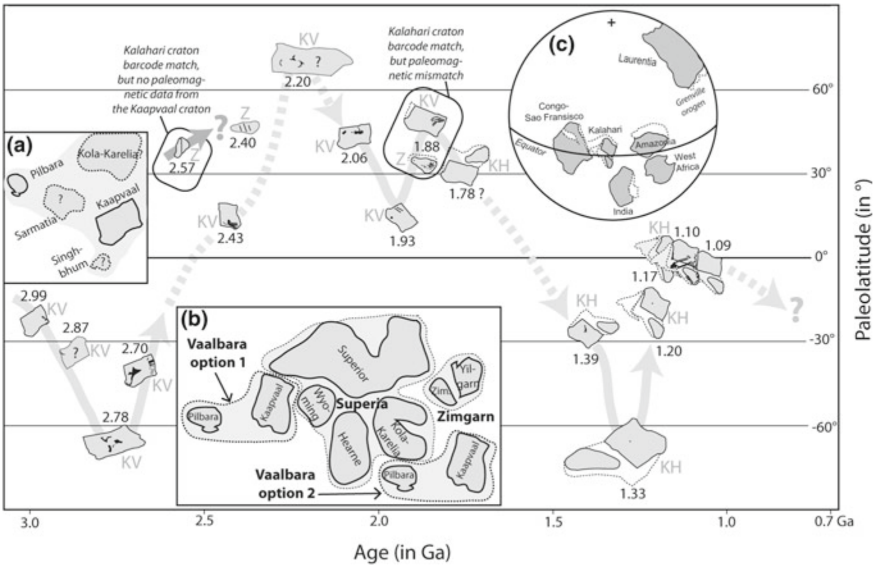

Fig. 11 Paleolatitudinal drift of the Kaapvaal (KV), Zimbabwe (Z) and Kalahari (KH) cratons between 3.0 and 0.7 Ga. Proposed relative reconstructions between the Kaapvaal, Zimbabwe and Kalahari cratons and other cratons are illustrated: **a** The Vaalbara reconstruction between 2.78 and 2.70 Ga (modified from De Kock et al. 2009)—now questionable at 2.78 Ga; **b** The Superia reconstruction, including Vaalbara and Zimgarn between 2.4 and 2.0 Ga (modified from Gumsley et al. 2017). Two possible placements of Vaalbara relative to Superia are shown; **c** Assembly of Rodinia at 1.11 Ga after De Kock et al. (2014)

In the Neoarchean, the ca. 2.78 Ga Derdepoort-Kanye-Modipe event can almost be perfectly matched with the similarly aged 2.77–2.76 Ga Black Range dykes and lower part of the Fortescue Group on the Pilbara craton (Wingate 1998; Evans et al. 2017). This match together with another approximate match between an age-bracketed 2.71–2.66 Ga Allanridge Formation and the upper part of the Fortescue Group, as well as other geological piercing points, has led to a proposal where these two cratons were nearest neighbors within a coherent crustal block named the Vaalbara "supercraton" (Cheney 1996). Based on paleomagnetic constraints a relative reconstruction of the Pilbara craton to the northwest of the present-day Kaapvaal craton was favored (De Kock et al. 2009; Fig. 11a), but better-constrained paleomagnetic results from the Kaapvaal craton's ca. 2.78 Ga Modipe gabbro has since suggest that the two blocks—although likely part of the same supercratons—were not necessarily nearest neighbors (Denyszyn et al. 2013). New paleomagnetic constraints from the 2.77–2.76 Ga Black Range dykes of the Pilbara craton, furthermore, do not support any attachment of the Kaapvaal and Pilbara cratons in the period 2.78–2.70 Ga (Evans et al. 2017; although not addressing this). During this time interval barcode matches have also been made between the Ventersdorp magmatism on the Kaapvaal craton and 2.80–2.75 Ga north-northeast-trending mafic dykes across the Singhbhum craton of India, which was attached to the south of the present-day Kaapvaal craton (Kumar et al. 2017). The Sarmartia block of eastern Europe (i.e., the combined Ukranian shield and Kursk block) has also been shown to record a very similar stratigraphic succession to the Kaapvaal craton between 2.78 and 2.04 Ga (Savko et al. 2017), thus suggesting a long-lived association between these cratons (Hunt et al. 2017). The volcanic units of the 2.78–2.60 Ga Mikhailovka Group and Krivoi Rog Formation were specifically compared with the Ventersdorp Supergroup (Savko et al. 2017).

The Great Dyke of Zimbabwe cannot be matched with any other crustal blocks at present, apart from a pair of ca. 2.57 Ga east- and southeast-trending dykes of the southeasternmost Kaapvaal craton (Larsson 2015). The ca. 2.51 Ga Crystal Springs and ca. 2.47 Ga Mtshingwe dykes are near-coeval with dykes within a Baltic LIP in the Kola-Karelia craton and Mistassini, River Valley and early Matachewan dykes in the Superior craton (e.g., Gumsley et al. 2017). Around the time of the Neoarchean-Paleoproterozoic boundary, similar geology and paleomagnetic records in supracrustal strata link the Kaapvaal craton to the Pilbara, Superior, Wyoming and Kola-Karelia cratons, although exact age barcode matches are yet to be made (Gumsley et al. 2017). The wide 2.51–2.41 Ga age range by Zimbabwean Sebanga dykes, however, overlaps with the Ringvassoy dykes (Kola-Karelia craton), Wigiemootha and Erayinia dykes (Yilgara craton), as well as the and du Chef dykes (Superior craton), suggesting that all these blocks could have been at least near-contiguous within "Superia" (Fig. 11b); i.e., the combined Superior, Kola-Karelia, Hearne and Wyoming cratons (Bleeker and Ernst 2006; Ernst and Bleeker 2010; Söderlund et al. 2010). Paleogeographic reconstructions with variable relative placements of the Zimbabwe and Yilgarn cratons have also been proposed (Smirnov et al. 2013; Pisarevsky et al. 2015). Smirnov et al. (2013) preferred a juxtaposition of the southern margin of the Zimbabwe craton to the eastern margin of the Yilgarn craton, which aligned the Sebanga Poort dyke with the Wigiemootha dyke swarm. Subsequent break-up of this configuration is envisaged to have occurred after 2.1 Ga, in order for each constituent to respectively, have collide with the Pilbara and Kaapvaal and Pilbara craton (Smirnov et al. 2013). Pisarevsky et al. (2015), however, lined up the present-day northern margin of the Zimbabwe craton with the western margin of the Yilgarn craton, in order to also align the Sebanga Poort dyke with the Wigiemootha dyke swarm (Fig. 11b). This combined "Zimgarn" block was then further restored with Superia. The discovery of a ca. 2.17 Ga dyke from the southeastern Kaapvaal craton possibly offers a further link with the Superior craton's Biscotasing dykes, as well as possibly the Dharwar craton (French and Heaman 2010). In a proposed long-lived Proterozoic reconstruction, Gumsley et al. (2017) placed Vaalbara to the northwest and Zimgarn towards the east of Superia, while Hunt et al. (2017) positioned both Vaalbara and Zimgarn along the eastern margin of Superia (Fig. 11b).

The Bushveld Complex and associated intrusions remain a globally unique mafic magmatic event. Bleeker et al. (2016) has reported near-coeval ages from the Superior craton, while Savko et al. (2017) highlighted the presence of 2.06–2.05 Ga mafic magmatic activity from eastern Sarmatia. These occurrences represent possible continuations of the Bushveld LIP that ends rather abruptly along its northern limb and far western satellite, the Molopo Farms Complex (Fig. 7).

A comparison between the Kaapvaal and Zimbabwe cratons shows firm correlations at both 1880–1830 Ma and at ca. 1110 Ma. This is consistent with these two cratons having remained together since the formation of the LMC's at either 2.70–2.60 Ga or ca. 2.05 Ga, yet do thereby not conclusively resolve this contentious issue. The ca. 1.88–1.83 Ga Mashonaland and the Waterberg sill provinces have numerous potential barcode matches from the Amazonian craton (Antonio et al. 2017), India (e.g., French et al. 2008; Belica et al. 2014), Australia (e.g., Blake et al. 1999), the North China craton (Peng et al. 2011; Peng 2015), the Baltica-Fenoscandian craton (e.g., Mertanen et al. 2006), the Superior craton (e.g., Ernst and Bleeker 2010; Ciborowski et al. 2017), the Wyoming craton (Kilian et al. 2016), and the Slave craton (e.g., Buchan et al. 2010; Mitchell et al. 2010), signifying a particularly global magmatic period. Although paleomagnetic data suggest that the Zimbabwe and Kaapvaal cratons were separated by a large distance at 1.88 Ga (Hanson et al. 2011b), and Antonio et al. (2017) proposed 1.88 and 1.83 Ga reconstructions wherein the Kalahari craton is isolated from other cratons, a later merger of these two cratons is not supported by any geological evidence. Instead, these anomalous paleomagnetic signatures may record a true polar wander event, which has been inferred elsewhere between 1.89 and 1.83 Ga (Mitchell et al. 2010; Antonio et al. 2017).

During the time interval spanning the intrusion of the ca. 1395 Ma Pilanesberg Complex up to the intrusion of the Premier kimberlite cluster at ca. 1150 Ma (Wu et al. 2013), the Kalahari craton was quite mobile (Fig. 11). It experienced latitudinal drift from a position 30° from the equator at 1.4 Ga to a high latitudinal position at 1.3 Ga, and back to a more equatorial position at 1.2 Ga (Gose et al. 2013). The Kalahari craton has also never been linked to any other cratonic unit during this time interval (e.g., 1.2 Ga reconstruction in Pesonen et al. 2003).

The voluminous Umkondo LIP event of the Kalahari craton occurred at the same time as the Keenawan LIP as well as the southwestern USA diabases of Laurentia were emplaced (Hanson et al. 2004a; Swanson-Hysell et al. 2015). Like the 1.88–1.83 Ga interval, however, 1.11 Ga is also a time of widespread global magmatism. Coeval events have been recognized from the Congo-Sao Francisco craton (Ernst et al. 2013), the Amazonian craton (Hamilton et al. 2012), and from India (Pradhan et al. 2012). Swanson-Hysell et al. (2015) preferred a reconstruction in which the Kalahari craton and Laurentia are far apart at 1110 Ma. This allowed the Namaqua-Natal orogen of the Kalahari craton to be conjugate to the Grenville margin of Laurentia, along which these two crustal units were joined to form Rodinia around 1.0 Ga. However, De Kock et al. (2014), following Ernst et al. (2013), positioned the Kalahari craton as a nearest neighbor to India, the Amazonian craton and the Congo-Sao Francisco craton at 1110 Ma (Fig. 11c), while still satisfying the paleomagnetic arguments presented by Swanson-Hysell et al. (2015).

The Gannakouriep, and perhaps also the Mutare mafic dyke swarms are near-coeval with the Gunbarrel and Franklin LIPs of Arctic Canada and the Siberia craton, respectively (e.g., MacDonnald et al. 2010; Rogers et al. 2016). These swarms are all regarded as signaling the beginning of break-up of the Rodinia supercontinent. It should be noted that only one dyke of ca. 724 Ma is dated within the Mutare dyke swarm, and it is unclear if it is representative for the whole swarm, or whether the swarm also includes some 1.11 Ga dykes. The Kalahari craton is commonly restored as conjoined with Laurentia along the Namaqua-Natal and Grenville margins, and abutting against the Congo-Sao Francisco craton in a present-day relative configuration (e.g., Dalziel 1997; Li et al. 2008). In these reconstructions the Grunehogna terrane of Dronning Maud Land (East Antarctica) is considered to be a fragment that had detached from the eastern margin of the Kalahari craton, during the breakup of Gondwanaland (Groenewald et al. 1991). The Grunehogna terrane has an established barcode that matches it firmly to the Kalahari craton at both ca. 1.11 Ga and ca. 0.18 Ga. If an age of Knoper et al. (2014) for the Grunehogna's Fingeren dyke swarm can be confirmed, this attachment is further strengthened by an additional match at ca. 0.72 Ga. Seafloor-spreading data suggests that the Grunehogna terrane is a fragment of the Kalahari craton, and serves to validate the magmatic barcode method for the to reconstruction of ancient cratons.

Several alternative reconstructions of Rodinia have, been proposed: Pisarevsky et al. (2003) presented a configuration where the eastern margin of the Kalahari-Grunehogna craton abuts against the western margin of Australia along the Maud and Pinjarra orogens, respectively, and where the Namaqua-Natal orogen remained an active continental margin against a subducting oceanic plate. Evans (2009) joined the northern margin of the Kalahari craton against both the East Antarctica craton and Australia, and thereby aligned the Albany-Fraser and the Namaqua-Natal orogens into a continuous belt. In this reconstruction, the Namaqua-Natal margin is facing the Eastern Ghats margin of cratonic India, as well as the eastern margin of the North China craton, while the Maud and Mozambique orogens of the Grunehogna terrane and the eastern Kalahari craton are interpreted as active continental margins against a subducting oceanic plate. Subsequent to this Evans (2013) revised parts of this interpretation.

4.2 Composite Nature of Dyke Swarms

Since the work of Wilson et al. (1987) and Hunter and Reid (1987), it has become apparent that many of the mafic dyke swarms across the Kalahari craton contain dykes with apparently similar trends yet distinctly different ages. This has led some authors to speculate in whether pre-existing dyke swarms form anisotropies within the crust, or the lithosphere has persisted 'weakness' zones, which are preferentially re-utilized by subsequent intrusions. Uken and Watkeys (1997) first proposed the re-utilization of pre-existing dyke trends by subsequent dyke swarms in southern Africa, but Jourdan et al. (2004) reported Ar–Ar reconnaissance work across the Kalahari craton that first showed how many Jurassic dykes appear to follow pre-existing and sub-parallel Precambrian dykes. Jourdan et al. (2004) also showed that the many northeast-trending dykes across the northeastern corner of the Kaapvaal craton did not include any Jurassic Karoo dykes, as previously inferred by, e.g., Uken and Watkeys (1997). More precise U–Pb geochronology work on this region's particularly closely-spaced SW–NE trending dykes, instead, revealed that it is made up of a Paleoproterozoic Black Hills dyke swarm (Olsson et al. 2016), that intruded sub-parallel Neoarchean dykes from the presumed northern branch of Olsson et al.'s (2011) radiating swarm. The southeast-trending branch of this proposed radiating swarm, in turn, overlaps and parallel dykes of the Mesoarchean Badplaas swarm (Olsson et al. 2010; Gumsley et al. 2015). Finally, the Sebanga dyke swarm was dated by Söderlund et al. (2010) at ca. 2512 Ma, ca. 2470 Ma and ca. 2408 Ma, indicating that the same zone of crustal weakness was (re-)activated at least three times during a remarkably long period of >100 million years.

From the many examples of overlapping or composite dyke swarms, it therefore seems relevant to note, that without absolute age constraints, any further tectonic, petrogenetic and paleomagnetic interpretations might have their limitations, and result in more speculative conclusions. An approach as demonstrated by Olsson et al. (2016) and Gumsley et al. (2015) is perhaps advisable for more complex dyke swarms, incorporating several overlapping generations, whereby only dated dykes are ideally combined with geochemical and paleomagnetic studies. However, we are also aware that interpretations have to be consistent with all available evidence, where any method has its own merit, and one must also be equally critical towards geochronological and paleomagnetic data. Thus, the implications of some dykes apparently coinciding with significantly older dykes, or even a pre-existing dyke swarm, needs to be interpreted with caution. Firstly, it is also important that dyke trends are properly documented and not just casually interpreted as overlapping and parallel, as even slightly deviating trends between two overlapping dyke generations out-rules the idea that younger dykes utilize pre-existing dyke swarms. One should also remember that several generations of cross-cutting dykes may roughly overlap other sub-parallel dykes purely by coincidence

With the above precautions in mind, it is still permissible to speculate on if/why some dykes, or even dyke swarms, appear to be overlapping in a sub-parallel fashion, and how any interpretation of such a field relationship might typically relate to magma generation in the mantle and subsequent fracture mechanics through the more brittle crust. Any intuitive thought of dykes preferentially propagating along (1) a pre-existing dyke swarm, (2) several swarms utilized a common crustal 'weakness', or (3) both scenarious, has to first and foremost be reconciled with a generally accepted fracture mechanical perception of individual dykes each generating and propagating along its own fracture, perpendicular to a least compressive stress field (e.g., Lister and Kerr 1991; Rubin 1995). This obviously applies within a more isotropic brittle crust, but where any oblique crustal weakness may intuitively offer a pathway that requires less energy for the dyke to propagate (e.g., Rivalta et al. 2015). As this is also where the topic becomes too complex to discuss further in this broad review paper, we just wish to urge readers to rigorously test any such deviations in sufficiently quantitative detail. One should, furthermore, note that it is not sufficient to quantitatively show that overlapping dyke swarms coincide with a zone of 'weaker' crust, or that it is significantly easier for a propagating dyke to follow any pre-exiting dyke swarm (or any other anisotropic basement fabric), rather than cut obliquely across, because such model interpretations also depend on whether mantle-derived mafic magmas were readily available at different times to follow such crustal anisotropies.

From the above, it is obvious that we still need to properly explain how it was possible for individual dykes, within, e.g., the Sebanga dyke swarm, to have been injected with roughly similar overlapping trends over a period of 100 Myr. This not only requires an equally permanent stress field (be it within an isotropic or anisotropic crust) but also that roughly the same underlying mantle was able to supply magmas over an equally long time interval. Our other examples of how the apparently radiating Neoarchean dyke swarm partially overlaps and parallels both an older Badplaas dyke swarm to the southeast and a younger Black Hills dyke swarm to the north-east, yet also follows 'its own' easterly Rykoppies dyke swarm trend, offer a multitude of intuitive model options, where we also note that these three 'radiating' Neoarchean branches formed over a period pf >40 Myr where each 'branch' also seem to have different geochemical signatures. While the latter discovery is interesting, it is also inconvenient that these different geochemical signatures appear to be host rock specific and conform with many older and younger dyke generations within the same basement terrain, rather than being age specific. Thus, the geochemistry has so far proved inadequate to discriminate between older and younger dyke generations within the overlapping north-eastern and south-eastern branch of the radiating Neoarchean dyke swarm. Nevertheless, whereas the south-eastern branch may have followed a pre-existing SE-trending and Mesoarchean Badplaas dyke swarm, there are no pre-existing dyke swarm to impose a similar explanation for the partially radiating north-eastern and eastern Rykoppies dyke swarm branches. Whether or not the Paleoproterozoic Black Hills dyke swarm followed the north-eastern branch of the radiating Neoarchean dyke swarm—which may also coincide with a major SW–NE trending rift zone across the Kaapvaal craton (e.g., McCarthy et al. 1990). Or simply, by coincidence, overlapped it within its own stress field, remains a speculation for further research. Some alternative model proposals are addressed by Gumsley et al (2016).

4.3 Recognition of LIPs

LIPs per definition usually cover large areas, reflecting the emplacement of large volumes of commonly mafic magma within relatively short durations (Coffin and Eldholm 1994, 2001). Ernst (2014) provided a more specific definition of LIPs as intraplate mafic magmatic provinces with or without ultramafic components, limiting both their extent (>10 Mkm^2) and volume (>0.1 Mkm^2) yet recognized that LIPs may also occur as a short magmatic pulse or multiple pulses (each pulse occurring in less than 1–5 million years) over a maximum period of <50 Myr. Ernst (2014) further noted that LIPs may be associated with silicic magmatism, carbonatites and kimberlites.

It is difficult to justify which of the above criteria and cut-off values should be used as LIP-discriminants, let alone estimate how well a heavily eroded and poorly exposed example compares to these. However, even sporadic outcrops and ages can provide some statistically valid minimum constraints that we find to be sufficient to classify the Bushveld Complex, the Great Dyke of Zimbabwe and the Umkondo as LIPs. For all of these three examples, sufficiently large areas and volumes of mafic igneous rocks were emplaced within just a few million years or less.

At the other end of the spectrum, ages derived from mafic dykes and sills associated with the Pongola, Ventersdorp and post-Waterberg/Mashonaland events indicate that these events were too long-lived to be classified as LIPs (*senso stricto)*, even if most of these candidates are sufficiently extensive and even voluminous (e.g., the thick flood basalts sequences within the Ventersdorp Supergroup). In some cases, one may argue that an age data sets records pulses within a coherent LIP event, where the proposed (1) main ca. 2.78 Ga Derdepoort-Kanye-Lobatse-Klipriviersberg pulse, (2) the ca. 2.73–2.71 Ga Platberg pulse, and (3) final emplacement of radiating ca. 2.68–2.66 Ga dyke swarms and associated proto-basinal fill volcanic rocks, pulsated for >100 Myr.

One may also argue that the ca. 1.93–1.92 Ga Hartley event is another sufficiently large and short-lived LIP event, although ages produced in the near future may link this event to a much more extended (or pulsating) event, including the subsequent ca. 1.89–1.83 Ga Black Hills dyke swarm and its associated sills and lavas, as already discussed by Olsson et al (2016). Other events, such as the Hlagothi Complex, although apparently short-lived, may not be sufficiently extensive, let alone voluminous enough to qualify as a LIP, and may also be part of a yet undisclosed longer lived, and possibly pulsating Mesoarchean LIP-event, possibly ranging from as far back as to (1) a ca. 3.07 Ga Dominion-pulse, passing through (2) a major Pongola-pulse between ca. 2.98–2.97 Ga, before terminating with (3) the ca. 2.87 Ga Hlagothi-event. Depending on whether or not the Dominon Group can be correlated to the Nsuze Group, this potential LIP could have been pulsating over a period of between 200 and 100 Myr. Alternatively, a combined Dominon-Nsuze event (including the Usushwana Complex, Badplaas dyke swarm and associated Nsuze lavas) may have been sufficiently voluminous and short-lived to be a LIP on its own.

As it is problematic to estimate magma volumes only from the dyke swarms roots of more deeply eroded Precambrian LIPs (*senso lato*), it becomes important to also correlate precisely dated mafic dykes and sills to other coeval intrusive and extrusive igneous rocks. While a lack of supracrustal successions renders this task impossible for the Zimbabwe craton, several dyke swarms across the Kaapvaal craton can now be shown to be coeval with volcanic units within the craton's better-preserved supracrustal stratigraphic record. Thus, it has become apparent that different volcanic packages in the Nsuze Group may correspond to coeval dykes present in the Badplaas mafic dyke swarm, as well as the Usushwana Complex (Gumsley et al. 2015). As mentioned, a link between the Nsuze Group and the Dominion Group requires further validation, as do potential links between the Hlagothi Complex and volcanic rocks within the Mozaan Group and Witwatersrand Supergroup. The start of Neoarchean volcanism during the so-called Ventersdorp event, is now well constrained at ca. 2.78 Ga, while its cessation at ca. 2.65 Ga coincided with the emplacements of dykes radiating across the eastern and southeastern Kaapvaal craton basement and deposition of proto-basinal fills to the Transvaal Supergroup. The compositionally bimodal volcanic rocks in the middle Ventersdorp Supergroup stratigraphy (i.e., the Platberg Group) appear to have erupted between 2730–2708 Ma (De Kock et al. 2012; Armstrong et al. 1991); whereas, more ages are needed to further resolve the older Klipriviersberg Group and younger Allanridge Formation. Regardless, U–Pb geochronology has yet to confirm the geochemical matching of Klipriviersberg Group lavas with potential dyke feeders within the Witwatersrand Supergroup (McCarthy et al. 1990). The sill-like Modipe gabbro represents the only possible feeder associated with the older flood basalt event of the Derdepoort Formation identified so far.

The Ongeluk LIP can now definitively be linked both geochronologically and paleomagnetically to the Ongeluk Formation in the Neoarchean-Paleoproterozoic Transvaal Supergroup overlying the Ventersdorp Supergroup. The volcanic rocks of the Ongeluk Formation were previously thought to be ca. 2.22 Ga (Cornell et al. 1996), and thereby correlated to the ≤2.25–2.24 Ga Hekpoort Formation volcanic rocks, further east (Schröder et al. 2016). However, a combined in situ SIMS, ID-TIMS and paleomagnetic study established a ca. 2.43 Ga age for the Ongeluk Formation and its associated LIP (Gumsley et al. 2017; Kampmann et al. 2015). The volcanic rocks of the Hekpoort Formation, Bushy Bend Member and Machadodorp Member within the Transvaal Supergroup remain undated by U–Pb, however, a ca. 2.17 Ga age established by Larsson (2015) may tentatively link to either of these unconstrained events. The middle Paleoproterozoic 2056–2055 Ma Bushveld Complex, and associated sills, complexes and volcanic rocks is now one of the most well-dated and best constrained magmatic events on the Kaapvaal craton. Evidence of its existence in Zimbabwe has never been documented, however. The same is true for the 1.93–1.92 Ga Hartley LIP event on the Kaapvaal craton. The Tsineng dyke swarm is coeval and temporally linked to the Hartley Formation within the Olifantshoek Supergroup. Dykes and sills of the 1.88–1.83 Ga post-Waterberg sills and Black Hills dyke swarm, however, are more problematic to link with volcanic units, although it has been suggested the Sibasa Formation volcanic rocks in the Soutpansberg Group are coeval (Geng et al. 2014). The 1.88–1.83 Ga magmatic events remains the first coeval match between Kaapvaal and Zimbabwe craton in the assembled Kalahari craton. This is followed by the ca. 1.11 Ga Umkondo LIP event, which is present as both dykes and sills across the whole Kalahari craton, and is coeval with volcanic rocks preserved in the Umkondo Group in Zimbabwe and Mozambique, and in the Kgwebe Formation and in subsurface in Botswana.

5 Summary

It is clear that since the pioneering work by Wilson et al. (1987), Hunter and Reid (1987), and later by Uken and Watkeys (1997), that knowledge of mafic dyke swarms and sill provinces and their relationship with volcanic successions and LIPs has advanced considerably in southern Africa. Many gaps in the knowledge of the Precambrian mafic record of the Kalahari craton remain, but with further multi-disciplinary studies combining the latest developments in U–Pb geochronology and either paleomagnetism or geochemistry, with continued mapping and sampling of relevant igneous rocks, the apparent puzzle is becoming more rigorously solved. Dykes and sills can now be linked conclusively to some key magmatic units in the supracrustal successions, allowing better constraints to be placed on regional stratigraphic frameworks, although other units remain undated. Paleomagnetic clues into paleogeography of the Kalahari craton and its relationship with other cratons, as well as the petrogenesis of the magmatic events can also now be better deduced. Other events, however, require further age constraints, and the use of the geospatial database presented in this study will help to bring together all aspects of the different studies for the future development of our knowledge of the Precambrian mafic record of the Kalahari craton and its relationship with other cratons in time and space.

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References

Alebouyeh Semami F, De Kock MO, Söderlund U, Gumsley AP, Da Silva R, Beukes NJ, Armstrong RA (2016) New U–Pb geochronologic and palaeomagnetic constraints on the late Palaeoproterozoic Hartley magmatic event: evidence for a potential large igneous province in the Kaapvaal Craton during Kalahari assembly, South Africa. GFF https://doi.org/10.1080/11035897.2015.1124917

Allsopp HL, Smith CB, Seggie AG, Skinner EMW, Colgan EA (1995) The emplacement age and geochemical character of the Venetia kimberlite bodies, Limpopo Belt, northern Transvaal. S Afr J Geol 98(3):239–244

Altermann W, Lenhardt N (2012) The volcano-sedimentary succession of the Archean Sodium Group, Ventersdorp Supergroup, South Africa: volcanology, sedimentology and geochemistry. Precambrian Res 214–215:60–81. https://doi.org/10.1016/j.precamres.2012.02.012

Antonio PYJ, D'Agrella-Filho MS, Trindade RIF, Nédélec A, de Oliveira DC, da Silva FF, Roverato M, Lana C (2017) Turmoil before the boring billion: paleomagnetism of the 1880–1860 Ma Uatumã event in the Amazonian craton. Gondwana Res 49:106–129. https://doi.org/10.1016/j.gr.2017.05.006

Armstrong RA, Compston W, Retief EA, Williams IS, Welke HJ (1991) Zircon ion microprobe studies bearing on the age and evolution of the Witwatersrand triad. Precambrian Res 53:243–266

Armstrong RA, Wilson AH (2000) A SHRIMP U-Pb study of zircons from the layered sequence of the Great Dyke, Zimbabwe, and a granitoid anatectic dyke. Earth Planet Sci Lett 180(1–2):1–12

Bailie R, Gutzmer J, Rajesh HM, Armstrong RA (2011) Age of ferroan A-type post-tectonic granitoids of the southern part of the Keimoes Suite, Northern Cape Province, South Africa. J Afr Earth Sci 60:153–174
Barnes S-J, Maier WD, Curl EA (2010) Composition of the marginal rocks and sills of the Rustenburg Layered Suite, Bushveld Complex, South Africa: Implications for the formation of the Platinum-group element deposits. Econ Geol 105:1491–1511
Bartholomew LT (2008) Paleomagnetism of neoproterozoic intraplate igneous rocks in the southwest Kalahari craton, Namibia and South Africa. Unpublished MSc thesis, Texas Christian University, USA
Barton JM (1979) The chemical compositions, Rb-Sr isotopic systematics and tectonic setting of certain post-kinematic mafic igneous rocks, Limpopo Mobile Belt, southern Africa. Precambrian Res 9:57–80
Barton JMJ, Blignaut E, Salnikova EB, Kotov AB (1995) The stratigraphical position of the Buffelsfontein Group based on field relationships and chemical and geochronological data. S Afr J Geol 98:386–392
Barton JMJ, Barton ES, Smith CB (1996) Petrography, age and origin of the Schiel alkaline complex, northern Transvaal, South Africa. J Afr Earth Sci 22(2):133–145
Becker T, Schreiber U, Kampunzu AB, Armstrong RA (2006) Mesoproterozoic rocks of Namibia and their plate tectonic setting. J Afr Earth Sci 46:112–140
Belica ME, Piispa EJ, Meert JG, Pesonen LJ, Plado J, Pandit MK, Kamenov GD, Celestino M (2014) Paleoproterozoic mafic dyke swarms from the Dharwar craton; paleomagnetic poles for India from 2.37 to 1.88 Ga and rethinking the Columbia supercontinent. Precambrian Res 244:100–122
Beukes NJ, Cairncross B (1991) A lithostratigraphic-sedimentological reference profile for the Late Archean Mozaan Group, Pongola Sequence: application to sequence stratigraphy and correlation with the Witwatersrand Supergroup. S Afr J Geol 94(1):44–69
Blake DH, Tyler IM, Griffin TJ, Sheppard S, Thorne AM, Warren RG (1999) Geology of the Halls Creek 1:100,000 Sheet area (4461), Western Australia. Australian Geological Survey, Canberra
Bleeker W, Ernst RE (2006) Short-lived mantle generated magmatic events and theri dike swarms: the key unlocking Earth's paleogeographic record back to 2.6 Ga In: Hanski E, Mertanen S, Rämö T, Vuollo J (eds) Dike swarms: time markers of crustal evolution. Taylor & Francis/Balkema, Leiden, pp 3–26
Bleeker W, Chamberlain K, Kamo SL, Hamilton M, Kilian TM, Buchan KL (2016) Kaapvaal, Superior and Wyoming: nearest neighbours in supercraton Superia. Paper presented at the 35th international geological congress, Cape Town, South Africa
Borg G, Kärner K, Buxton M, Armstrong RA, Van der Merwe SW (2003) Geology of the Skorpion supergene zinc deposit, Southern Namibia. Econ Geol 98:749–771
Briden JC, Duff BA, Kröner A (1979) Palaeomagnetism of the Koras Group, Northern Cape province, South Africa. Precambrian Res 10:43–57
Buchan KL, Ernst RE, Bleeker W, Davies W, Villeneauve M, Van Breemen O, Hamilton M, Söderlund U (2010) Proterozoic magmatic events of the Slave craton, Wopmay orogen and environs. In: Geological Survey of Canada, Open File 5985. Geological Survey of Canada
Burke K, Kidd WSF, Kusky TM (1985) The Pongola structure of southeastern Africa: the world's oldest preserved rift? J Geodyn 2:35–49
Cawthorn RG, Davies G, Clubley-Armstrong A, McCarthy TS (1981) Sills associated with the Bushveld Complex, South Africa: an estimate of the parental magma composition. Lithos 14:1–16
Cawthorn RG, Eales HV, Walraven F, Uken R, Watkeys MK (2006) The bushveld complex. In: Johnston MR, Anhaeusser CR, Thomas RJ (eds) The geology of South Africa. The Geological Society of South Africa and Council for Geosciences, Pretoria, South Africa, pp 261–281
Cheney ES (1996) Sequence stratigraphy and plate tectonic significance of the Transvaal succession of southern Africa and its equivalent in Western Australia. Precambrian Res 79:3–24
Ciborowski T, Minifie M, Kerr AC, Baragar B, Millar IL (2017) A mantle plume origin for the Palaeoproterozoic Circum Superior Large Igneous Province. Precambrian Res 294:189–213

Clarke B, Uken R, Reinhardt J (2009) Structural and compositional constraints on the emplacement of the Bushveld Complex, South Africa. Lithos 111:21–36. https://doi.org/10.1016/j.lithos.2008.11.006

Clifford TN (1970) The structural framework of Africa. In: Clifford TN, Gass IG (eds) African magmatism and tectonics. Oliver and Boyd, Edinburgh, pp 1–26

Coffin MF, Eldholm O (1994) Large igneous provinces: crustal structure, dimensions, and external consequences. Rev Geophys 32:1–36

Coffin MF, Eldholm O (2001) Large igneous provinces: progenitors of some ophiolites? In: Ernst RE, Buchan KL (eds) Mantle plumes: their identification through time. Special Paper, vol 352. Geological Society of America, Boulder, CO, pp 59–70

Cole EG (1994) Lithostratigraphy and depositional environment of the Archaean Nsuze Group, Pongola Supergroup. Unpublished PhD thesis, Rand Afrikaans University, Johannesburg, South Africa

Cole J, Webb SJ, Finn CA (2014) Gravity models of the Bushveld Complex—have we come full circle? J Afr Earth Sci 92:97–118

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. Precambrian Res 79:101–123

Cornell DH, Armstrong RA, Walraven F (1998) Geochronology of the Proterozoic Hartley Basalt Formation, South Africa: constraints on the Kheis tectogenesis and the Kaapvaal Craton's earliest Wilson Cycle. J Afr Earth Sci 26(1):5–27

Cornell DH, Van Schjindel V, Simonsen SL, Frei D (2015) Geochronology of Mesoproterozoic hybrid intrusions in the Konkiep Terrane, Namibia, from passive to active continental margin in the Namaqua-Natal Wilson Cycle. Precambrian Res 265:166–188

Cornell DH, Zack T, Anderson T, Corfu F, Frei D, Van Schjindel V (2016) Restricted access Th-U-Pb zircon geochronology of the Palaeoproterozoic Hartley Formation porphyry by six methods, with age uncertainty approaching 1 Ma. S Afr J Geol 119:473–494. https://doi.org/10.2113/gssajg.119.3.473

Cornell DH, Meintjies PG, Van der Westerhuizen WA, Frei D (2018) Microbeam U-Pb zircon dating of the Makwassie and Goedgenoeg formations in the Ventersdorp Supergroup of South Africa. S Afr J Geol 120(4):525-540

Corner B, Verran DR, Hildebrand PR (2012) Geophysical interpretation of the nature and extent of the Xade Mafic Complex, Botswana. S Afr J Geol 115(4):485–498

Dalziel IWD (1997) Neoproterozoic-Paleozoic geography and tectonics: review, hypothesis, environmental speculation. Geol Soc Am Bull 109:16–42

De Kock MO, Evans DAD, Dorland HC, Beukes NJ, Gutzmer J (2006) Paleomagnetism of the lower two unconformity-bounded sequences of the Waterberg Group, South Africa: towards a better-defined apparent polar wander path for the Paleoproterozoic Kaapvaal Craton. S Afr J Geol 109(1):157–182

De Kock MO, Evans DAD, Beukes NJ (2009) Validating the existence of Vaalbara in the late Neoarchean. Precambrian Res 174:145–154

De Kock MO, Beukes NJ, Armstrong RA (2012) New SHRIMP U-Pb zircon ages from the Hartswater Group, South Africa: implications for correlations of the Neoarchean Ventersdorp Supergroup on the Kaapvaal craton and with the Fortesque Group on the Pilbara craton. Precambrian Res 204–205:66–74

De Kock MO, Ernst RE, Söderlund U, Jourdan F, Hofmann A, Le Gall B, Bertrand H, Chisonga BC, Beukes NJ, Rajesh HM, Moseki LM, Fuchs R (2014) Dykes of the 1.11 Ga Umkondo LIP, Southern Africa: clues to a complex plumbing system. Precambrian Res 249:129–143. https://doi.org/10.1016/j.precamres.2014.05.006

De Kock MO, Ravhura L, Vorster C, Beukes NJ, Gumsley AP (2016) Constraining the timing of the Molopo Farms Complex emplacement and provenance of its country rock. Acta Geol Sin 90:78. https://doi.org/10.1111/1755-6724.12898

De Waal SA, Armstrong RA (2000) The age of the Marble Hall diorite, its relationship to the UItkomst Complex, and evidence for a new magma type associated with the Bushveld igneous event. S Afr J Geol 103(2):128–140
De Waal SA, Graham IT, Armstrong RA (2006) The Lindeques Drift and Heidelberg intrusions and the Roodekraal Complex, Vredefort, South Africa: comagmatic plutonic and volcanic products of a 2055 Ma ferrobasaltic magma. S Afr J Geol 109:270–300
De Waal SA, Schweitzer JK, Graham I, Gauert CDK, Ripley E (2008) A Bushveld-related high-Ti igneous suite (HITIS) derived from an alkali to transitional basaltic magma, South Africa. S Afr J Geol 111:201–224
De Wit MJ, Roering C, Hart RJ, Armstrong RA, De Ronde CEJ, Green RWE, Tredoux M, Peberdy E, Hart RA (1992) Formation of an Archaean continent. Nature 357:553–562
Denyszyn SW, Feinberg JM, Renne PR, Scott GR (2013) Revisiting the age and paleomagnetism of the Modipe Gabbro of South Africa. Precambrian Res 238:176–185. https://doi.org/10.1016/j.precamres.2013.10.002
Donnelly CL, Griffin WL, O'Reilly SY, Pearson A, Shee SR (2011) The kimberlites and related rocks of the Kuruman kimberlite province, Kaapvaal craton, South Africa. Contrib Mineral Petrol 161:351–371
Donnelly CL, Griffin WL, Yang J-H, O'Reilly SY, Li Q-L, Pearson NJ, Li X-H (2012) In situ U-Pb dating and Sr-Nd isotopic analysis of Perovskite: constraints on the age and petrogenesis of the Kuruman kimberlite province, Kaapvaal craton, South Africa. J Petrol 53(12):2497–2522
Dorland HC, Beukes NJ, Gutzmer J, Evans DAD, Armstrong RA (2006) Precise SHRIMP U-Pb zircon age constraints on the lower Waterberg and Soutpansberg Groups, South Africa. S Afr J Geol 109(1):139–156
Eglington BM, Armstrong RA (2004) The Kaapvaal Craton and adjacent orogens, southern Africa: a geochronological database and overview of the geological development of the craton. S Afr J Geol 107:13–32
Elburg M, Cawthorn RG (2017) Source and evolution of the alkaline Pilanesberg Complex, South Africa. Chem Geol 455:148–165. https://doi.org/10.1016/j.chemgeo.2016.10.007
Emerman SH (1991) Correlation of a dyke swarm in southeastern Botswana with the Pilanesberg dyke swarm, South Africa. J Afr Earth Sci 12(4):525–531
Eriksson PG, Engelbrecht JP, Res M, Harmer RE (1994) The Bushy Bend lavas, a new volcanic member of the Pretoria Group, Transvaal Sequence. S Afr J Geol 97:1–7
Eriksson PG, Altermann W, Hartzer FJ (2006) The Transvaal Supergroup. In: Johnson MR, Anhaeusser C, Thomas RJ (eds) The geology of South Africa. Geological Society of South Africa/Council for Geoscience, Johannesburg/Pretoria, pp 237–260
Erlank AJ (1984) Petrogenesis of the volcanic rocks of the Karoo Province (Special Publication No 13). Geological Society of South Africa, South Africa
Ernst RE (2014) Large igneous provinces. Cambridge University Press, Cambridge, United Kingdom
Ernst RE, Bleeker W (2010) Large igneous provinces (LIPs), giant dyke swarms, and mantle plumes: significance for breakup events within Canada and adjacent regions from 2.5 Ga to the present. Can J Earth Sci 47:695–739
Ernst RE, Head JW, Parfitt E, Grosfils EB, Wilson L (1995) Giant radiating dyke swarms on Earth and Venus. Earth Sci Rev 39:1–58
Ernst RE, Pereira E, Hamilton MA, Pisarevsky SA, Rodriques J, Tassinari CCG, Teixeira W, Van-Dunem V (2013) Mesoproterozoic intraplate magmatic 'barcode' record of the Angola portion of the Congo craton: newly dated magmatic events at 1500 and 1110 Ma and implications for Nuna (Columbia) supercontinent reconstructions. Precambrian Res 230:103–118
Evans DAD (2009) The palaeomagnetically viable, long-lived and all-inclusive Rodinia supercontinent reconstruction. In: Murphy JB, Keppie JD, Hynes AJ (eds) Ancient orogens and modern analogues, vol 327. Geological society. London, Special Publications, pp 371–404
Evans DA (2013) Reconstructing pre-Pangean supercontinents. Geol Soc Am Bull 125(11–12):1735–1751

Evans DA, Beukes NJ, Kirschvink JL (1997) Low-latitude glaciation in the Palaeoproterozoic era. Nature 386:262–266

Evans DAD, Smirnov AV, Gumsley AP (2017) Paleomagnetism and U-Pb geochronology of the Black Range dykes, Pilbara Craton, Western Australia: a Neoarchean crossing of the polar circle. Aust J Earth Sci . https://doi.org/10.1080/08120099.2017.1289981

French JE, Heaman LM (2010) Precise U-Pb dating of Paleoproterozoic mafic dyke swarms of the Dharwar craton, India: implications for the existence of the Neoarchean supercraton Sclavia. Precambrian Res 183(3):416–441

French JE, Heaman LM, Chacko T, Srivastava RK (2008) 1891–1883 Ma Southern Bastar-Cuddapah mafic igneous events, India: a newly recognized large igneous province. Precambrian Res 160(3–4):308–322. https://doi.org/10.1016/j.precamres.2007.08.005

Friese AEW, Charlesworth EG, McCarthy TS (1995) Tectonic processes within the Kaapvaal Craton during the Kimbaran (Grenville) orogeny: structural, geophyscial and isotopic constraints from the Witwatersrand Basin and environs, vol 292. Economic geology research unit information circular. University of the Witwatersrand, Johannesburg

Frimmel HE, Klötzli US, Siegfired PR (1996) New Pb-Pb single zircon age constraints on the timing of Neoproterozoic glaciation and continental break-up in Namibia. J Geol 104(4):459–469

Frimmel HE, Zartman RE, Späth A (2001) The Richtersveld Igneous Complex, South Africa: U-Pb zircon and geochemical evidence for the beginning of Neoproterozoic continental breakup. J Geol 109:493–508

Geng H, Brandl G, Sun M, Wong J, Kröner A (2014) Zircon ages defining deposition of the Palaeoproterozoic Soutpansberg Group and further evidence for Eoarchaean crust in South Africa. Precambrian Res 249:247–262. https://doi.org/10.1016/j.precamres.2014.05.020

Gold DJC (2006) The Pongola Supergroup. In: Johnson MR, Anhaeusser CR, Thomas RJ (eds) Geology of South Africa. Geological Society of South Africa/Council for Geoscience, Johannesburg/Pretoria, pp 135–147

Goldberg AS (2010) Dyke swarms as indicators of major extensional events in the 1.9–1.2 Ga Columbia supercontinent. J Geodyn 50:176–190

Gose GA, Hanson RE, Dalziel IWD, Pancake JA, Seidel EK (2006) Paleomagnetism of the 1.1 Ga Umkondo large igneous province in southern Africa. J Geophys Res 111:1–18

Gose WA, Hanson RE, Harmer RE, Seidel EK (2013) Reconnaissance paleomagnetic studies of Mesoproterozoic alkaline igneous complexes in the Kaapvaal craton, South Africa. J Afr Earth Sci 85:22–30. https://doi.org/10.1016/j.jafrearsci.2013.04.005

Gough DL, Hales AL (1956) A paleomagnetic study of the palaeomagnetism of the Pilanesberg dykes. Mon Not R Astron Soc Geophys Suppl 7:196–213

Griffin WL, Batumike JM, Greau Y, Pearson NJ, Shee SR, O'Reilly SY (2014) Emplacement ages and sources of kimberlites and related rocks in southern Africa: U-Pb ages and Sr-Nd isotopes of groundmass perovskite. Contrib Mineral Petrol 168:1032

Grobler DF, Walraven F (1993) Geochronology of Gabarone Granite Complex extensions in the area north of Mafikeng, South Africa. Chem Geol 105:319–337

Groenewald PB, Grantham GH, Watkeys MK (1991) Geological evidence for a Proterozoic to Mesozoic link between southeastern Africa and Donning Maud Land, Antarctica. J Geol Soc London 148:1115–1123

Gumsley AP, de Kock MO, Rajesh HM, Knoper MW, Söderlund U, Ernst RE (2013) The Hlagothi Complex: the identification of fragments from a Mesoarchean large igneous province on the Kaapvaal Craton. Lithos 174:333–348. https://doi.org/10.1016/j.lithos.2012.06.007

Gumsley AP, Olsson JR, Söderlund U, De Kock MO, Hofmann A, Klausen M (2015) Precise U-Pb baddeleyite age dating of the Ushushwana Complex, southern Africa—implications for the Mesoarchaean magmatic and sedimentological evolution of the Pongola Supergroup, Kaapvaal Craton. Precambrian Res 257:174–185. https://doi.org/10.1016/j.precamres.2015.06.010

Gumsley AP, Rådman J, Söderlund U, Klausen M (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, Söderlund U, De Kock MO, Larsson ER, Bekker A (2017) Timing and tempo of the Great Oxidation Evenet. Proc Natl Acad Sci USA 114:1811–1816. https://doi.org/10.1073/pnas.1608824114

Gutzmer J, Beukes NJ, Pickard A, Barley ME (2000) 1170 Ma SHRIMP age for Koras Group bimodal volcanism, Northern Cape Province. S Afr J Geol 103:32–37

Hamilton MA, Sadowski GR, Teixeira W, Ernst RE, Ruiz AS (2012) Precise, matching U-Pb ages for the Rincon del Tigre mafic layered intrusion and Huanchaca gabbro sill, Bolivia: evidence for a late Mesoproterozoic LIP in SW Amazonia? In: Geoscience at the Edge, GAC-MAC Joint Annual Meeting, St. John's

Hammerbeck ECI, Allcock RJ (1985) 1:4,000,000 Geological map of Southern Africa. The Geological Society of South Africa, Pretoria, South Africa

Hanson RE (2003) Proterozoic geochronology and tectonic evolution of southern Africa. In: Yoshida M, Windley BF, Dasgupta S (eds) Proterozoic East Gondwana: Supercontinent assembly and breakup, vol 1. Geological society special publication no 206. The Geological Society, London, pp 427–463

Hanson RE (Pers. comm.) TIMS ages for main felsic igneous rocks associated with the Gannakouriep dykes

Hanson RE, Martin MW, Bowring SA, Munyanyiwa H (1998) U-Pb zircon age for the Umkondo dolerites, eastern Zimbabwe: 1.1 Ga large igneous province in southern Africa-East Antarctica and possible Rodinia correlations. Geology 26(12):1143–1146

Hanson RE, Crowley JL, Bowring SA, Ramazani J, Gose WU, Dalziel IWD, Pancake JA, Seidel EK, Blenkinsop TG, Mukwakwami J (2004a) Coeval large-scale magmatism in the Kalahari and Laurentian cratons during Rodinia assembly. Science 304:1126–1129

Hanson RE, Gose WA, Crowley JL, Ramezani J, Bowring SA, Bullen DS, Hall RP, Pancake JA, Mukwakwami J (2004b) Paleoproterozoic intraplate magmatism and basin development on the Kaapvaal Craton: Age, paleomagnetism and geochemistry of ~1.93 to ~1.87 Ga post-Waterberg dolerites. S Afr J Geol 107:233–254

Hanson RE, Harmer RE, Blenkinsop TG, Bullen DS, Dalziel IWD, Gose WA, Hall RP, Kampunzu AB, Key RM, Mukwakwami J, Munyanyiwa H, Pancake JA, Seidel EK, Ward SE (2006) Mesoproterozoic intraplate magmatism in the Kalahari Craton: A review. J Afr Earth Sci 46:141–167

Hanson RE, Rioux M, Bowring SA, Gose GA, Bartholomew LT, Kilian TM, Evans DA, Panzik JE, Hoffmann KH, Reid DL (2011a) Constraints on Neoproterozoic intraplate magmatism in the Kalahari craton: geochronology and paleomagnetism of ~890–795 Ma extension-related igneous rocks in SW Namibia and adjacent parts of South Africa. In: Geological Society of America Abstracts with Programs, vol 5, p 371

Hanson RE, Rioux M, Gose WA, Blackburn TJ, Bowring SA, Mukwakwami J, Jones DL (2011b) Paleomagnetic and geochronological evidence for large-scale post 1.88 Ga displacement between the Zimbabwe and Kaapvaal cratons along the Limpopo belt. Geology 39(5):487–490

Hargraves RB (1989) Paleomagnetism of Mesozoic kimberlites in southern Africa and the Cretaceous apparent polar wander curve for Africa. J Geophys Res 94(B2):1851–1866

Harmer RE (1999) The petrogenetic association of carbonatite and alkaline magmatism: constraints from the Spitskop Complex, South Africa. J Petrol 40:525–548

Hart R, Moser D, Andreoli M (1999) Archean age for the granulite facies metamorphism near the center of the Vredefort structure, South Africa. Geology 27(12):1091–1094

Hartnady CJH, Joubert P, Stowe C (1985) Proterozoic crustal evolution in southwestern Africa. Episodes 8:236–244

Hatton CJ (1995) Mantle plume origin for the Bushveld and Ventersdorp magmatic provinces. J Afr Earth Sci 21(4):571–577

Heaman LM, LeCheminant AN (1993) Paragenesis and U-Pb systematics of baddeleyite (ZrO_2). Chem Geol 110:95–126

Heaman LM (2009) The application of U-Pb geochronology to mafic, ultramafic and alkaline rocks. An evaluation of three mineral standards. Chem Geol 261(1–2):43–52

Hegner E, Kröner A, Hunt P (1994) A precise U-Pb zircon age for the Archaean Pongola Supergroup volcanics in Swaziland. J Afr Earth Sci 18:339–341. https://doi.org/10.1016/0899-5362(94)90072-8

Henderson DR, Long LE, Barton JM Jr (2000) Isotopic ages and chemical and isotopic composition of the Archaean Turfloop Batholith, Pieterburg granite-greenstone terrane, Kaapvaal Craton, South Africa. S Afr J Geol 103(38):46

Hofmann A, Kröner A, Hegner E, Belyanin GA, Kramers JD, Bolhar R, Slabunov A, Reinhardt J, Horváth P (2015) The Nhlangano gneiss dome in south-west Swaziland—a record of crustal destabilization of the eastern Kaapvaal craton in the Neoarchaean. Precambrian Res 258:109–132. https://doi.org/10.1016/j.precamres.2014.12.008

Holzer L, Frei R, Barton JM Jr, Kramers JD (1998) Unraveling the record of successive high grade events in the Central Zone of the Limpopo Belt using Pb single phase dating of metamorphic minerals. Precambrian Res 87:87–115

Horn I, Rudnick RL, McDonough WF (2000) Precise elemental and isotope ratio determination by simultaneous solution nebulization and laser-ablation-ICP-M.S.: application to U-Pb geochronology. Chem Geol 167:405–425

Humbert F, Sonnette L, De Kock MO, Robion P, Horng CS, Cousture A, Wabo H (2017) Palaeomagnetism of the early Palaeoproterozoic, volcanic Hekpoort Formation (Transvaal Supergroup) of the Kaapvaal craton, South Africa. Geophys J Int 209:842–865. https://doi.org/10.1093/gji/ggx055

Hunt JP, Hatton C, De Kock MO, Bleeker W (2017) Plume activity related to the Kaapvaal craton and implications for Rhyacian plate reconstructions and ore deposits. Paper presented at the SGA Quebec 2017, Quebec City, Canada, 20–23 Aug 2017

Hunter DR, Reid DL (1987) Mafic Dyke Swarms in Southern Africa. In: Halls HC, Fahring WF (eds) Mafic Dyke Swarms. Geological Association of Canada, pp 445–456

Jacobs J, Pisarevsky S, Thomas RJ, Becker T (2008) The Kalahari Craton during the assembly and dispersal of Rodinia. Precambrian Res 160:142–158

Jelsma HA, de Wit MJ, Thiart C, Dirks PHGM, Viola G, Basson IJ, Anckar E (2004) Preferential distribution along transcontinental corridors of kimberlites and related rocks of Southern Africa. S Afr J Geol 107:301–324

Johnson SP, Rivers T, De Waele B (2005) A review of the Mesoproterozoic to early Palaeozoic magmatic and tectonothermal history of south-central Africa: implications for Rodinia and Gondwana. J Geol Soc 162(3):433–450

Johnson SP, De Waele B, Evans DM, Banda W, Tembo F, Milton JA, Tani K (2007) Geochronology of the Zambezi Supracrustal Sequence, southern Zambia: A record of Neoproterozoic divergent processes along the southern margin of the Congo Craton. J Geol 115:355–374

Jones DL, McElhinny MW (1966) Paleomagnetic correlation of basic intrusions in the Precambrian of southern Africa. J Geophys Res 71:543–552

Jones DL, Robertson IDM, McFadden PL (1974) A paleomagnetic study of the Precambrian dyke swarms associated with the great Dyke of Rhodesia. Trans Geol Soc S Afr 78:57–65

Jones DL, Bates MP, Li ZX, Corner B, Hodgkinson G (2003) Palaeomagnetic results from the ca. 1130 Ma Borgmassivet intrusions in the Ahlmannryggen region of Dronning Maud Land, Antarctica, and tectonic implications. Tectonophysics 375:247–260

Jourdan F, Féraud G, Bertrand H, Kampunzu AB, Tshoso G, Le Gall B, Tiercelin JJ, Capiez P (2004) The Karoo triple junction questioned: evidence from Jurassic and Proterozoic $^{40}Ar/^{39}Ar$ ages and geochemistry of giant Okovango dyke swarm (Botswana). Earth Planet Sci Lett 222:989–1006

Jourdan F, Féraud G, Bertrand H, Watkeys MK, Kampunzu AB, Le Gall B (2006) Basement control on dyke distribution in Large Igneous Provinces: case study of the Karoo triple junction. Earth Planet Sci Lett 241:307–322

Kampmann TC, Gumsley AP, De Kock MO, Söderlund U (2015) U-Pb geochronology and paleomagnetism of the Westerberg Sill Suite, Kaapvaal Craton - Support for a coherent Kaapvaal-Pilbara Block (Vaalbara) into the Paleoproterozoic? Precambrian Res 269:58–72

Kasbohm JJ, Evans DAD, Panzik JE, Hofmann M, Linnemann U (2016) Paleomagnetic and geochronologic data from late Mesoproterozoic red bed sedimentary rocks on the western margin of Kalahari craton. In: Li ZX, Evans DAD, Murphy JB (eds) Supercontinent cycles through earth history. Geological Society of London Special Publication, 424. Geological Society of London, London, pp 145–165

Katongo C, Koller F, Kloetzli U, Koeberl C, Tembo F, De Waele B (2004) Petrography, geochemistry, and geochronology of granitoid rocks in the Neoproterozoic-Paleozoic Lufilian-Zambezi belt, Zambia: Implications for tectonic setting and regional correlation. J Afr Earth Sci 40(5):219–244

Key R, Mapeo R (1999) The Mesoproterozoic history of Botswana and the relationship of the NW Bostwana Rift to Rodinia. Episodes 22(2):118–122

Kilian TM, Chamberlain K, Evans DAD, Bleeker W, Cousens BL (2016) Wyoming on the run—-towards final Paleoproterozoic assembly of Laurentia. Geology 44(10):863–866. https://doi.org/10.1130/G38042.1

Klausen MB, Söderlund U, Olsson JR, Ernst RE, Armoogam M, Mkhize SW, Petzer G (2010) Petrological discrimination among Precambrian dyke swarms: Eastern Kaapvaal craton (South Africa). Precambrian Res 183(3):501–522. https://doi.org/10.1016/j.precamres.2010.01.013

Knoper MW, Ernst RE, Kamo SL, Bleeker W, Söderlund U (2014) Three LIPs on two and half cratons. In: 2014 GSA Annual Meeting, Vancouver, Canada, 19–22 Oct 2014

Kramers JD, Mouri H (2011) The geochronology of the Limpopo Complex: a controversy solved. In: Van Reenen DD, Kramers JD, McCourt S, Perchuk LL (eds) Origin and evolution of precambrian high-grade Gneiss Terranes, with special emphasis on the Limpopo Complex of South Africa: geological society of America Memoir 207. The Geological Society of America, pp 85–106

Kramers JD, McCourt S, Roering C, Smit CA, Van Reenen DD (2011) Tectonic models proposed for the Limpopo Complex: mutual compatibilities and constraints. Geol Soc Am Mem 207:311–324

Krogh TE (1973) A low-contamination method for hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determinations. Geochim Cosmochim Acta 37(3):485–494

Krynauw JR, Watters BR, Hunter DR, Wilson AH (1991) A review of the field relationships, petrology and geochemistry of the Borgmassivet intrusions in the Grunehogna province, western Dronnig Maud Land, Antarctica. In: Thomson MRA, Crame JA, Thomson JW (eds) Geological evolution of Antarctica. Cambridge University Press, Cambridge, UK, pp 33–39

Kumar A, Parashuramulu V, Shankar R, Besse J (2017) Evidence for a Nearchean LIP in the Singhbhum craton, eastern India: implications to Vaalbara supercontinent. Precambrian Res 292:163–174. https://doi.org/10.1016/j.precamres.2017.01.018

Larsson ER (2015) U-Pb baddeleyite dating of intrusions in the south-easternmost Kaapvaal Craton (South Africa): revealing multiple events of dyke emplacement. MSc Thesis, Lund University, Lund, Sweden

Laurent O, Zeh A (2015) A linear Hf isotope-age array despite different granitoid sources and complex Archean geodynamics: example from the Pietersburg block (South Africa). Earth Planet Sci Lett 430:326–338. https://doi.org/10.1016/j.epsl.2015.08.082

Laurent O, Paquette J-L, Martin H, Doucelance R, Moyen J-F (2013) LA-ICP-MS dating of zircons from Meso- and Neoarchean granitoids of the Pieterburg block (South Africa): crustal evolution at the northern margin of the Kaapvaal craton. Precambrian Res 230:209–226. https://doi.org/10.1016/j.precamres.2013.02.009

Layer PW, Kröner A, McWilliams M, Burghele A (1988) Paleomagnetism and age of the Archean Usushwana Complex, Southern Africa. J Geophys Res 93(B1):449–457

Layer PW, Kröner A, McWilliams M, York D (1989) Elements of the Archean thermal history and apparent polar wander of the eastern Kaapvaal craton, Swaziland, from single grain dating and paleomagnetism. Earth Planet Sci Lett 93:23–24

Letts S, Torsvik TH, Webb SJ, Ashwal LD, Eide EA, Chunnett G (2005) Palaeomagnetism and $^{40}Ar/^{39}Ar$ geochronology of mafic dykes from the eastern Bushveld Complex (South Africa). Geophys J Int 162:36–48

Letts S, Torsvik TH, Webb SJ, Ashwal LD (2009) Palaeomagnetism of the 2054 Ma Bushveld Complex (South Africa): implications for emplacement and cooling. Geophys J Int 179:850–872. https://doi.org/10.1111/j.1365-246X.2009.04346.x

Letts S, Torsvik TH, Webb SJ, Ashwal LD (2010) New Palaeoproterozoic palaeomagnetic data from the Kaapvaal Craton, South Africa. Geol Soc Lond Spec Publ 357:9–26

Li ZX, Bogdanova SV, Collins AS, Davidson A, De Waele B, Ernst RE, Fitzsimons ICW, Fuck RA, Gladkochub DP, Jacobs J, Karlstrom KE, Lu S, Natapov LM, Pease V, Pisarevsky SA, Thrane K, Vernikovsky V (2008) Assembly, configuration, and break-up history of Rodinia: a synthesis. Precambrian Res 160:179–210

Lister JR, Kerr RC (1991) Fluidmechanical models of crack propagation and their application to magma transport in dikes. J Geophys Res 96(B6):10049–10077

Lubnina N, Ernst RE, Klausen M, Söderlund U (2010) Paleomagnetic study of Neoarchean-Paleoproterozoic dykes in the Kaapvaal Craton. Precambrian Res 183:523–552. https://doi.org/10.1016/j.precamres.2010.05.005

MacDonnald FA, Schmitz MD, Crowley JL, Roots CF, Jones DS, Maloof AC, Strauss JV, Cohen PA, Johnston DT, Schrag DP (2010) Calibrating the cryogenian. Science 327:1241–1243

Maier WD, Peltonen P, Grantham G, Mänttäri I (2003) A new 1.9 Ga age for the Trompsburg intrusion, South Africa. Earth Planet Sci Lett 212:351–360. https://doi.org/10.1016/S0012-821X(03)00281-4

Maier WD, Prevec SA, Scoates JS, Wall CJ, Barnes S-J, Gomwe T (2017) The Uitkomst intrusion and Nkomati Ni-Cu-Cr-PGE deposit, South Africa: trace element geochemistry, Nd isotopes and high-precision geochronology. Miner Depos 1–22. https://doi.org/10.1007/s00126-017-0716-x

Majaule T, Hanson RE, Key R, Singletary SJ, Martin MW, Bowring SA (2001) The Magondi Belt in northeast Botswana: regional relations and new geochronological data from the Sua Pan area. J Afr Earth Sci 32(2):257–267

Manyeruke TD, Blenkinsop TG, Buchholz P, Love D, Oberthür T, Vetter UK, Davis DW (2004) The age and petrology of the Chimbadzi Hill Intrusion, NW Zimbabwe: first evidence for early Paleoproterozoic magmatism in Zimbabwe. J Afr Earth Sc 40(5):281–292

Mapeo RBM, Armstrong RA, Kampunzu AB, Ramokate LV (2004a) SHRIMP U-Pb zircon ages of granitoids from the Western Domain of the Kaapvaal Craton, Southeastern Botswana: implications for crustal evolution. S Afr J Geol 107:159–172

Mapeo RBM, Kampunzu AB, Ramokate LV, Corfu F, Key RM (2004b) Bushveld-age magmatism in southeastern Botswana: evidence from U-Pb zircon and titanite geochronology of the Moshaneng Complex. S Afr J Geol 107:219–232

Maré LP, Fourie CJS (2012) New geochemical and palaeomagnetic results from Neoarchaean dyke swarms in the Badplaas-Barberton area, South Africa. S Afr J Geol 115(2):145–170

Marsh JS, Bowen MP, Rogers NW, Bowen TB (1989) Volcanic rocks of the Witwatersrand Triad, South Africa. II: Petrogenesis of mafic and felsic rocks of the Dominion Group. Precambrian Res 44:39–65. https://doi.org/10.1016/0301-9268(89)90075-2

Master S (1991) Stratigraphy, tectonic setting and mineralization of the Early Proterozoic Magondi Supergroup, Zimbabwe: a review, vol 238. Economic geology research institute information circular. University of the Witwatersrand, Johannesburg, South Africa

McCarthy TS, McCallum K, Myers RE, Linton P (1990) Stress states along the northern margin of the Witwatersrand Basin during Klipriviersberg Group volcanism. S Afr J Geol 93:245–260

McCourt S, Hilliard P, Armstrong RA, Munyanyiwa H (2001) SHRIMP U-Pb zircon geochronology of the Hurungwe granite northwest Zimbabwe: age constraints on the timing of the Magondi orogeny and implications for correlation between the Kheis and Magondi Belts. S Afr J Geol 104:39–46

McDougall I (1963) Potassium-argon age measurements on dolerites from Antarctica and South Africa. J Geophys Res 68:1535–1545

McElhinny MW (1966) The palaeomagnetism of the Umkondo Lavas, Eastern Southern Rhodesia. Geophys J Roy Astron Soc 10:375–381

McElhinny MW, Opdyke ND (1964) The paleomagnetism of the Precambrian dolerites of eastern Southern Rhodesia, an example of geologic correlation by rock magnetism. J Geophys Res 69:1465–1475

Meier DL, Heinrich CA, Watts MA (2009) Mafic dikes displacing Witwatersrand gold reefs: evidence against metamorphic-hydrothermal ore formation. Geology 37:607–610. https://doi.org/10.1130/G25657A

Mertanen S, Hölttä P, Pesonen LJ, Paavola L (2006) In: Hanski E, Mertanen S, Rämö T, Vuollo J (eds) Dyke Swarms—time markers of crustal evolution: selected papers of the fifth international dyke conference in Finland, Rovaniemi, Finland, 31 July–3 Aug 2005 & Fourth international dyke conference, Kwazulu-Natal, South Africa 26–29 June 2001. CRC Press, London, pp 243–256

Miller RM (2008) The geology of Namibia, vol 1, Archean to Mesoproterozoic, vol 1. Ministry of Mines and Energy, Geological Survey of Namibia, Windhoek

Miller RM (2012) Review of Mesoproterozoic magmatism, sedimentation and terrane amalgamation in southwestern Africa. S Afr J Geol 115(4):417–448

Mitchell RN, Hoffman PF, Evans DAD (2010) Coronation loop resurrected: oscillatory apparent polar wander of Orosirian (2.05–1.8 Ga) paleomagnetic poles from Slave craton. Precambrian Res 179:121–134

Moen HFG (1999) The Kheis Tectonic Subprovince, southern Africa: a lithostratigraphic perspective. S Afr J Geol 102(1):27–42

Moore M, Davis DW, Robb LJ, Jackson MC, Grobler DF (1993) Archean rapakivi granite-anorthosite-rhyolite complex in the Witwatersrand basin hinterland, southern Africa. Geology 21:1031–1034

Mukasa SB, Wilson AH, Young KR (2013) Geochronological constraints on the magmatic and tectonic development of the Pongola Supergroup (Central Region), South Africa. Precambrian Res 224:268–286

Mukwakwami J (2005) Structural geology of the Umkondo Group in eastern Zimbabwe and geochronology of associated mafic rocks and possible correlatives in Zimbabwe. Unpublished PhD thesis, University of Zimbabwe, Harare, Zimbabwe

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. https://doi.org/10.1038/ncomms13385

Munyanyiwa H (1999) Geochemical study of the Umkondo dolerites and lavas in the Chimanimani and Chipinge districts (eastern Zimbabwe) and their regional implications. J Afr Earth Sci 28(2):349–365

Nhleko N (2003) The Pongola Supergroup in Swaziland. Unpublished PhD thesis, Rand Afrikaans University, Johannesburg, South Africa

Oberthür T, Davis DW, Blenkinsop TG, Höhndorf A (2002) Precise U-Pb mineral ages, Rb-Sr and Sm-Nd systematics for the Great Dyke, Zimbabwe—constraints on late Archean events in the Zimbabwe craton and Limpopo belt. Precambrian Res 113(3–4):293–305

Olsson JR, Söderlund U, Klausen MB, Ernst RE (2010) U-Pb baddeleyite ages linking major Archean dyke swarms to volcanic-rift forming events in the Kaapvaal craton (South Africa), and a precise age for the Bushveld Complex. Precambrian Res 183:490–500

Olsson JR, Söderlund U, Hamilton MA, Klausen MB, Helffrich GR (2011) A late Archean radiating dyke swarm as possible clue to the origin of the Bushveld Complex. Nat Geosci 4:865–869

Olsson JR, Klausen M, Hamilton M, März N, Söderlund U, Roberts RJ (2016) Baddeleyite U-Pb ages and geochemistry of the 1875–1835 Ma Black Hills Dyke Swarm across north-eastern South Africa: part of a trans-Kalahari Craton back-arc setting? GFF 138(1):183–202. https://doi.org/10.1080/11035897.2015.1103781

Panzik JE, Evans DAD, Kasbohm JJ, Hanson RE, Gose WA, Desormeau J (2016) Using palaeomagnetism to determine late Mesoproterozoic palaeogeographic history and tectonic relations of the Sinclair Terrane, Namaqua orogen, Namibia. In: Li ZX, Evans DAD, Murphy JB (eds) Supercontinent cycles through earth history. Geological Society of London Special Publication, 424. Geological Society of London, London, pp 119–143

Peng P (2015) Precambrian mafic dyke swarms in the North China Craton and their geological implications. Sci China: Earth Sci 58:649–675

Peng P, Guo J, Windley BF, Li X (2011) Halaqin volcano-sedimentary succession in the central-northern margin of the North China Craton: products of Late Paleoproterozoic ridge subduction. Precambrian Res 187:165–180

Pesonen LJ, Elming SÅ, Mertanen S, Pisrevsky S, D'Agrella-Filho MS, Meert JG, Schmidt PW, Abrahamsen N, Bylund G (2003) Palaeomagnetic configuration of continents during the Proterozoic. Tectonophysics 375:289–324

Pettersson Å, Cornell DH, Moen HFG, Reddy S, Evans D (2007) Ion-probe dating of 1.2 Ga collision and crustal architecture in the Namaqua-Natal Province of southern Africa. Precambrian Res 158(1–2):79–92. https://doi.org/10.1016/j.precamres.2007.04.006

Pisarevsky SA, Wingate MTD, Powell CM, Johnson S, Evans DAD (2003) Models of Rodinia assembly and fragmentation. In: Yoshida M, Windley BF, Dasgupta S (eds) Proterozoic East Gondwana: supercontinent assembly and breakup. Geological society, London, Special Publication, vol 206. Geological Society, London, pp 35–55

Pisarevsky S, De Waele B, Jones S, Söderlund U, Ernst RE (2015) Paleomagnetism and U-Pb age of the 2.4 Ga Erayinia mafic dykes on the south-western Yilgarn, Western Australia: paleogeographic and geodynamic implications. Precambrian Res 259:222–231. https://doi.org/10.1016/j.precamres.2014.05.023

Polteau S, Moore JM, Tsikos H (2006) The geology and geochemistry of the Paleoproterozoic Makganyene diamictite. Precambrian Res 148:257–274. https://doi.org/10.1016/j.precamres.2006.05.003

Poujol M, Kiefer R, Robb LJ, Anhaeusser CR, Armstrong RA (2005) New U-Pb data on zircons from the Amalia greenstone belt Southern Africa: insights into the Neoarchean evolution of the Kaapvaal Craton. S Afr J Geol 108(3):317–332

Powell C, Jones DL, Pisarevsky SA, Wingate MTD (2001) Palaeomagnetic constraints on the position of the Kalahari craton in Rodinia. Precambr Res 110 (1–4):33–46

Pradhan VR, Meert JG, Pandit MK, Kamenov G, Mondal MEA (2012) Paleomagnetic and geochronological studies of the mafic dyke swarms of Bundelkhand craton, central India: implications for the rectonic evolution and paleogeographic reconstructions. Precambrian Res 198–199:51–76

Rasmussen B, Bekker A, Fletcher IR (2013) Correlation of Paleoproterozoic glaciations based on U-Pb zircon ages for tuff beds in the Transvaal and Huronian Supergroups. Earth Planet Sci Lett 382:173–180. https://doi.org/10.1016/j.epsl.2013.08.037

Reid DL (1997) Sm-Nd age and REE geochemistry of Proterozoic arc-related igneous rocks in the Richtersveld Subprovince, Namaqua Mobile Belt, southern Africa. J Afr Earth Sci 24:621–633

Reid DL, Ransome IGD, Onstott TC, Adams CJ (1991) Time of emplacement and metamorphism of Late Precambrian mafic dykes associated with the Pan-African Gariep orogeny, Southern Africa: implications for the Nama Group. J Afr Earth Sci 13(3):531–541

Reischmann T (1995) Precise U/Pb age determination with baddeleyite (ZrO2), a case study from the Palaborwa Igneous Complex, South Africa. S Afr J Geol 98:1–4

Rioux M, Bowring SA, Dudás F, Hanson RE (2010) Characterizing the U-Pb systematics of baddeleyite through chemical abrasion: application of multi-step digestion methods to baddeleyite geochronology. Contrib Mineral Petrol 160:777–801. https://doi.org/10.1007/s00410-010-0507-1

Rivalta E, Taisne B, Bunger AP, Katz RF (2015) A review of mechanical models of dike propagation: schools of thought, results and future diections. Tectonophysics 638:1–42

Robb LJ, Armstrong RA, Waters DJ (1999) The history of granulite-facies metamorphism and crustal growth from single zircon U-Pb geochronology, Namaqualand, South Africa. J Petrol 40:1747–1770

Roering C, Van Reenen DD, Smit CA, Barton JM Jr, De Beer JH, De Wit MJ, Stettler EH, Van Schalkwyk JF, Stevens G, Pretorius S (1992) Tectonic model for the evolution of the Limpopo Belt. Precambrian Res 55:539–552

Rogers C, Mackinder A, Ernst RE, Cousens B (2016) Mafic magmatism in the Belt-Purcell Basin and Wyoming Province of western Laurentia. Geol Soc Am Spec Pap 522

Rubin AM (1995) Propagation of magma-filled cracks. Annu Rev Earth Planet Sci 23:287–336

Savko KA, Samsonov AV, Kholin VM, Bazikov NS (2017) The Sarmatia Megablock as a fragment of the Vaalbara Supercontinent: correlation of geological events at the Archean-Paleoproterozoic transition. Stratigr Geol Correl 25(2):123–145. https://doi.org/10.1134/S0869593817020058

Schaller M, Steiner O, Studer I, Holzer L, Herwegh M, Kramers JD (1999) Exhumation of Limpopo Central Zone granulites and dextral continent-scale stranscurrent movement at 2.0 Ga along the Palala Shear Zone, Northern province, South Africa. Precambrian Res 96:263–288

Schmitz MD, Bowring SA, De Wit MJ, Gartz V (2004) Subduction and terrane collosion stabilize the western Kaapvaal craton tectosphere 2.9 billion years ago. Earth Planet Sci Lett 222:363–376

Schreiner GDL, Van Niekerk CB (1958) The age of the Pilanesberg dyke from the Central Witwatersrand. Trans Proc Geol Soc S Afr 61:198–199

Schröder S, Beukes NJ, Armstrong RA (2016) Detrital zircon constraints on the tectonostratigraphy of the Paleoproterozoic Pretoria Group, South Africa. Precambrian Res 278:362–393. https://doi.org/10.1016/j.precamres.2016.03.016

Sharpe MR (1981) The chronology of magma influxes to the eastern compartment of the Bushveld Complex as exemplified by its marginal border groups. J Geol Soc Lond 138:307–326

Sharpe MR (1982) Petrology, classification and chronology of the intrusion of mafic sills beneath the eastern Bushveld Complex, vol 37. Institute for the geological research on the Bushveld Complex, Pretoria, South Africa

Singletary SJ, Hanson RE, Martin MW, Crowley JL, Bowring SA, Key RM, Ramokate LV, Direng BB, Krol MA (2003) Geochronology of basement rocks in the Kalahari Desert, Botswana, and implications for regional Proterozoic tectonics. Precambrian Res 121:47–71

Smirnov AV, Evans DAD, Ernst RE, Söderlund U, Li Z-X (2013) Trading partners: tectonic ancestry of southern Africa and western Australia, in Archean supercratons Vaalbara and Zimgarn. Precambrian Res 224:11–22. https://doi.org/10.1016/j.precamres.2012.09.020

Söderlund U, Johansson L (2002) A simple way to extract baddeleyite (ZrO_2). Geochem Geophys Geosystems 3(2). https://doi.org/10.1029/2001gc000212

Söderlund U, Hofmann A, Klausen MB, Olsson JR, Ernst RE, Persson P-O (2010) Towards a complete magmatic barcode for the Zimbabwe craton: Baddeleyite U-Pb dating of regional dolerite dyke swarms and sill complexes. Precambrian Res 183(3):388–398. https://doi.org/10.1016/j.precamres.2009.11.001

Strik G, De Wit MJ, Langereis CG (2007) Palaeomagnetism of the Neoarchaean Pongola and Ventersdorp Supergroups and an appraisal of the 3.0–1.9 Ga apparent polar wander path of the Kaapvaal Craton, Southern Africa. Precambrian Res 153:96–115

Swanson-Hysell NL, Killian TM, Hanson RE (2015) A new grand mean paleomagnetic pole for the Umkondo Igneous Province with implications for paleogeography and the geomagnetic field. Geophys J Int 203:2237–2247

Thomas RJ, Jacobs J, Eglington BM (2000) Geochemistry and isotopic evolution of the Mesoproterozoic Cape Meredith Complex. West Falkland Geol Mag 137(5):537–553

Tinker J, De Wit MJ, Grotzinger J (2002) Seismic stratigraphic constraints on Neoarchean-Paleoproterozoic evolution of the western margin of the Kaapvaal Craton, South Africa. S Afr J Geol 105:107–134

Treloar PJ (1988) The geological evolution of the Magondi Mobile Belt, Zimbabwe. Precambrian Res 38(1):55–73

Uken R, Watkeys MK (1997) An interpretation of mafic dyke swarms and their relationship with major mafic magmatic events on the Kaapvaal Craton and Limpopo Belt. S Afr J Geol 100:341–348

Van der Westhuizen WA, De Bruiyn H, Meinties PG (1991) The Ventersdorp Supergroup; an overview. J Afr Earth Sci 13(1):83–105

Van der Westhuizen WA, De Bruiyn H, Meintjies PG (2006) The Ventersdorp Supergroup. In: Johnson MR, Anhaeusser C (eds) The geology of South Africa. Geological Society of South Africa/Council for Geoscience, Johannesburg/Pretoria, pp 187–208

Van Niekerk CB (1962) The age of the Gemspost dyke from the Venterspost Gold Mine. Trans Geol Soc S Afr 65:105–111

Van Tongeren JA, Zirakparvar NA, Mathez EA (2016) Hf isotopic evidence for a cogenetic magma source for the Bushveld Complex and associated felsic magmas. Lithos 248:469–477

Verwoerd WJ (2006) The Pilanesberg Alkaline Province. In: Johnston MR, Anhaeusser C (eds) The geology of South Africa. The Geological Society of South Africa and the Council for Geoscience, Pretoria, pp 381–393

Wabo H, De Kock MO, Klausen M, Söderlund U, Beukes NJ (2015a) Paleomagnetism and chronology of B-1 marginal sills of the Bushveld Complex from the eastern Kaapvaal Craton, South Africa. GFF. https://doi.org/10.1080/11035897.2015.1099566

Wabo H, Olsson JR, De Kock MO, Humbert F, Söderlund U, Klausen M (2015b) New U-Pb age and paleomagnetic constraints from the UItkomst Complex, South Africa: clues to the timing of intrusion. GFF. https://doi.org/10.1080/11035897.2015.1098726

Wabo H, Humbert F, De Kock MO, Söderlund U, Maré L, Beukes NJ (2019) Constraining the chronology of the Mashishing dykes from the eastern Kaapvaal craton in South Africa. In: Srivastava RK, Ernst RE, Peng P (eds) Dyke Swarms of the World: A Modern Perspective. Springer Geology. https://doi.org/10.1007/978-981-13-1666-1_6

Walraven F, Hattingh E (1993) Geochronology of the Nebo granite, Bushveld Complex. S Afr J Geol 96:31–41

Walraven F, Pape J (1994) Pb-Pb whole-rock ages for the Pongola Supergroup and the Usushwana Complex, South Africa. J Afr Earth Sci 18:297–308. https://doi.org/10.1016/0899-5362(94)90069-8

Walraven F, Smith CB, Kruger FJ (1991) Age determinations of the Zoetlief Group—a Ventersdorp Supergroup correlative. S Afr J Geol 94(2):220–227

Walraven F, Froick C, Lubala RT (1992) Pb-isotope geochronology of the Schiel Complex, northern Transvaal, South Africa. J Afr Earth Sci 15:103–110

Walraven F, Grobler DF, Key RM (1996) Age equivalents of the Plantation Porphyry and the Kanye Volcanic Formation, southeastern Botswana. S Afr J Geol 99:23–31

Walraven F (1997) Geochronology of the Rooiberg Group, Transvaal Supergroup, South Africa. EGRI Information Circular 316, University of the Witwatersrand, 21pp

Ward SE, Hall RP, Huges DJ (2000) Guruve and Mutare dykes: preliminary geochemical indication of complex Mesoproterozoic mafic magmatic systems in Zimbabwe. J Afr Earth Sci 30(3):689–701

Wilson JF, Jones DL, Kramers JD (1987) Mafic dyke swarms of Zimbabwe. In: Halls HC, Fahring AF (eds) Mafic Dyke Swarms, vol 34. Geological Association of Canada Special Papers, pp 433–444

Wilson JF, Nesbitt RW, Fanning M (1995) Zircon geochronology of Archean felsic sequences in the Zimbabwe Craton: a revision of the greenstone belt stratigraphy and model for crustal growth. In: Coward MP, Reis AC (eds) Early Precambrian Processes, Geological Society, London, Special Publication, vol 95, pp 109–126

Wingate MTD (1998) A palaeomagnetic test of the Kaapvaal-Pilbara (Vaalbara) connection at 2.78 Ga. S Afr J Geol 101(4):257–274

Wingate MTD (2000) Ion microprobe U-Pb zircon and baddeleyite ages for the Great Dyke and its satellite dykes, Zimbabwe. S Afr J Geol 103(1):74–80

Wingate MTD (2001) SHRIMP baddeleyite and zircon ages for an Umkondo dolerite sill, Nyanga Mountains, Eastern Zimbabwe. S Afr J Geol 104:13–22

Woodhead J, Hergt J, Phillps D, Paton C (2009) African kimberlites revisited: in situ Sr-isotope analysis of groundmass perovskite. Lithos 112(Supplement 1):311–317

Wu F-Y, Yang Y-H, Li Q-L, Mitchell RH, Dawson JB, Brandl G, Yuhara M (2011) In situ determinations of U-Pb ages and Sr-Nd-Hf isotopic constraints on petrogenesis of the Phalaborwa carbonatite Complex, South Africa. Lithos 127:309–322

Wu F-Y, Mitchell RH, Li Q-L, Sun J, Liu C-Z, Yang Y-H (2013) In situ U-Pb age determination and Sr-Nd isotopic analysis of perovskite from the Premier (Cullinana) kimberlite, South Africa. Chem Geol 353:83–95

Xie H, Kröner A, Brandl G, Wan Y (2017) Two orogeneic events separated by 2.6 Ga mafic dykes in the Central Zone, Limpopo Belt, southern Africa. Precambrian Res 289:129–141

Zegers TE, De Wit MJ, Dann J, White SH (1998) Vaalbara, Earth's oldest assembled continent? A combined structural, geochronological, and palaeomagnetic test. Terra Nova 10:250–259

Zeh A, Ovtcharova M, Wilson AH, Schaltegger U (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