Journal of African Earth Sciences 205 (2023) 105002

Contents lists available at ScienceDirect

Journal of African Earth Sciences

journal homepage: www.elsevier.com/locate/jafrearsci

The discovery and petrogenetic significance of komatiites

Eugene G. Grosch[a,*], Allan Wilson[b]

[a] Geology Department, Rhodes University, Artillery Road, Makhanda, Eastern Cape, South Africa
[b] School of Geosciences, University of the Witwatersrand, Johannesburg, 2050, South Africa

ARTICLE INFO

Handling Editor: Dr Mohamed Mohamed G Abdelsalam

Keywords:
Komatiite
Archean
Barberton Greenstone Belt
Ultramafic

ABSTRACT

This review paper reports on the discovery of komatiites and the impact this has had on the geosciences internationally. Komatiites were first discovered by Richard and Morris Viljoen in the Barberton greenstone belt of South Africa and proposed as a new class of ultramafic volcanic rock with >18 wt% MgO. Komatiites are in places associated with spinifex textures (elongated bladed and plumose olivine crystals). The discovery and petrological study of komatiites and understanding of the field controls have given rise to intense debate about their mantle origin, water content and geodynamic setting of eruption. The observation that komatiites are found predominantly in the Archean and to some extent in the Palaeoproterozoic, has led to the proposition that the early Earth was much hotter (by c. 400 °C) than the present day. However, some workers have challenged this model involving secular cooling of the Earth since Archean times. These workers argue that komatiites formed in a cooler Archean subduction zone, rather than in a mantle plume. Komatiites of the mid-to late-Archean have also proven to be important economically (e.g. Yilgarn Craton, Australia; Superior Craton, Canada) as they host important nickel-sulphide deposits. Today, novel petrological techniques (e.g. secondary ion microprobe analyses of olivine melt inclusions) are being applied to komatiites to address important outstanding questions in the geosciences, including the question of whether or not plate tectonics was operating in the early Archean.

1. Background and significance of discovery

Ultramafic rocks have held a particular fascination for geologists because of the occurrence of olivine which defines the end of the wide spectrum of silicate rocks. However, in the early days of research the link between ultramafic rocks and specific melt types remained elusive. Canadian geologists at the Ontario Department of Mines (ODM) recognized rocks with enigmatic textures while mapping in the Munro Township area and the earliest observations and field description by Bruce (1926) showed a photograph of the unusual rock textures made up of elongated olivine crystals (later termed spinifex), and mapped these rocks as lava flows. Other Canadian geologists who mapped the spinifex-textured rocks as volcanic flows include, Berry (1940), Prest (1950), Satterly (1951), and Abraham (1953). Although these rock units were mapped as unusual lava flows, the dominant paradigm at the time was that ultramafic lava flows did not exist. This was in part due to the experimental work of Bowen (1922) who indicated that the high liquidus temperatures of ultramafic lavas was not observed in present day volcanic settings. Satterly (1951), in the absence of whole rock geochemical analyses, interpreted the spinifex texture as a contact metamorphic effect in metabasaltic flows due to picrite sill intrusions. Naldrett in his 1964 PhD thesis made the connection between the elongated olivine crystals found in nature and those formed from rapidly cooled basaltic liquid in experiments, and proposed on this basis the possible existence of ultramafic liquids. Naldrett and Mason (1968), described skeletal olivine crystals in ultramafic lenses from Dundonald Township, not far from Munro. These workers concluded that the rock units were ultramafic sills intruded at high-level, but did not exclude the possibility that they could have been lava flows derived from unusually high magnesian liquids, but the significance of the textures in the context of true lava flows was at that stage not known.

The first scientists to provide unequivocal evidence of the existence of extrusive ultramafic rocks were the twin brother geologists, Morris and Richard Viljoen who conducted their PhD studies in the Komati Formation of the Paleoarchean Barberton Greenstone Belt, South Africa. They achieved this by conducting an integrated study on mafic-ultramafic rocks of the Komati Formation, by combining detailed field mapping, petrography and whole-rock geochemistry. As such they presented a range of evidence that for the first time supported the existence of volcanic ultramafic lava flows. This included the close

* Corresponding author.
E-mail address: E.Grosch@ru.ac.za (E.G. Grosch).

https://doi.org/10.1016/j.jafrearsci.2023.105002
Received 20 February 2023; Received in revised form 18 June 2023; Accepted 21 June 2023
Available online 22 June 2023

interlayering with pillow basalt flows (subaqueous volcanic extrusions), the chilled flow tops, hyaloclastite breccias and what they called 'crystalline quench texture'. Their remarkable results were presented at an international conference in Pretoria (South Africa) in July 1969. A series of papers by the Viljoens followed making a strong petrological case for a new class of igneous rock that they called 'komatiite' (Viljoen and Viljoen, 1969a-c), and so named after the type locality close to the Komati River. At the time, Professor Harry Hess of Princeton University helped to promote and establish the idea of ultra-high temperature ultramafic lavas as a major new class of volcanic rock.

After the discovery of komatiites by the Viljoen brothers in South Africa, komatiites were soon reported from other areas (Archean greenstone belts) around the world. For example, Pyke (1970) presented evidence for ultramafic lava flows from the Abitibi greenstone belt and later helped to establish the classic outcrops of Munro Township as ultramafic volcanic rocks (Pyke et al., 1973). Between 1971 and 1973, a number of scientists working in Australia reported the occurrence of ultramafic volcanic rocks throughout the Yilgarn belt of Western Australia (McCall and Leishman, 1971; Williams, 1972; Hallberg and Williams, 1972). The komatiites in Western Australia were of particular economic interest as they hosted large Ni-sulphide deposits. At about the same time in 1971, Nesbitt (1971) introduced the term 'spinifex' into the literature to describe the spiky appearance (reminiscent of an Australian grass) of some komatiites due to the presence of elongated, skeletal olivine hopper crystals (Fig. 1 a – d). The geological and petrological aspects of komatiites were also reported from the Belingwe greenstone belt of Zimbabwe (Bickle et al., 1975; Nisbet et al., 1977).

Komatiites are now recognized in many greenstone belts around the world and in some places associated with high-magnesium, high silica basalts called boninites (e.g. Angerer et al., 2013). A geographical map of komatiite occurrences globally can be found in Arndt et al. (2008). The discovery of komatiites is important as it gives a window into early Earth processes. The high MgO content (>30 wt%) indicates high liquidus temperatures (c. 1600 °C), and that komatiites erupted with very low viscosity at such high temperatures, mainly subaqueously (under seawater), on the early Earth surface. Together with the rare occurrences of komatiites from the Proterozoic rock record, the presence of komatiites in Archean greenstone belts provides evidence for a much hotter early Earth (Campbell and Griffiths, 1992; Herzberg, 1992, 1995). Studying the composition of komatiites has also contributed to our understanding of the composition of the Earth's deep mantle. Komatiites are also of economic importance as they are associated with nickel and platinum-group elements and have been exploited world-wide.

2. Spinifex texture

The association of komatiite lava and spinifex textured units (the most striking of the associated rock-types) is well known but the petrogenetic relationship remains a point of important debate. When komatiites were first reported in Barberton by Viljoen and Viljoen (1969a,b), initially they described the spiky rock texture as a 'crystalline quench texture', and noted that the dominant texture was similar to that of crystals that form by crystallization during rapid cooling of high-temperature olivine basalt (see Fig. 1 a – d). This crystallization quenching effect was also shown in some experimental studies (Donaldson, 1976, 1982). The term 'spinifex' originates from the similar appearance of an Australian spiky grass - *Triodia spinifex* and the term was coined by Nesbitt (1971). In its simplest definition, a komatiite is an ultramafic volcanic rock with >18 wt% MgO (Arndt and Nisbet, 1982), but a more holistic definition includes the associations with spinifex texture (Nesbitt, 1971). A komatiite flow typically has an upper spinifex-textured part and a lower cumulate part with the definitive textural forms detailed by Pyke et al. (1973; Fig. 2a–c). The uppermost part is typically a brecciated flow top, which has been used as evidence to support the extrusive nature of komatiites (Fig. 2a). This unit is typically underlain by a spinifex textured rock-type and that overlies an olivine cumulate (Fig. 2a). Nesbitt (1971) also put forward what became known as the *spinifex paradox*: the skeletal, bladed morphology of the olivine crystals suggest rapid cooling/quenching near the brecciated flow top margins, but the coarse spinifex textures are found deep within the lava flows and therefore cannot represent a true quench texture.

Donaldson (1976, 1982) was the first to attempt to replicate formation of skeletal olivine crystals in laboratory experiments. Based on

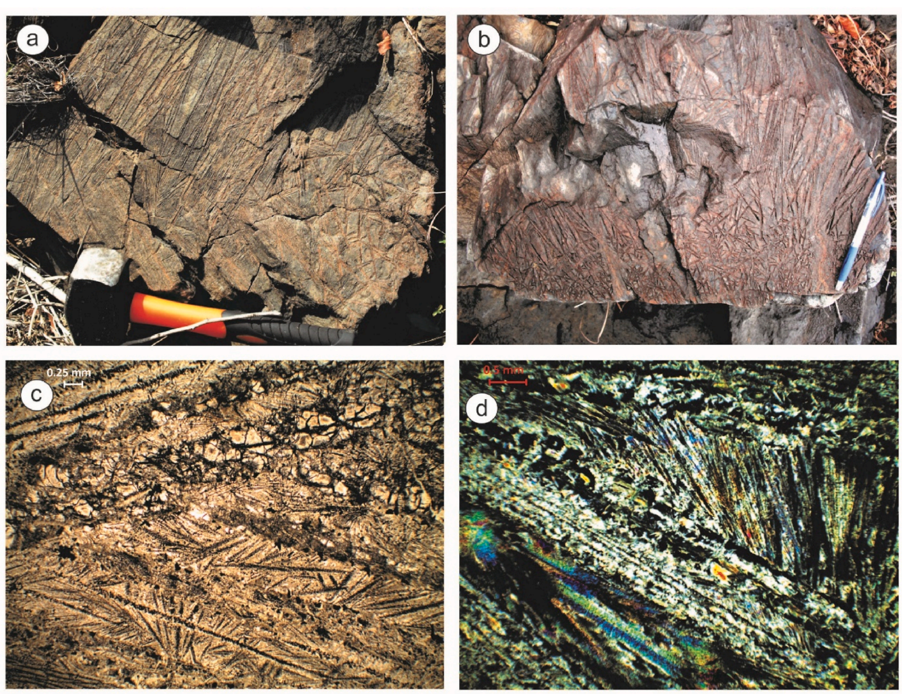

Fig. 1. Spinifex textures observed in komatiite. (a–b) Spinifex textures observed in komatiite, Komati Formation type-section, BGB. (c–d) Petrographic images of partially serpentinized bladed and plumose olivine structures observed in thin section. Scale bar shown top left.

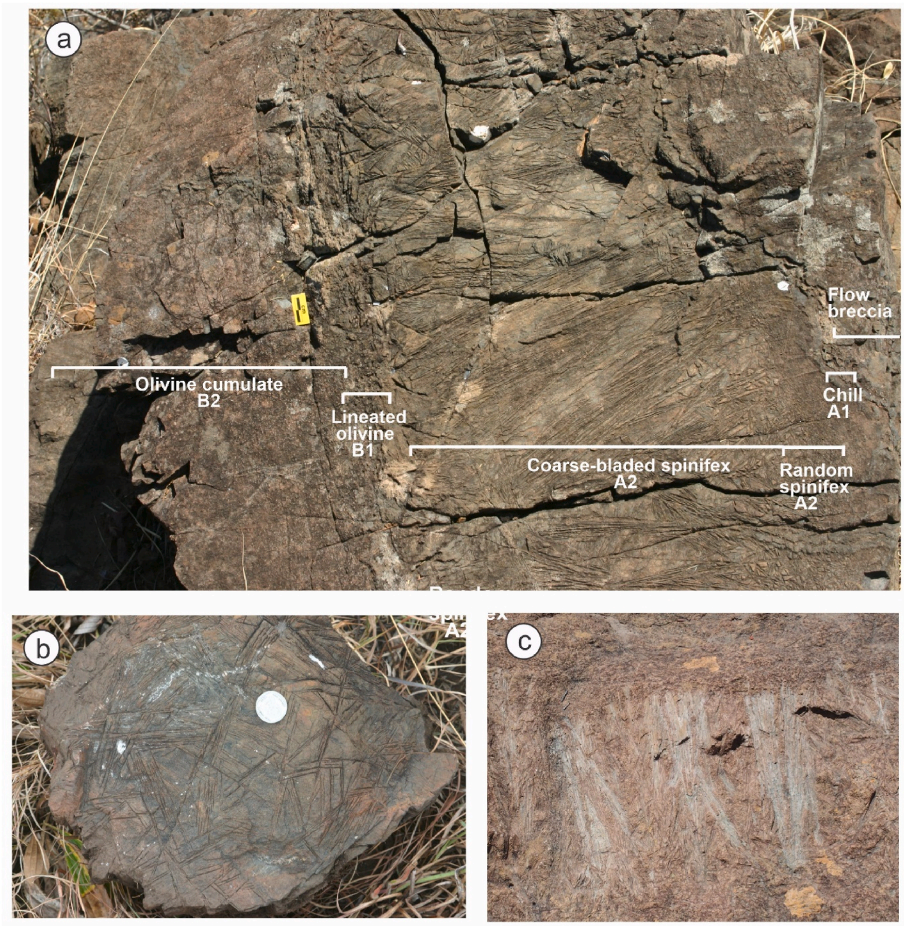

Fig. 2. (a) Typical structure of a spinifex-textured Barberton komatiite flow with clearly observable sub-divisions and units. On the right side is the flow-top breccia overlying the chill zone (A1). This is underlain by a zone of random olivine spinifex and coarse-bladed spinifex unit (A2). This passes into a thin zone of highly lineated olivine crystals (B1) with a sharp contact underlain by an olivine cumulate (B2). The yellow scale is 10 cm. (b) Widely spaced acicular random olivine spinifex. Coin diameter is 2 cm. (c) Pyroxene spinifex in komatiitic basalt. Splayed crystals of clinopyroxene overlie a zone of random pyroxene spinifex (top of photo). Width of view is 40 cm.

his experimental work he noted that the formation of skeletal crystals is due to the high MgO contents of komatiite liquids and rapid crystal growth. It was suggested that rapid cooling rate was not a major controlling factor, but the model did not explain how growth rate could be separated from cooling rate (Arndt and Fowler, 2004). Shore and Fowler (1998, 1999) observed that the long axes (crystallographic a axes) were mostly and consistently oriented at high angles, or normal to the lava flow top. In their model, they argued that heat transfer was more efficient along the olivine long axes (or crystallographic a axes) and that this strong thermal anisotropy promoted olivine skeletal growth from highly magnesian liquids. It was noted, however, that this mechanism of crystal formation would not be applicable at lower temperature and for less magnesian liquids involving pyroxene spinifex growth. Spinifex textured pyroxene is observed in Archean komatiitic basalt lava flows with magnesium contents as low as 10 wt % MgO (e.g. Wilson and Riganti, 2022). The upper limit for komatiitic basalt is taken as 18 wt% MgO.

Grove et al. (1994, 1997) proposed that spinifex texture in the interiors of komatiite units from Barberton in South Africa formed due to the water content in the parental magma. Water would act to suppress the crystal nucleation rate and accelerate diffusion rate leading to the rapid growth of large crystals from the liquid phase. This mechanism requires that the komatiites intruded as sills, contrary to the extensive field observations of Dann (2000, 2001) that indicates komatiites are extrusive. The studies of Grove et al. (1994, 1997) led to the 'wet' versus 'dry' komatiite debate in the literature. Arndt et al. (1998) challenged the hydrous komatiite magma model of Grove et al. (1994, 1997). In a more recent study, Faure et al. (2006) concluded that spinifex texture formed during slow cooling of ultramafic liquid in a thermal gradient within a layer that separates liquid from the outer solidified crust. It is now understood that fine random spinifex near the top of the flow approximates to the parent melt composition (see Fig. 2a). Coarse random spinifex and bladed olivine spinifex likely represent fractionated melt that has been depleted in olivine (Fig. 2a–c). For a more detailed review of spinifex texture formation and other textures that form in komatiites see Arndt and Nisbet (1982) and Arndt and Fowler (2004).

3. Barberton komatiites

Since the discovery of komatiites in the Komati Formation in the Onverwacht Group of the Barberton greenstone belt (BGB), South Africa, komatiites have been found in other parts of the Onverwacht Group

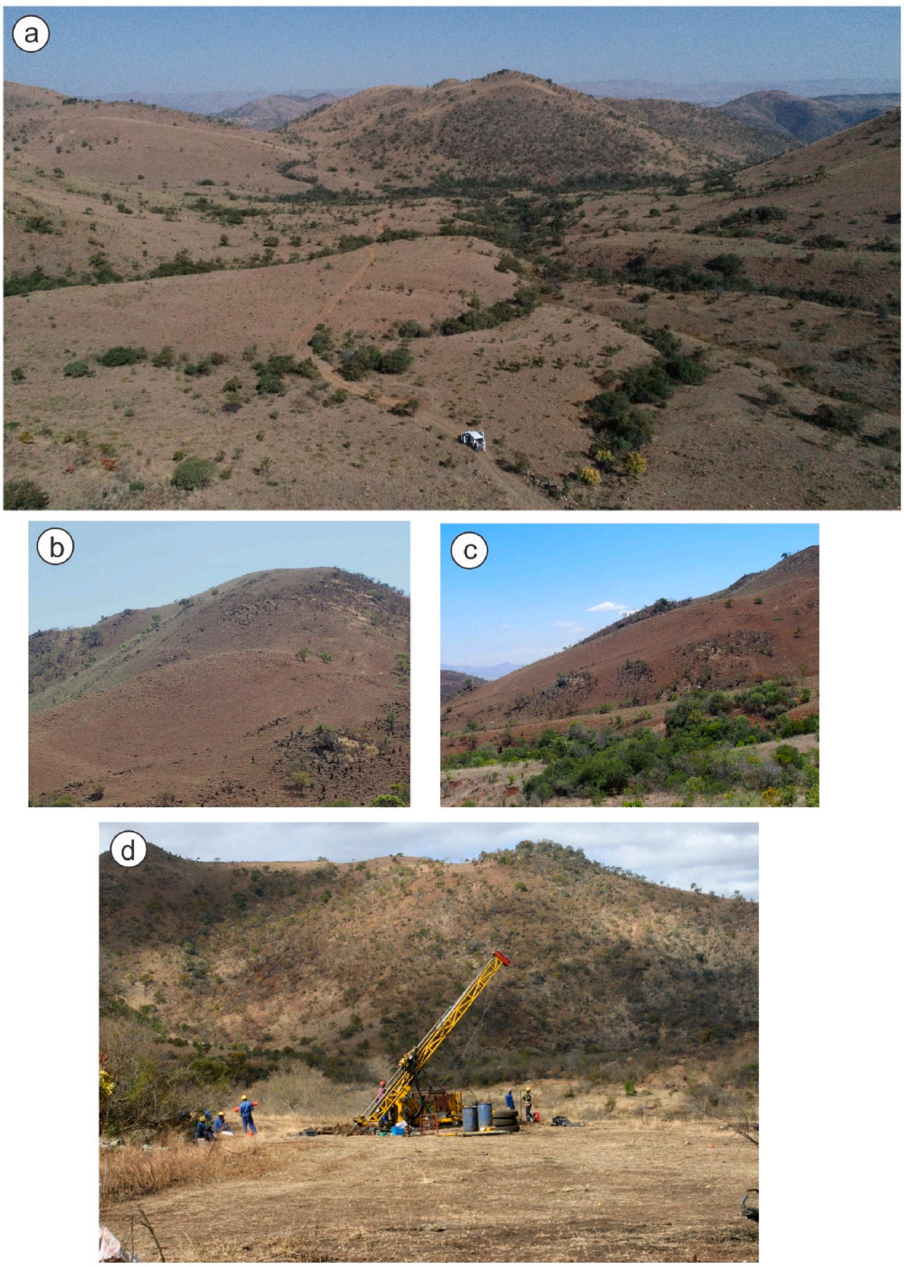

Fig. 3. Field views of the Komati Formation. (a) Drone view to the west of the Komati Formation type section. In the mid-far distance is the basal felsic Theespruit Formation. The heavily wooded hills in the mid-distance are layers of komatiitic basalt. Note vehicle for scale in lower part of the image. (b and c) Komatiite flow units with flows of more resistant komatiitic basalt. (d) Diamond drilling of the Komati type section as part of the ICDP Barberton drilling program in 2011. Behind the drill-rig are komatiite and komatiitic basalt flows.

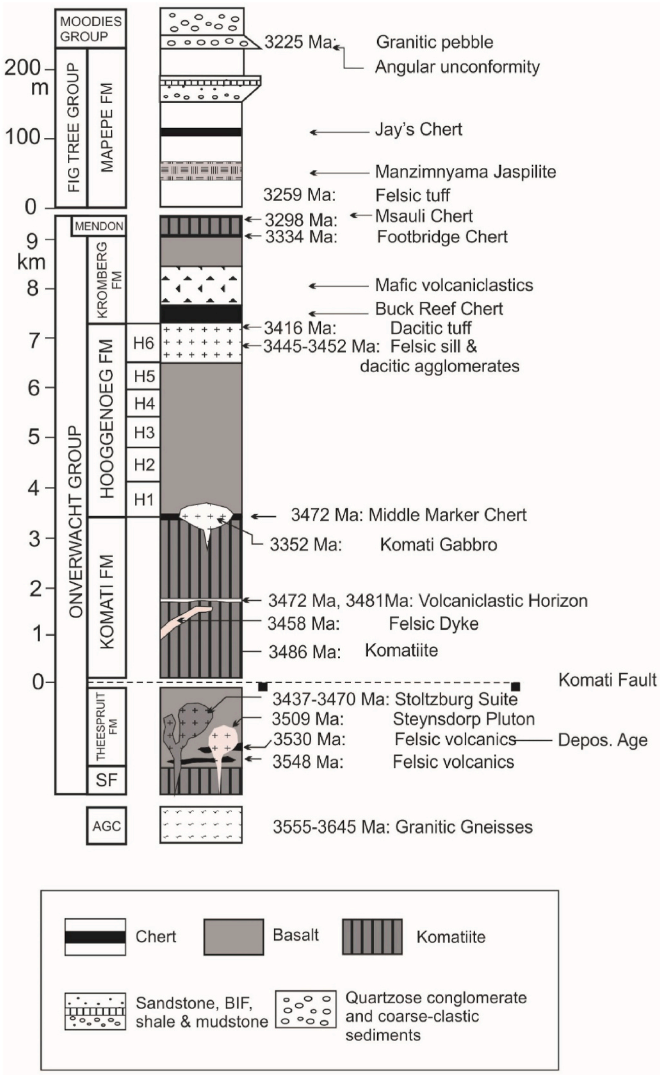

Fig. 4. Stratigraphy model for the Onverwacht Group of the Barberton greenstone belt modified after Lowe and Byerly (2007) and Van Kranendonk et al. (2009).

and in other smaller greenstone belts on the Kaapvaal Craton. However, the Barberton komatiites remain the quintessential occurrences. Field photographs showing the Komati Formation type-section and related outcrops in the Barberton greenstone belt are provided in Fig. 3a–d. This section provides a review of the age and geology of the Onverwacht Group komatiite suites. An overview of the Onverwacht Group stratigraphy of the BGB is presented in Fig. 4. This includes the Komati Formation, Mendon Formation and Weltevreden komatiite suites and are shown on a geological map of the Barberton greenstone belt in Fig. 5. The main focus is on the Komati Formation of the BGB, namely where komatiite was first officially discovered.

The Komati Formation of the (BGB) is the type locality for komatiites (see maps in Figs. 5 and 6). A U–Pb zircon age of c. 3482 ± 8 Ma has been derived from zircons in a volcanic tuff layer in the middle part of the type-section (unpublished data of S. Bowring, reported in Dann, 2000). A slightly younger age 3426 ± 16 Ma was obtained by Sm–Nd dating using drill core (Blichert-Toft et al., 2015). The Komati Formation has a maximum thickness of 3500 m (Brandl et al., 2006) and is regarded as the oldest and best preserved formation of interlayered komatiites and basalts in the world (Fig. 6; Dann, 2000). The extrusive origin for the komatiites was suggested by Viljoen and Viljoen (1969c), argued from the interlayered pillowed komatiitic basalts that indicate eruption under seawater. The Komati Formation comprises mainly low-grade metamorphosed komatiites, komatiitic basalts and to a lesser extent meta-tholeiites, and is divided into the Upper and Lower Komati Formations (see Dann, 2000, Fig. 7). The lower part of the Komati Formation has olivine-dominated, spinifex textured komatiites with a magnesian (MgO) composition of at least 24 wt%, interlayered with massive serpentinite and pyroxene-dominated pillowed, ocelli bearing, komatiitic basalts. The upper part of the Komati Formation comprises pyroxene-dominated komatiitic basalts with massive, spinifex-textured and irregularly-shaped meta-tholeiitic pillow lavas (Brandl et al., 2006). It is less ultramafic than the lower Komati Formation. Dann (2000) produced a geological map of the Komati Formation and proposed a volcanic architecture for the type-section (Fig. 7). Recent geological and petrological work on the type-section has provided a new, high-resolution volcanic stratigraphy model (Fig. 5; Grosch and Slama, 2021). In this model, massive and spinifex-textured komatiites were shown to be rare making up only c. 19% of the lower type-section volcanic stratigraphy and not 50% as previously proposed by Dann (2000). In addition, Dann (2000) did not distinguish between tholeiitic basalt and komatiitic basalt, whereas the new volcanic architecture model of Grosch and Slama (2021) distinguishes between these two rock types (Fig. 8)

Komatiites have also been found in the Mendon Formation, which conformably overlies the c. 3333 Ma Kromberg Formation in the upper Onverwacht Group (Grosch and Slama, 2017; see Figs. 4 and 5). It is younger than the Komati Formation, with maximum ages determined by Sm–Nd dating of 3310 ± 150 Ma for the komatiites of the Mendon Formation (Chauvel et al., 1987). Recent geochronological work has indicated volcanism and deposition of tuff layers between c. 3261 and 3287 Ma (Decker et al., 2015).

Rocks of the Mendon Formation are divided into cycles of komatiitic volcanism separated by thin chert layers: units were designated as M1, M2, M3, M4, M5, with the volcanic sequences termed M1v, M2v, M3v, etc., and the chert layers M1c, M2c, M3c, etc. (Lowe and Byerly, 1999). M1v at the base of the Mendon Formation comprises >200 m of massive peridotitic komatiites, which at the top of some peridotite sections contain a 10 m thick olivine spinifex-textured flow. M1v is weathered and hydrothermally altered in places such as in the Msauli Gorge where the Msauli Chert type-section crops out (Lowe and Byerly, 1986).

Overlying the M1v is the M1c Msauli Chert comprising fine-grained ash and lapilli of komatiitic composition that can also be found in M2c and M3c (Lowe and Byerly, 1999). Overlying the M1c in the southernmost parts of the Mendon Formation, are black cherts overlain by the Fig Tree Group (Fig. 4; Lowe and Byerly, 1999). M2v consists of komatiitic lavas of variable thickness. A 150 m thick komatiite with no interbedded sediments is also present (Byerly, 1999). The lower section consists of cumulate-textured komatiites while the upper section consists of spinifex-textured flows, or spinifex zones comprising single flows. The uppermost flows are silicified and overlain by the M2c black chert interbedded with silicified pyroclastic rock. M3v komatiites are poorly

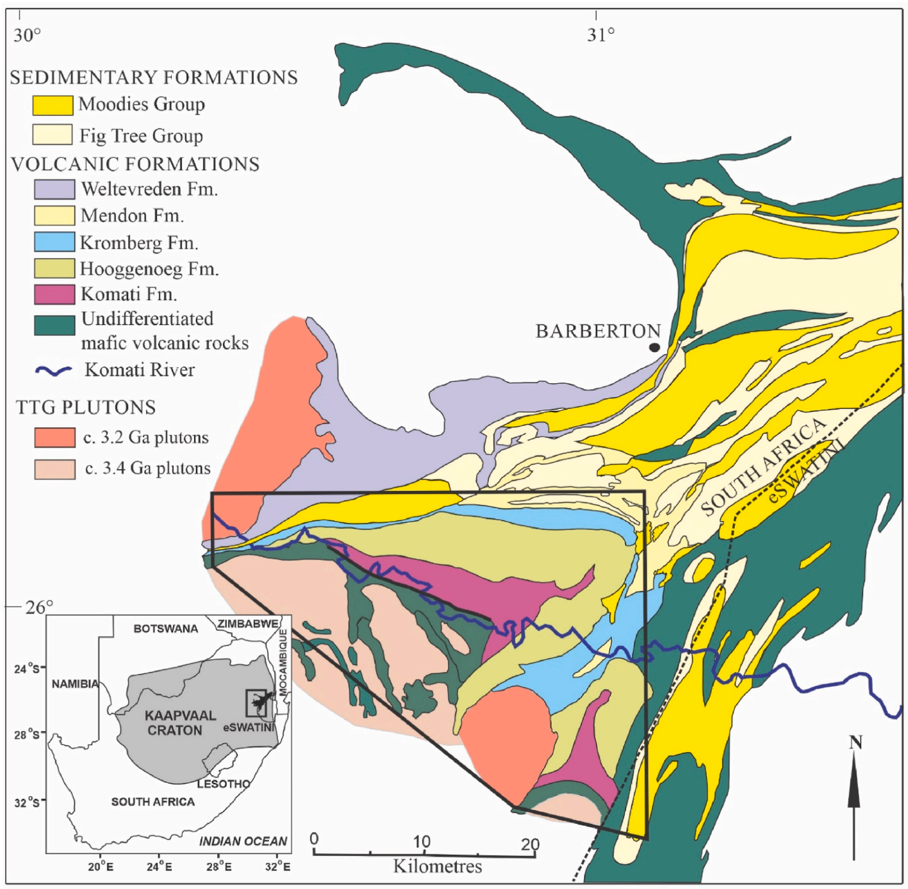

Fig. 5. Geological map of the Barberton greenstone belt (modified after Lowe and Byerly, 1999), showing the Onverwacht, Fig Tree and Moodies Groups. The formations that host the main komatiite units, namely the Komati, Mendon and Weltevreden Formations are highlighted. The marked inset is the outline of the map in Fig. 6. The regional map inset shows the Barberton greenstone belt in relation to the Kaapvaal Craton in southern Africa.

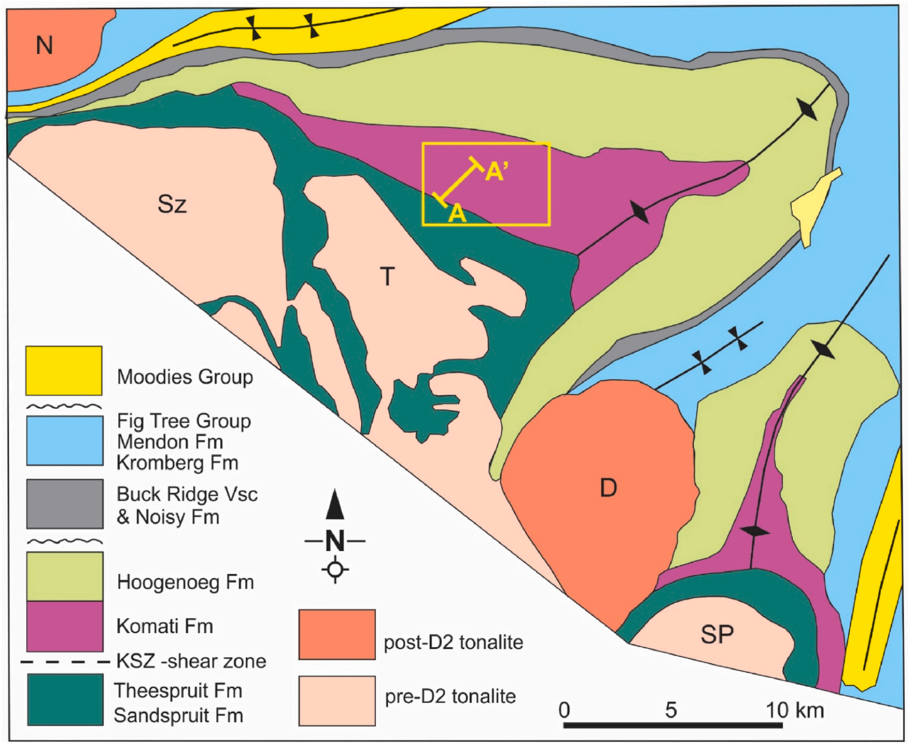

Fig. 6. Simplified geological map of the south-western part of the BGB highlighting the Onverwacht Group and the Komati Formation (modified after Dann, 2000). The profile line A – A′ corresponds to the Komati Formation type-section (lower Komati Formation, see Figs. 7 and 8 for detailed geological profiles). N = Nelshoogte Pluton, Sz = Stolzburg Pluton, T = Theespruit Pluton, D = Dalmein Pluton, SP = Steynsdorp Pluton.

exposed, except for a few highly silicified occurrences. In one section, between the M2c and M3c, lies a thin 50 m highly altered lava flow with a spinifex texture. A zircon age in a sub-centimetre tuff layer of the M3c chert was measured to be 3298 ± 3 Ma (Byerly et al., 1996). M4v and M5v consists of spinifex and variolitic komatiite interlayered with chert units.

Lowe and Byerly (1999) recognized komatiites and related rocks in the Weltevreden Formation (Fig. 5). The Weltevreden Formation is less well-studied compared to other komatiite formations in the BGB. Using Sm–Nd isotope systematics, Lahaye et al. (1995) determined an isochron age of 3286 ± 29 Ma for the age of Weltevreden komatiitic volcanism. The Weltevreden Formation consists of four main lithologicial units, namely komatiitic and basaltic rocks, layered ultramafic intrusive rocks, komatiitic tuffs and banded chert. Lowe and Byerly (1999) indicated that the Weltevreden Formation geology is similar to the upper volcanic cycles of the Mendon Formation in the south and suggested those formations are correlated (rather than with the Komati Formation as previously suggested by Viljoen and Viljoen, 1969a). For a detailed description of the volcanological and petrogenetic characteristics of the Weltevreden Formation komatiites and related rocks see Huber and Byerly (2018).

4. Geochemistry

Initially, Viljoen and Viljoen (1969c) and Viljoen et al. (1983) proposed that komatiites and related rocks in the Barberton greenstone belt be classified based on whole-rock MgO (wt%) content specifically related to the following types: black serpentinized olivine komatiites which have MgO (wt%) contents of between 23 and 36 wt%, komatiitic basalts comprising green amphibole rich rocks with MgO contents of between 11 and 24 wt%, and tholeiitic basalts with MgO of 4–9 wt (%). Subsequently, it was recognized that komatiites and related rocks have undergone low-temperature metamorphism and metasomatism (e.g. Cloete, 1991; Grosch, 2019) and that some of the major elements and large ion lithophile elements have been mobilized. As major elements such as Al_2O_3 and TiO_2 remain immobile, Al_2O_3/TiO_2 ratios have therefore been used in conjunction with MgO (wt%) to classify komatiites (Nesbitt et al., 1979). More recently, the sole control by Al was considered sufficient for the holistic classification of komatiites (Sossi et al., 2016).

Based on Al_2O_3/TiO_2 ratio, two main compositional types of komatiites have been identified (Arndt et al., 1977; Nesbitt et al., 1979): Aluminium-depleted komatiites (ADKs; Barberton-type) and Aluminum-undepleted komatiites (AUKs; Munro or Abitibi-type; see Figs. 9 and 10). Al-depleted komatiites (ADK) have Al_2O_3/TiO_2 ranging between ~ 10 and 12, and high CaO/Al_2O_3 of ~2–2.5 with REE patterns

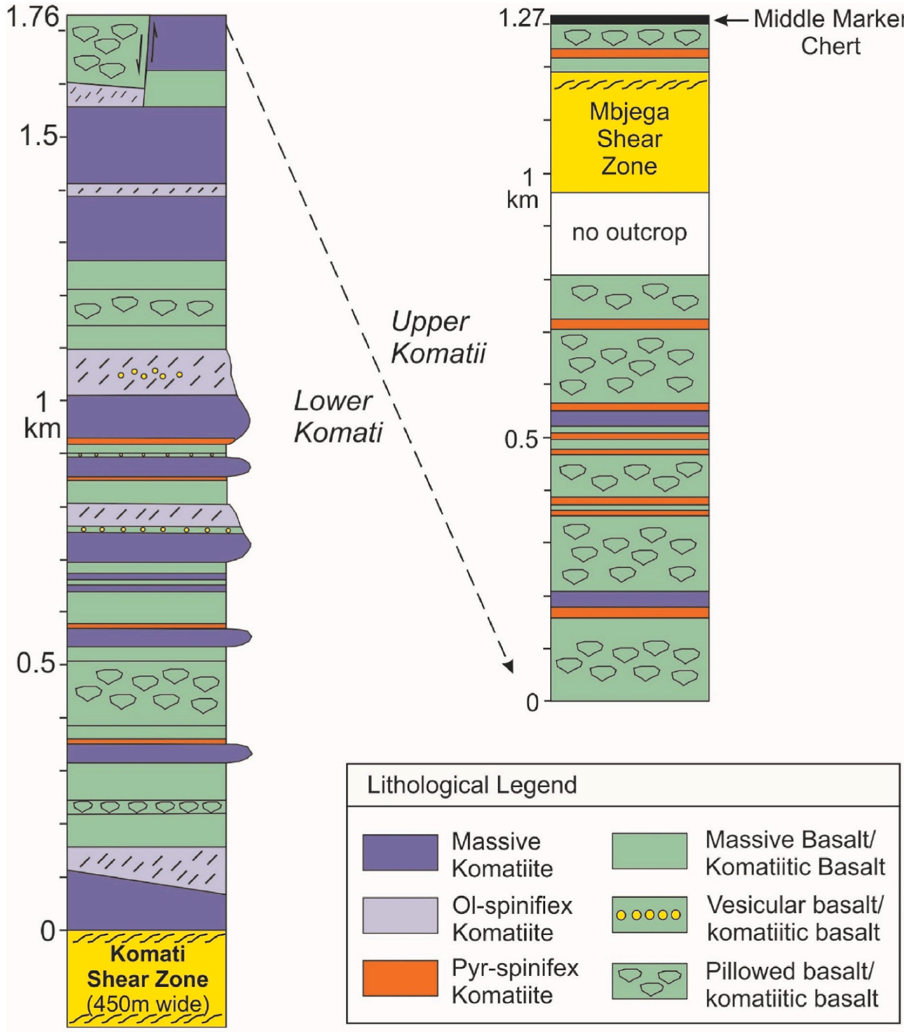

Fig. 7. Volcanic stratigraphy of the upper and lower Komati Formation according to Dann (2000). Figure modified after Dann (2000).

giving (Gd/Yb)n > 1.3. The ADKs are interpreted to have formed by mantle partial melting in the presence of residual majoritic garnet, which retains Al and heavy rare earth elements in the mantle source (Nesbitt et al., 1979). Because of the inferred presence of garnet during melting, ADKs are considered to have formed at relatively high pressures of between 8 and 13 GPa (e.g Herzberg, 1995; Robin-Popieul et al., 2012) with relatively intermediate degrees of partial melting. In contrast AUKs have Al_2O_3/TiO_2 ratios of ~20, CaO/Al_2O_3 ~ 1 and (Gd/Yb)n ~ 1. Their geochemistry is similar to that of the primitive mantle, and AUKs are believed to have formed by a larger degree of partial melting under lower pressure and garnet-absent conditions (Arndt, 2003). Aluminium-enriched komatiites have been found in the Mendon Formation of the Onverwacht Group (see Fig. 9). For recent in-depth reviews on the geochemistry of komatiites see Sossi et al. (2016), Schneider et al. (2019), Grosch and Slama (2021) and Puchtel et al. (2022).

Some komatiites and komatiitic basalts are host to magmatic Ni-sulphide mineralization, and can be important economic targets for nickel, copper and platinum group elements (PGEs). Well-known Archean deposits include komatiites of the Yilgarn and Pilbara cratons of Western Australia and the Abitibi greenstone belt of Canada (Dostal, 2008). Important ore minerals include pyrrhotite, pentlandite, pyrite and chalcopyrite. In some places gold and antimony mineralization can be found in komatiites as is the case in the Murchison greenstone belt of South Africa (Pearton, 1982). Immiscible sulphide liquid is thought to have separated from the ultramafic silicate magma and scavenged chalcophile metal elements from it (e.g. Yao and Mungall, 2021). However, komatiite liquids are characteristically undersaturated with respect to sulphur. Crustal contamination involving melting of sulphidic country rock or basaltic xenoliths can lead to early magmatic sulphur saturation and consequently Ni–Cu-PGE sulphide precipitation (e.g. Dostal, 2008). Some of the main factors controlling the sulphide mineralization in komatiites are as follows (see Pearton, 1982; Barnes, 1998; Dostal, 2008; Yao et al., 2019; Yao and Mungall, 2021; Yao and Mungall, 2022):

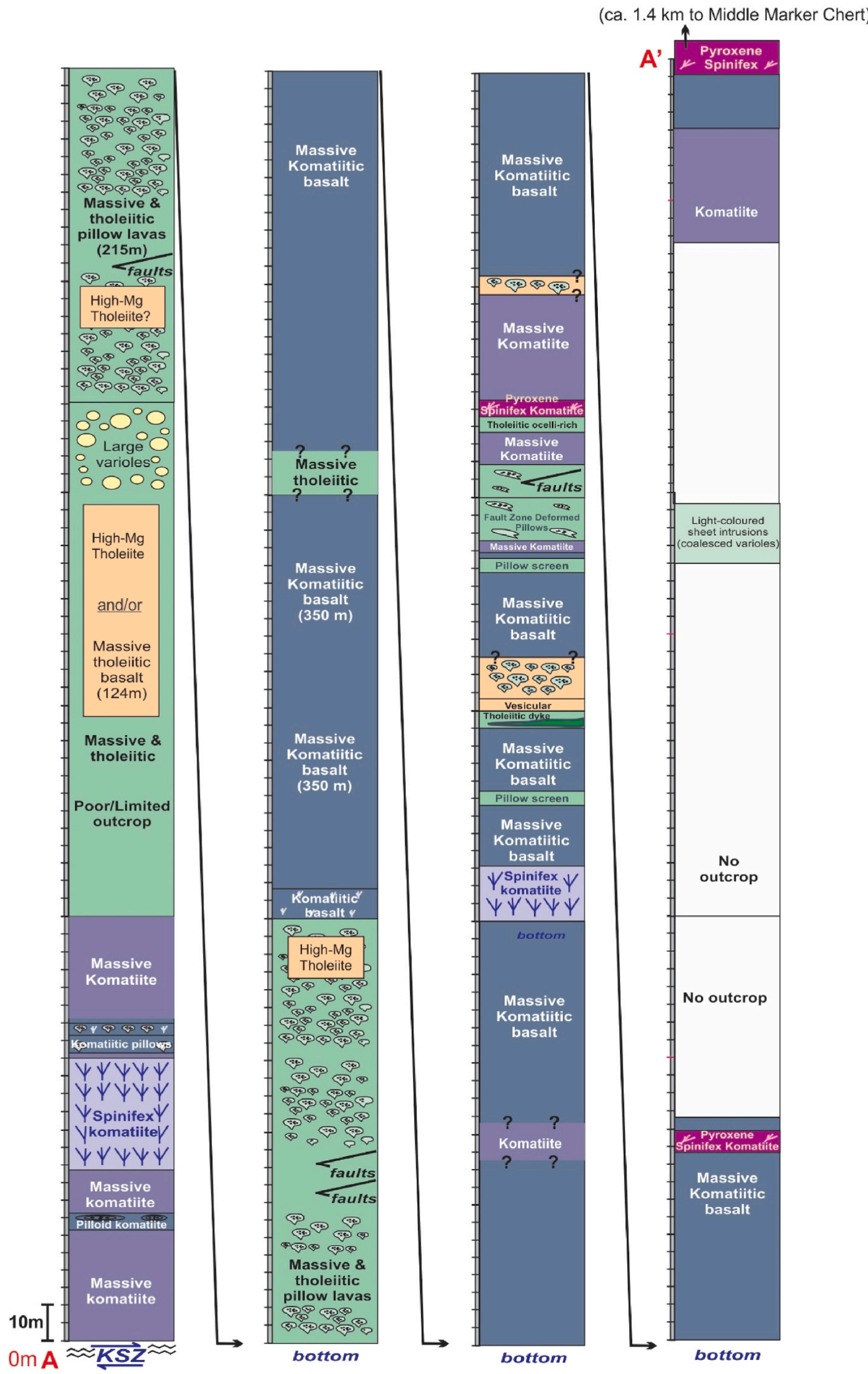

Fig. 8. High-resolution volcanic stratigraphy of the Komati-type section (mid-to lower Komati Formation. From Grosch and Slama (2021), published with permission of the Geological Society of South Africa.

- The composition and temperature of the komatiitic magma, which affects its ability to dissolve and transport sulphur and metals.
- The availability and origin of sulphur, which can be derived from external sources such as country rocks or seawater, or from internal sources such as magmatic degassing or sulphide immiscibility.
- The degree of supercooling and nucleation of chromite, which influences the saturation state of the magma with respect to sulphur and the distribution of chalcophile elements.
- The kinetics of diffusion and reaction between sulphide and silicate melts, which determines the extraction and segregation of sulphide droplets and their compositional evolution.
- The flow dynamics and cooling history of komatiitic lava, which affects the transport and accumulation of sulphide droplets and their interaction with trapped intercumulus liquid.

5. Mantle melting and the possible role of water

The MgO content of mantle derived melts is allied to higher melting

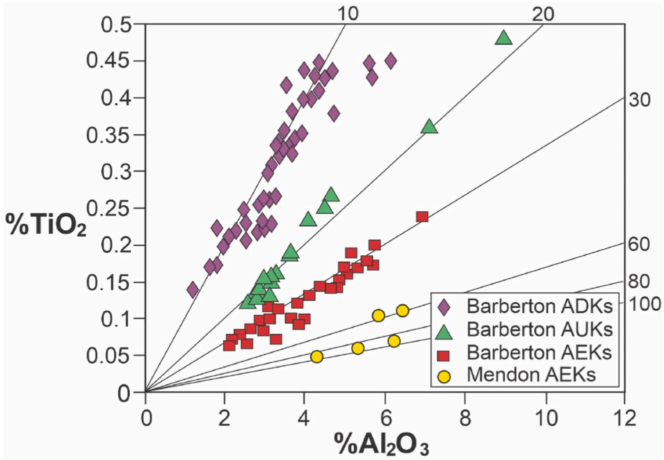

Fig. 9. Compositional characterization of Barberton komatiites based on Al and Ti. Oblique lines show the ratio Al_2O_3/TiO_2. Data sources: Grosch and Slama (2021); Wilson (2019); Robin-Popieul et al. (2012); Byerly (1999).

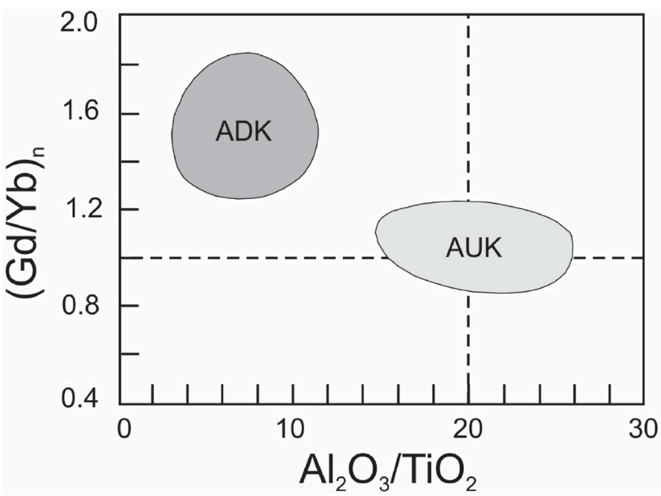

Fig. 10. A geochemical plot of Al_2O_3/TiO_2 vs $(Gd/Yb)_n$ showing the compositional difference between Al-depleted komatiites (ADK) and Al-undepleted komatiites (AUK). Modified after Dostal (2008).

temperature and so the eruption temperature of mantle derived peridotitic melt with <0.6% H_2O on Earth's surface would have been about 1650 °C (e.g. Green et al., 1975). Most petrologists accept that the Archean – Proterozoic Earth was hotter than today (e.g. Herzberg, 1992; Campbell and Griffiths, 1992), and that komatiites would have erupted at conditions much hotter than present day Mid-Ocean Ridge Basalts (MORB, 1200–1350 °C). However, this theory was challenged by an alternative view that komatiites formed by hydrous mantle melting and that the presence of water would have lowered the melting temperature to be similar to present day mantle melting conditions (Grove et al., 1997; Grove and Parman, 2004). This gave rise to the vigorous 'wet' versus 'dry' debate for the origin of komatiites as contested in Arndt et al. (1998). Vesicular komatiites are found in the Komati Formation within flows up to 15 m thick, and the most persistent vesicular unit extends along a strike of 1.2 km (Dann, 2000). The presence of vesicles indicates volatile incorporation during eruption but is not unique evidence for magmatic water (Arndt et al., 1998). Spinifex textures associated with komatiites were also used as evidence to support a wet origin for komatiites and are argued to have formed through hydrous crystallization in sills and dykes, not as lava flows (Grove et al., 1997).

Arguments presented against 'wet' melting hypothesis for komatiites include the following:

- Faure et al. (2006) reproduced spinifex textures under anhydrous experimental conditions.
- Geological observations indicate that komatiites are extrusive and not intrusive sills or dykes (Viljoen and Viljoen, 1969a)
- Komatiite magma containing water would have erupted explosively or show extensive degassing textural evidence (Arndt et al., 1998). Barberton komatiite lava eruption was highly mobile, non-explosive and long-lived (Arndt and Lesher, 2004), typical of a low-viscosity anhydrous magma.
- Major and trace element compositions provide consistent and plausible evidence that komatiites formed at great depths in hot mantle plumes (Arndt, 2003), and is discussed further in the geodynamic context.

The debate has continued because further studies have revealed the presence of significant amounts of water in remnant melt inclusions in komatiites. Komatiite melt inclusions in chromite from the Belingwe greenstone belt recorded water contents of 0.8–0.9 wt% (Shimizu et al., 2001) and Arndt et al. (2008), initially challenged results that pointed to significant (but still relatively minor) water contents in komatiitic melts. Evidence from the Phanerozoic Gorgona (Colombia) komatiites revealed preserved melt inclusions with 0.2–1.0 wt% H_2O. Sobolev et al. (2016) reported that olivine melt inclusions in komatiites from the Abitibi greenstone belt contained about 0.6 wt% H_2O. Similar results were also reported for the 3.3 Ga Weltevreden Formation komatiites of the Barberton greenstone belt (Sobolev et al., 2019). These state-of-the-art petrological data now indicate that komatiites were at least 'damp' and derived from partially hydrated mantle sources (Sobolev et al., 2019; Wyman, 2020). However, a mantle source with 0.3% H_2O would not lower the melting temperature sufficiently to negate a plume origin (Herzberg, 2022)

6. Geodynamic models and the sources of komatiites

Since the discovery of komatiites in 1969 in South Africa, a wide range of geodynamic settings have been proposed for the c. 3.48 Ga Barberton komatiite suite. These include, komatiitic magmas derived from within a hot mantle plume (e.g. Jarvis and Campbell, 1983; Herzberg, 1992, Arndt et al., 2008; see Fig. 11a); eruption in a mid-ocean ridge system linked to a juvenile oceanic plateau (Chavagnac, 2004); magmas derived from shallow, hydrated mantle above a subduction zone (Parman et al., 2001; Grove and Parman, 2004; see Fig. 11b); and eruption of komatiites in a back-arc setting (Furnes et al., 2012). Related to the debate concerning the geodynamic setting of komatiites, is the controversy centered around the melt-source composition.

The temperature at which komatiite erupted and began to crystalize olivine can be constrained by the magnesian content of the magma and the Fo (Forsterite) composition of the olivine (Herzberg and Asimov, 2015; Nisbet, 1982). This in turn can be related to the potential temperature of the mantle from which the magma originated by partial melting (Herzberg and Asimov, 2015). The temperature of formation of Archean komatiites is shown to be significantly higher than for ambient mantle as modelled by Korenaga (2008; Fig. 12) therefore making a strong case for the origin of the Barberton komatiites from a mantle plume and not simply by partial melting of upwelling ambient mantle. It is noted that the highest mantle plume temperature for a komatiite in the Kaapvaal craton is from the Commondale greenstone belt (Wilson and Bolhar, 2022; Wilson, 2019). Komatiitic basalts from the Barberton Kromberg Formation formed by melting of ambient mantle (Fig. 12). A further point of reference is that the low-magnesian komatiites (and komatiitic basalts) of the Paleoproterozoic Circum-Superior LIP were derived from ambient mantle, most likely in a plate tectonic setting (Herzberg, 2022). This provides strong evidence that the mantle source

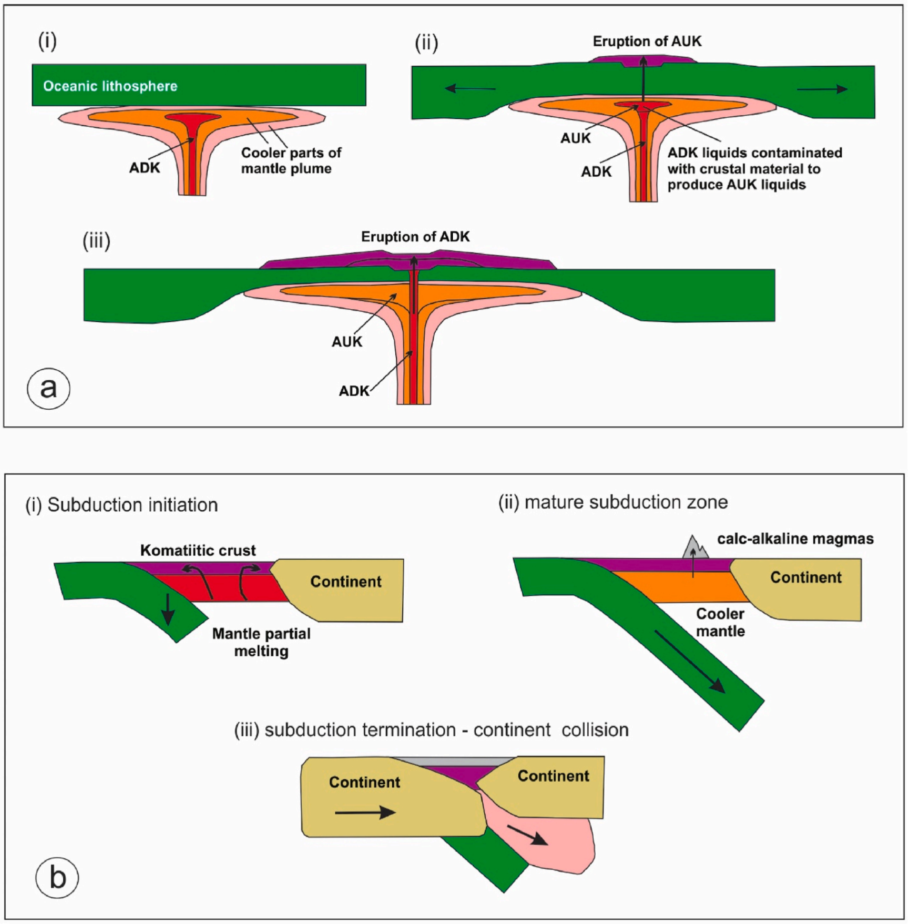

Fig. 11. End-member geodynamic models depicting possible settings for the eruption of komatiites. (a) Progressive stages (i to iii) of an Archean plume-oceanic plateau model showing komatiite generation (modified after Sproule et al., 2002). ADK = Al-depleted komatiites and AUK = Al-undepleted komatiites. Grosch and Slama (2021) found that AUK (crustally contaminated komatiititc lavas) are overlain stratigraphically by ADK lavas in the Komati Formation of the Barberton greenstone belt, South Africa. (b) Progressive stages (i to iii) of an Archean subduction zone model showing komatiite generation (modified after Grove and Parman, 2004).

of Barberton komatiites was 350–400 °C hotter than the depleted mantle source at mid-ocean ridges (Fig. 12).

Some workers have proposed partial melting of a mantle source containing subducted silicified seafloor cherts (Blichert-Toft et al., 2015). Alternatively, Herzberg (2016) proposed partial melting of 'çarbonated wetspots' in the mantle triggered by mantle plume upwelling. In more recent studies, Sobolev et al. (2019) and Wyman (2020) proposed melting by plumes of deep lower-mantle transition zone (MTZ) reservoirs containing recycled oceanic crust. Grosch and Slama (2021) argued that the Barberton komatiite suite was most likely derived from a hot mantle plume and that eruption involved crustal contamination. The debates on the geodynamic setting and mantle source composition(s) of the Barberton and other Kaapvaal komatiites continue unabated. Either way, based on isotopic evidence, the Archean mantle is interpreted to have been compositionally heterogeneous (Puchtel et al., 2022). However, the picture could be even more complicated. Recent studies have provided evidence of a Hadean influence in the compositions of Barberton komatiites (Tusch et al., 2022). Using decay products for extant isotope systems, patterns of these isotopes point to the presence of recycled mafic restites from Hadean crust which became incorporated into the mantle source of the Barberton komatiites.

Oxygen isotope studies of olivines from the Weltevreden komatiites (Byerly et al., 2017) indicated a deficit in $\delta^{18}O$ postulated to have been derived during fractionation from the deep magma ocean during the Hadean period and ultimately the mantle source that gave rise to the komatiites. However, a later study (Wang et al., 2023) has shown that the measured O isotope deficit in that study is entirely an artefact arising from the presence of small amounts of secondary serpentine in the olivines analysed and has no petrogenetic significance.

Komatiites not only provide insights into potential crustal geodynamic processes but also into the thermal state of the mantle in deep time. The occurrence of komatiites in the Archean and Paleoproterozoic, suggests that parts of the Earth's mantle may have been much hotter than today (i.e. by 300–400 °C). As an ultramafic volcanic rock, komatiites together with komatiitic basalts dominated in the Archean, whereas komatiitic basalts dominated in the Proterozoic. Picrites are common in the Phanerozoic. The decreasing MgO content with geologic time, in the rocks mentioned above, can be interpreted to represent secular cooling of the Earth's mantle through time. However, some workers have challenged the theory that the Earth's mantle was hotter in the Archean (e.g. Grove and Parman, 2004). For example, through early studies, some komatiites of the 3.33 Ga Commondale greenstone belt of South Africa were shown to have high SiO_2 contents and could possibly have been derived from melting in a shallow, hydrated mantle above a subduction zone (Wilson et al., 2003). More recent studies argue that the majority of the Commondale lavas are derived from dry or 'damp' melting in plumes originating from the core-mantle boundary (Wilson and Bolhar, 2022). Komatiites are thus a window into early Earth geodynamic processes and provide insights into the thermal and compositional complexities of the Archean mantle.

7. Komatiites: the lasting legacy

The discovery of komatiite in the Barberton greenstone belt of South Africa as a new class of volcanic rock led to the widespread recognition of similar rocks in other parts of the world. These include the Abitibi greenstone belt (Canada), the Yilgarn craton (Western Australia) and greenstone belts in Zimbabwe and Finland. Komatiites are also important to the mining economy as some host major nickel deposits. The field exposures of komatiites in the Onverwacht Group in the Barberton

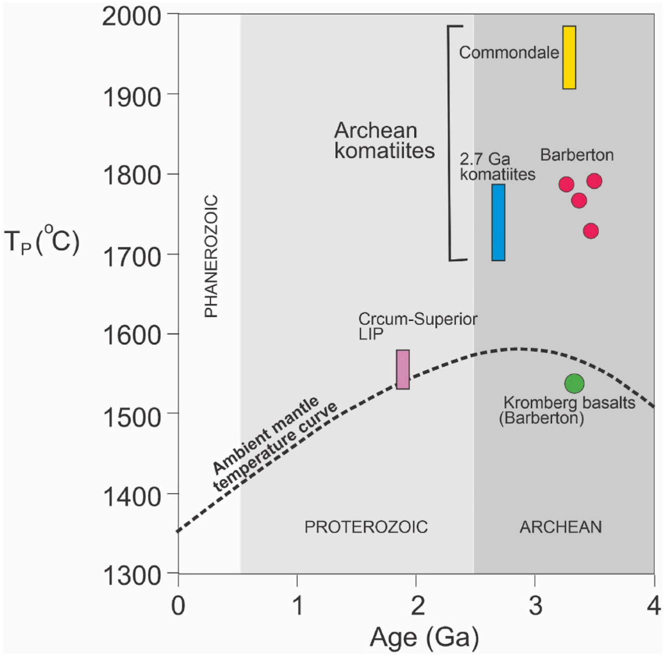

Fig. 12. Calculated mantle potential temperatures as adapted from Herzberg (2022) showing the source of komatiites in relation to the ambient mantle temperature curve through geological time. Komatiites are considered to have been derived from plume sources rather than by partial melting of ambient mantle. Data for Barberton komatiites, the 2.7Ga komatiites world-wide and Circum-Superior LIP are from Herzberg (2022). The highest mantle potential temperature is for the Commondale komatiites (Wilson, 2019). The source temperature of the Barberton Kromberg Formation (c. 3.3 Ga) komatiitic basalts is from Grosch and Slama (2017).

Mountain Land are encompassed as a world geoheritage site and sampling is restricted. Since their discovery there have been hundreds of academic publications on komatiites from various localities across the globe. The Barberton komatiites in particular have taken center stage in terms of international petrological studies. For example, a number of novel isotope systems have been applied to understand the petrogenesis of komatiites. These include, for instance, the application of whole-rock Lu–Hf isotope systematics (Gruau et al., 1990; Blichert-Toft et al., 2015; Grosch and Slama, 2021) and tungsten isotope systematics (Puchtel et al., 2022). State-of-the-art analytical techniques such as secondary ion microprobe analysis has been applied to melt inclusions in komatiites (e. g. Shimizu et al., 2001; Byerly et al., 2017; Sobolev et al., 2019; Tusch et al., 2022; Wang et al., 2023). Studies on the petrogenetic origin of komatiites have generated, intense scientific debate and continue to do so. Controversial debates include how much water was present in the Archean mantle, whether the Archean mantle temperature was similar to today, and whether or not plate tectonic operated on the early Earth. Low-temperature hydrothermal serpentinization of komatiite would have released hydrogen, which may have supported early microbial life in early Archean subseafloor environments (e.g. Grosch et al., 2014). A recent hyperspectral study has shown that serpentinized komatiite can be used as a petrological analogue in the search for serpentine minerals and water on Mars (Grosch et al., 2021). The future of komatiite research remains alive and bright.

Declaration of competing interest

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

Data availability

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

Acknowledgements

This review paper is dedicated to Prof. Richard Viljoen and the late Prof. Morris Viljoen, the discoverers of komatiites. The Rhodes Research Office is thanked for a University Capacity Development Grant awarded to EG. Prof. Nicholas Arndt is thanked for helpful comments on an early draft of this paper. Prof. Claude Herzberg and an anonymous reviewer are thanked for helpful comments. Prof. Barbara Tewksbury is thanked for constructive comments and for inviting us to write this review paper.

References

Abraham, E.M., 1953. Geology of sothman township. Ontario Department of Mines Annual Report 52 (6), 1–36.
Angerer, T., Kerrich, R., Hagemann, S.G., 2013. Geochemistry of a komatiitic, boninitic, and tholeiitic basalt association in the Mesoarchean Koolyanobbing greenstone belt, Southern Cross Domain, Yilgarn craton: implications for mantle sources and geodynamic setting of banded iron formation. Precambrian Res. 224, 110–128.
Arndt, N., 2003. Komatiites, kimberlites, and boninites. J. Geophys. Res. Solid Earth 108 (B6).
Arndt, N.T., Nisbet, E.G., 1982. What is a komatiite? In: Arndt, N.T., Nisbet, E.G. (Eds.), Komatiites. George Allen and Unwin, London, pp. 19–28.
Arndt, N., Fowler, A., 2004. Textures in komatiites and variolitic basalts. In: Erikson, K., et al. (Eds.), The Precambrian Earth: Tempos and Events. Elsevier, pp. 298–311.
Arndt, N., Lesher, C.M., 2004. Komatiite. In: Encyclopedia of Geology. Elsevier, pp. 260–268.
Arndt, N.T., Naldrett, A.J., Pyke, D.R., 1977. Komatiitic and iron-rich tholeiitic lavas of Munro Township, northeast Ontario. J. Petrol. 18 (2), 319–369.
Arndt, N., Ginibre, C., Chauvel, C., Albarede, F., Cheadle, M., Herzberg, C., Jenner, G., Lahaye, Y., 1998. Were komatiites wet? Geology 26 (8), 739–742.
Arndt, N., Lesher, M.C., Barnes, S.J., 2008. Komatiite. Cambridge University press, p. 487.
Berry, L.G., 1940. Geology of the Langmuir-Sheraton area. Ontario Department of Mines Annual Report 49 (4), 1–21.
Bickle, M.J., Martin, A., Nisbet, E.G., 1975. Basaltic and peridotitic komatiites and stromatolites above a basal unconformity in the Belingwe greenstone belt, Rhodesia. Earth Planet Sci. Lett. 27 (2), 155–162.
Blichert-Toft, J., Arndt, N.T., Wilson, A., Coetzee, G., 2015. Hf and Nd isotope systematics of early Archean komatiites from surface sampling and ICDP drilling in the Barberton Greenstone Belt, South Africa. Am. Mineral. 100 (11–12), 2396–2411.
Barnes, S.J., 1998. Chromite in komatiites, 1. Magmatic controls on crystallization and composition. J. Petrol. 39 (10), 689–1720.
Bowen, N.L., 1922. The Evolution of Igneous Rocks. Princeton University Press.
Brandl, G., Cloete, M., Anhaeusser, C.R., 2006. Archaean greenstone belts. In: Johnson, M.R., Anhaeusser, C.R., Thomas, R.J. (Eds.), The Geology of South Africa. Geological Society of South Africa, Johannesburg/Council for Geoscience, Pretoria, pp. 9–51.
Bruce, E.L., 1926. Geology of McArthur, bartlett, douglas and geikie townships (redstone river area), district of timiskamong. Ontario Department of Mines Annual Report 35 (6), 37–56.
Byerly, G.R., 1999. Komatiites of the Mendon Formation: Late-Stage Ultramafic Volcanism in the Barberton Greenstone Belt, vol. 329. Geological Society of America Special Paper, Special Paper, pp. 189–211.
Byerly, B.L., Kareem, K., Bao, H., Byerly, G.R., 2017. Early Earth mantle heterogeneity revealed by light oxygen isotopes of Archaean komatiites. Nat. Geosci. 10, 871–875.
Byerly, G.R., Kröner, A., Lowe, D.R., Todt, W., Walsh, M.M., 1996. Prolonged magmatism and time constraints for sediment deposition in the early Archean Barberton greenstone belt: evidence from the Upper Onverwacht and Fig Tree groups. Precambrian Res. 78, 125–138.
Campbell, I.H., Griffiths, R.W., 1992. The changing nature of mantle hotspots through time: implications for the chemical evolution of the mantle. J. Geol. 100 (5), 497–523.
Chauvel, C., Arndt, N.T., Gruau, G., Hofmann, A.W., 1987. Composition of the Archean mantle: evidence from Nd isotopes. Terra Cogn. 7, 272.
Chavagnac, V., 2004. A geochemical and Nd isotopic study of Barberton komatiites (South Africa): implication for the Archean mantle. Lithos 75 (3–4), 253–281.
Cloete, M., 1991. An overview of metamorphism in the Barberton greenstone belt. In: Ashwal, L.D. (Ed.), Two Cratons and an Orogen - Excursion Guidebook and Review Articles for a Field Workshop through Selected Archean Terranes of Swaziland, South Africa and Zimbabwe: Johannesburg, IGCP Project 280. Dept. of Geology, Univ. Witwatersrand, pp. 84–98.
Dann, J.C., 2000. The 3.5 Ga Komati Formation, Barberton Greenstone Belt, South Africa, part I: new map and magmatic architecture. S. Afr. J. Geol. 6, 681–730.
Dann, J.C., 2001. Vesicular komatiites, 3.5-Ga Komati Formation, Barberton Greenstone Belt, South Africa: inflation of submarine lavas and origin of spinifex zones. Bull. Volcanol. 63, 462–481.

Decker, N.B., Byerly, G.R., Stiegler, M.T., Lowe, D.R., Stefurak, E., 2015. High resolution tephra and U/Pb chronology of the 3.33–3.26 Ga Mendon Formation, Barberton greenstone belt, South Africa. Precambrian Res. 261, 54–74.
Donaldson, C.H., 1976. An experimental investigation of olivine morphology. Contrib. Mineral. Petrol. 57, 187–213.
Donaldson, C.H., 1982. Spinifex-textured komatiites: a review of textures, compositions and layering. In: Arndt, N.T., Nisbet, E.G. (Eds.), Komatiites. Allen and Unwin (London).
Dostal, J., 2008. Igneous rock associations 10. Komatiites. Geosci. Can. 35 (1), 21–31.
Faure, F., Arndt, N., Libourel, G., 2006. Formation of spinifex texture in komatiites: an experimental study. J. Petrol. 47 (8), 1591–1610.
Furnes, H., Robins, B., De Wit, M.J., 2012. Geochemistry and petrology of lavas in the upper Onverwacht suite, Barberton Mountain Land, South Africa. S. Afr. J. Geol. 115 (2), 171–210.
Green, D.H., Nicholls, I.A., Viljoen, M., Viljoen, R., 1975. Experimental demonstration of the existence of peridotitic liquids in earliest Archean magmatism. Geology 3, 11–14.
Grosch, E.G., 2019. Metamorphic processes preserved in early Archean supracrustal rocks of the Barberton Greenstone Belt, South Africa. Geological Society, London, Special Publications 478 (1), 315–334.
Grosch, E.G., Slama, J., 2017. Evidence for 3.3-billion-year-old oceanic crust in the Barberton greenstone belt, South Africa. Geology 45 (8), 695–698.
Grosch, E.G., Slama, J., 2021. On the volcanic architecture, petrology and geodynamic setting of the 3.48 Ga Barberton komatiite suite, South Africa. S. Afr. J. Geol. 124 (2), 343–352, 2021.
Grosch, E.G., McLoughlin, N., Lanari, P., Erambert, M., Vidal, O., 2014. Microscale mapping of alteration conditions and potential biosignatures in basaltic-ultramafic rocks on early Earth and beyond. Astrobiology 14 (3), 216–228.
Grosch, E.G., Bishop, J.L., Mielke, C., Maturilli, A., Helbert, J., 2021. Early Archean alteration minerals in mafic-ultramafic rocks of the Barberton greenstone belt as petrological analogs for clay mineralogy on Mars. Am. Mineral.: Journal of Earth and Planetary Materials 106 (5), 672–684.
Grove, T.L., Parman, S.W., 2004. Thermal evolution of the Earth as recorded by komatiites. Earth Planet Sci. Lett. 219 (3), 173–187.
Grove, T.L., Gaetani, G.A., de Wit, M.J., 1994. Spinifex Textures in 3.49 Ga Barberton Mountain Belt Komatiites: Evidence for Crystallization of Water-Bearing, Cool Magmas in the Archean: Eos, vol. 75. Transactions, American Geophysical Union, p. 354 (spring).
Grove, T.L., de Wit, M.J., Dann, J., 1997. Komatiites from the Komati type section, Barberton, South Africa. In: de Wit, M.J., Ashwal, L.D. (Eds.), Greenstone Belts: Oxford. Oxford Science Publications, pp. 422–437.
Gruau, G., Chauvel, C., Arndt, N.T., Cornichet, J., 1990. Aluminum depletion in komatiites and garnet fractionation in the early Archean mantle: hafnium isotopic constraints. Geochem. Cosmochim. Acta 54 (11), 3095–3101.
Hallberg, J.A., Williams, D.A.C., 1972. Archaean mafic and ultramafic rock associations in the Eastern Goldfields region, Western Australia. Earth Planet Sci. Lett. 15 (2), 191–200.
Herzberg, C.T., 1992. Depth and degree of melting of komatiites. J. Geophys. Res. 97, 4521–4540.
Herzberg, C.T., 1995. Generation of plume magmas through time: an experimental perspective. Chem. Geol. 126, 1–16.
Herzberg, C.T., 2016. Petrological evidence from komatiites for an early Earth carbon and water cycle. J. Petrol. 57, 2271–2288.
Herzberg, C., 2022. Understanding the paleoproterozoic circum-superior large igneous province constrains the thermal properties of Earth's mantle through time. Precambrian Res. 375, 106671.
Herzberg, C., Asimov, P.D., 2015. PRIMELT3 MEGA.XLSM software for primary magma calculations: peridotite primary magma MgO contents from the liquidus to the solidus. G-cubed 16, 563–578.
Huber, M.S., Byerly, G.R., 2018. Volcanological and petrogenetic characteristics of komatiites of the 3.3 Ga saw mill complex, Weltevreden Formation, Barberton greenstone belt, South Africa. S. Afr. J. Geol. 121 (4), 463–486, 2018.
Jarvis, G.T., Campbell, I.H., 1983. Archean komatiites and geotherms: solution to an apparent contradiction. Geophys. Res. Lett. 10 (12), 1133–1136.
Korenaga, J., 2008. Urey ratio and the structure and evolution of Earth's mantle. Rev. Geophys. 46, RG2007.
Lahaye, Y., Arndt, N.T., Byerly, G., Chauvel, C., Fourcade, S., Gruau, G., 1995. The influence of alteration on the trace element and Nd isotopic compositions of komatiites. Chem. Geol. 126, 43–64.
Lowe, D.R., Byerly, G.R., 1986. Early Archean silicate spherules of probable impact origin, South Africa and Western Australia. Geology 14 (1), 83–86.
Lowe, D.R., Byerly, G.R., 1999. Stratigraphy of the west-central part of the Barberton greenstone belt, South Africa. In: Lowe, D.R., Byerly, G.R. (Eds.), Geologic Evolution of the Barberton Greenstone Belt, South Africa, vol. 329. Geological Society of America Special Paper, pp. 1–36.
Lowe, D.R., Byerly, G.R., 2007. An overview of the geology of the Barberton Greenstone Belt and vicinity: implications for early crustal development. Dev. Precambrian Geol. 15, 481–526.
McCall, G.J.H., Leishman, J., 1971. Clues to the Origin of Archean Eugeosynclinal Peridotite and the Nature of Serpentinization, vol. 3. Special Publications of the Geological Society, Australia, pp. 281–299.
Naldrett, A.J., 1964. Ultrabasic Rocks of the Porcupine and Related Nickel Deposits: Unpublished Ph. D (Doctoral Dissertation, Thesis. Queen's University, Canada).
Naldrett, A.J., Mason, G.D., 1968. Contrasting archean ultramafic igneous bodies in Dundonald and clergue townships, Ontario. Can. J. Earth Sci. 5 (1), 111–143.
Nesbitt, R.W., 1971. Skeletal Crystal Forms in the Ultramafic Rocks of the Yilgarn Block, Western Australia: Evidence for an Archean Ultramafic Liquid, vol. 3. Special Publications of the Geological Society of Australia, pp. 331–347.
Nesbitt, R.W., Sun, S.S., Purvis, A.C., 1979. Komatiites; geochemistry and genesis. Can. Mineral. 17 (2), 165–186.
Nisbet, E.G., 1982. The tectonic setting and petrogenesis of komatiites. In: Arndt, N., Nisbet, E.G. (Eds.), Komatiites. Allen & Unwin, London, pp. 501–520.
Nisbet, E.G., Bickle, M.J., Martin, A., 1977. The mafic and ultramafic lavas of the Beligwe greenstone belt, Rhodesia. J. Petrol. 18, 521–566.
Parman, S.W., Grove, T.L., Dann, J.C., 2001. The production of Barberton komatiites in an Archean subduction zone. Geophys. Res. Lett. 28 (13), 2513–2516.
Pearton, N.T., 1982. Gold and antimony mineralization in altered komatiites of the Murchison greenstone belt, South Africa. In: Arndt, N.T., Nisbet, E.G. (Eds.), Komatiites. George Allen and Unwin, London, pp. 459–475.
Prest, V.K., 1950. Geology of the keith-muskego townships area. Ontario Department of Mines Annual Report 49 (7), 1–44.
Puchtel, I.S., Blichert-Toft, J., Horan, M.F., Touboul, M., Walker, R.J., 2022. The komatiite testimony to ancient mantle heterogeneity. Chem. Geol., 120776
Pyke, D.R., 1970. Geology of Langmuir and blackstock townships, district of timiskaming. Ontario Department of Mines Annual Report 80 (1), 1–23.
Pyke, D.R., Naldrett, A.J., Eckstrand, O.R., 1973. Archean Ultramafic Flows in Munro Township, Ontario, vol. 84. Geological Society of America Bulletin, pp. 955–978.
Robin-Popieul, C.C., Arndt, N.T., Chauvel, C., Byerly, G.R., Sobolev, A.V., Wilson, A., 2012. A new model for Barberton komatiites: deep critical melting with high melt retention. J. Petrol. 53 (11), 2191–2229.
Satterly, J., 1951. Geology of Munro township. Ontario Department of Mines Annual Report 60 (8), 1–60.
Schneider, K.P., Hoffmann, J.E., Münker, C., Patyniak, M., Sprung, P., Roerdink, D., Garbe-Schönberg, D., Kröner, A., 2019. Petrogenetic evolution of metabasalts and metakomatiites of the lower Onverwacht group, Barberton greenstone belt (South Africa). Chem. Geol. 511, 152–177.
Shimizu, K., Komiya, T., Hirose, K., Shimizu, N., Maruyama, S., 2001. Cr-spinel, an excellent micro-container for retaining primitive melts - implications for a hydrous plume origin for komatiites. Earth Planet Sci. Lett. 189, 177–188.
Shore, M., Fowler, A.D., 1998. Optical and thermal anisotropy of olivine, hydrothermal cooling of komatiites and the origin of spinifex texture. In: GAC-MAC, Program and Abstracts. Geological Association of Canada-Mineralogical Association of Canada.
Shore, M., Fowler, A.D., 1999. The origin of spinifex texture in komatiites. Nature 397, 691–693.
Sobolev, A.V., Asafov, E.V., Gurenko, A.A., Arndt, N.T., Batanova, V.G., Portnyagin, M. V., Garbe-Schönberg, D., Krasheninnikov, S.P., 2016. Komatiites reveal a hydrous Archaean deep-mantle reservoir. Nature 531 (7596), 628–632.
Sobolev, A.V., Asafov, E.V., Gurenko, A.A., Arndt, N.T., Batanova, V.G., Portnyagin, M. V., Garbe-Schönberg, D., Wilson, A.H., Byerly, G.R., 2019. Deep hydrous mantle reservoir provides evidence for crustal recycling before 3.3 billion years ago. Nature 571 (7766), 555–559.
Sossi, P.A., Eggins, S.M., Nesbitt, R.W., Nebel, O., Hergt, J.M., Campbell, I.H., O'Neill, H. S.C., Van Kranendonk, M., Davies, D.R., 2016. Petrogenesis and geochemistry of Archean komatiites. J. Petrol. 57 (1), 147–184.
Sproule, R.A., Lesher, C.M., Ayer, J.A., Thurston, P.C., Herzberg, C.T., 2002. Spatial and temporal variations in the geochemistry of komatiites and komatiitic basalts in the Abitibi greenstone belt. Precambrian Res. 115 (1–4), 153–186.
Tusch, J., Hoffmann, J.E., Hasenstab, E., Fischer-Gödde, M., Marien, C.S., Wilson, A.H., Münker, C., 2022. Long-term preservation of Hadean protocrust in Earth's mantle. Proceedings of the National Academy of Sciences of the U.S.A. 119, 1–12 article e2120241119.
Van Kranendonk, M.J., Kröner, A., Hegner, E., Connelly, J., 2009. Age, lithology and structural evolution of the c. 3.53 Ga Theespruit Formation in the Tjakastad area, southwestern Barberton Greenstone Belt, South Africa, with implications for Archaean tectonics. Chem. Geol. 261 (1–2), 115–139.
Viljoen, M.J., Viljoen, R.P., 1969a. An Introduction to the Geology of the Barberton, Granite-Greenstone Terrain, vol. 9. Special Publication Geological Society of South Africa, pp. 1–20.
Viljoen, M.J., Viljoen, R.P., 1969b. The Geology and Geochemistry of the Lower Ultramafic Unit of the Onverwacht Group and a Proposed New Class of Igneous Rocks, vol. 2. Geological Society of South Africa Special Publication, pp. 55–86.
Viljoen, M.J., Viljoen, R.P., 1969c. The Geological and Geochemical Significance of the Upper Formations of the Onverwacht Group, vol. 2. Geological Society of South Africa Special Publication, pp. 113–152.

Viljoen, M.J., Viljoen, R.P., Smith, H.S., Erlank, A.J., 1983. Geological, textural and geochemical features of komatiitic flows from the Komati Formation. Spec. Publ. Geol. Soc. S. Afr. 9, 1–20.
Wang, H., Wilson, A., Yang, J., Li, Q., Tang, G., Feng, L., Jia, L., 2023. No 18O-depleted mantle source for Archean komatiite. Sci. Bull. 68, 53–55.
Wilson, A.H., 2019. The late-Paleoarchean ultra-depleted Commondale komatiites: earth's hottest lavas and consequences for eruption. J. Petrol. 60, 1575–1620.
Wilson, A., Bolhar, R., 2022. Olivine in komatiite records origin and travel from the deep upper mantle. Geology 50 (3), 351–355.
Wilson, A., Riganti, A., 2022. Architectural and compositional diversity of early Earth ocean floor evidenced by the Paleoarchean Nondweni greenstone belt, South Africa. J. Petrol. 63 (11), egac108.
Wilson, A.H., Shirey, S.B., Carlson, R.W., 2003. Archaean ultra-depleted komatiites formed by hydrous melting of cratonic mantle. Nature 423 (6942), 858–861.
Williams, D.A.C., 1972. Archaean ultramafic, mafic and associated rocks, Mt Monger, Western Australia. J. Geol. Soc. Aust. 19 (2), 163–188.
Wyman, D., 2020. Komatiites from mantle transition zone plumes. Front. Earth Sci. 8, 540744.
Yao, Z.S., Mungall, J.E., 2021. Kinetic controls on the sulfide mineralization of komatiite-associated Ni-Cu-(PGE) deposits. Geochem. Cosmochim. Acta 305, 185–211.
Yao, Z., Mungall, J.E., 2022. Transport and deposition of immiscible sulfide liquid during lateral magma flow. Earth Sci. Rev. 227, 103964.
Yao, Z., Mungall, J.E., Qin, K., 2019. A preliminary model for the migration of sulfide droplets in a magmatic conduit and the significance of volatiles. J. Petrol. 60 (12), 2281–2316.