

# The legacy of African kimberlite and diamond research and exploration for the earth sciences

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## ARTICLE INFO

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## ABSTRACT

Kimberlite is a rare and volumetrically insignificant magmatic rock, which nevertheless has an outsized economic importance as the world's principal source for natural diamonds. Discovered in 1870, in South Africa, it was named after Kimberley, the town that grew around the first mines developed in the pipe-shaped bodies of the newly discovered, ultramafic diamond source rock. Apart from their economic significance, kimberlites are of enormous scientific interest. Originating at great depth, they have entrained a variety of ultramafic and ultrabasic rock fragments (xenoliths) and their disaggregated mineral grains (xenocrysts) that provide a direct window into the upper mantle, making it possible to identify regional variations in the nature of the upper mantle and to understand mantle processes. After a flurry of studies on the heels of the initial kimberlite discoveries, there was a long hiatus in publications between the 1930's and mid-1960's. Kimberlite, diamond, and upper mantle studies received a lasting stimulus in the early 1970's, largely as the result of the seminal First International Kimberlite Conference (1 IKC), held at the University of Cape Town in 1973, and 10 follow-up conferences held since on every continent except Antarctica. This review explores examples of advances and controversies resulting from African-centered research on the subject. The definition and nomenclature of "kimberlite" progressed from applying the term to all igneous rocks with diamond, to distinguishing two types of diamond-bearing kimberlite (Groups I and II), and eventually recognizing that Group I ("archetypal" kimberlite) and Group II (formerly orangeite, now assigned to the olivine lamproite clan) are entirely different rock types, originating below and within the lower part of the lithosphere, respectively. As to the shape of kimberlite pipes, the classic southern African model of a carrot-shaped magmatic system, consisting of a root zone, a steep-sided diatreme, and a crater zone, was based on a composite of the highly eroded Kimberley and Jagersfontein pipes, for the lower part, and the significantly less eroded Orapa pipe in Botswana, for the upper part. Restriction of diamond-bearing igneous rocks to the ancient cratons of Africa led to the formulation of "Clifford's Rule", an important tool in diamond exploration worldwide. Studies of peridotite xenoliths and Mesoarchean ages determined on peridotitic garnet inclusions in diamond xenocrysts from the Kaapvaal craton revealed that the craton is underlain by a deep diamondiferous lithospheric root which is older, cooler, and more refractory (harzburgitic) than the shallower lithosphere under adjacent Proterozoic orogenic belts, in fact providing a petrologic explanation for Clifford's rule. The correlation between harzburgitic garnet and diamond was expanded into a powerful exploration tool, developed, and tested in Africa, that was successfully applied in many other parts of the world. Interpretations of eclogite xenoliths changed from being cognate nodules in kimberlite, to pieces of an eclogite layer, to high-pressure cumulates from eclogitic melts in a peridotitic mantle, to fragments of subducted oceanic crust. Combining the latter interpretation with Archean ages for eclogitic mineral inclusions in diamond xenocrysts, it was recognized that plate tectonic processes began as early as ca. 2.9 Ga and were involved in the formation of the Kaapvaal craton, the oldest major Archean craton in the world. Based on the model developed for typical kimberlite pipes in southern Africa, it has been possible to quantify erosion processes across the southern part of the continent, particularly since the disruption of Gondwana. Dispersion of "pathfinder" kimberlitic indicator minerals (KIMs), including diamond, into drainage networks provide tracers to reconstruct past river systems. Being well endowed with kimberlite pipes, Africa has also been central to the important debate about the relevance of plumes as triggers for kimberlite and other alkaline magmatism.

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Nevertheless, despite the importance of resolving this geological conundrum, it remains highly controversial. Many kimberlites are capped by well-preserved crater-lake facies sediments, most of which are dated as Cretaceous to early Cenozoic, within the time of the proposed Angiosperm Terrestrial Revolution. As the associated plant fossil records are the only ones for the interior of southern Africa during this time interval, they may contribute to solving what has been coined as “Darwin’s Abominable Mystery”, the poorly understood origin of angiosperms (flowering plants).

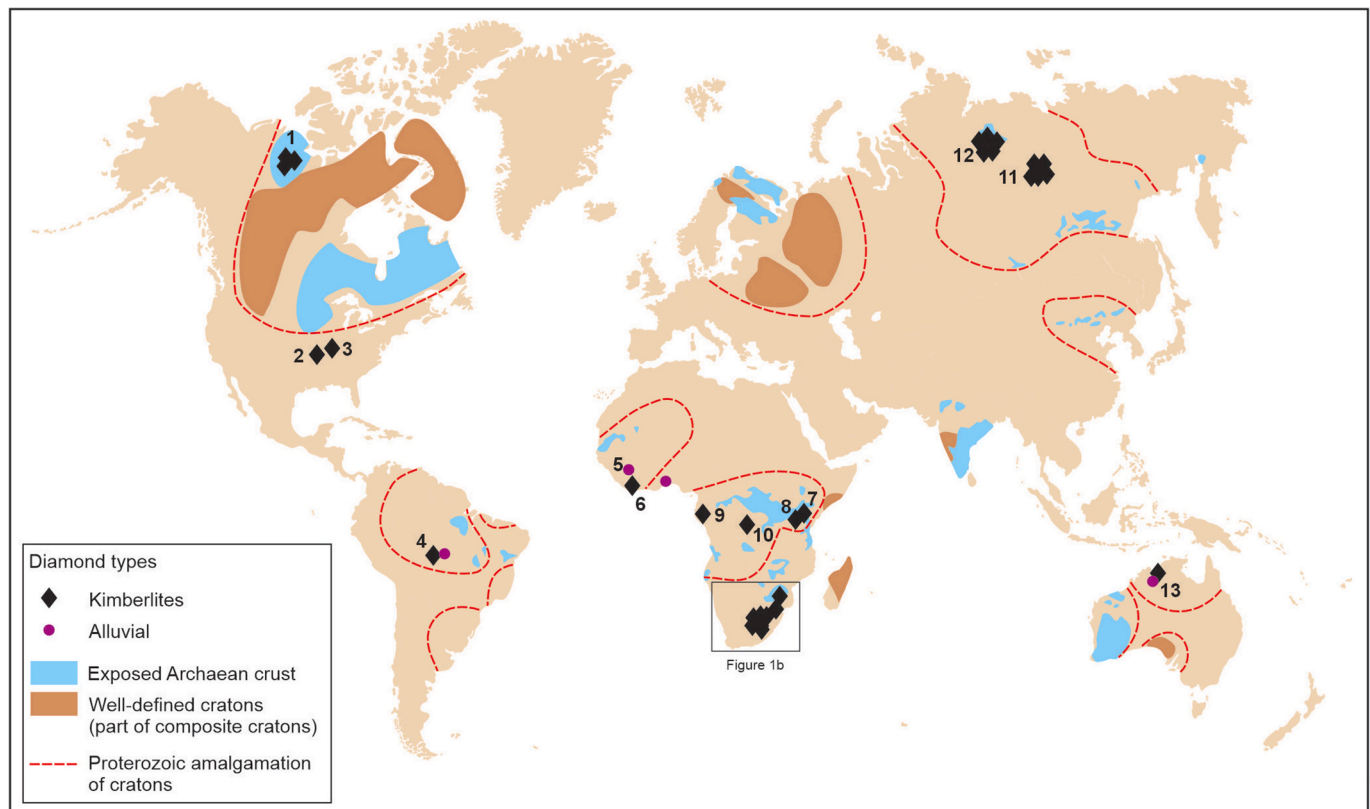
## 1. Introduction

The first reliably recorded diamond was found in late 1866 on the De Kalk farm, near the Orange River, in South Africa (Janse, 1995). Prior to this, individual diamonds had been found in numerous countries, but a steady supply had come only from alluvial placer deposits in India, Borneo, and Brazil. In 1836, alluvial diamonds in the Diamantina area of Brazil had been traced into consolidated bedrock (Janse, 1984), not an igneous source, but a Middle Proterozoic micaceous quartzite (Itacolumite formation), which became known as the “mother rock” for diamond, but later turned out to be the first recognized paleo-placer.

Following the De Kalk and several other diamond finds near the Orange and Vaal rivers, alluvial diamond miners converged on the area and initially mined unconsolidated sands and gravels in stream beds and river terraces, much as it had been done in the diamond fields of India, Borneo, and Brazil. When claims in these river diggings became harder to obtain in 1869 and 1870, prospective miners spread onto the Karoo Plateau, where they encountered diamonds in shallow round depressions, also known as pans, first at Jagersfontein (August 1870), and Dutoitspan (September 1870), but soon thereafter also on the Bultfontein

and Vooruitzicht farms, the latter owned by Jan de Beer. As these diggings were not obviously related to any river course, they became known as “dry” diggings. Initially the miners did not realize it, but after going through some surficial sands and calcrete, they were digging in the yellow and blueish weathering products of a diamondiferous bedrock soon afterwards recognized as igneous rock (Cohen, 1872). The first detailed descriptions of the rock were given by Lewis (1887, 1888, 1897) who named it for the town (and later city) of Kimberley, which had grown up around the first mines developed in the newly discovered diamond source rock. Africa thus gave the world the type locality and name for “kimberlite”, and kimberlitic diamond deposits became known as “primary” diamond deposits. Alluvial placer and paleo-placer deposits, previously the only known diamond sources, were relegated to “secondary” diamond deposits after it was realized that most detrital diamonds are derived from some primary diamond host rock.

Although compared to other igneous rock types, “kimberlite is a rare and volumetrically insignificant rock” (Dawson, 1980, p. 1), it has become the most important primary source of diamonds. Following their initial discovery, diamondiferous kimberlites were found in many other parts of South Africa and after 1940 in many other African countries



**Fig. 1a.** Localities mentioned in this review. 1: Lac de Gras; 2: Mufreesboro; 3: Hamilton Branch; 4: Juina kimberlites and alluvials; 5: Kankan alluvials; 6: Zimmi; 7: Mwadui; 8: Igwisi Hills; 9: Miztik; 10: Mbuji Mayi; 11: Malo-Bituobiya kimberlite field, which includes Mir; 12: Daldyn-Alakit kimberlite field, which includes Zarnitsa and Udachnaya; 13: Argyle. The box shows the location of Fig. 1b which provides locations of southern African localities referred to in the text. Data from Shirey and Richardson, 2011). Note that this figure is intended primarily to show these localities. As discussed in the text, it is inherently difficult to define precise craton boundaries, and those shown by different authorities may accordingly differ in detail from the configuration shown in the figure (see for example, Kjarsgaard et al., 2022).





**Fig. 1b.** Location of southern African kimberlites referred to in the text. The large numbers of kimberlites within the Kimberley cluster are illustrated in Fig. 15a. B-W = Barkley West

(Janse, 1996). As diamondiferous kimberlites were not found outside Africa until the mid-1950's, Africa has dominated the world's diamond production ever since kimberlites were discovered. Kjarsgaard et al. (2022) and de Wit et al. (2016) estimated that from the time of diamond discovery in Africa until the end of 2019, Africa has produced almost 3.6 billion carats, which compares to a total global production of about 5.9 billion carats. Of the total African production, about 1.3 billion carats have come from secondary deposits, i.e., placer and paleo-placers, including marine deposits, representing 22% of the total global production.

Apart from their economic importance, kimberlites are of enormous scientific interest. They have entrained a variety of ultramafic and ultrabasic rock fragments (xenoliths) and their disaggregated mineral grains (xenocrysts) that were shown to be mantle-derived, providing a direct window into the upper mantle of the Earth and making it possible to identify regional variations in the nature of the upper mantle and to understand mantle processes. As diamondiferous kimberlites were not found outside Africa until after World War II, all studies of kimberlites and their mantle cargo until then were based on African examples and samples. Even after the first diamondiferous kimberlites were discovered by Russian geologists on the Siberian craton, in the mid-1950s,

using the tectonic setting of the South African kimberlites as a template, western geoscientists continued to depend mainly on African research material well into the latter part of the 20th century.

The study of kimberlites and their mantle cargo has resulted in major scientific advances to a remarkably diverse variety of geological disciplines, including mantle mineralogy and processes, igneous petrology, palaeontology, and geomorphology. It is impossible to review them all in this paper, but our aim is to explore some of the more important impacts of kimberlite and diamond studies on the earth sciences, with particular focus on geological evidence from Africa, and contributions made by African-based scientists. It should be said at the outset, that until the 1970's, all non-Russian contributions to the geology of diamondiferous kimberlites are based on African examples and research materials. But it should be stressed that from the days of the first African kimberlite discoveries, the resulting contributions to kimberlite geology are nested within a remarkable contribution also by international geoscientists. Again, we cannot do justice to all individual contributions, and in particular many of the early African studies. However, of the latter, three are highlighted, that remain important historic records and continue to be widely referenced. The first, a two-volume work by Gardner F. Williams on the "The Diamond Mines of South Africa"

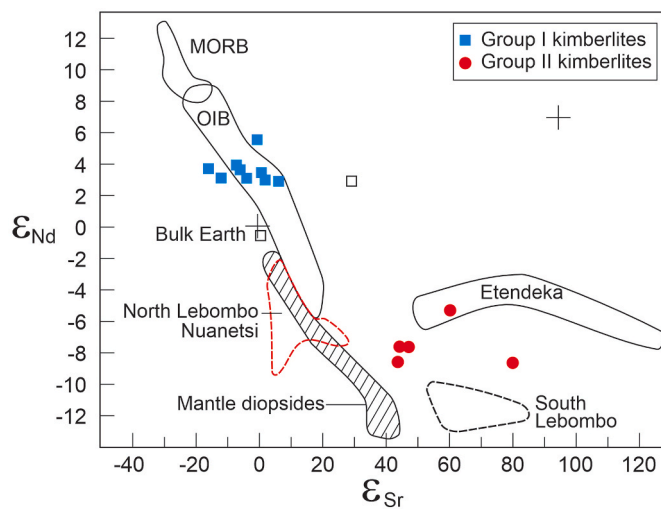


Fig. 2. Contrasting Nd–Sr isotopic signatures of the two isotopically distinctive kimberlite Groups recognized by Smith (1983) - Group I (formerly designated basaltic) and Group II (formerly designated micaceous) kimberlites relative to mid-ocean ridge basalts (MORB), ocean island basalts (OIB) and southern African Karoo volcanic provinces (Data from Smith, 1983).

(Williams, 1906), begins a synopsis of early diamond mining worldwide and continues with an in-depth overview of initial diamond mining activities in South Africa. The second, a book by Wagner (1914), has invaluable descriptions of kimberlite petrography and diamond characteristics and grades of the most important economic kimberlites in southern Africa, many of which are no longer being mined. The third is the two-volume work by Alpheus Williams, son of Gardner Williams, a mining engineer and General Manager of De Beers Consolidated Mines Ltd. (Williams, 1932). This provides an update of mining activities in South Africa with details of kimberlite and cognate inclusion petrography and chemistry as well as an invaluable description of the extensive suite of diamonds that he collected in the line of his duties.

When discussing kimberlites and their mantle cargo, including diamonds, many of the topics overlap. For this review, we have nevertheless divided this vast field into separate sections to discuss some of the more important findings relating to African contributions to kimberlite and diamond geology. These include sections on kimberlites and olivine lamproites, the role of International Kimberlite Conferences, the mantle cargo of kimberlites, including xenolith of peridotites, eclogites and megacrysts as well as the information that can be gleaned from diamonds and the minerals included in diamonds. This is followed by a section on the contributions of mantle studies to diamond exploration, one on using kimberlite studies to solve problems of geomorphology, and one discussing whether mantle plumes are first order controls for kimberlite magmatism. The final section concentrates on contributions to paleontology, based on studies of crater-facies sediments of Cretaceous to Tertiary African kimberlites. Localities of kimberlites referred to in this review are shown in Fig. 1a and b.

## 2. Kimberlite

### 2.1. Kimberlite nomenclature

The original definition of kimberlite from the Kimberley type locality as a “diamondiferous, porphyritic mica-bearing peridotite” (Lewis, 1888) was rather broad and did not recognize that kimberlites are complex hybrid ultrabasic rocks, which in addition to a primary igneous component (phenocrysts and groundmass) contain a wide variety of inclusions (xenoliths and xenocrysts) of upper mantle and crustal rocks that were picked up during rapid ascent to the surface. As the definition included diamond as an essential component, it later led to other

diamondiferous ultrabasic rock types being called kimberlite. As a result, nomenclature problems arose early. In his review of southern African kimberlites, Wagner (1914) recognized two distinct petrographic kimberlite varieties in southern Africa, one described as a basaltic variety, poor in mica, and the second a mica-rich lamprophyric variety. Although Wagner used “basaltic” to denote textural appearance rather than implying that the rock contained feldspar, the term was confusing to many geologists. Mitchell (1970) and Dawson (1980) proposed that the word “basaltic” be dropped, and that henceforth the two varieties should be referred to as kimberlite and micaceous kimberlite.

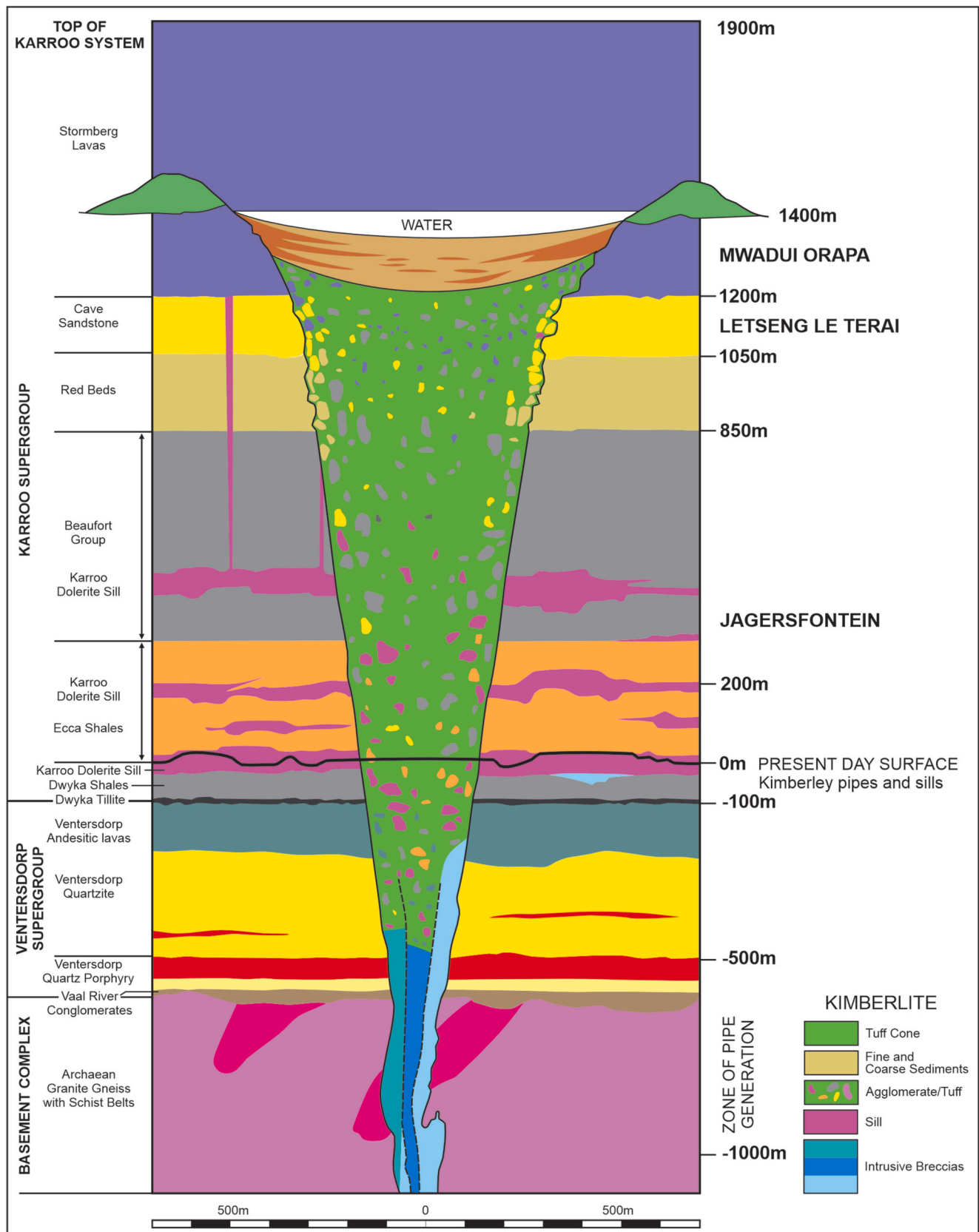
An isotope study by Craig Smith of the Bernard Price Institute of Physics, University of the Witwatersrand, demonstrated that the basaltic and micaceous kimberlite varieties recognized by Wagner (1914) were characterized by discrete Sr, Nd and Pb isotopic signatures (Fig. 2), which he designated Group I and Group II kimberlites respectively (Smith, 1983). This study is a landmark contribution in African kimberlite studies, for it established that the mica-poor (Group I) kimberlites, consisting mainly of olivine, monticellite, serpentine, and calcite, have primitive mantle isotopic ratios. They are enriched in light rare earth elements (LREE), and depleted in Rb with respect to a bulk earth reference composition, and appear to have been derived from asthenospheric sources. The micaceous (Group II) kimberlites, consisting mainly of rounded olivine macrocrysts in a matrix of phlogopite, diopside, and calcite, have evolved isotopic ratios and are enriched in LREE and Rb. They are thought to have originated from metasomatized lithospheric sources.

Whereas Group I kimberlites occur worldwide and carry minerals of the Cr-poor megacryst suite, Group II kimberlites often lack Cr-poor megacrysts, and their occurrence appears to be restricted to southern Africa. As did Dawson (1987), Mitchell and Bergman (1991) pointed out that, in terms of chemical and mineralogical compositions, Group II kimberlites more closely resemble certain lamproites than archetypal (Group I) kimberlites and should be recognized as a separate rock type. Mitchell and Bergman (1991) also noted that the absence of Group II kimberlites outside southern Africa is mirrored by the absence of lamproites from the Kaapvaal craton and surrounding mobile belts, suggesting differences in metasomatic enrichment of the lithospheric sources of these rocks.

Although Mitchell (1995) reintroduced the name “orangeite”, originally suggested by Wagner (1928), who also recognized the micaceous kimberlites found in the Orange Free State of South Africa as a different rock type, the two kimberlite groups designated by Smith (1983) became established in the literature and remain widely used.

In a recent review of kimberlites, Pearson et al. (2019) have refined the definition of kimberlite to exclude rocks previously called Group II kimberlites or orangeites, re-classifying these as a variety of lamproite (carbonate-rich olivine lamproite), as originally suggested by Dawson (1987). This follows Kjarsgaard et al. (2009), who noted that archetypal kimberlites should not be referred to as potassic or even alkaline in nature. Rather, their bulk composition is best classified as ultrabasic, CO<sub>2</sub>-rich, silica undersaturated, high-Mg and Al-poor with variable-to-low alkali contents and low Na/K ratios.

Subsequently, further subdivisions have been proposed for southern African rocks which were formerly loosely designated kimberlites. However, a recent study by Anton Viljoen (2022) demonstrated that kimberlites on the Man Craton in Sierra Leone have mineral chemistry characteristics which do not readily permit assignment to one or other of the proposed kimberlite sub-groups. This highlights the general petrologic challenge to shoehorn rocks characterized by multi-element chemical variation into discrete populations. It also underlines the wry observation made at the First International Kimberlite Conference by the late Barry Dawson - one of the pioneers of kimberlite studies - that the only common feature of kimberlites is their variability. Consensus on classification of kimberlites and other diamond-bearing igneous rocks in southern Africa remains elusive.



**Fig. 3.** Model of a southern African Group I kimberlite pipe (modified from Hawthorne (1975) and Field et al. (2008), with the kind permission of the latter authors). The wall-rock contact of the upper (diatreme) section is flared upwards at a constant angle of  $\sim 80^\circ$ . Fragments (xenoliths) of wall rock material, showing a coarse stratification, are concentrated along the diatreme margins.

The ascent of kimberlite magmas from mantle depths to the surface involves large relative changes in pressure and temperature, particularly in the late stages of emplacement in the upper crust. Decreasing pressure and temperature will trigger crystallization, while the escape of volatiles such as CO<sub>2</sub> and H<sub>2</sub>O dissolved in the kimberlite magma results in complex changes in  $f_{O_2}$ . In addition, the kimberlite magma may interact with groundwater in the upper crust. The late-stage  $P$ - $T$ - $f_{O_2}$  path of the kimberlite magma will in turn influence the nature of late-crystallizing phases. However, the high water contents of late-stage kimberlite magmas result in an alteration overprint, which commonly masks kimberlite groundmass mineralogy and textures. To address this issue, De Beers geologists, led by Roger Clement and Mike Skinner, and supported by a team which included Jock Robey and Barbara Scott-Smith, embarked on a meticulous, detailed kimberlite petrographic study. This resulted in the formulation of a mineralogic classification system, based on the relative proportion of the minerals diopside, monticellite, phlogopite, calcite and serpentine - for example, phlogopite kimberlite and calcite-serpentine kimberlite. (e.g., Skinner and Clement, 1979; Clement and Skinner, 1985). Stephen Haggerty (1975) made a further ground-breaking contribution based on his study and characterization of kimberlite oxide minerals, which had previously been recorded simply as "opaque phases".

## 2.2. The kimberlite volcano and kimberlite emplacement

Kimberlites vary widely in morphology and may occur as pipes (diatremes), dikes and sills, the latter typically of limited size. The dry diggings in the Kimberley area turned out to be exploiting the tops of pipes with a carrot-shaped morphology, narrowing downwards into complex root zones occupied by one or more intrusive phases of hypabyssal kimberlite including the feeder dikes (e.g., Clement, 1982). The classic model of the carrot-shaped kimberlite magmatic system, consisting of a root zone, a steep-sided diatreme, divided into a lower and an upper part, and a crater zone (Fig. 3), was based on a composite of southern African kimberlites, in particular the highly eroded Kimberley and Jagersfontein pipes, for the lower part, and the significantly less eroded Orapa pipe in Botswana, for the upper part (Hawthorne, 1975). To date, no complete diamond-bearing volcano has been exposed (Nixon, 1973). The steep diatreme part flares upward at an angle of about 80° towards the maar-like crater around which ejected volcanic material may have resulted in the deposition of a tuff ring on the paleo-eruptive land surface. The crater may have been filled by a lake, where a capping of crater-fill sediments was deposited (e.g., Dawson, 1967; Hawthorne, 1975; Kjarsgaard et al., 2022). In terms of dimensions, the diatreme zone may extend vertically up to 1000 m, and the crater and root zones each up to 500 m, suggesting that a complete volcanic structure can reach a total depth of 2 km, as per Hawthorne's (1975) original estimate (see Fig. 4c).

The kimberlite geometry proposed by Hawthorne (1975) was long considered as the standard kimberlite pipe model. However, with hindsight, this model strictly applies to southern African Group I kimberlites. Field and Scott Smith (1999) subsequently demonstrated the pipe geometry is strongly influenced by the nature of the upper crustal country rocks.

The terminology of the kimberlite filling the three zones of the kimberlite volcano has changed over time from kimberlite-specific to a standard volcanology terminology. The feeder dykes consist of hypabyssal kimberlite (HK), and the root zone may be composed of HK, coherent kimberlite (CK), massive volcanoclastic kimberlite (MVK), and even pyroclastic kimberlite (PK). The lower part of the diatreme may consist of non-bedded fill (massive volcanoclastic kimberlite, MVK) and/or bedded fill (pyroclastic kimberlite, PK). The upper part of the diatreme is filled with stratified PK overlain by re-sedimented volcanoclastic kimberlite (RVK) (e.g., Kjarsgaard et al., 2022).

Early discussions of the physical aspects of kimberlite emplacement and diatreme formation (e.g., Dawson, 1984; Lorenz, 1975, 1985;

Clement and Reid, 1989) focused on the model of Hawthorne (1975). An important aspect of this debate was the question of whether explosive emplacement of the diatreme was caused by juvenile volatile phases, i. e., exsolved from the kimberlite magma, or whether diatreme formation was predominantly a phreatomagmatic (hydrovolcanic) process that occurred when the rising magma encountered hydraulically active zones in the upper crust. Clement and Reid (1989) suggested that diatremes formed by explosive degassing and fluidization following breakthrough to surface of volatile-charged kimberlite magmas. In contrast, Lorenz (1985) and Lorenz et al. (1999) proposed that the diatreme forms by multiple, downward-migrating phreatomagmatic eruptions resulting from successively deeper melt-groundwater interactions with time. Mitchell (1986) suggested that embryonic pipe development may occur by explosive exsolution of juvenile gases but that diatremes deepen by downward-moving hydrovolcanic explosions. Although there is general agreement that phreatomagmatic processes, in which a hot magma interacts with ground or surface water in a highly explosive manner, is key to understanding magma fragmentation in olivine lamproites, the two models for kimberlite pipe formation continue to be debated. However, it is now clear that a multitude of models with variable combinations of both magmatic and phreatomagmatic processes are possible (e.g., Kjarsgaard et al., 2022).

## 2.3. Distribution and tectonic controls of kimberlites

Although kimberlites have been discovered in all continents, including Antarctica, Africa is particularly richly endowed (e.g., Janse, 1995, 1996), and furthermore includes probably the youngest known kimberlites - the Upper Pleistocene to Holocene (ca. 12,000 to 6000 years old) Ingwizi Hills volcanics in Tanzania (Reid et al., 1975; Brown et al., 2012; Shaikh et al., 2021), and some of the oldest documented occurrences - metamorphosed kimberlite dykes near Mitzik in Gabon, dated at 2849 Ma (de Wit et al., 2016). As 3.2 Ga diamonds have been found, together with indicator minerals, in the 2.8 Ga sedimentary rocks of the Witwatersrand Supergroup in South Africa (e.g., Gurney et al., 2005; Smart et al., 2016), even older kimberlitic diamond source rocks may have existed in Africa, though they remain to be discovered.

Following the discoveries near Kimberley and Jagersfontein, numerous other diamondiferous kimberlites, including those now reclassified as carbonate-rich olivine lamproite, were discovered in South Africa. Although alluvial diamond deposits were found in numerous other African countries soon after their discovery in South Africa, it was not until 1940 that a diamondiferous kimberlite was found outside South Africa (Janse, 1996). This was the Mwadui pipe in Tanzania (then Tanganyika), which turned out to be the world's largest (though not richest) economic kimberlite pipe. Janse and Sheahan (1995, 1996) gave a detailed account of the kimberlite discoveries in other African countries, in particular Zaire (now Democratic Republic of Congo), Lesotho, Botswana, Angola, and Sierra Leone.

Diamondiferous kimberlite discoveries outside Africa were reviewed by Dawson (1980) and Janse and Sheahan (1995). Although kimberlites were known early in the USA, mainly in Kentucky and New York State, they were not diamondiferous. However, diamonds were found in a lamproite intrusion in Murfreesboro, Arkansas, though not in sufficient quantities to be economic. The first and most spectacular discovery outside Africa was the Yakutian diamondiferous kimberlite province on the Siberian craton, in the 1950's, in the former Soviet Union (now the Russian Federation). In the post-war years, the Soviet Union was in dire need of industrial diamonds, and Academician Victor S. Sobolev, having noticed the similarities in tectonic settings between the South African craton and the Siberian platform, decided to use the South African example as a template for a massive diamond exploration program on the northern part of the Siberian platform (Sobolev, 1951). The first kimberlite pipe (Zarnitsa) was discovered in 1954, and the Mir and Udachnaya pipes were found in 1955 (Sobolev, 1959) in what turned out to be two major diamondiferous kimberlite fields (Daldyn/Alakit



and Malo Botuobiya). Unfortunately, the early literature on this newly found kimberlite province was in Russian, and detailed information in English did not become available until the early 1970's (e.g., Sobole, 1974).

What V.S. Sobolev had recognized about the setting of South African and other African diamondiferous kimberlites, namely that they occur on stable cratons, was later validated by Kennedy (1964) and Clifford (1966), who stated that deposits of diamond (together with those of gold, platinum and chromium) are restricted to the "older" cratons of Africa, at the time known to be older than 1500 Ma. Kimberlites emplaced in the older cratons are likely to contain diamonds, whereas those emplaced in surrounding younger mobile belts are typically barren. Clifford's map showed the Rhodesia-Transvaal craton, the Tanzania craton, the Angola-Kasai craton and the West African craton, all now known to include large areas underlain by Archean rocks (>2500 Ma) with deep lithospheric roots (see also section 3.2). This relationship is now often referred to as Clifford's rule (e.g., Janse, 1994) and has been largely supported by subsequent kimberlite discoveries elsewhere in the world.

The African experience thus provided the world with Clifford's Rule, an important tool for area selection, the first essential step in successful exploration for diamondiferous kimberlites (e.g., Helmstaedt and Gurney, 1995). Exceptions to this rule were discussed by Janse (1994), but most of these appear to be lamproites or kimberlites in younger rocks overlying unexposed older basement. For example, the economic Orapa kimberlite in Botswana appears to have been emplaced into the terrain covered by the Palao-Proterozoic (~2 Ga) Magondi Belt (Carney et al., 1994), although it is possible that these cover rocks were thrust over older Archean rocks of the Zimbabwe Craton. Indeed, Mesoproterozoic Re-Os ages for sulfide inclusions in Orapa diamonds have been identified by Shirey et al. (2008), confirming the presence of an Archean lithospheric root under Orapa.

The Cambrian Venetia kimberlites, emplaced into the Precambrian rocks of the central zone of the Limpopo Belt, were also thought of as an exception, as their host rocks were considered to be part of a Proterozoic mobile belt between the Kaapvaal and Zimbabwe cratons (e.g., Kamber et al., 1995). However, Venetia does not contravene Clifford's Rule, as Barton et al. (2003) showed that >3 Ga rocks, preserved in the Venetia klippe, have been refolded by Proterozoic tectonism. This tectonic history is also reflected in the mantle sample of the kimberlites that includes >3 Ga peridotite xenoliths (Carlson et al., 1999). Griffin et al. (2003) showed that the Central Zone of the Limpopo belt is underlain by the most depleted and probably least modified sub-continental lithosphere (SCLM) of the entire Kalahari craton (defined to include the Kaapvaal and Zimbabwe cratons as well as the Limpopo belt). Venetia diamonds contain >3 Ga sulfide inclusions, but also younger diamonds of ca.2.3 Ga age (Richardson et al., 2009), suggesting post-Archean tectonic reactivation. These examples underscore the importance of tectonic studies during area selection.

Definite exceptions to Clifford's rule are some lamproite-hosted diamond deposits, including the rich Argyle lamproite in Australia, dated at approximately 1253–1048 Ma, which was emplaced into the Mesoproterozoic Halls Creek mobile belt forming the eastern margin of the North Kimberley Craton (Jaques et al., 1986).

As noted earlier, craton margins may be masked by overthrust younger mobile belts or sedimentary/volcanic cover sequences. This makes it difficult to define craton areal extents, and boundaries inferred by different authorities may differ slightly in detail. In discussing different contributions to African kimberlite geology, we have retained the craton boundaries used in each study.

#### 2.4. Kimberlite conferences

The early 1970's were a watershed in the study of kimberlites and their mantle cargo, including diamonds. With an increasing interest in the composition of the Earth's upper mantle, many Earth scientists

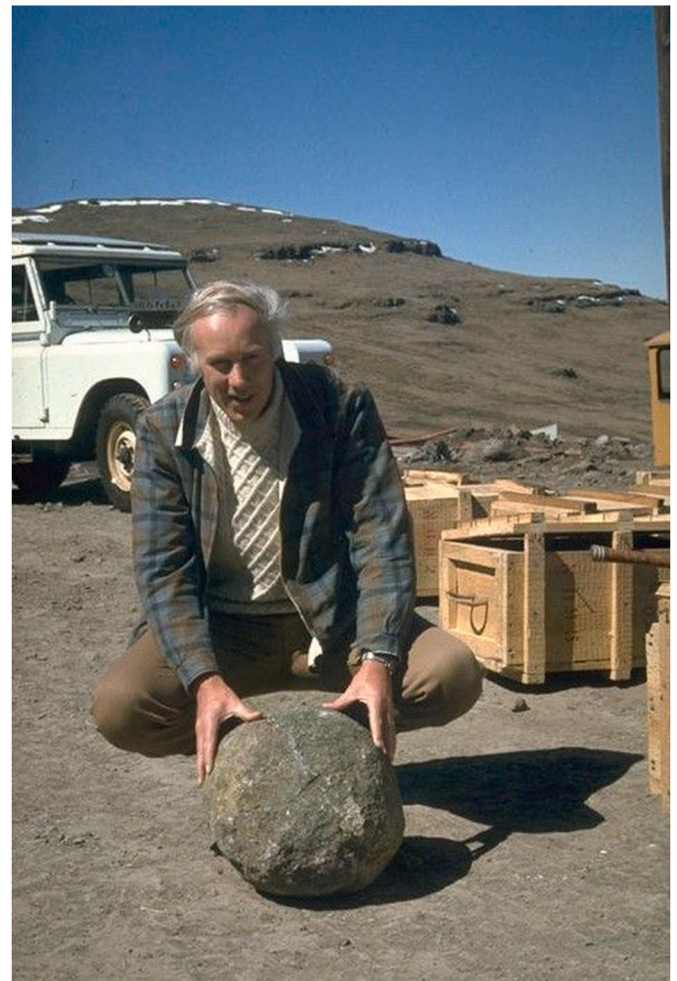


Fig. 4a. Barry Dawson and the "mothae monster".

realized that "as a source of upper mantle materials, kimberlite is perhaps the most important rock-type, having originated at greater depth and carried during its ascent to the surface, a more extensive sampling of the upper mantle than any other type of magmatic activity" (J.B. Dawson, 1975, p. xi, Preface to the proceedings volume of the First International Conference of kimberlites held in Cape Town, in September 1973). The electron microprobe analyser had become available in many labs, and it was time to test hypotheses about the constitution of the upper mantle by quantitative analytic and experimental techniques.

Three USA based Earth scientists, Joe Boyd, Henry Meyer, and Ian MacGregor, saw the need for research samples and an interchange of ideas on a global basis and, in 1971, approached Professor L. H. Ahrens and colleagues A.J. Erlank, A.R. Duncan, and J.J. Gurney of the Department of Geochemistry of the University of Cape Town to organize a kimberlite conference. The group was joined by J.B. Dawson and P.H. Nixon of the Leeds University Research Institute of African Geology, the latter having just published his highly influential book on Lesotho Kimberlites (Nixon, 1973). The conference (now known as I1KC) held in 1973 was a great success, and pre- and post-conference field trips to active and dormant diamond mines in southern Africa provided delegates from all over the world the opportunity to collect kimberlite and mantle xenolith research samples. A noteworthy aspect of the field trips was the generosity of De Beers Consolidated Mines, through J.B. Hawthorne, in providing access to many of their operating mines. Hawthorne, who headed prospecting activities carried out by De Beers in South Africa, presented the first paper at the conference, titled *Model of a kimberlite pipe* (Hawthorne, 1975). His model, described in section 2.2





Fig. 4b. John gurney (JJG).



Fig. 4c. De Beer's petrologists Mike Skinner, Barbara Scott-Smith and Jock Robey with Barry Hawthorne, who made such a major contribution to stimulating kimberlite and diamond research, in the background.. (Photograph taken in 2003 and kindly provided by Barbara Scott-Smith.)

and illustrated in Fig. 3, remains one of the more widely cited kimberlite papers.

Access to samples of the kimberlite mantle cargo was serendipitously facilitated by early methods of kimberlite mining in southern Africa. This involved spreading the mined kimberlite out on “floors” to weather and disaggregate prior to recovering the diamonds. While the

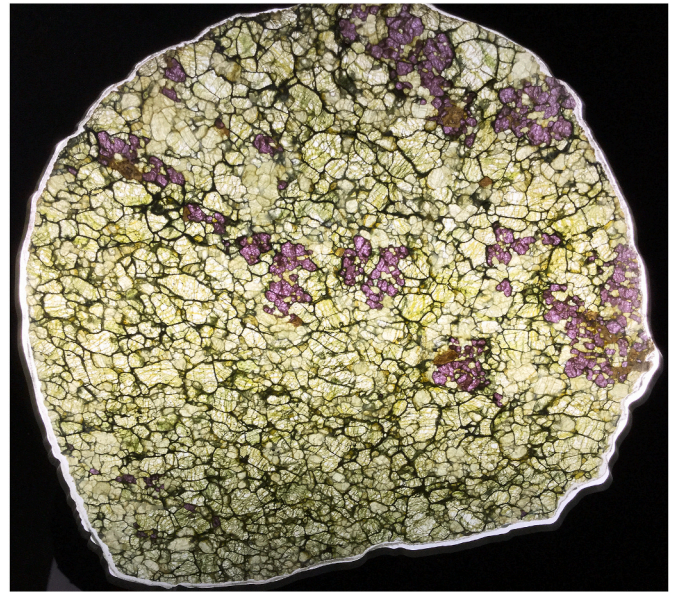


Fig. 5a. Coarse granular garnet harzburgite, with lilac garnets set in a mosaic of interlocking olivine and orthopyroxene (green) (plane polarized light) (horizontal length of image ~ 120 mm).

chemically unstable kimberlite decomposed readily, the more resistant mantle xenoliths survived, providing large mantle specimens for study. A similar process occurred naturally over kimberlite pipes, where weathering and accompanying winnowing of the kimberlite resulted in a relative concentration of dense, more chemically resistant mantle-derived xenoliths on the surface. One of the more spectacular of these was a peridotite xenolith from the Mothae kimberlite in Lesotho, almost 0.5 m in diameter, dubbed the “Mothae Monster” (Fig. 4a). Fortunately, many larger samples are stored and available for study at the Mantle Room Collection founded by J. J. Gurney (Fig. 4b) of the University of Cape Town. While remarkably large mantle specimens could be sampled on the “floors” of early South African mines, modern mining methods, applied also elsewhere in the world, required crushing of the kimberlite, with the result that mantle samples are now typically small (<~25 mm in diameter).

This First Kimberlite Conference, and linked field trips, was so successful that a follow-up was held in Santa Fe in the USA in 1977. A notable aspect of this 2nd International Kimberlite Conference (2IKC) was the number of papers documenting samples collected during the field trips organized during the inaugural South African kimberlite conference. To date, the pioneering International Kimberlite Conference (1 IKC) has spawned a total of 11 further conferences, of which three have been held in southern Africa – two in Cape Town (South Africa), and one in Gaborone (Botswana). Conferences have also been held in the USA, Australia, Brazil, Russia, Canada, Germany, and India, and the next conference in the series is projected to be in Canada in July 2024. A notable feature of all of the conferences has been to maintain the tradition of linked field trips, which have made it possible for an international fraternity of geoscientists to collect mantle samples with a wide geographic distribution.

### 3. The mantle cargo carried by kimberlites

Kimberlites and carbonate-rich olivine lamproite (formerly referred to as Group II kimberlites or orangeites) may carry an enormous variety of mantle xenoliths, mainly members of the peridotite-pyroxenite (including lherzolite, harzburgite, and websterite) and eclogite suites, but also various metasomatized peridotites, glimmerites and MARID-suite rocks (Field et al., 2008). Most of these xenoliths are rounded, probably resulting from abrasion during transport to the surface. The



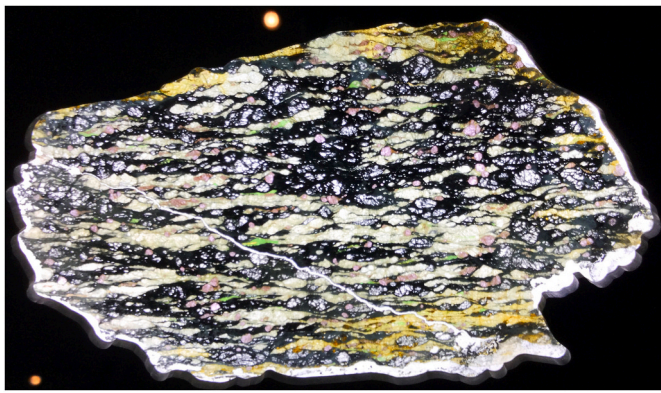


Fig. 5b. Flaser-textured deformed garnet harzburgite (horizontal length of image ~ 100 mm).

constituent minerals of these rock types, resulting from break-up during transport, are referred to as xenocrysts, and they form the heavy mineral concentrates resulting from processing of the kimberlite. These concentrates contain diamond as well as various kimberlite and diamond indicator minerals utilized during diamond exploration. Large single crystals (>1 cm) of garnet, clinopyroxene and other mantle minerals, referred to as discrete nodules or megacrysts, are often found in archetypal kimberlites, and they are thought to have formed as cumulates or pegmatitic phases from a differentiating magma at depth.

Peridotites (Fig. 5) are largely composed of the Mg-rich minerals olivine and orthopyroxene and may also have subordinate proportions of purple pyrope (Cr- and Mg-rich garnet), emerald-green Cr-rich clinopyroxene and occasionally Cr-rich spinel. Eclogites are typically composed of roughly equal proportions of a Ca-rich garnet and Na-bearing clinopyroxene, sometimes accompanied by subordinate proportions of kyanite, coesite, and a variety of other minerals. Both rock types were recognized during early diamond mining but were considered to represent cognate inclusions in the kimberlite magma (Wagner, 1914; Williams, 1932). When diamonds were first discovered in eclogite (Bonney, 1899), a great debate ensued among contemporary petrologists as to their possible origin. According to Williams (1932) four possible modes of origin were proposed for the eclogite hosting the diamonds: 1. Water-worn fragments of ancient crystalline rocks (this was the view expressed in Bonney's original paper); 2. in situ segregations of original magma (e.g., cognate inclusions); 3. xenoliths of rocks through which the kimberlite intruded; 4. inclusions related to the kimberlite. At the time, Williams considered both the eclogite and diamonds as part of the kimberlite, and it took several more decades before it was generally accepted that diamond is a xenocryst in kimberlite.

Peridotites and eclogite xenoliths vary in proportion from one kimberlite to another, but sampling of African kimberlites with a wide geographic distribution has shown that collectively, peridotite xenoliths dominate in most pipes (Gurney et al., 1991), whereas eclogite abundances vary from being absent to more than half of the xenolith total (such as in the Orapa kimberlite and the Roberts Victor olivine lamproite). Eclogite has a better chance of surviving as xenoliths, because it is harder and generally less friable than peridotite. Schulze (1989) showed that the relative abundance of eclogite in the xenolith population at the Roberts Victor pipe is not a measure of the eclogite abundance in the upper mantle column sampled by this pipe. He found that the ratio of peridotitic to eclogitic garnets in heavy mineral concentrates from Roberts Victor is about 40:60. Assuming modal abundances of garnets in eclogites and peridotites of 50% and 6%, respectively, he calculated that these garnets would be representative of a mantle consisting of 85% peridotite and 15% eclogite. A slightly revised estimate (Schulze, 1992) shows 16% eclogite and breaks the peridotites down into 61% lherzolite, 21% harzburgite, and 3% wehrlites. He found an even lower eclogite proportion under Bobbejaan (3%), South Africa, and Zagadochnaya

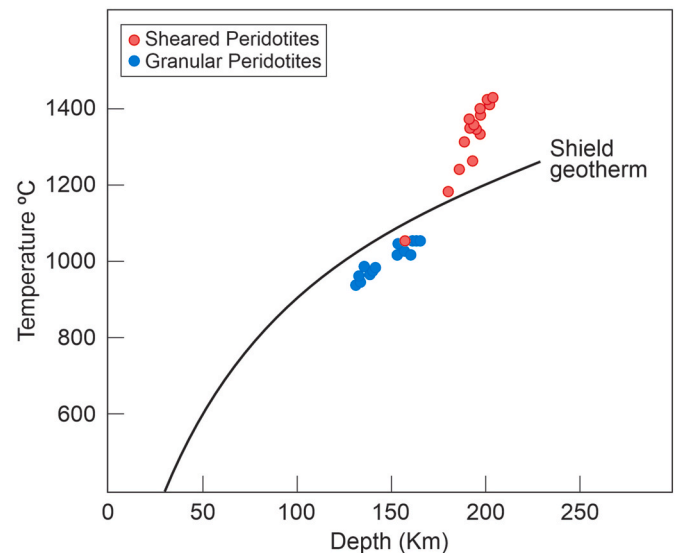


Fig. 6. Estimated equilibration  $P$ - $T$  conditions for coarse granular and deformed peridotites from the Lesotho kimberlites (data from Boyd, 1973) relative to the shield geotherm of Clark and Ringwood (1964).

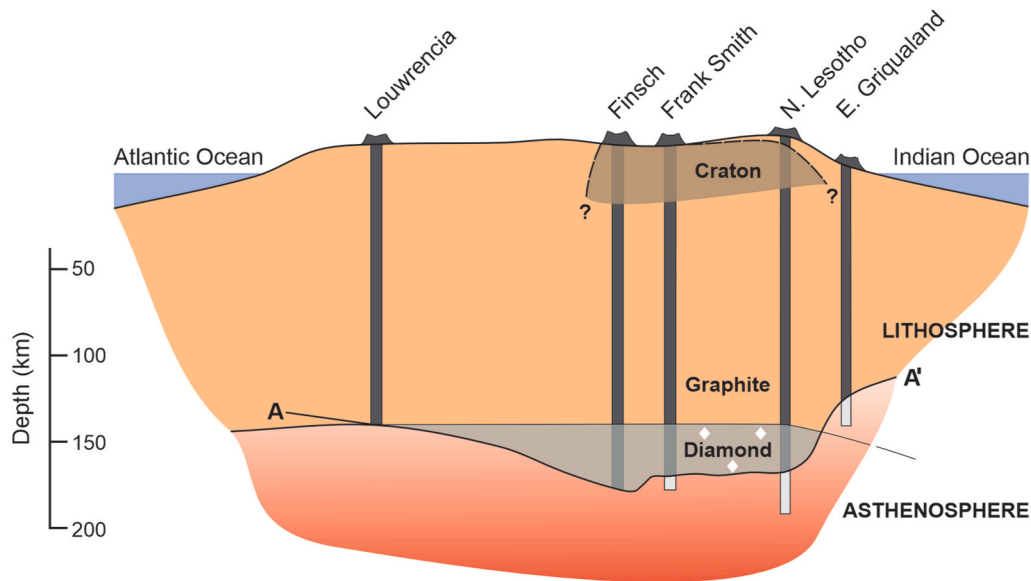
(8%), Siberia, representing other examples of pipes with abundant eclogite xenoliths. Eclogite sampled by the eclogite-rich South African pipes thus may range overall from 3% to locally up to 15%. However, as eclogite xenoliths in most African pipes are extremely rare, Schulze (1989) estimated that the actual abundance of eclogite in the upper mantle is no more than 1 % by volume.

### 3.1. Mantle peridotites

Experimental studies show that the compositions of coexisting minerals in mantle peridotites and eclogites re-equilibrate in response to changing pressure and temperature. Consequently, mineral chemistry equilibrium of coexisting phases in mantle xenoliths provide the basis for developing geothermometers and geobarometers (collectively geothermobarometers), which can be used to estimate the pressure and temperature of origin of mantle samples. This made it possible to construct  $P$ - $T$  profiles of the mantle section that had been sampled by kimberlites, reflecting the geotherm at the time of their eruption (Boyd, 1973).

An investigation of mantle xenoliths from the Cretaceous kimberlites in the Lesotho highlands (Boyd, 1973; Nixon and Boyd, 1973) led to the recognition of deformed peridotites with sheared textures (Fig. 5 b) and characterized by higher equilibration temperatures compared to associated coarse granular varieties. The sheared peridotites define a pronounced kink in the overall Pressure-Temperature ( $P$ - $T$ ) profile defined by the Lesotho mantle suite, which was inferred to reflect the underlying mantle geotherm (Fig. 6). Studies of xenolith suites from a variety of other kimberlites produced closely comparable results – for example the xenolith suites from the Mesoproterozoic (1150 Ma) Premier kimberlite, South Africa documented by Danchin (1979). A common characteristic of all of the mantle suites studied is a relative Fe- and Ti-enrichment of the sheared rocks compared to the shallower and cooler granular peridotites (Nixon and Boyd, 1973).

Nixon and Boyd (1973) proposed that the deformation textures and elevated temperatures of the sheared peridotites reflects shearing over a depth interval of some 50 km, which was interpreted to represent the interface between lithosphere - the rigid upper section of the Earth's mantle - and the underlying relatively ductile, convecting asthenosphere. This elegant interpretation was well-received and is still implicitly assumed in many studies of kimberlite mantle xenolith suites. In view of the elevated Fe and Ti of the sheared peridotites, a corollary of



**Fig. 7.** Model of the diamondiferous lithospheric root under southern Africa based on geothermobarometry on peridotite xenolith suites from East Griqualand, northern Lesotho, Frank Smith, Finsch (F), Lowrecia (Namibia). Ratio of depth scale to horizontal scale is 4: 1 below sea level; the topography is greatly exaggerated. Vertical bars represent xenolith suites, and the maximum depths shown are for clusters of xenoliths of deepest origin in each suite. The line A-A' is approximately the locus of points of inflection in the xenolith geotherms (see Fig. 6). Note that the on-craton pipes (NL, FS, F) have xenoliths that are derived from the diamond stability field, whereas off-craton pipes (EG, L) do not have such xenoliths (modified from [Boyd and Gurney, 1986](#)). Note that the precise margin of the craton is uncertain, as it is masked by younger cover rocks and, in the east, the overthrust 1 Ga Namaqualand-Natal mobile belt.

this model is that the asthenosphere is Fe- and Ti-rich relative to shallower lithosphere.

In contrast to the interpretation tabled by [Nixon and Boyd \(1973\)](#), [Mercier \(1979\)](#) demonstrated that the textures of sheared peridotites are transient rather than steady state features at mantle pressures and temperatures. This is consistent with the earlier conclusion of [Harte et al. \(1975\)](#) that coarse and sheared peridotites from the Matsoku kimberlite (northern esotho) reflect a continuous cycle of deformation and recrystallization within the mantle envelope surrounding the kimberlite magma at depth. [Mercier \(1979\)](#) argued that the sheared peridotites, rather than representing a thick (~50 km) laterally extensive zone of deformation, marking the interface between the lower lithosphere and upper asthenosphere, reflects a narrow, transient mantle perturbation associated with the vertical interface of mantle wall rocks surrounding the host kimberlite magma shortly prior to kimberlite eruption.

Mercier's interpretation was supported by evidence that garnets in sheared peridotites may be zoned, which was interpreted to reflect metasomatic reaction with a magma shortly prior to kimberlite eruption ([Griffin et al., 1989](#)). Consistent with this conclusion, [Moore and Lock \(2001\)](#) demonstrated that mineral phases in the sheared peridotites have compositions intermediate between those of corresponding phases in coarse granular peridotites and a suite of large (>10 mm) single crystals termed megacrysts. The latter were interpreted to have crystallized from a magma body in the mantle ([Gurney et al., 1979](#); [Harte and Gurney, 1981](#)). [Moore and Lock \(2001\)](#) suggested that the magma parental to the megacryst suite, and thus responsible for the metasomatism, was in fact the host kimberlite.

The contrasting models of [Boyd and Gurney \(1986\)](#) and [Mercier \(1979\)](#) have profoundly different implications for models of the mantle. The former envisages a horizontal extensive thermally perturbed mantle zone, some 50 km thick, which marks a major chemical boundary separating the lithosphere from the underlying asthenosphere. In contrast, the second interpretation envisages a transient, narrow vertical boundary separating a hot kimberlite magma from the surrounding cooler ambient mantle. In terms of Mercier's model, the relatively Fe- and Ti-rich character of the sheared peridotites would reflect chemical

interaction between the kimberlite and the surrounding mantle wall rocks. Following the first two kimberlite conferences, the two contrasting interpretations were widely debated (see also [Dawson, 1980](#)), but with more regional studies and the development of improved geothermometers and geobarometers, systematic results were achieved when xenolith geotherms are used (e.g., [Finnerty and Boyd, 1987](#)), allowing the first characterization of the upper mantle structure beneath the Kaapvaal craton.

Temperature-depth estimates were made by [Boyd and Gurney \(1986\)](#) for peridotite xenoliths from five pipes along a SE-NW section from East Griqualand across the Kaapvaal craton (Northern Lesotho, Frank Smith, Finsch) to Louwrecia in Namibia (Fig. 7). They showed that the depth of origin of the high-temperature xenoliths is systematically greater for those erupted within the boundaries of the craton (on-craton) than those that erupted off-craton, in East Griqualand and Namibia, respectively. All lower-temperature xenoliths plot along the continental shield geotherm, but the higher-temperature xenoliths deviate from the geotherm at higher temperatures in the on-craton xenolith suites than in the off-craton suites, suggesting that the depth of the lithosphere was about 170–190 km within the craton at the time of eruption compared to about 140 km off-craton. The section (Fig. 7), showing that the craton root extends into the diamond stability field only under the craton, was the first petrological demonstration that the lithosphere under Archean cratons is cooler and more refractory than that of the adjacent upper mantle. A Mesoarchean formation age of this part of the lithosphere was confirmed by *P*-Type garnet inclusions ages of 3.2–3.3 Ga in diamonds from the Kimberley kimberlites (e.g., [Richardson et al., 1984](#); [Shirey et al., 2004](#)). The model thus provides a petrological explanation of Clifford's Rule and is compatible with seismic tomography (e.g., [Grand, 1987](#); [James et al., 2001](#)) and heat flow data (e.g., [Ballard and Pollack, 1987](#); [Morgan, 1995](#)).

A detailed study by [Griffin et al. \(2003\)](#) of >3400 peridotitic garnets from more than 50 kimberlites and olivine lamproites (still referred to as Group II kimberlites by the authors) of the Kalahari craton (including the Kaapvaal and Zimbabwe cratons and the Limpopo belt) used the 4D lithosphere mapping methodology of [O'Reilly and Griffin \(1996\)](#) to map the compositional structure and thermal state of the sub-continental



lithospheric mantle (SCLM) in time slices represented by the eruption ages of the kimberlites/olivine lamproites. The technique involves the determination of the equilibration temperature of each garnet grain, using its Ni content and the Ni thermometer as calibrated by Ryan et al. (1996). The Ni temperature for each grain is referred to a local paleo-geotherm derived either directly from the garnet data or from geothermobarometric analyses of local xenolith suites, if available. Estimates of the depth to the base of the lithosphere were derived from garnet data, using the assumption that depleted peridotites are diagnostic of the lithosphere. As the median Y content of Cr-pyrope garnets from Archean SCLM is ca. 12 ppm, values less than 8–10 ppm can be regarded as evidence of depleted peridotites. T (Ni) vs. Y plots show a relatively sharp high-temperature limit for distribution of Y depleted garnets (referred to as “Y edge”), which was interpreted to represent the temperature at the base of the depleted lithosphere. A significant finding was that, in the western part of the Kaapvaal craton, the Y edge for xenocrysts from olivine lamproites (the former Group II kimberlites) was at 1100 °C, corresponding to a depth of the depleted lithosphere at ca. 190 km, whereas a well-defined Y edge at ca 1100 °C suggests that the base of the depleted lithosphere under the kimberlites lies near 160–170 km, representing a significant decrease in the thickness of the lithosphere from the time of olivine lamproite emplacement (average age >110 Ma) to that of the kimberlites (average age 95 Ma).

Through a technique described as Cluster Analysis by Recursive Partitioning (CARP), Griffin et al. (2003) assigned the garnet analyses to four major rock types, including *depleted harzburgite* (G10 garnets depleted in Y, Ga, Zr, and HREE, Fo > 92); *depleted lherzolites* (G9 garnets depleted in HREE, HFSE, and Ga); *depleted/metasomatized peridotites* (garnets depleted in Y and HREE, and enriched in Zr and LREE); *fertile peridotites* (garnets with high HREE, normal HFSE, and no evidence of a depletion event). An additional rock group, referred to as melt-metasomatized peridotites (garnets enriched in Zr, Ti, Y, and Ga), corresponds to the sheared peridotite nodules found in many kimberlites and by Boyd and Gurney (1986) assigned to the asthenosphere. Comparing the relative proportions of these rock types, it is seen that the rise in the geotherm between the olivine lamproite and kimberlite events was accompanied by a refertilisation of the depleted mantle. In the depth range of 130–170 km, this is shown by a decrease in the proportion of subcalcic harzburgites (from a mean of 24% in olivine lamproites to 17% in kimberlites) and an increase in the proportion of depleted/metasomatized and fertile lherzolites from ca. 30% to ca. 50%.

The work by Griffin et al. (2003) may be viewed as “geochemical tomography”, because there are strong correlations between the mantle composition and structure mapped by them, and the distribution of seismic velocities shown by the tomographic work of James et al. (2001) on the Kalahari craton. Areas of relatively low Vp within the craton largely reflect the progressive re-fertilisation of the Archean root during episodes of intraplate magmatism, including the Bushveld (2.05 Ga) and Karroo (ca. 180 Ma) and the Zambesi rifting events as well as the olivine lamproite and kimberlite events. Areas of high Vp map out the distribution of relatively less metasomatized Archean SCLM. The strong correlation between post-diamond metasomatism of different kinds and ages with the seismic tomographic data (which reflect the properties of the present-day lithosphere) throws doubt on attempts to correlate differences in composition of diamonds (E-type vs P-type) and their syngenetic inclusions with variations in seismic P-wave velocities (e.g., Shirey et al., 2002).

Kobussen et al. (2009) expanded the work of Griffin et al. (2003) along a southwest-northeast traverse across the Kaapvaal craton to further quantify the Cretaceous thermo-chemical modifications of the Kaapvaal cratonic lithosphere between the diamond-bearing olivine lamproite and kimberlite events. Using the vertical and lateral distribution of Ti and Zr concentrations and the Zr/Y ratio in garnets as well as the calculated  $X_{Mg}$  of olivine, coexisting with the garnet xenocrysts, they outlined three domains with different metasomatic styles along the traverse studied. In the “Prieska” domain, making up the southwest part

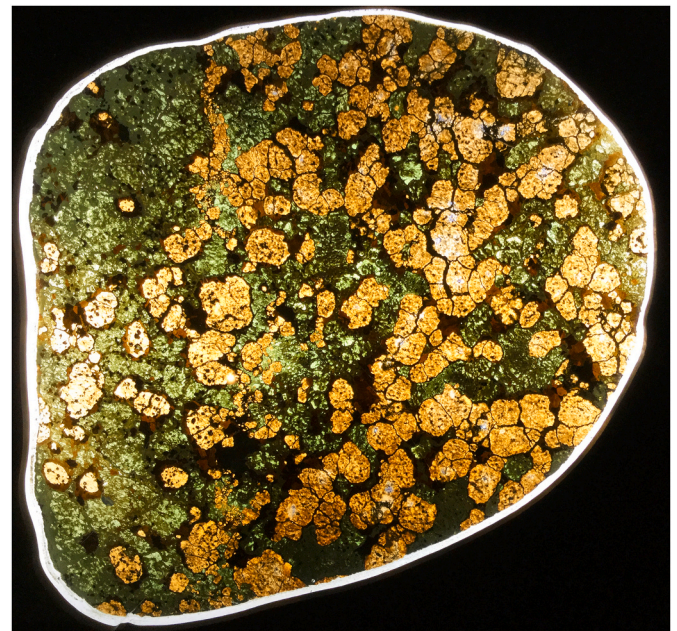
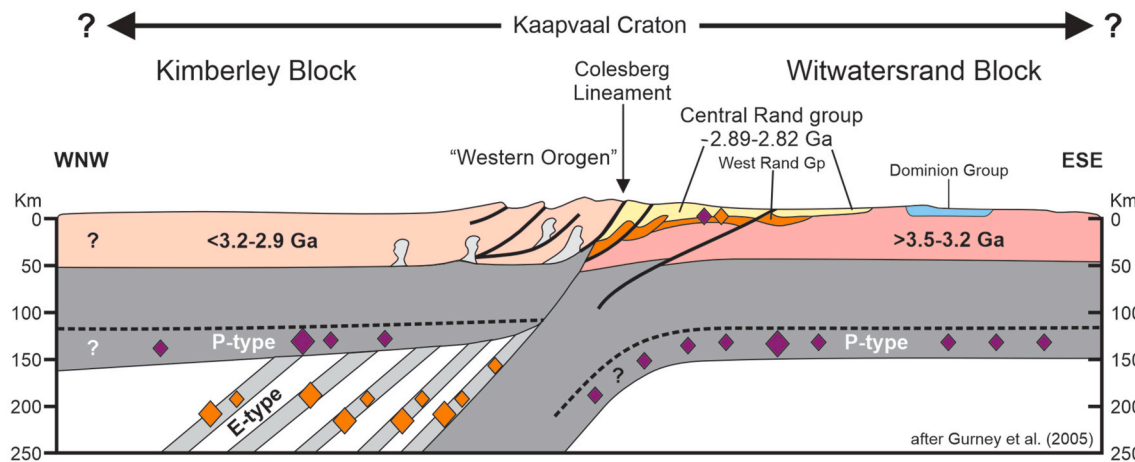


Fig. 8. Section of a bimineralic eclogite xenolith comprised of approximately equal proportions of orange, Ca-rich garnet and green Na-rich clinopyroxene. Horizontal width of image ~100 mm.

of the traverse, including all areas off-craton and approximately the first 200 km on-craton, metasomatism was dominated by interaction of the lithosphere with mafic silicate melts, resulting in garnets with high Ti, Fe and Zr, and low Zr/Y. The “Kimberley” domain, comprising the central part of the traverse northeast of Prieska, and including the Kimberley area, metasomatic signatures are consistent with the interaction of the host peridotite with a hydrous, highly alkaline fluid, resulting in high Zr and high Zr/Y, but low Ti and moderate Fe. This is interpreted as reflecting the phlogopite-style metasomatism observed in many of the xenoliths from the kimberlites at Kimberley and some other localities on the Kaapvaal Craton. In the “Swartruggens” domain, comprising the northeast part of the traverse, including kimberlites near the western boundary of, and just within, the Bushveld Complex, a high-Fe signature, probably related to the emplacement of the Bushveld complex, predates further phlogopite-style metasomatism during the olivine lamproite/kimberlite interval. Kobussen et al. (2009) inferred that the upper mantle metasomatism related to mafic fluids is accompanied by significant heating, whereas the potassic (phlogopite-style) metamorphism is not.

While the studies by Griffin et al. (2003) and Kobussen et al. (2009) present very detailed interpretations of the nature of the lithosphere in southern Africa, both assume that garnet temperatures are related to the local geotherm, in turn forming the basis for inferring pressure and thus depth of formation. They do not address the model proposed by Mercier (1979), which envisages a restricted transient thermal anomaly (aureole) surrounding the kimberlite conduit, and thus implicitly follow the model proposed by Nixon and Boyd (1973).

In a paper presented at the 1 IKC, Lloyd and Bailey (1975) described peridotites with subordinate proportions of K-rich minerals, such as phlogopite and K-richrichterite, in mantle xenoliths from southwest Uganda and the West Eifel, Germany, that were interpreted as reflecting one or more episodes of metasomatism in the mantle. These authors noted that reactions of metasomatic fluids with peridotitic mantle minerals would result in a decrease in density, providing a potential explanation for the previously observed anomalously lower density mantle observed beneath the East African Rift System (EARS). This, in turn, was linked to the observed geologically long-lived surface uplift associated with the East African Rift System (EARS). The study thus provided one of the



**Fig. 9.** Hypothetical cross-section depicting the collision of eastern domain (Witwatersrand block) and western domain (Kimberley block) of the Kaapvaal craton at ca. 2.9 Ga, showing structural setting of Central Rand Group east of the Colesberg lineament (adapted from Gurney et al. (2005), with surface geological constraints from Cheney and Winter (1995), de Wit et al. (1992) and data by Schmitz et al. (2004)]. Pink: crust; grey tones: lithosphere; white: asthenosphere. Occurrences of earlier P-type diamond in the lithosphere of both domains are indicated by purple diamond symbols; occurrences of E-type diamond forming in the imbricate zone under the western domain are marked in orange. Note that the detrital diamond occurrences in the foreland basin of the Central Rand Group (marked by the purple and orange diamond) would have had their source in a “western orogen” in the Kimberley region, brought to the surface by what may have been the oldest kimberlite or olivine lamproite (see also Smart et al., 2016).

early insights into the links between upper mantle processes and surface geological and geomorphic responses.

Stimulated by the observations of Lloyd and Bailey (1975), Tony Erlank (University of Cape Town) and co-workers studied a suite of metasomatized peridotites from the Bultfontein kimberlite in the Kimberley cluster (Erlank et al., 1987; Hawkesworth et al., 1990). They concluded that the metasomatism occurred at  $\sim 150 \pm 20$  Ma, thus postdating the  $\sim 181$  Ma Karoo volcanism, but prior to the mid-Cretaceous age of the host Bultfontein kimberlite (ca. 84 Ma). The estimated age of the mantle metasomatic event which they recognized corresponds broadly with the commencement of Group II kimberlite volcanism (now recognized as a carbonate-rich variety of olivine lamproite), between  $\sim 140$  and  $115$  Ma, which in turn overlapped the opening of the Atlantic at  $\sim 125$  Ma (Moore et al., 2008). This study under-scored the link between mantle metasomatism and igneous-tectonic processes.

### 3.2. Mantle eclogites

Mantle eclogites (Fig. 8) from South Africa played an important role in our understanding of the origin of the world's diamondiferous cratons. It began with Cohen (1879), who recognized eclogite together with peridotite among the nodules of the diamond-bearing kimberlite of Jagersfontein, in South Africa, and was followed soon afterwards by the discovery of diamond in a rounded eclogite nodule (ca. 100 by 75 by 50 mm in size) in the Newlands olivine lamproite (then considered to be a kimberlite) which clearly identified the eclogite as being the parental rock of diamond (Bonney, 1899). Bonney described it as a “boulder” of eclogite that is “truly waterworn” and dismissed the idea of it having been rounded during ascent in the kimberlite by a “sort of cup and ball game played by a volcano” as “practically impossible” (Bonney, 1899, p. 235). Bonney pointed to the Dwyka conglomerate at the base of the Karoo beds as a possible source for the boulder, pushing the date of diamond genesis back at the very least to the Paleozoic.

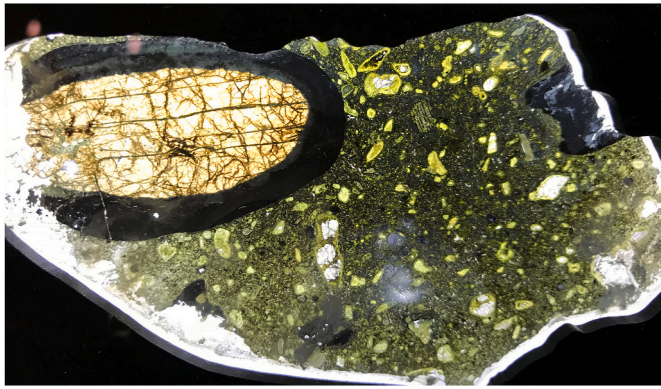
Although eclogite had been known since the 1700's (for a review, see Godard, 2001), its origin –whether metamorphic or magmatic – was highly debated by petrologists. Many, including Bonney (1907), Wagner (1914) and Williams (1932) considered eclogite as cognate nodules related to the kimberlite magma and derived from great depth. However, soon after Becke (1903), intrigued by the basaltic composition of both gabbro and eclogite and comparing the molar volume of both,

concluded that eclogite represents the high-pressure equivalent of gabbro, the hypothesis of an eclogite layer below the crust was born. This implied that eclogite was a major constituent of the mantle. As its presence at depth was established by the xenoliths of eclogite (some of them with diamond) in kimberlites of South Africa, and its high density ( $>3.5$  g/cm<sup>3</sup>) appeared to satisfy the seismic velocity jump at the Mohorovicic discontinuity, the eclogite-layer hypothesis became well entrenched for several decades (e.g., Birch, 1952) and was abandoned only after eclogite was produced by high-pressure experiments (e.g., Ringwood and Green, 1964, 1966).

By the time of the 1 IKC, eclogite was generally considered a high-pressure cumulate in a peridotitic upper mantle (e.e., MacGregor and Carter, 1970; Lappin and Dawson, 1975; O'Harte et al., 1975; Hatton and Gurney, 1987), though an alternate origin for eclogite xenoliths by subduction of oceanic crust was proposed by Helmstaedt and Doig (1975), also at the 1 IKC. Many workers now interpret certain kyanite- and coesite-bearing eclogites as fragments of subducted oceanic crust. These conclusions are based on similarities between eclogite xenoliths and crustal rocks (oceanic basalts and subduction zone “crustal eclogites”), in major elements (e.g., Ringwood and Major, 1971; Smyth and Hatton, 1977; Ater et al., 1984), and mineral assemblages, trace elements and isotopic ratios (e.g., Jagoutz et al., 1984; MacGregor and Manton, 1986; Shervais et al., 1988; Schulze and Helmstaedt, 1988; Taylor and Neal, 1989; Schulze et al., 2000, 2003, 2004). Jacob (2004), in a comprehensive review of mantle eclogite, concluded that most eclogite xenoliths from kimberlites can satisfactorily be explained as samples of subducted oceanic crust. Stachel et al. (2022), based on a detailed review of eclogitic inclusions in lithospheric diamond, stated that their trace element systematics are broadly similar to those of mantle eclogites, which originated as variably differentiated oceanic crust. They also stated that formation of eclogite directly from a magma at mantle pressures is not supported by their data.

Considering their subduction-related origin, eclogite and diamond eclogite xenoliths as well as eclogitic inclusions in diamond indicate that early plate-margin processes played an important role in the formation of the Kaapvaal craton, making it possible to attempt an integration of its crustal history with that of its underlying upper mantle. As described by de Wit et al. (1992) and Poujol (2007), the Kaapvaal Craton is not a homogeneous Archean province but consists of several subprovinces, referred to as tectonostratigraphic terranes, at least some of which appear to represent amalgamated Archean tectonic “terranes” in the





**Fig. 10a.** Well-rounded Cr-poor garnet megacryst surrounded by a black kelyphytic rim set the host Monastery kimberlite matrix. Megacryst dimensions, including the kelyphyte rim, approximately 85 × 55 mm.

modern plate-tectonic sense. The core region, in the eastern part of the province, is the ca. 3.644 Ga Ancient Gneiss terrane, which was tectonically juxtaposed with the southern Barberton greenstone belt ca. 3.5 Ga and the northern Barberton greenstone belt ca. 3.2–3.3 Ga to form the Witwatersrand block. The eastern Witwatersrand block is juxtaposed against the ca. 3.22 Ga western Kimberley block (Schmitz et al., 2004) along Colesberg magnetic lineament (Corner, 1998) (Fig. 9). Both blocks had developed their own separate roots in which peridotitic diamond budgets were developed prior to accretion (e.g., Richardson et al., 1984; Gurney et al., 2005).

The now well-constrained ca. 2.93 Ga date for the collision between the Kaapvaal Shield or the Eastern domain and the Western domain along the Colesberg lineament (Schmitz et al., 2004) coincides with ages determined for eclogitic inclusions in diamonds from the Kimberley kimberlites (Richardson et al., 2001), temporally linking the eclogitic diamond formation event at depth to tectonic processes observed on the Earth's surface. The polarity of subduction prior to collision is generally thought to have been westward, with the eastern Kaapvaal Shield (Witwatersrand block) representing the lower plate after suturing (Schmitz et al., 2004). Using these constraints, Gurney et al. (2005) developed the hypothetical cross-section illustrated on Fig. 9.

The amalgamation of the Kaapvaal craton is further documented by the first complete overlap sequence belonging to the upper part of the Neoarchen (ca. 2.7 Ga) Ventersdorp Supergroup (Cheney and Winter 1995), which was followed by break-up along the western margin of the craton and deposition of the passive margin sequence of the Transvaal Supergroup.

On the Kaapvaal craton, the Jwaneng, Orapa, Koffiefontein, Finsch, Jagersfontein, Premier, and Venetia pipes carry multiple generations of eclogitic diamonds with ages in the 2 to 1 Ga range based on Sm–Nd (e.g., Richardson, 1986; Richardson et al., 1990, 1999; Smith et al., 1991) and Re–Os (e.g., Pearson et al., 1998; Richardson et al., 2004; Richardson and Shirey, 2008; Shirey et al., 2008; Aulbach et al., 2009) isochron relationships. These younger eclogitic inclusion ages may be related to the various Proterozoic collisional events (e.g., Magondi-Kheis and Namaqua-Natal orogens) that have affected the Kaapvaal craton (e.g., Shirey et al., 2004; Smit et al., 2022).

In West Africa, three eclogitic diamonds from Zimmi in Sierra Leone have yielded identical ~650 Ma ages (Smit et al., 2016), which is temporally related to subduction along the SW margin of the Man craton, recorded in the Rokelide orogen (700–550 Ma; Lytwyn et al., 2006).

The model linking eclogitic diamonds to subduction processes provides a framework for understanding the origin of these diamonds in world-wide kimberlite and lamproite deposits. Thus, for example, the Argyle olivine lamproite pipe in NW Australia is dominated by diamonds derived from eclogitic source rocks. This pipe is emplaced in the



**Fig. 10b.** Unusually large (~5 kg) apple-green (“granny smith”) clinopyroxene megacryst of the Cr-rich suite from the Bultfontein kimberlite (Kimberley) dump. Coin diameter = 25 mm.

Palaeoproterozoic (~1.85 Ga) Halls Creek Orogenic belt, which bounds the eastern margin of the Archean Kimberley Craton, and is thus one of the major exceptions to Clifford's rule. Stachel et al. (2018) proposed that the eclogitic diamonds in this deposit are related to subduction along the margin of the Kimberley Craton, likely during the Halls Creek orogeny. Similarly, Helmstaedt and Pehrsson (2012) and Kopylova et al. (2016) presented evidence to propose that eclogitic diamonds in the Lac de Gras kimberlites, emplaced in the Slave Craton in the Canadian Northwest Territory, can be related to subduction beneath the craton, linked to the Palaeoproterozoic (1.88–1.84 Ga) Wopmay Orogeny.

### 3.3. Megacrysts

Megacrysts in kimberlites (Fig. 10) are defined by Harte (1978) as monomineralic single crystals of olivine, ortho- and clinopyroxene, garnet, ilmenite, phlogopite and rare zircon that are coarser (>1–20 cm) than the minerals found in ultramafic nodules (<1 cm), such as xenoliths of peridotite and eclogite. Investigations of megacrysts began in Africa, with a study by Nixon and Boyd (1973) of the “discrete nodules” from kimberlites of Northern Lesotho. This was followed by the classic papers of Gurney et al. (1979) and Harte and Gurney (1981) on the megacrysts from the Monastery kimberlite in the northern Free State of South Africa. The former proposed that megacrysts are linked by isobaric fractional crystallization over a wide temperature range from a magma that must have been present shortly before or at the time of eruption of the host kimberlite. To explain the observed isobaric crystallization over a wide temperature range, the latter proposed that the Monastery megacryst suite formed by injection of small volumes of magma, derived from a stalled parental magma body, into a fracture network within the surrounding thermal aureole.

Griffin et al. (1989), reporting that some garnets in sheared peridotites were zoned with marginal Ti enrichment, concluded that this indicated metasomatism by the megacryst magma very shortly prior to eruption of the host kimberlite. Moore and Lock (2001) subsequently presented evidence from the Lesotho-Free State kimberlites supporting this interpretation. However, despite this elegant model, the origin of the megacryst suite and the nature of the parental liquid remain controversial (e.g., Bell and Moore, 2004; Nkere et al., 2021; Cone and Kopylova, 2021).

Egger et al. (1979) showed that the cluster of kimberlites straddling the Wyoming-Colorado border (USA) is characterized by the presence of apparently chemically discrete Cr-poor and Cr-rich megacrysts



populations. The chemical and textural characteristics of the Cr-poor megacryst suite are well documented for a variety of localities with a wide geographical distribution. Examples are the Lesotho kimberlites (Nixon and Boyd, 1973), Monastery (Gurney et al., 1979; Moore et al., 1992), Orapa (Shee and Gurney, 1979), the Gibeon kimberlites (Mitchell, 1987) and Jagersfontein (Hops et al., 1989, 1992) in southern Africa. In North America, this group of megacrysts is well documented for the Colorado-Wyoming kimberlites (Eggler et al., 1979) the Hamilton Branch kimberlite, Kentucky (Schulze, 1984) and kimberlites of the Slave Province (e.g., Kopylova et al., 1999, 2009).

The Cr-rich megacryst suite has received far less attention, though there is growing evidence suggesting it occurs in kimberlites with a wide geographic distribution. Thus, Shee and Gurney (1979) recognized both Cr-rich and Cr-poor clinopyroxene megacryst populations in the Orapa kimberlite in Botswana, and inferred that these are chemically comparable to the two megacryst suites in the Colorado-Wyoming pipes. Data presented by Mitchell (1987) indicate that compositionally discrete Cr-poor and Cr-rich clinopyroxene megacryst populations are also present in the Gibeon pipes in Namibia. Phases from other megacryst suites, such as garnets from the diamond-poor Kundelungu kimberlites (Lower Oligocene) and the diamond-rich Mbuji-Mayi kimberlites (Cretaceous) in the Democratic Republic of Congo, display lower Ti, Fe and Al and higher Cr contents than other garnet megacrysts worldwide, while clinopyroxenes display higher Mg and Cr and lower Ti and Fe contents (Pivin et al., 2009). As their compositions are intermediate between those of minerals from mantle peridotites and those of magmatic-related megacrysts, and they do not display the classical bi-element correlations observed for many other megacryst suites that are interpreted as resulting from fractional crystallization processes, the authors suggested an origin by metasomatic transformation of mantle peridotites.

Moore and Belousova (2005) noted that chromium-poor and chromium-rich megacryst suites coexist in many kimberlites with worldwide geographic distribution. Close similarities between compositions of Cr-rich megacryst phases and those in granular lherzolites are consistent with early crystallization from a primitive kimberlite liquid, whereas the low-Cr megacryst suite is thought to crystallize subsequently from residual Cr-depleted liquids. Nkere et al. (2021) studied clinopyroxene and garnet megacrysts from two southern African kimberlites, Colossus and Orapa (on the Zimbabwe craton), and two olivine lamproites, Kalkput and Bellsbank (on the western Kaapvaal craton). Chrome-poor megacrysts are present at Orapa, Colossus and Kalkput, whereas chrome-rich megacrysts occur also at Orapa, but represent the only megacryst variety at Bellsbank. Nkere et al. (2021) proposed a hybrid model for their origin in which the megacrysts are formed as result of fractional crystallization, assimilation and melt-rock interaction in stockwork-like melt-filled chambers of variable size at lower to mid-lithospheric depths with associated melt vein networks, derived from a parental kimberlite magma, extending into the surrounding and overlying lithospheric mantle. Their model envisaged that large melt bodies with high melt/wall rock ratios tend to lead to megacrysts assemblages dominated by Cr-poor megacrysts, whereas chrome-rich megacrysts are associated with small melt bodies with low melt to wall rock ratios.

Given the potential importance of the sheared (deformed) peridotites in understanding mantle structure, further investigation is necessary to understand the processes involved in the formation of the megacryst suite, the nature of the parental megacryst magma, and how and where the latter interacted with the sheared peridotites.

### 3.4. Diamonds

Although mineral inclusions in diamond had been known since the beginning of the 20th Century (e.g., Wagner, 1914; Williams, 1932), it was the invention of the electron microprobe that enabled the first non-destructive method to determine their chemical composition

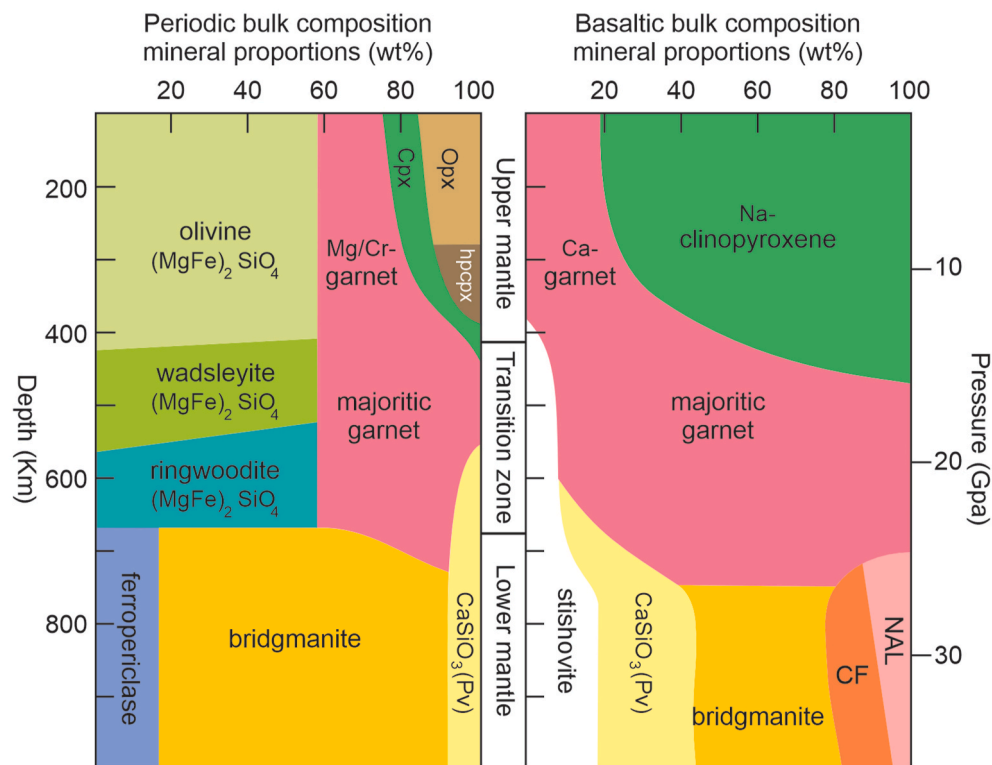
(Meyer and Boyd, 1968). Subsequent studies, mainly on African and Siberian diamonds (Meyer and Tsai, 1976, and references therein), soon revealed the presence of two distinct suites of mineral inclusions, a peridotitic suite and an eclogitic suite, the minerals of which do not coexist in the same diamond. A more recent review by Stachel and Harris (2008) lists various silicates, oxides, and sulphides in lithospheric diamonds, with a majority (~65%) linked to peridotitic suites (including both harzburgitic (20.3%) and lherzolitic (6.2%) parageneses), and a subordinate proportion (~33%) related to the eclogitic suite with a minor websterite (~2%) contribution. According to Stachel and Harris (2008), a comparison of inclusions from several cratonic areas worldwide shows that diamondiferous lithospheric mantle beneath the Kalahari Craton is uniquely depleted as seen by the very strong dominance of highly subcalcic garnet inclusions for the interior of the Kaapvaal Block. Olivine inclusions from Yakutia, the Slave and the West African Craton show modes in Mg# between 92.0 and 93.0, as opposed to 93.5 to 94.0 for the Kalahari Craton. These results reflect regional differences in the nature of the lithosphere beneath different cratons.

A major African advance in understanding the timing of diamond formation was a study of peridotitic garnet inclusions from the mid-Cretaceous Finsch and Kimberley pipes, carried out by Stephen Richardson and co-workers from the University of Cape Town (Richardson et al., 1984). It demonstrated that the garnets are of Archean age (~3.3–3.2 Ga) and that they formed following a chemical enrichment event in the sub-cratonic Mesoarchean mantle. An important corollary of this study is that these inclusion-bearing diamonds represent xenocrysts in the much younger kimberlite and olivine lamproite hosts, putting to rest the long-standing argument about whether diamonds are phenocrysts or xenocrysts in their igneous transport media.

A subsequent study of eclogitic diamond inclusions from the Premier kimberlite (now known as the Cullinan) (Richardson, 1986) showed that these had a much younger age, and thus reflected a Proterozoic diamond formation event distinct from that recognized in the earlier study. Some of the eclogitic diamond ages in southern African kimberlites are broadly contemporaneous with orogenic events that have been recognized on the margin of the Kaapvaal craton (see Section 3.2). Such a link between eclogitic diamond formation and tectonic-magmatic processes has recently been underlined by Gress et al. (2021), based on a study of the ages of diamonds from kimberlites in the Orapa cluster, central Botswana. The latter study shows that some diamonds are also closely coeval with kimberlite emplacement.

The much-debated geological question of when plate tectonic processes began, was answered by Richardson et al. (2001) when 2.9 Ga eclogitic diamonds were recognized in the Kimberley kimberlites (see also chapter 3.2). Gurney et al. (2005) and Shirey and Richardson (2011) showed that, world-wide, inclusions in diamonds older than 3 Ga are all peridotitic (P-type), and that diamonds with eclogitic inclusions (E-type) so far have yielded only ages that are younger than 3 Ga. This was interpreted as reflecting the commencement of subduction processes at about 2.9 Ga, indicating a major change in Earth tectonic processes. While most eclogitic diamond ages on the Kaapvaal craton range from 2.9 to about 1.2 Ga (e.g., Gurney et al., 2005), a zircon inclusion-bearing diamond from M'buji-Mayi on the Congo craton has been dated at ~0.6 Ga (Kinny and Meyer, 1994), representing the only kimberlitic zircon diamond inclusion ever dated. As the zircon is most likely part of the eclogitic inclusion suite, this age suggests that the Pan-African assembly of the Congo craton also involved subduction. Pan-African orogenic processes affecting the Archean Man craton were also inferred by Smit et al. (2016) based on 0.65 Ga eclogitic diamond ages from Zimni in Sierra Leone.

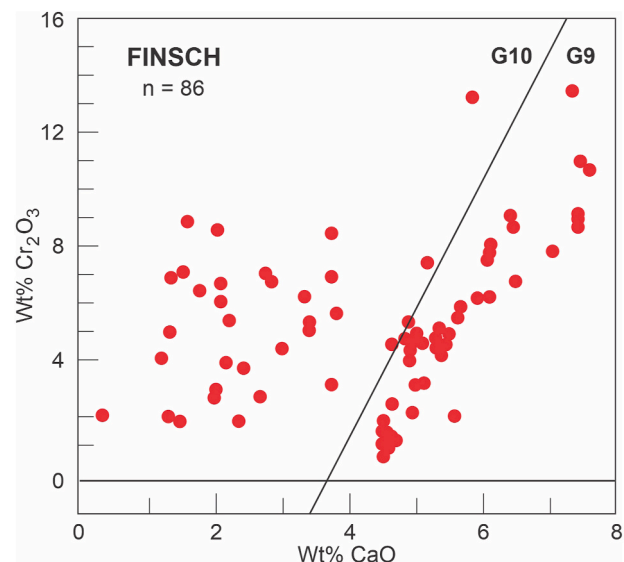
Another major African contribution, by Rory Moore and John Gurney of the University of Cape Town kimberlite research group, was the recognition of garnets with pyroxene solid solution in a diamond recovered from the Monastery kimberlite (South Africa) (Moore and Gurney, 1985; Moore et al., 1991). Garnets with such compositions, now



**Fig. 11.** Model for  $P$ - $T$  phase stability in bulk compositions of peridotitic and eclogitic composition, modified from data in Harte (2010).  $\text{CaSiO}_3$ -Pv: perovskite-structured  $\text{CaSiO}_3$ .

named majorite, had previously been produced experimentally at high pressures (Ringwood and Major, 1971), and Moore and Gurney (1985) concluded that the host diamonds had been recovered from a depth range of 200–480 km, thus extending into the asthenosphere. This was the first report of sub-lithospheric diamonds (now also referred to as “superdeep” diamonds) from a kimberlite in South Africa, and it flagged the potential for using diamond inclusions for refining understanding of sub-lithospheric petrology.

Sub-lithospheric diamonds have subsequently been reported from kimberlites with a wide geographic distribution, including many from the Kalahari craton (e.g., Haggerty and Sautter, 1990; Stachel and Harris, 2008; Haggerty, 2017). They have been particularly well studied from Kankan, Guinea, in West Africa, and from Juina, Brazil (e.g., Harte, 2010; Stachel and Harris, 2008; Smit et al., 2022; Timmerman et al., 2023). Identification of the associated high-pressure inclusions, including ringwoodite (as discovered by Pearson et al., 2012; in a diamond from Brazil) confirms earlier experimental studies that had predicted the presence of these minerals in the deeper parts of the Earth’s mantle (Fig. 11). It also demonstrated that the “superdeep” minerals had crystallized from rocks with either peridotitic or eclogitic (i.e., basaltic) compositions, i.e., broadly like the two dominant rock types found in the overlying lithosphere. Harte and Richardson (2012) suggested that the Juina sublithospheric diamonds document a series of events involving diamond formation during emplacement of a subducted megalith beneath west Gondwanaland (e.g., Helmstaedt and Gurney, 1997) followed by diapiric rise between ca. 190 and 90 Ma. Timmerman et al. (2023) extended this model to include both the Juina and Kankan diamonds. Their isotopic data appear to be consistent with sublithospheric diamond formation in the megalith between 650 and 450 Ma at both localities, followed by diapiric rise to the base of the lithosphere prior to the emplacement of the Cretaceous kimberlites.

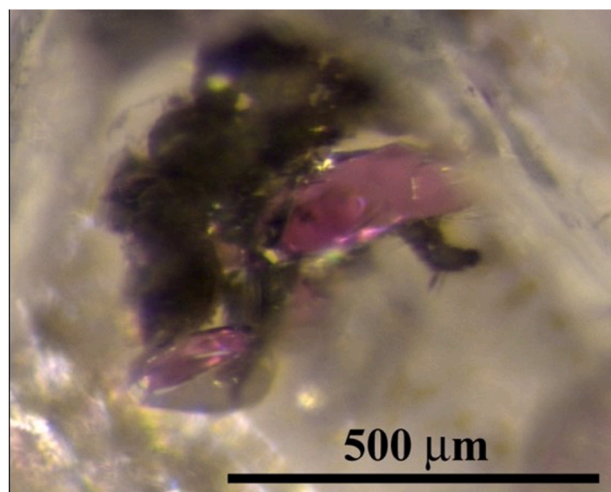


**Fig. 12a.** Ca–Cr variation of garnets in concentrates from the Finsch kimberlite (data from Gurney and Zweistra, 1995) relative to the fields for G10 and G9 garnets.

#### 4. Economic spin-offs from African kimberlite research

The study of diamond inclusions has had important economic applications first pioneered in Africa. A statistical classification of garnets associated with kimberlites showed that peridotitic inclusions in diamonds defined two compositional fields on  $\text{CaO}$ – $\text{Cr}_2\text{O}_3$  plots, one characterized by calcium-saturated garnets along the lherzolite trend (Fig. 12a) and another, characterized by low Ca and high Cr contents relative to the garnets along the lherzolite trend. Garnets with





**Fig. 12b.** Lilac peridotitic (G10) garnet inclusion in diamond (Image kindly provided by Maya Kopylova).

compositions falling within the low-Ca field are harzburgitic, and readily recognized by their characteristic lilac colour (Fig. 12b) and were designated G10, whereas the lherzolitic garnets were designated as G9 (Dawson and Stephens, 1975). Gurney and Switzer (1973) investigated garnets recovered from the high grade (diamond-rich) Finsch olivine lamproite in South Africa. They demonstrated that sub-calcic pyrope diamond inclusions (i.e. G10 compositions) are highly represented and also occurred in the heavy mineral concentrate at Finsch (Fig. 8a), but they noted that such garnets are absent from the non-diamondiferous Rietfontein pipe. They proposed that sub-calcic pyrope garnets in kimberlites provide a proxy that reflects the presence of associated diamonds. Similar observations were also made by Sobolev et al. (1973) in Siberian diamondiferous kimberlites.

This application was developed further and subsequently tested by investigating the geographic distribution of kimberlites with G10 garnets in southern Africa (Gurney, 1984). This ground-breaking study is, to the authors' knowledge, the first regional compilation of this nature. It was demonstrated that G10 garnets, pointing to the presence of diamond-prospective kimberlites and olivine lamproites, are confined to on-craton localities on the Archean Kaapvaal and Zimbabwe cratons (Fig. 13). In contrast, the younger tectonic terranes (off-craton localities) surrounding the two cratons lacked G10 garnets indicating that associated kimberlites and lamproites were not likely to be diamond-prospective (Fig. 13). This underlined and refined the observations originally made by Tom Clifford (1966) and demonstrated that Archean cratons provide the greatest potential for discovering economic kimberlites. It also elevated the G10 garnet from a kimberlite indicator to a diamond indicator mineral. The on-/off-craton principle, which has become one of the basic tenets underlying world-wide diamond exploration, thus has its origin firmly in Africa, and reflects the remarkable contribution made by John Gurney to diamond exploration worldwide.

The application was subsequently discussed in greater detail by Gurney and Zweistra (1995), while Helmstaedt and Gurney (1995) stressed the importance of understanding the tectonic evolution of different cratons and their underlying mantle in selecting target areas for kimberlite (i.e. diamond) exploration. The Gurney method is credited to have been instrumental in the discovery of the rich kimberlites in the Slave Province of northwestern Canada (Helmstaedt et al., 2021). The link between G10 garnets and the presence of diamonds was a ground-breaking observation for diamond exploration and highlights the remarkable cross-pollination of ideas between academic studies and industry, which has been a striking aspect of kimberlite investigations, particularly since the 1 IKC.

The Gurney refinement of Clifford's rule was underlined by a study

of peridotite mantle xenoliths from the Murowa kimberlite in Zimbabwe (Smith et al., 2009) that showed the mantle section underlying the Zimbabwe Craton to be unusually refractory (i.e., enriched in Mg and Cr) relative to mantle samples beneath the Kaapvaal craton to the south. Smith et al. (2009) further noted that, in contrast to the mantle beneath the Kaapvaal Craton, clinopyroxene was absent or rare in most of the mantle samples of the Zimbabwe Craton. It was suggested that the higher proportion of clinopyroxene in samples from the Kaapvaal Craton mantle reflected an Archean episode of mantle metasomatism that had not affected the Zimbabwe Craton. The important corollary, that different cratons worldwide have records of different mantle histories, which directly impacts on their diamond potential, has been explored in greater detail by Helmstaedt (2018).

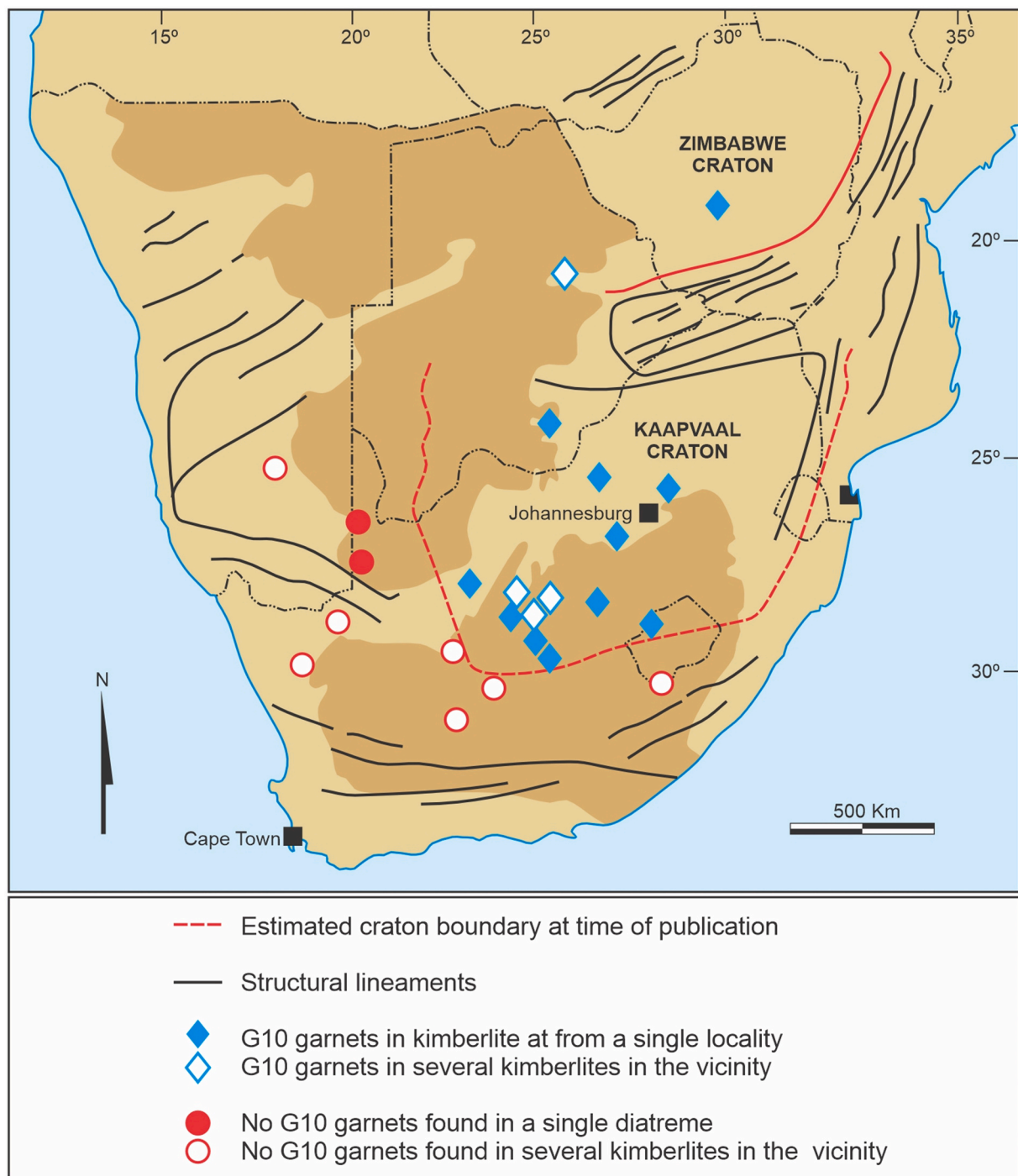
## 5. Geomorphology

### 5.1. Regional erosional history

At the time of their discovery, the economic kimberlites in the Kimberley cluster had surface areas ranging from 3.7 ha (the Kimberley or "Big Hole" kimberlite (Fig. 14a) to 10.6 ha (Dutoitspan). In contrast, the Orapa kimberlite in central Botswana is far larger, with dimensions of approximately 1000 m × 1500 m, and a surface area of approximately 110 ha. (Fig. 14b). Further, the upper sections of the Orapa pipe include a sequence of crater lake sediments. Barry Hawthorne (1975) pointed out that his model for the geometry of kimberlites, illustrated in Fig. 1, provides a yard stick for estimating the extend of surface erosion that had taken place following emplacement. Based on this model, he concluded that approximately 1000–1500 m of erosion of the Kimberley pipes had taken place since their emplacement in the mid-Cretaceous (~85–90 Ma). While the Orapa kimberlite is of similar (mid-Cretaceous) age to the Kimberley pipes, the large size and preservation of the crater lake deposits point to minimal (<300 m) erosion since emplacement. Kimberlites thus provide a gauge for making estimates of regional variations in post-emplacement erosion.

The use of kimberlites to constrain erosion histories was refined by Emily Hanson, John Moore and co-workers from Rhodes University (Hanson et al., 2009). They investigated differences between assemblages of crustal xenoliths in South African olivine lamproites (formerly Group II kimberlites) emplaced in the early Cretaceous (~140–114 Ma), and those in the younger mid-Cretaceous (100–75 Ma) kimberlite pipes (Fig. 15a). This study showed that Jurassic (~180 Ma) Karoo lava xenoliths were present in the older olivine lamproites but absent in the younger kimberlite pipes in the Kimberley region. This was interpreted to reflect the presence of an extensive residual Karoo basalt carapace covering much of southern Africa in the early Cretaceous, which had been extensively stripped by the mid-Cretaceous. This study thus provided a series of "snap shots" of southern African erosional history (Fig. 15b).

An additional refinement in linking kimberlites to landscape evolution was an apatite (U–Th)/He thermochronometry study on 15 Cretaceous kimberlites from an ~600 km long transect across the Kaapvaal Craton by Jessica Stanley and Rebecca Flowers of the University of Colorado (USA) (Stanley et al., 2013a,b, 2015). Apatites studied were extracted from both the host kimberlite and associated crustal xenoliths. The apatite fission track modelling provided constraints on the erosional history of the individual kimberlites, and further refined the geomorphic evolution of southern Africa subsequent to the breakup of Gondwana. Stanley et al. (2013) concluded that a wave of erosion, from west to east across the transect line, occurred from ~120 Ma to < 60 Ma. Erosion was initially focussed along palaeo-rivers, and then as an eastward retreating scarp, resulting in an overall lowering of the land surface by almost 2 km over this time period.



**Fig. 13.** Distribution of kimberlites with associated G10 garnets and those lacking G10 garnets relative to the Kaapvaal and Zimbabwe cratons and surrounding younger mobile belts (modified from Gurney (1984)). Dark brown tone represents areas overlain by Phanerozoic cover sequences. Note that the craton boundaries are partially masked by overthrust younger mobile belts and sedimentary cover, and thus not precisely defined. The margins shown are taken from the original publication by Gurney (1984).

## 5.2. Paleo-drainage reconstruction

Erosion of kimberlites liberates diamonds and a characteristic heavy mineral assemblage, including peridotitic and eclogitic garnets, ilmenite and spinels, which are dispersed by fluvial and glacial activity. Sampling of drainage lines to recover these kimberlitic indicator minerals (KIMs) has proved to be a highly successful prospecting technique for tracing these “pathfinder” minerals back to their kimberlite source rocks. In Zimbabwe, the source of the Permian Karoo-age Somabula alluvial

diamond deposit, which straddles the central watershed separating the Limpopo and Zambezi river systems (Fig. 16), has long been enigmatic. Exploration carried out in Zimbabwe during the 1990’s and early 2000’s led to the discovery of economic Murowa-Sese kimberlites, as well as a number of other previously unknown kimberlite clusters, all of lower Palaeozoic age, to the south of the modern central Zimbabwe watershed (Fig. 16).

Linley Lister (1990) had inferred that the pre-Karoo drainage system extended to the south of the modern divide, with headwaters in southern





**Fig. 14 a.** The Kimberley kimberlite (or Big Hole), Kimberley cluster, with an original surface area of  $\sim 3.7$  ha at the time of discovery. Wall rocks are Ventersdorp lavas (dated between  $\sim 2.7$  and  $2.8$  Ga, Cornell et al., 2011) overlain by Phanerozoic Karoo sediments.

Zimbabwe (Fig. 16). Moore et al. (2009, 2012) pointed out that with this more extensive Karoo drainage network, the diamond-bearing Mur-owe-Sese kimberlites represented a potential source of the Somabula diamond deposit. It was noted further that, with the more extensive Karoo drainage network, unexplained KIM concentrations at Maitengwe and Nyamandhlovu, north of the modern central Zimbabwe watershed, and at Daiseyfield, on the watershed, could have been sourced from the kimberlites to the south of the modern divide. Thus, the evidence linking kimberlite clusters to unexplained KIM anomalies in Zimbabwe provided strong support for the pre-Karoo drainage network which had originally been proposed by Lister (1990). Moore et al. (2009a,b) noted that this northeasterly oriented pre-Karoo drainage network would have

been in accord with the west-draining proto-Zambezi system.

Another classic example of the use of KIMs to understand palaeo-drainage systems was the study by De Wit et al. (2009) of the Cretaceous Mahura Muthla alluvial diamond deposit on the Ghaap Plateau in the Northern Province of South Africa. The study demonstrated that the compositions of ilmenites from the Mahura Muthla deposit could be matched with those in kimberlites to the south of this deposit, pointing to a north-flowing palaeo-river, and thus resolving the long-standing enigma of the provenance of the Mahura Muthla diamonds.

## 6. Implications for mantle plumes

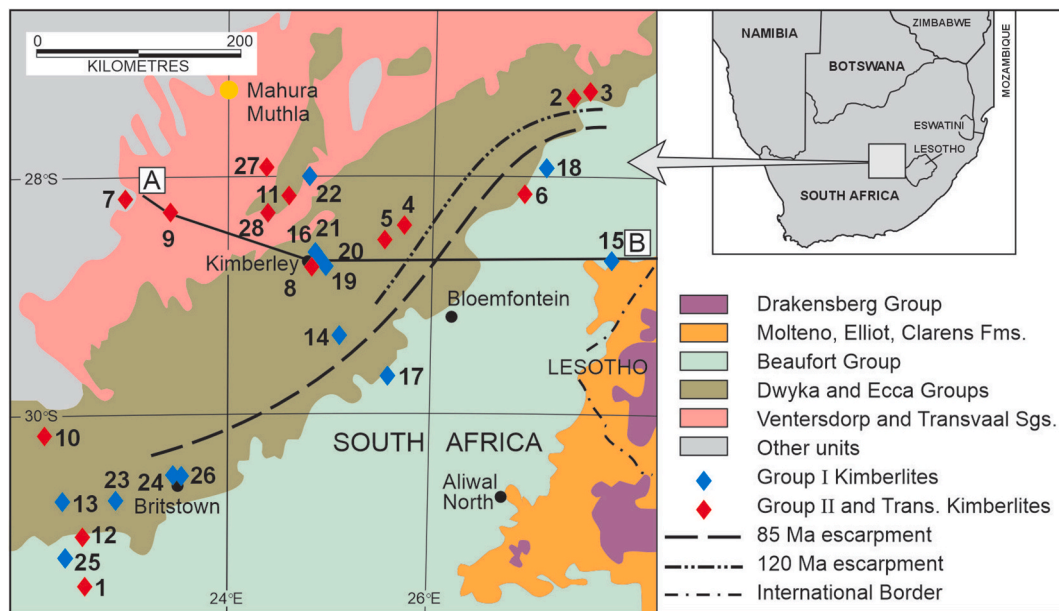
Plate tectonics provides a coherent conceptual framework to explain volcanic activity at plate boundaries. However, the origin of intra-plate volcanism, such as the Hawaiian archipelago and associated time-progressive chain of volcanic sea mounts, remains controversial. The Plume Hypothesis (Morgan, 1971) appeared to provide a simple, elegant explanation for such intra-plate volcanic lineaments, and rapidly gained widespread acceptance. Morgan (1971) envisaged that plumes were also linked to the break-up of continents, and they have been invoked as triggers for associated flood basalt volcanism. For example, plumes have been proposed to explain Karoo and Paraná large igneous provinces (LIPs) respectively (e.g., Cox, 1989; Torsvik et al., 2006). Kimberlites and other alkaline pipe clusters in southern Africa have also been ascribed to plumes (e.g., Haggerty, 1986, 1994). Torsvik et al. (2010) proposed that global kimberlite emplacement over time showed a spatial relationship to two major seismic velocity anomalies in the lower mantle, referred to as Large Low-Shear-Velocity Provinces (LLSVP). They inferred that plumes rising from the margins of the LLSVP were responsible for triggering kimberlite volcanism. Thus, initiation of plumes was ascribed to thermal instability at the core-mantle boundary (e.g., Torsvik et al., 2010), implying a “bottom-up” trigger for magmatic activity. The anomalously high elevation of East Africa and the southern African plateau relative to other continental shields has been linked to dynamic uplift associated with an African superplume (e.g., Gurnis et al., 2000).

However, there were early challenges to the plume model. Turcotte and Oxburgh (1973) proposed their “membrane tectonic” concept, which envisaged that lithospheric stresses linked to plate motion over a non-spherical globe could result in propagating intra-plate lines of weakness. They proposed that this provided an alternative, “top-down” trigger to account for time-progressive igneous lineaments such as the Hawaiian volcanic chain. Furthermore, the structural architecture of Africa (e.g., Begg et al., 2009) shows that the African coastline is closely correlated with late Proterozoic Pan African mobile belts, which appear to have played a major role in controlling the line of break-up of the

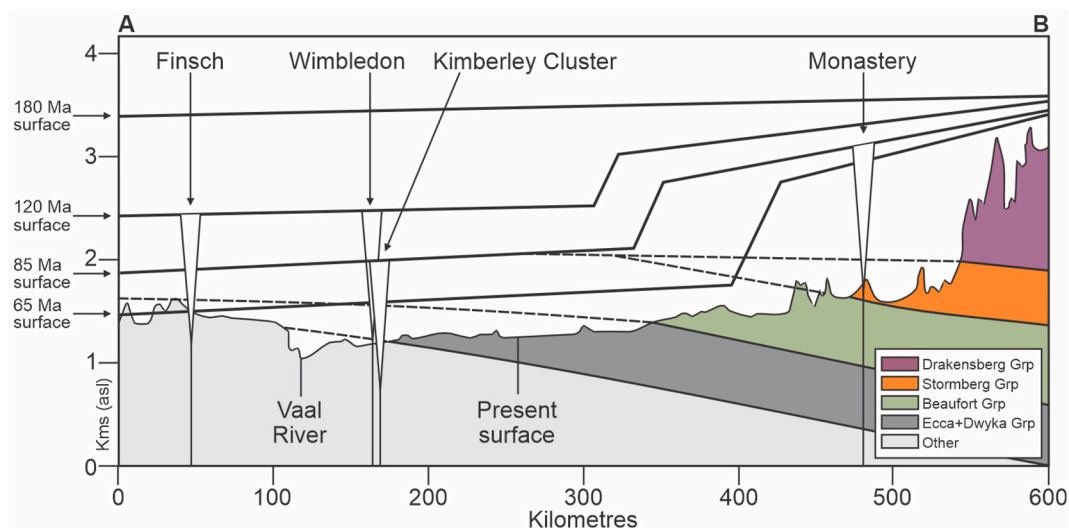


**Fig. 14b.** The Orapa (AK1) kimberlite, with a surface area of  $\sim 110$  ha at the time of discovery, looking down the long axis of the pipe. Dimension of the pit is approximately  $1.5 \text{ km} \times 1.0 \text{ km}$  (Image kindly provided by Prof. Frank Eckardt of the University of Cape Town).





**Fig. 15a.** Distribution of Group I kimberlites and carbonate-rich olivine lamproites (formerly Group II kimberlites) surrounding Kimberley investigated by [Hanson et al. \(2009\)](#) for the presence or absence of Karoo basalt xenoliths. Line A-B shows the location of the section depicted in [Fig. 15b](#). 1: Melton Wold; 2: Lace; 3: Voorspoed; 4: Roberts Victor; 5: New Elands; 6: Phoenix/Star; 7: West End; 8: Wimledon; 9: Finsch; 10: Markt; 11: Frank Smith; 12: Pampoenpoort; 13: Uintjiesberg; 14: Koffiefontein; 15: Monastery; 16: Kimberley; 17: Jagersfontein; 18: Kaal Vallei; 19: De Beers; 20: Bultfontein; 21: Kamfersdam; 22: Leicester/Balmoral; 23: Lushof; 24: Britstown; 25: Hebron; 26: Lovedale; 27: Bellsbank; 28: Newlands.



**Fig. 15b.** Modelled landscape evolution to the west of the Lesotho highlands since the disruption of Gondwana (~180 Ma) based on crustal xenoliths in kimberlites (adapted from [Hanson et al., 2009](#)).

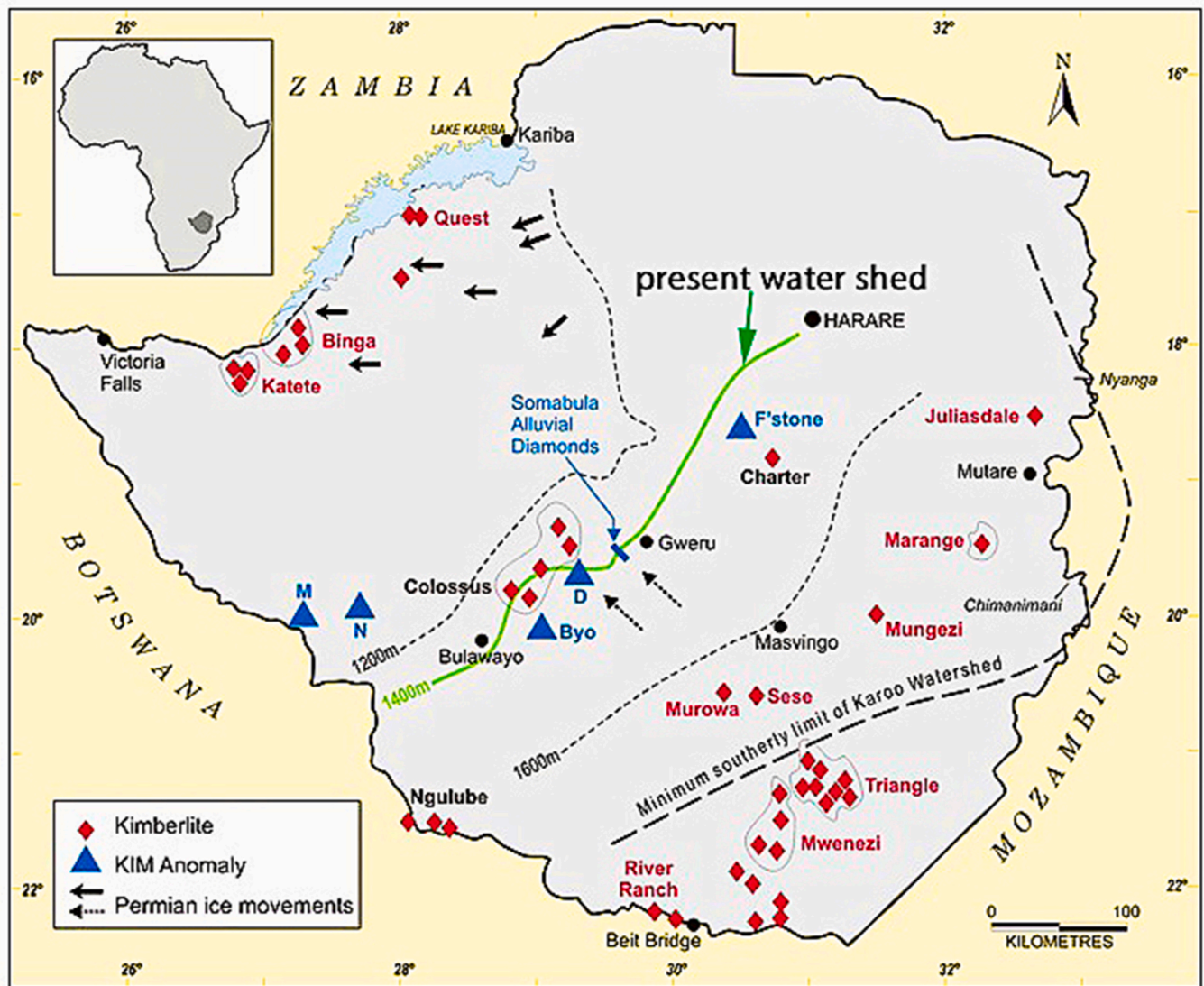
Gondwana supercontinent. If the disruption of Gondwana was triggered by the putative Karoo and Paraná plumes, initiated at the core-mantle boundary, this would require the remarkable co-incidence that both impinged on the lithospheric plates beneath the late Proterozoic Pan-African fold belts. To address this problem, it has been suggested that plume heads may be channelled laterally towards zones of lithospheric weakness such as mobile belts ([Ebinger and Sleep, 1998](#); [Schilling, 1991](#)). However, such *ad hoc* modifications to the plume concept make the model essentially non-falsifiable.

There are also problems in ascribing the anomalous elevation of the southern African plateau to dynamic uplift associated with a plume. The plume model predicts that this region should display a domal topography (e.g., [Gurnis et al., 2000](#)), but in contrast, the interior of the southern African plateau is the site of the Cenozoic Kalahari basin

([Moore, et al., 2009](#)), and tomographic studies (e.g., [Ritsema and Heijst, 2000](#); [Fouche et al., 2004](#)) have failed to identify the putative super-plume beneath southern Africa.

The proposed link between plumes and kimberlites and alkaline volcanism in Africa has also been challenged. Ken [Bailey \(1992, 1993\)](#) demonstrated that post-Gondwana alkaline volcanism across the Africa has been widespread but episodic, with synchronous activity in widely separated areas. He pointed out that this pattern of activity cannot be explained in terms of a single plume, but would require multiple episodic, synchronized plumes.

Moore et al. (2008) noted that the episodic alkaline volcanism recognized across Africa by [Bailey \(1992\)](#) is reflected in the eruptive ages of kimberlites and other alkaline pipes in southern Africa. These authors noted a systematic younging of alkaline pipes from the



**Fig. 16.** Distribution of kimberlite indicator mineral (KIM) anomalies and known kimberlites relative to the modern central Zimbabwe watershed (green line) and inferred pre-Karoo (~300 Ma) topography (after Lister, 1990) (dashed lines). Heavy dash-line denotes the southerly limit of the Karoo watershed, as inferred by Lister (1990). Arrows with solid tails denote Permian ice movements in the north of Zimbabwe. Arrows with dashed tails show inferred flow directions of palaeo-drainages which exploited former glacial valleys south of the modern watershed M = Maitengwe; N = Nyamdhlovu; D = Daiseyfield; Byo = Bulawayo. (Adapted from Moore et al., 2009a,b).

continental interior to the east, south and west continental margins (Fig. 17), and concluded that this pattern of episodic, outward radiating volcanism is not readily explained by migration across a mantle plume. It was suggested instead that alkaline volcanic episodes were triggered by intra-plate stresses linked to changes in the ocean ridge spreading axes. Although the subject of tectonic controls of kimberlites remains controversial, there is increasing evidence against a direct relationship between kimberlites and plumes.

Helmstaedt and Gurney (1997) examined the relative role of hotspots and plate tectonics as triggering and enrichment processes for the kimberlite and olivine lamproite magmatism in southern Africa. Plate tectonic reconstructions of known hotspot tracts are incompatible with a significant role of hotspots and plumes in enriching upper mantle source rocks. The same reconstructions are consistent, however, with the presence of a deep megalith of remnants of subducted oceanic lithosphere under much of southern Gondwana that may have been responsible for the enriched geochemical signatures of olivine lamproites (formerly Group II kimberlites) and DUPAL-type hotspots. Helmstaedt and Gurney (1997) suggested that melting of these rocks

was triggered by slab-derived volatiles or diapiric upwellings as southern Africa slid off the megalith before and after opening of the South Atlantic.

Jelsma et al. (2009) suggested that the trigger for kimberlite magmatism appears to be related to thermal perturbations (thermal insulation, mantle upwelling) beneath a stagnant or sluggish supercontinent and associated tectonic change, i.e., stress changes induced within the continental plate because of supercontinent fragmentation or supercontinent assembly. As many kimberlites are associated with trans-lithospheric structural corridors, changes in plate motions may have caused shearing with strain accommodation along lithospheric discontinuities. In the African case in particular, such lithospheric discontinuities were interpreted to reflect the continental continuations of oceanic fracture zones.

Julian et al. (2015), challenging the model linking kimberlites to LLSVPs, noted that Cenozoic kimberlites and lamproites in Canada and Australia do not show any spatial association with lower mantle seismic velocity anomalies. They also pointed out that the most compelling spatial relationship between LLSVPs and African kimberlites was for the



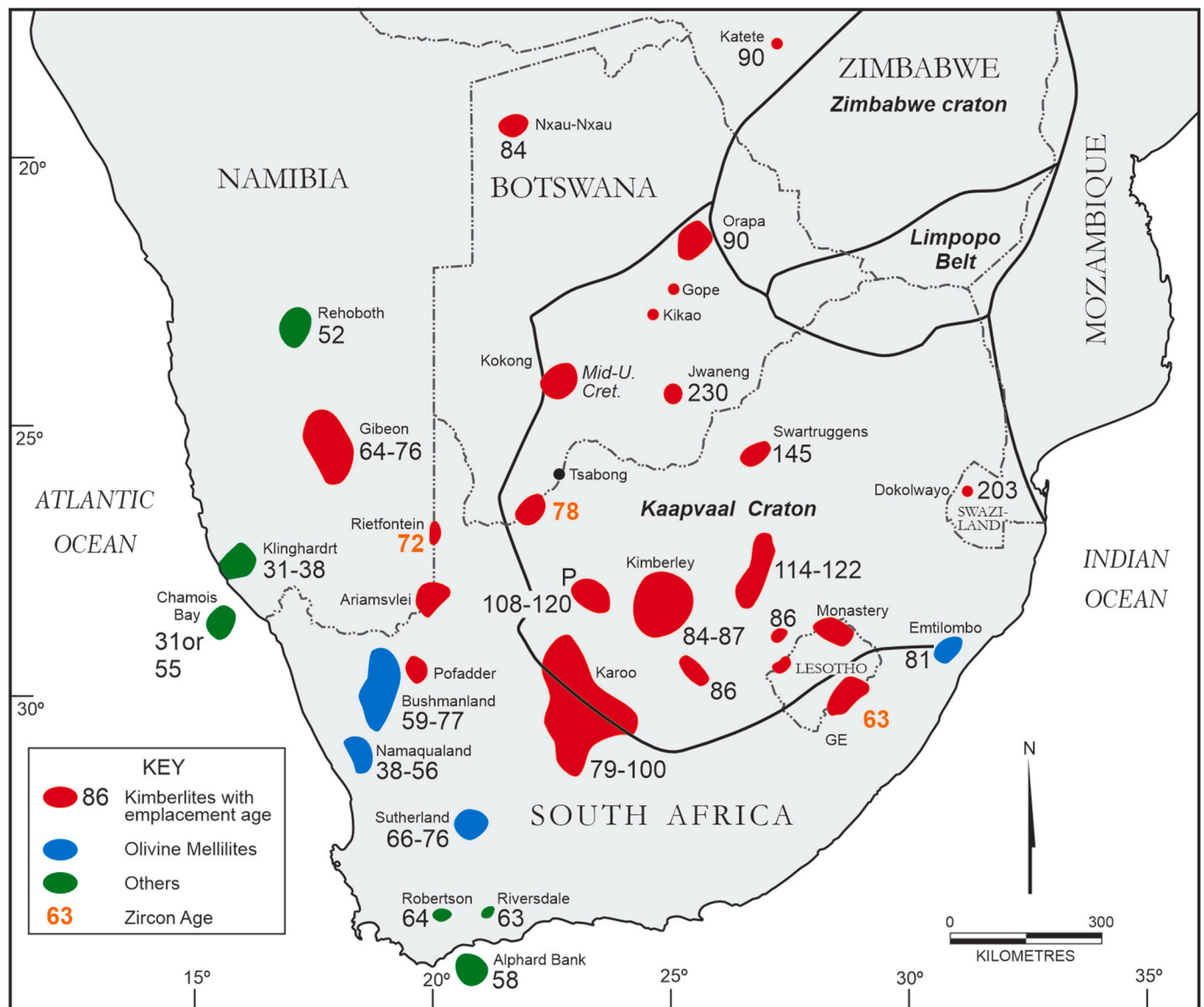


Fig. 17. Distribution and ages (Ma) of the major post-Gondwana kimberlite and other alkaline volcanic pipe clusters in southern Africa (modified from Moore et al., 2008).

period 160–150 Ma, which was characterized by very low intensity kimberlite activity. The inferred spatial relationship became much less compelling for the period of intense kimberlite activity from 120 to 70 Ma. They concluded that kimberlite eruptions are primarily sensitive to stress in the lithosphere.

Gernon et al. (2023) showed that kimberlite magmatism is strongly related to continental break-up. As both breakup and kimberlite magmatism are commonly attributed to mantle plumes, the question to be answered is whether rifting itself is the primary driver of kimberlite or whether mantle plumes drive both rifting and kimberlite magmatism. They showed that most kimberlites spanning the past billion years erupted about 30 million years after continental breakup, suggesting an association with rifting processes. This compares to a statistically significant time difference between large igneous provinces (LIPs, the accepted main surface expression of mantle plumes) and subsequent continental fragmentation of  $+7 \pm 4$  million years, suggesting that rifting is the first-order control. The analysis of Gernon et al. (2023) analysis suggests that kimberlite melting beneath cratons occurs through convective removal of parts of the keel that has been enriched by volatiles over a prolonged time. However, their conclusion that

kimberlites initially erupted closer to the rifted margin, with younger activity migrating towards the cratonic interior, conflicts with the data presented in Fig. 17.

The relevance (or otherwise) of plumes to understanding triggers for kimberlite and other alkaline volcanics is clearly an important geological question, and Africa has been central to this important debate. However, despite the importance of resolving this geological conundrum, it remains highly controversial, with proponents arguing for and against the model, seemingly isolated in opposing camps.

## 7. Kimberlites and palaeontology

As shown by Hawthorne (1975) (Fig. 18), kimberlite pipes with preserved crater-lake facies are restricted to the west of a northeast-trending line stretching from the Atlantic coast near Bushmanland, in the southwest, to the east coast of Tanzania, well to the east of the Mwadui kimberlite. Fine-grained sediments in the inferred short-lived crater lakes have preserved the local fauna and flora in exquisite detail, providing a rare glimpse into the past environment and vegetation of the Cretaceous to Cenozoic in southern and eastern Africa



**Fig. 18.** Distribution of kimberlites in central and southern Africa with known and possible preserved crater-lake sedimentary sequences, which are separated by the NE-SW diagonal line from eroded pipes lacking crater-fill sedimentary cappings. (Adapted from Hawthorne, 1975).

(see Fig. 19b).

As far as southern Africa is concerned, these fossil records are the only ones for the interior during the Cretaceous and early Cenozoic. However, their preserved fossil record has wider relevance for understanding global faunal and floral evolution. Thus, for example, as discussed in the following sections, the southern African crater sediment sequences straddle the period of the major evolutionary radiation of the Angiosperms (flowering plants). This represented a major puzzle to Darwin, which he described as “an abominable mystery”, as the limited palaeontological record of his day lacked evidence for the Angiosperm precursors.

In this section we briefly review the fossil record preserved in kimberlite pipes based on evidence from the Bushmanland kimberlites and Saltpeterkop alkaline igneous suite (South Africa), Orapa (Botswana) and Mwadui (Tanzania).

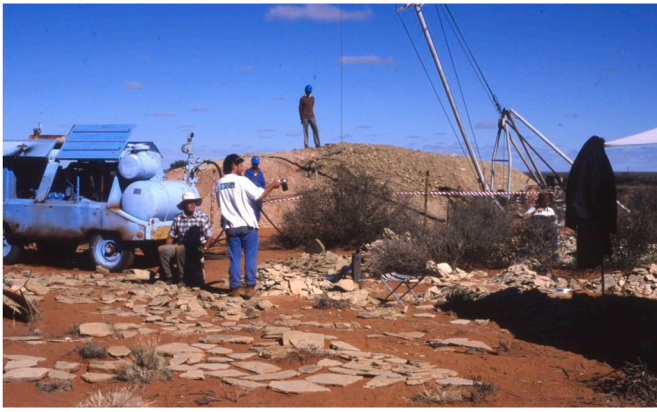
### 7.1. Bushmanland kimberlites

Fossil leaves and pollen from kimberlite pipe crater-lake facies were first described in 1931 from the Arnot Pipe on the farm Banke in



**Fig. 19a.** Arnot pipe leaf – part and counterpart of a leaf found in a borehole core of 7 cm diameter. Note the marginal teeth of the leaf, identified as *Myrica* sp. (Rennie, 1931).





**Fig. 19b.** Stompoor pipe. A photograph taken of the excavation in 2000 of a simple bucket and pulley system to lower researchers and excavators into the 10 m deep test pit into the lake facies.



**Fig. 19c.** Example of one of the numerous anuran frogs recovered from the shales, Stompoor pipe.

Bushmanland (Rennie, 1931) (Fig. 1b & 19a). This is located within a cluster of some 270 kimberlite and olivine melilitite pipes, (the Bushmanland Cluster, Northern Cape Province), with radiometric ages in the range 85–55 Ma (Upper Cretaceous to Paleocene), centered on the village of Gamooep (Moore and Vervoerd, 1985; Jelsma et al., 2004). Crater sediments are preserved over several pipes, indicating limited erosion subsequent to emplacement.

Rennie (1931) examined 70 specimens, recognizing 12 angiosperm species, a single fern frond, a fruit or seed, and a piece of wood. This material is housed now in the Cape Town Museum and should be studied again. Rennie (1931) compared the most abundant leaf with *Myrica*. Adamson (1931) identified *Ficus*-like wood, but the small stem is not well preserved.

Kirchheimer (1934) found six pollen types from the Arnot pipe: two bisaccate grains and four angiosperms including *Proteacidites* type, *Tricolpites* sp., two other triaperturate types, all are unnamed. These samples were studied in more detail by Scholtz (1985) who identified 64 types of pollen, representing 28 plant families. Some of the main families are Proteaceae, Restionaceae, Ericaceae, Epacridaceae, Euphorbiaceae, Thymeliaceae, Chloranthaceae, Casuarinaceae, Cornaceae, Caesalpinaceae and Anacardiaceae. There are no direct dates, but Scholtz (1985) inferred an age of between 64 and 71 Ma based on the surrounding pipes. Not only are these the oldest records of angiosperm pollen for South Africa, but the presence of some families at that time is critical in recent discussions about where in Gondwana the families originated and the dispersal routes to their current distributions. For example, for the Proteaceae, molecular phylogenies and fossil records do

not always agree on the origins (time and place) of plant families (He and Lamont, 2022). Other families present in the Arnot pipe palynoflora are the Restionaceae, Ericaceae and Thymeliaceae which together with the Proteaceae, are key members of the Fynbos (Cowling and Holmes, 1992). The age of the fynbos is also a contentious issue and should be considered in a broader manner by consulting the fossil records. Another family that was present in the Arnot pipe flora is the Casuarinaceae, that also has been found in the Miocene of the western Cape (Coetzee and Pragowski, 1984; Roberts et al., 2017), but the family no longer occurs in Africa.

The time represented in these fine-grained lake sediments is mostly only a few million years (Smith, 1986), but they provide an important window into the Late Cretaceous biota. De Wit et al. (1992) reported that crater facies have been recorded in over 150 of the Bushmanland pipes, which flags this cluster as an important focus for future research.

A non-diamondiferous pipe, Stompoor, in the northern Cape (Fig. 1b) has crater-lake facies with poorly preserved dinosaur bones of Cretaceous age. A single maple-like leaf impression (Fig. 19a) and fossil wood were mentioned by Smith (1986). The remarkably abundant frog fauna (Fig. 19c) has been described by Trueb et al. (2005). Palynological studies by Scholtz (1987) concluded that the crater-lake was broadly Senonian but not younger than Campanian in age.

Kangnas, also known as Henkries Valley, south of the Orange River in Namaqualand, 60 km east of Springbok (29° 31' 13" S, 18° 25' 10" E) (Fig. 1b), was found in 1913, and a dinosaur was described by Rogers (1915) (revised in 1975 by Cooper). Fossil wood and a poorly preserved leaf fragment from 35 m below surface in a well were reported by de Wit et al. (1992). It is not certain whether the pipe is Upper or Lower Cretaceous, but the location of the Kangnas site supports a Late Cretaceous age, as the geographic age distribution pattern tends to have the older pipes in the north (Kangnas region).

Although the Cretaceous plant record is rather fragmented for southern Africa, there is a clear indication of a complete floral change (timing unknown) from the fern-cycad-bennettitalean-conifer flora of the Jurassic and Early Cretaceous to an angiosperm flora with rare gymnosperm elements by the early Late Cretaceous. The notophyllous (small) angiosperm leaves and rare conifers and (a few pollen grains) of the inland Late Cretaceous floras do not support the hypothesis of Axelrod and Raven (1978) that the continental interior was forested. The fossil record and climate models (Rees et al., 2000; Sellwood and Valdes, 2006) suggest that the interior was dry with low vegetation. Conifers probably grew in lowland coastal regions (Demko et al., 1998; Bamford, 1990).

## 7.2. Saltpeterkop alkaline igneous suite

Although not strictly a kimberlite pipe, the Saltpeterkop volcanic edifice, close to the village of Sutherland (Northern Cape Province) (Fig. 1b) forms part of the Upper Cretaceous Sutherland Suite of alkaline rocks, an igneous province composed of olivine melilitites, carbonatites, trachytes and ultramafic lamprophyres (De Wit and Bamford, 2021). Crater-lake sediments were formed in the depression of Saltpeterkop and the summit tuff ring structure that is almost 1 km in diameter. Silicified wood from the sediments has been identified as the conifer *Cupressinoxylon widdringtonioides*. This is the first example of the fossil genus in South Africa and is of interest because only one member of the Cupressaceae *sensu lato* occurs in southern Africa today. From the wide and indistinct growth rings in the fossil wood, the authors interpreted the local climate as warm and humid with little or no seasonality, in support of global records of a warm Late Cretaceous. For broader geomorphological indicators, the preservation of the crater signifies the low level of erosion the region has experienced since its emplacement (De Wit and Bamford, 2021; De Wit, 2022). With a date of ca 70 Ma the preservation of the Saltpeterkop crater and its associated volcanoclastics highlights the change of intense landscape denudation, that was caused by the Gondwana break-up to the end of the Cretaceous, to a period of

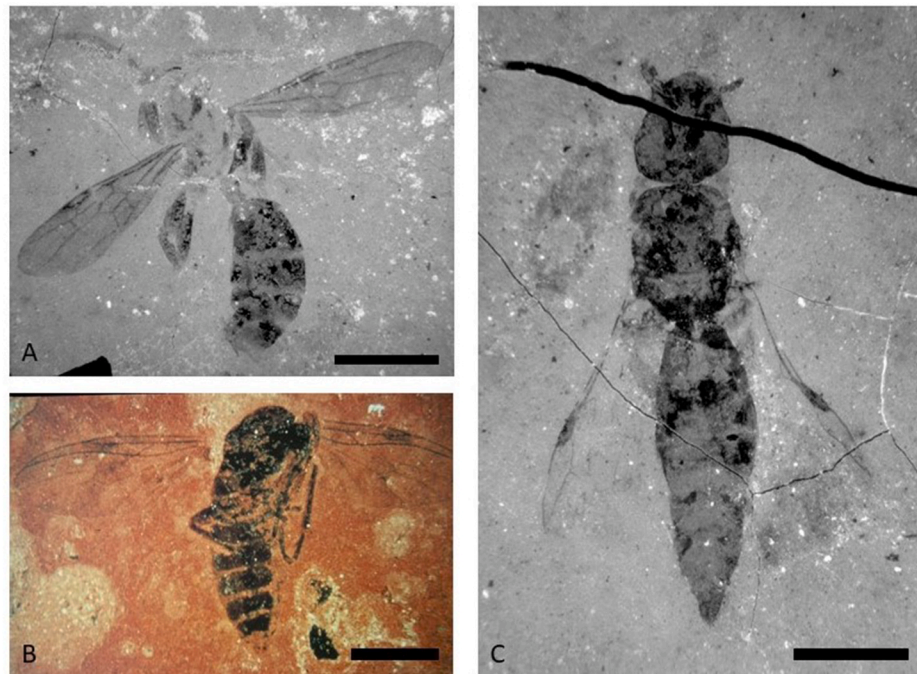


Fig. 20a. Orapa pipe insects – hymenopterans (wasps, bees and ants). Scale bars = 10 mm.

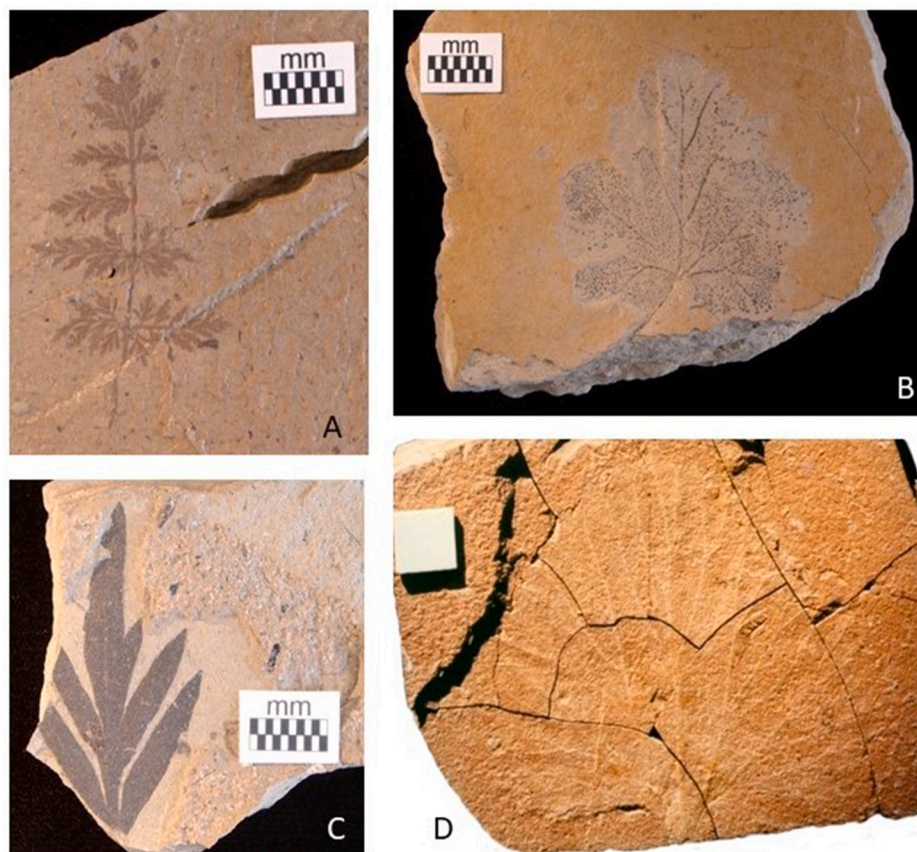


Fig. 20b. Orapa pipe plants – A – fragment of a fern leaf. B – D angiosperm leaves.

drastically reduced erosion rates during the Cenozoic Era (de Wit, 2022).

### 7.3. Orapa kimberlite

The Orapa Pipe in north central Botswana (Fig. 1b) is mined for diamonds, and a large collection of fossil insects and plants (Fig. 20a and



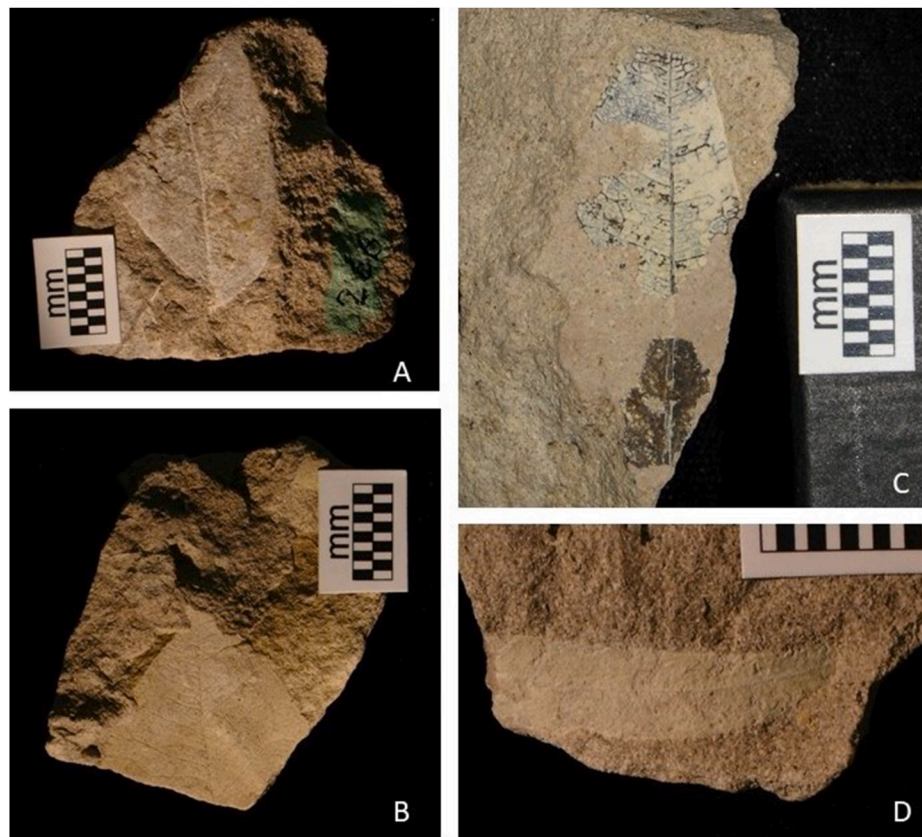


Fig. 21a. Mwadui angiosperm leaves. Note the variety of leaf shapes and venation.

b) has been recovered (Bamford, 1990; Rayner et al., 1997 and references therein). The pipe contained a shallow lake, about 600 m in diameter in the early Late Cretaceous (zircon date:  $93.1 \pm 1.4$  Ma, Davis, 1977; fission track date:  $87.4 \pm 4.7$  to  $92.4 \pm 6.1$  Ma, Haggerty et al., 1983). This age is supported by a preliminary palynological study by Scholtz (1984) who identified Araucariaceae types, Cupressaceae types, *Ephedrites* types, *Classopollis* cf. *jardinei*.

The insects are diverse, and only a few groups have been studied to date. Insect groups such as ants (Dlussky et al., 2004), aphids (Rayner and Waters, 1989), beetles (McKay, 1990, 1991; Woolley, 2016), a spider (Rayner and Dippennaar-Schoeman, 1995), wasps (Brothers, 1992; Brothers and Rasnitsyn, 2003, 2008; Rasnitsyn and Brothers, 2007, 2009) and weevils (Kuschel et al., 1994) have been published and more taxa are being studied currently.

Bamford (1990) identified 29 leaf types, 6 flowers, 14 seed and fruit types, two ferns and possible bryo/hepatophytes. Well-preserved and diverse insects have been described (Rayner et al., 1997 and references therein, and more recent ones above). This inland flora is probably the oldest angiosperm flora described to date from southern Africa. The leaves are taxonomically problematic and there are no conifers or cycads present.

#### 7.4. Mwadui pipe, Tanzania

According to Stiefenhofer and Farrow (2004) who reviewed the geology and proposed an emplacement model, the Mwadui pipe (Fig. 1b) represents the largest diamondiferous kimberlite ever mined and is an almost perfectly preserved example of a kimberlitic crater in-fill. Alex Du Toit collected fossil leaf impressions from the Mwadui pipe and in the 1960s, Dr Edna Plumstead collected more leaf material which is housed in the Evolutionary Studies Institute, University of the Witwatersrand. In 2002 Mike de Wit collected more samples of wood and plant material

which was studied by Cantrill et al. (2013).

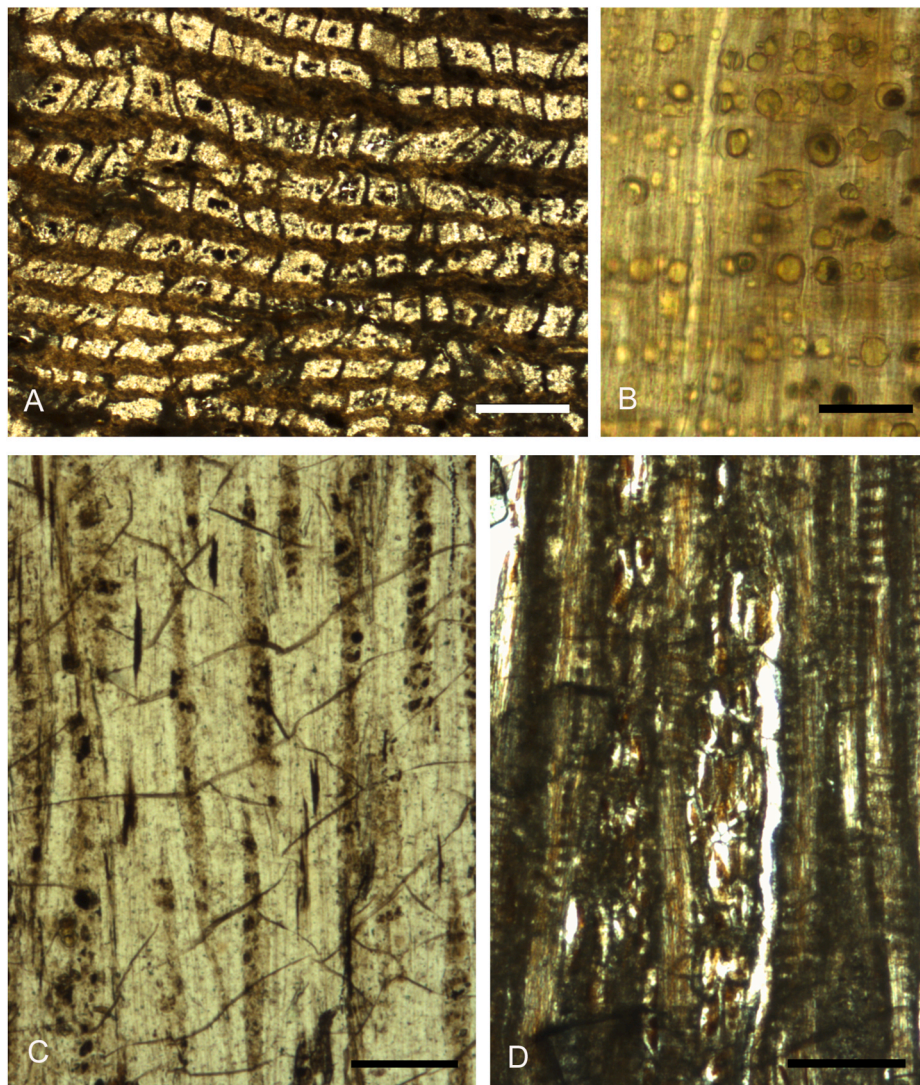
Among the early Cenozoic crater lake sediments of Mwadui ( $52 \pm 2$  Ma), nine leaf types, wood of *Cynometroxylon* (Fabaceae), pollen of Proteaceae, and possibly one each of Fabaceae, Anacardiaceae, Sapindaceae, Cucurbitaceae, Rosaceae and Solanaceae were recognized (Fig. 21a and b). Spores of ferns and bryophytes are also present. Charcoal fragments are abundant, indicating the presence of fires. Cantrill et al. (2013) interpreted the vegetation to be an open woodland-like setting, with a humid microclimate possibly with marked wet-dry seasonal fluctuations.

#### 7.5. Kimberlite fossil record and the debate on the evolution of the angiosperms

Coined as Darwin's Abominable Mystery, the origin of the angiosperms (flowering plants) remains poorly understood (Cascales-Miñana et al., 2016). Even the lower age limit of the group is unresolved, and estimates for their origin, ranging from Permian (270 Ma) to Early Cretaceous (140 Ma), are based on the fossil record and molecular dating (reviewed by Coiro et al., 2019; Sauquet et al., 2022). Along similar lines, Benton et al. (2021) consider the period between 100 and 50 Ma as the Angiosperm Terrestrial Revolution (a refinement of the Cretaceous Terrestrial Revolution first proposed by Lloyd et al. (2008)). Most of the African kimberlites with crater-lake facies are dated within the time of the proposed Angiosperm Terrestrial Revolution, though the information from the kimberlite pipes' fossil record towards the debate on the angiosperm origins and migrations has not been fully exploited.

Dated at ca 93 Ma, the Orapa kimberlite pipe in Botswana has angiosperm leaves (Fig. 20b) that have not been attributable to any clade in the macroplant record (Bamford, 1990; Rayner et al., 1997). In the microfossil record, pollen of both angiosperms and gymnosperms are represented (Scholtz in Rayner et al., 1997). Insect pollinators (Fig. 20a)





**Fig. 21b.** A-D – photomicrographs of fossil wood recovered from the Mwadui pipe in northern Tanzania, identified as *Cynometroxylon* (Cantrill et al., 2013). A – transverse section to show the vessels (dark ovals), rays (dark vertical lines) and banded parenchyma (light horizontal lines). (Scale bar = 200 µm). C – tangential longitudinal section to show the biseriate rays (longitudinal lenses). (Scale bar = 100 µm). B & D – tangential longitudinal section with procumbent ray cells (horizontal lines) enlarged in D to show globular cell contents (B scale bar = 50 µm); vertical lines are the vessels and fibres. (D Scale bar = 100 µm).

are also present, such as wasps (Brothers, 1992; Brothers and Rasnitsyn, 2003, 2008; Rasnitsyn and Brothers, 2007, 2009), weevils (Kuschel et al., 1994) and crane flies (Rayner and Waters, 1990).

The Arnot pipe on Farm Banke in Bushmanland is dated as ca 70 Ma and has no insects but has a diverse angiosperm (pollen and leaves) and gymnosperm pollen fossil record (Scholtz, 1985; Rennie, 1931). Only the Proteaceae pollen from this pipe, and from the ca 52 Ma Mwadui pipe in Tanzania have been considered for the origins and dispersal of that clade (He and Lamont, 2022). Other plant and insect clades are yet to be examined from the aspect of angiosperm evolution.

In summary, the few African kimberlite crater-lake facies that have been studied provide short duration but important windows into the past vegetation and fauna of the Late Cretaceous and Early Cenozoic. This was a period of major worldwide floral and faunal change, which has shaped the modern landscape. However, not enough details are known yet, highlighting the fossil record preserved in kimberlite crater sediments as an important focus for further research.

## 8. Concluding remarks

From the time of the Kimberlite discoveries in South Africa, diamond

exploration has been driven by the search for further new economically viable primary diamond deposits. Efforts to develop improved exploration techniques and scientific investigations of these rare magmatic rocks and their mantle cargo went hand in hand, impacting a remarkably diverse range of geoscientific disciplines. As economic diamondiferous kimberlites were not found outside Africa until the mid-1950's, all initial breakthroughs, highlighted in this review, were achieved in Africa or on African research samples investigated elsewhere. It took another 20 years, until the First International Kimberlite Conference in Cape Town, in 1973, before samples collected from African kimberlites were more widely distributed, and knowledge gained in Africa could be tested in other parts of the world. An exception was the former Soviet Union, where diamondiferous kimberlites had been found in Siberia, in the 1950's, using the African geo-tectonic template for area selection, stimulating parallel scientific investigations. However, results of Russian studies did not reach the English-speaking world until the mid-1970's, and research material did not become widely available until much latter.

The African experience gave us the first realistic model for a kimberlite pipe that stimulated continuing discussions about kimberlite magmatic systems, including the mechanics of diatreme formation. The

distribution of diamondiferous and non-diamondiferous kimberlite pipes on the African continent was explained by what became known as “Clifford’s Rule”, stating that diamondiferous kimberlites are confined to the oldest cratons, later shown to be of Archean age. Interestingly, studies of peridotitic xenoliths from the Archean Kaapvaal craton soon provided support for Clifford’s Rule, as it was revealed that the craton is underlain by a deep diamondiferous lithospheric root which is older, cooler, and more refractory (harzburgitic) than the shallower, non-diamondiferous lithosphere under adjacent Proterozoic orogenic belts. Ages of harzburgitic garnets included in diamonds were found to be Mesoarchean (ca. 3.3–3.2 Ga), verifying the great antiquity of the depleted root, and also clearly showing that most lithospheric diamonds are xenocrysts in their host kimberlites. Eclogite xenoliths were found to represent fragments of subducted oceanic crust, and ages of eclogitic mineral inclusions in diamonds suggested that plate tectonics processes began as early as 2.9 Ga and played an important role in the amalgamation of the Kaapvaal craton.

When mantle xenoliths from kimberlites in other parts of the world were studied, it was discovered that the rock types first identified in Africa occur worldwide, and that the diamond-forming processes deduced from the African mantle sample were active also in other cratons of the world. However, while processes leading to the formation of primary diamond deposits have operated worldwide, the timing of the individual diamond-forming events and transport to the surface are craton specific. Harzburgitic garnet inclusions in diamonds from all cratons are Mesoarchean (ranging from 3.5 to 3.2 Ga) (e.g., Gurney et al., 2005), but ages of the eclogitic mantle sample range from ca. 2.9 Ga to much younger, reflecting the tectonic history of individual cratons, thus far limiting the involvement of oceanic crust in the formation of craton roots to about 2.9 Ga.

Many other branches of the Earth Sciences have benefitted from kimberlite studies. Understanding kimberlite emplacement processes has made it possible to develop semi-quantitative models of erosion patterns across the African continent, particularly since the disruption of Gondwana. Tracing the halos of dense indicator minerals (pathfinders) back to the parental kimberlites and olivine lamproites has provided a framework for understanding the evolution of continental drainage systems. As discussed above, the important question as to what triggers kimberlite and lamproite magmatism has caused a continuing controversy, especially about the possible involvement of mantle plumes, that is unlikely to be solved soon. Less well known than the many petrological, volcanological and geomorphological aspects of kimberlite geology are applications to palaeontology. Crater lake sediments preserved at the top of many kimberlite pipes are an important, yet still underutilized, source of invertebrate, insect and plant fossils in the interior of the continent, where time-equivalent strata have been eroded. Most of the kimberlites discussed in the last chapter of this review are dated as Cretaceous to early Cenozoic, falling within the time interval of the proposed Angiosperm Terrestrial Revolution. The well-preserved plant remnants thus have the potential to make a major contribution towards the debate on the angiosperm origin. And finally, many of the conclusions drawn in the diverse geological fields discussed in this review remain controversial, but this will help to ensure that studies on African kimberlites will remain an important focus of future research in the geosciences.

#### CRedit authorship contribution statement

**Andy Moore:** Writing – review & editing, Writing – original draft, Conceptualization. **Herwart (Herb) Helmstaedt:** Writing – review & editing, Writing – original draft, Conceptualization. **Marion Bamford:** Writing – review & editing, Writing – original draft, Conceptualization.

#### Declaration of competing interest

None of the authors have conflicting interests.

#### Data availability

No data was used for the research described in the article.

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