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A reevaluation of Archean intracratonic terrane boundaries on the Kaapvaal Craton, South Africa: Collisional suture zones?

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ABSTRACT

Increasing support for the adoption of plate-tectonic processes to account for Archean geotectonic events has led to the reevaluation of selected terranes in southern Africa in order to determine the viability of plate tectonics as a mechanism for terrane accretion and the growth of continents. Geotectonic reconstructions indicate that a number of Archean ultramafic complexes and associated volcanic rocks are developed in three linear zones on the Kaapvaal Craton that may represent the fossil traces of Archean sutures or oceanic crustal collisional zones. The ultramafic complexes consist primarily of massive and schistose serpentinitic and pyroxenitic rocks derived from dunite, harzburgite, lherzolite, pyroxenite (ortho- and clinopyroxenite), and lesser gabbroic bodies believed to have been derived from high-Mg, komatiitic-type parent magmas. The ultramafic complexes have previously been interpreted to have formed as a result of differentiation processes and were emplaced either magmatically or tectonically into the early Archean crust. An alternative view suggests that the ultramafic bodies may be likened to oceanic crust or "layered series" assemblages of Phanerozoic ophiolites. Serpentinized ultramafic components of ophiolites are, in turn, commonly encountered in orogenic belts where they mark the positions of suture zones.

The three areas where extraordinary developments of serpentinized ultramafic rocks are to be found on the Kaapvaal Craton include: (1) the northern flank of the Barberton greenstone belt; (2) the area south of the Murchison greenstone belt; and (3) the region extending across the southern portion of the Johannesburg Dome. The age of the ultramafic bodies has not been determined directly, but intrusive granitoid rocks suggest they are mostly older than ca. 3200 Ma and in some cases may be as old as ca. 3600 Ma. In each of the three regions discussed the proposed suture zones mark the position of collisional convergent plate boundaries, now represented by intracratonic terrane boundaries. The suture zones separate protocontinental crustal blocks that formed as a result of the amalgamation of multicomponent, continental basement rocks, which initially developed as volcanic arcs and which are today preserved on the Kaapvaal Craton as Archean granite-greenstone complexes ranging in age between ca. 3600 and 2700 Ma. The suggested linear suture zones, which have not yet been examined in detail geophysically, are shown to be part of more extensive intracratonic linear features, such as the Thabazimbi-Murchison and Barberton Lineaments, and are believed to represent the only physical expression of terrane boundaries on the Kaapvaal Craton.

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INTRODUCTION

Ultramafic and related rocks are of widely differing types and occur in a broad range of geological and geotectonic environments (Wyllie, 1967). Some occur in variably sized stratiform intrusions like the Bushveld, Great Dyke, Stillwater, Skaergaard, and Muskox igneous complexes (Eales and Cawthorn, 1996; Irvine and Smith, 1967; McCallum, 1996; McBirney, 1996; Wilson, 1996), while others occur as alkalic ring complexes or kimberlite intrusions (Gold, 1967; Dawson, 1967). Close scrutiny worldwide, however, reveals that most ultramafic rocks not associated with igneous complexes and Archean greenstone belts occur as remnants of oceanic crust and upper mantle and are restricted to suture zones in Proterozoic and Paleozoic orogenic belts as a result of plate-tectonic processes (Burke et al., 1977). These include: (1) the Alpine-type peridotite-serpentinite bodies distributed along deformed mountain chains (e.g., the Zagros Crush Zone and the Indus Suture occurring along the Alpine-Himalayan continental collision zone); (2) ancient and modern island arcs (Thayer, 1967; Dewey, 1969, 1977; Hamilton, 1970); and (3) concentrically zoned dunite-peridotite intrusive complexes like those of southeastern Alaska and the Ural Mountains of Russia (Irvine, 1967; Taylor, 1967). Most Alpine-type ultramafic-mafic associations are regarded as being synonymous with ophiolite suites, the latter considered to be slices of oceanic crust and mantle tectonically emplaced in orogenic belts. Some of the best-known ophiolite occurrences include those of Troodos in Cyprus (generally regarded as the classic type example; Moores and Vine, 1971; Robertson and Xenophontos, 1993), the ophiolites of the Oman Tethys (Semail Ophiolite along the coastline of the Gulf of Oman; Lippard et al., 1986), and the Appalachian ophiolites of Newfoundland (Smith, 1958; Dewey and Bird, 1971).

Ophiolite suites were described by Dewey and Bird (1970, 1971) as having been generated at oceanic ridges and by slow spreading in marginal basins behind and within island-arc complexes. They showed that many ophiolites in orogenic belts occur in a variety of tectonic settings, including those found as severely deformed and serpentinized bodies in suture zones, in sutured mélange terranes, and as thrust wedges. Terrane accretion has also been considered a viable mechanism of ophiolite emplacement, with ophiolites commonly occurring at terrane margins (Coleman, 1971; Kearey and Vine, 1995).

Because serpentinized ultramafic rocks are a common feature of most early Archean greenstone belts (Arndt and Nisbet, 1982; Nisbet, 1987; Arndt et al., 1997) there have been attempts to equate these rock associations with Phanerozoic ophiolite complexes (De Wit et al., 1987; Fripp and Jones, 1997). However, adherence to the Geological Society of America Penrose Conference definition of an ophiolite (Anonymous, 1972) shows several important differences (one of these being the complete absence of mafic sheeted dyke complexes in Archean terranes), making direct comparison untenable. Applying the Penrose ophiolite definition in its strict sense to Archean or even Proterozoic terranes has thus proved to be controversial (Bickle et al., 1995; Hamilton, 1998; McCall, 2003). Recently, in part to overcome this difficulty, Dewey (2003) referred to the Penrose ophiolites as *ophiolites sensu stricto* and reserved the term *ophiolites sensu lato* for other heterogeneous remnants of ocean floors now embedded in the continents. Şengör and Natal'in (2004) went a step further, restricting the term *ophiolite* to the more or less complete suite and called its various fragments formed by processes incorporating them into continental crust *ophirags*.

Thus, if the "strict definition" of an ophiolite suite were to be disregarded it could be argued that some Archean greenstone belts may contain fragmented ophiolites (the ophirags of Şengör and Natal'in, 2004). These Archean ophirags would, in turn, represent dismembered pieces of oceanic lithosphere produced as prototypes to present-day, plate-tectonic–related oceanic crust. This would add further strength to theoretical and actualistic models that are increasingly pointing to a Mesozoic to Archean tectonic regime not fundamentally different from that of today (Talbot, 1973; Dewey and Spall, 1975; Windley, 1976; Lowe, 1994, 1999).

Increasing support for plate-tectonic processes to account for Archean geotectonic events has led to the reevaluation of selected terranes in southern Africa in order to determine the viability of such processes as a mechanism for Archean terrane accretion and continental growth.

Evidence suggests that magmatic arc formation began on the Kaapvaal Craton ca. 3600 Ma (Poujol et al., 2003; Eglington and Armstrong, 2004) and continued episodically at intervals of between 100 and 200 m.y., resulting in the construction of discrete microcontinents that eventually coalesced to form the Kaapvaal Craton (De Wit et al., 1992; Poujol et al., 2003).

In an attempt to verify the existence of at least some of the possible boundary zones between the various terranes postulated by De Wit et al. (1992), this paper examines the nature and distribution of various mafic and ultramafic rocks found on the Kaapvaal Craton. These distinctive, yet relatively sparsely distributed rock types may, it is contended, represent ophirag remnants, which could mark the traces of collisional zones between ancient protocontinental blocks. Three separate localities on the Kaapvaal Craton have been identified that display exceptional developments of serpentinized ultramafic rocks and may signal possible suture zones formed during the late Paleoarchean to Mesoarchean (ca. 3500–2700 Ma). These include ultramafic rocks distributed linearly along: (1) the northern flank of the Barberton greenstone belt; (2) the terrane south of the Murchison greenstone belt; and (3) the southern sector of the Johannesburg Dome (see Fig. 1 for localities).

BARBERTON GREENSTONE BELT

Ultramafic and mafic rocks are extensively developed in the Barberton greenstone belt and comprise large volcanic outpourings of komatiite, komatiitic basalt, and high-Mg tholeiite as well as intrusive or tectonically emplaced layered ultramafic complexes (Viljoen and Viljoen, 1969, 1970; Anhaeusser, 1972, 1976a, 1985, 2001; Wuth, 1980; Viljoen et al., 1983). The ultramafic-mafic lava successions have been likened to modern oceanic plateau assemblages (Cloete, 1999; Dann, 2000; Anhaeusser, 2001), whereas the layered ultramafic complexes have been regarded as sill-like intrusive bodies formed contemporaneously with the lavas in shallow-seated magma chambers where they underwent differentiation from komatiitic parent magmas (Viljoen and Viljoen, 1970; Anhaeusser, 1985). It has also been recognized that many of the layered complexes appear to be fault-bounded and may have been tectonically emplaced (Anhaeusser, 1985, 2001).

De Wit et al. (1987) and De Wit and Tredoux (1988) were of the opinion that the ultramafic to mafic rocks of the Barberton greenstone belt formed a pseudostratigraphy comparable to that of Phanerozoic ophiolites, which they named the Jamestown Ophiolite Complex in deference to the pioneering geological endeavors of Hall (1918) and Visser (1956). Although objections to the ophiolite analogy have been raised (Hamilton, 1998, 2003; McCall, 2003) there may be merit in the broader application of the ophiolite/ophirag concept mentioned earlier. One significant difference with respect to the Barberton terrane (and indeed Archean terranes worldwide) remains the complete absence of sheeted dykes, which have been considered to be a fundamental component of ophiolites *sensu stricto*. For example McCall (2003), in comparing Archean and Phanerozoic tectonics, emphasized that sheeted dykes are uncharacteristic of Archean eruptive suites. Some examples have, however, been reported from a ca. 2500 Ma ophiolite complex in China (Kusky et al., 2001) and from the Archean Yilgarn Craton in Western Australia (Fripp and Jones, 1997), but these are regarded as contentious (Zhai et al., 2002; McCall, 2003). In view of the ophirag suggestion of Şengör and Natal'in (2004) outlined earlier, the absence of the sheeted-dyke component of ophiolites in Archean terranes may be a consequence of their dismemberment, or more likely, their position within the orogenic edifice. Some additional factors, not yet fully understood, may also have played a role. Archean magmas are, for example, generally believed to have formed in high-heat flow environments (e.g., melting in plumes; Arndt et al., 1997). The eruptive environment of these dominantly low viscosity komatiitic and high-Mg tholeiitic magmas may have favored fissure-style eruptions rather than feeder dyke intrusions that are generally rare in Archean terranes (Arndt, 1999).

Anhaeusser (1985) recorded the presence of 27 ultramafic complexes in the Barberton greenstone belt, most of which show pronounced magmatic differentiation and the common development of cyclically repeated layering consisting dominantly of dunite, orthopyroxenite, and harzburgite and volumetrically subordinate websterite and anorthositic gabbro-norite units. Although Archean ultramafic complexes are known from around the world, most are considerably less magnesian than the Barberton examples, which appear to have developed from parental komatiite magmas containing ~28% MgO. It has been estimated that dunite, harzburgite, and lherzolite constitute as much as 80% by volume of some of the complexes, the remainder consisting of ortho- and clinopyroxenites and minor gabbro-norite phases (Wuth, 1980; Anhaeusser, 1985; Rodel, 1993). Most of the ultramafic rocks in these complexes have been extensively serpentinized and steatized and have also been altered to various talc ± tremolite ± chlorite ± carbonate schists. The complexes display variable effects of heterogeneous strain with both massive and schistose rock assemblages being represented in places, in different parts of the same body.

Anhaeusser (1969, 2002) showed that many of the Barberton ultramafic complexes occur along the northern flank of the greenstone belt (Fig. 2A) and proposed a model reconstruction suggesting that they may once have formed a continuous, northeast-southwest–trending, sheetlike intrusion, or a series of related, but probably discontinuous sill-like bodies traceable over a distance of ~110 km (Fig. 2B). Because younger cover sequences obscure the northeastern and southwestern extensions of the Barberton greenstone belt it is not known whether the ultramafic bodies continue beyond the exposed limits.

Barberton Granitoid History

The model reconstruction referred to above involves the "removal" of the intrusive granitoid bodies that forced their way, balloonlike, into the northern Barberton terrane and which were, in turn, responsible for the prising apart of the supracrustal greenstones to form such prominent features as the northwest-trending Jamestown and Nelshoogte schist belts (Fig. 2A). The Kaap Valley tonalite pluton, dated at 3227 ± 1 Ma (Kamo and Davis, 1994), and the Nelshoogte trondhjemite pluton, dated at 3236 ± 1 Ma (De Ronde and Kamo, 2000), are regarded as responsible for the structural disturbance and dismemberment of the ultramafic complexes in the northwestern sector of the Barberton belt (Anhaeusser, 1966, 1969, 2002). The actual ages of the ultramafic complexes have not yet been determined directly because of the unsuitability of the rocks for dating. Visser (1956) was of the opinion that the ultramafic rocks were post-Moodies in age. Moodies Group deposition is bracketed between ca. 3225 Ma (Kröner et al., 1991) and the ca. 3079 Ma age determined by Heubeck et al. (1993) for the Salisbury Kop pluton, which intrudes folded Moodies Group rocks. However, field relationships combined with evidence

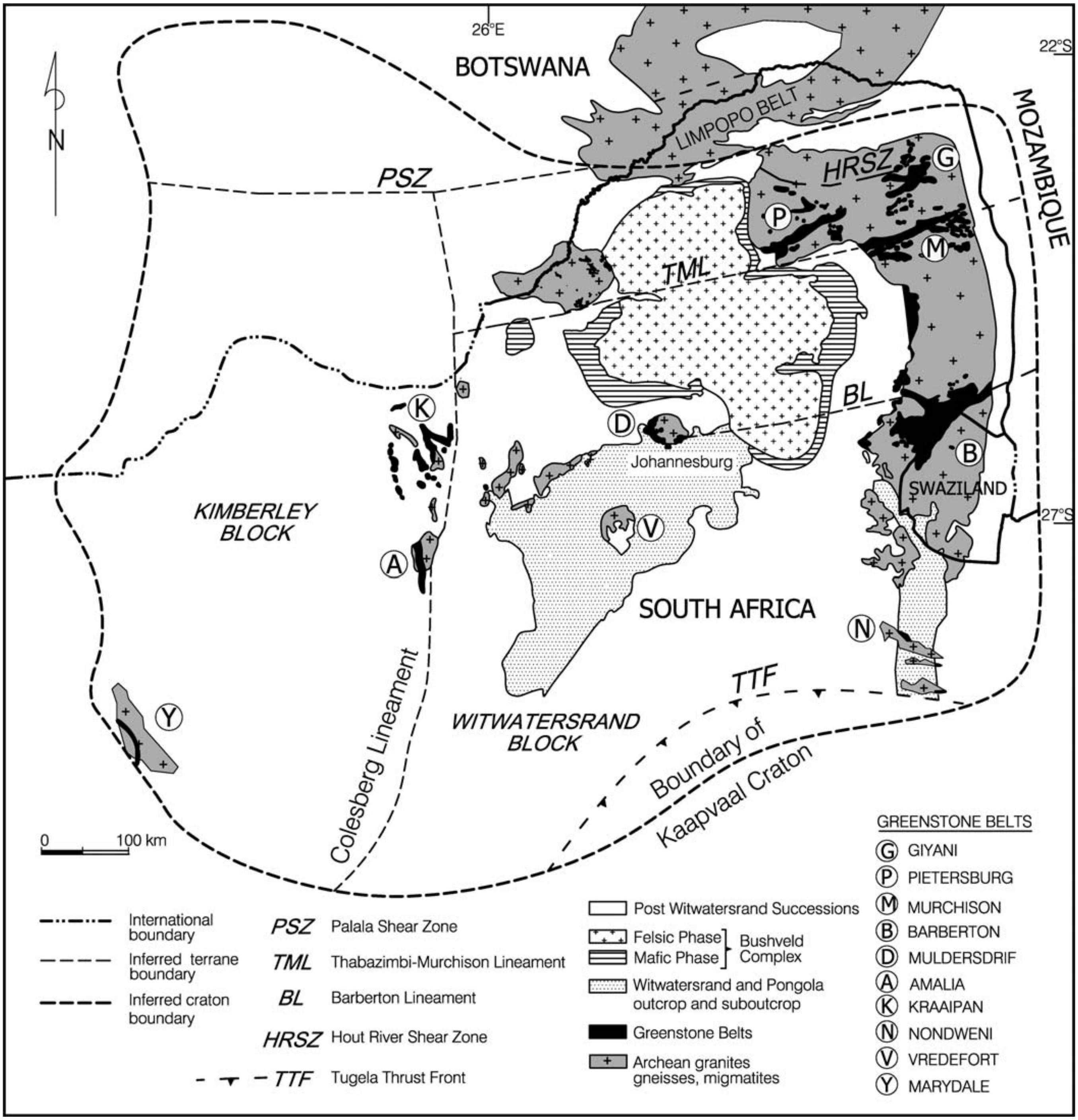

Figure 1. Simplified regional geological map showing the main linear structural features that have been described on the Kaapvaal Craton and the locations of the ultramafic-mafic rocks defining the positions of the postulated Archean suture zones proposed in the paper.

suggesting a minimum age of ca. 3226 Ma for the ultramafic complexes in the Weltevreden area southwest of Barberton (De Ronde and Kamo, 2000) places the age of the ultramafic rocks considerably older than the Moodies sedimentary sequence. Further confirmation of an older age for the ultramafic complexes relates to the previously discussed ca. 3236–3227 Ma ages determined for the Nelshoogte and Kaap Valley plutons, which intrude and deform the ultramafic rocks.

In the northeast, the Stentor pluton embays into the northern sector of the Barberton greenstone belt and, like its counterparts to the west, had a structurally disruptive influence on the ultramafic bodies in the vicinity (Fig. 2). Kohler (1994)

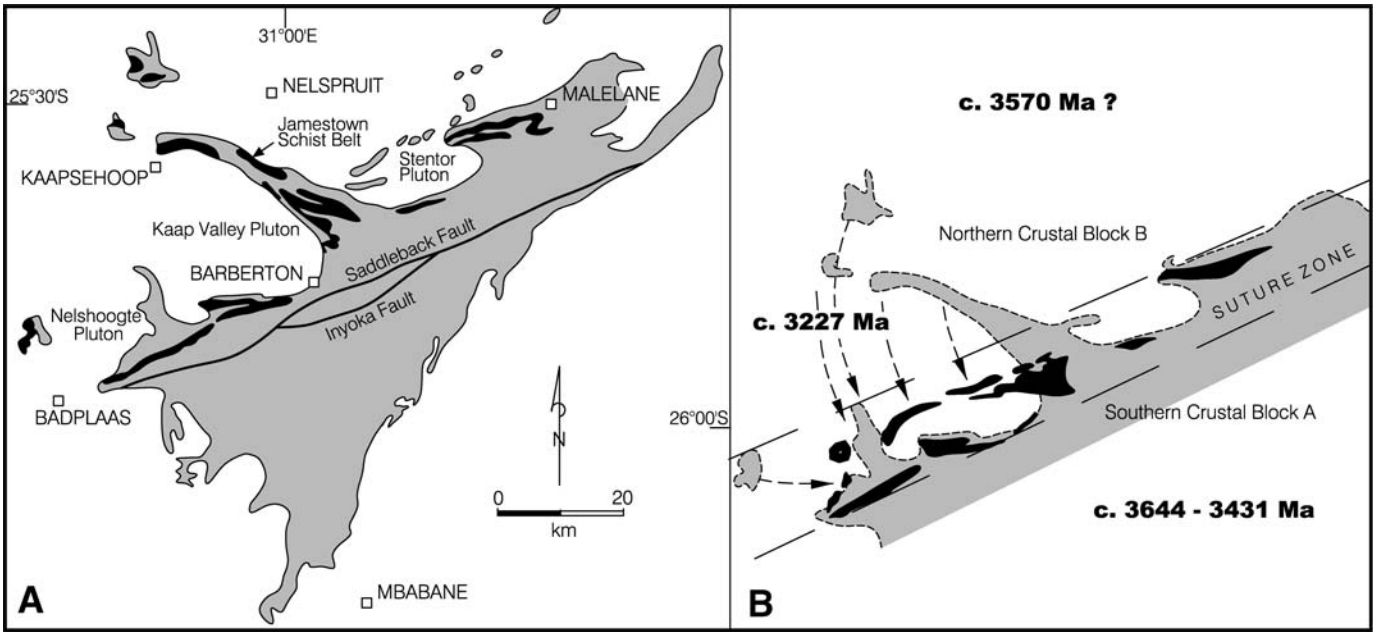

Figure 2. (A) Simplified map showing the present distribution of layered ultramafic complexes (black) along the northern flank of the Barberton greenstone belt (gray shaded). The location of the possible terrane boundary envisaged by previous workers coincides with the position of the Saddleback and Inyoka Faults (see text for details). The granitoid plutons that fragment and deform the ultramafic complexes were emplaced at ca. 3227 Ma. (B) Schematic reconstruction, minus the influence of the Kaap Valley, Nelshoogte, and Stentor granitoid plutons, showing the alignment of the ultramafic complexes along a possible suture or convergence zone (as proposed in this paper) separating a southern crustal block (ca. 3644–3431 Ma) from a northern block (possibly ca. 3570 Ma; see text).

regarded the Stentor pluton as a phase of the Nelspruit batholith, but geochemical, petrological, and geochronological investigations have shown that this pluton is more complex than either the Kaap Valley or Nelshoogte plutons further to the west. Granitoid ages reported from the Stentor pluton range from 3347 +67/–60 Ma to 3250 ± 30 Ma (Tegtmeyer and Kröner, 1987). Ages ranging from 3107 ± 5 Ma to 3082 ± 3 Ma were also recorded from this pluton by Kamo and Davis (1994). The ca. 3250 Ma age of Tegtmeyer and Kröner (1987) closely coincides with ages obtained for the Kaap Valley and Nelshoogte plutons, whereas the younger age of ca. 3107 Ma coincides with the 3105 ± 2 Ma age established for the Nelspruit batholith by Kamo and Davis (1994). The oldest age of ca. 3347 Ma also closely corresponds, within error, to the age of 3303 ± 6.4 Ma recorded by Kamo and Davis (1994) for tonalitic xenoliths found in porphyritic granodiorites of the Nelspruit batholith north of the Sabie River near Hazyview (Robb, 1977).

The view that the terrane north of the Barberton greenstone belt contains remnants of older granitic crust was first recorded by Visser (1956), who described granite pebbles in Moodies Group conglomerates in the Eureka syncline northeast of Barberton (Sheba Siding vicinity). These authors noted that "the granite pebbles represent a parent body which has hitherto not been recognized in outcrop in the area" (Visser, 1956, p. 78). The deformed granitoid pebbles, which have a distinctive graphic or granophyric texture (Anhaeusser, 1966), occur predominantly along the northern flank of the syncline (Anhaeusser, 1969, 1976b), suggesting their source was largely from the north, the terrane now occupied by the ca. 3105 Ma Nelspruit batholith. Van Niekerk and Burger (1978) established that the granite boulders in the conglomerates were derived from granitoid terranes older than the ca. 3227 Ma Kaap Valley pluton. This was later confirmed by Kröner and Compston (1988), who undertook ion microprobe analyses on zircons from the granitoid clasts, establishing their age at between 3570 ± 6 Ma and 3518 ± 11 Ma. Thus, it appears that the granitoid terrane north of the Barberton greenstone belt formed as a result of successive plutonic events that began coalescing into a microcontinent in late Eoarchean times (ca. 3600 Ma), but which was subsequently transformed in Paleoarchean to early Mesoarchean times (ca. 3500–3000 Ma) by later crust-forming granitoid emplacement episodes that culminated with the emplacement of the Nelspruit batholith at ca. 3105 Ma. During approximately the same period, similar crust-forming events were taking place elsewhere on the evolving Kaapvaal Craton, which led to the amalgamation of the granitoid terrane that presently occupies the regions south and southeast of the Barberton greenstone belt in the Komati River valley and in Swaziland. This southern terrane, including the Barberton greenstone belt, has been viewed as a compound terrane formed through long-term magmatic activity (ca. 3644–3431 Ma) and late-stage tectonic accretion (Compston and Kröner, 1988; Lowe et al., 1989; De Wit et al., 1992; Kröner et al., 1992, 1996; De Ronde and De Wit, 1994). Lowe (1994, 1999) divided the southern region into four major blocks or protocontinents, each comprising an ultramafic-mafic oceanic volcanic stage followed by a felsic tonalite-trondhjemite-granodiorite (TTG) magmatic stage that had characteristics akin to subduction-related volcanic arcs. More recently, Kisters et al. (2003) have suggested that the granitoids and enclosed metavolcanic and metasedimentary remnants that occur in the southern Barberton region constitute an exhumed ancient core complex containing peak metamorphic assemblages indicative of burial to mid- to lower-crustal levels.

Barberton Tectonic History

A number of attempts have been made to describe the tectonic history of the Barberton granite-greenstone terrane. Regional mapping led to the recognition of numerous isoclinal folds, which are commonly bounded by major, generally steeply dipping faults that partitioned or segmented the greenstone belt into a number of preferentially developed synclinoria (Visser, 1956; Anhaeusser et al., 1968, 1969; Anhaeusser, 1984). Stratigraphic and sedimentological studies led to the recognition of different facies of Fig Tree and Moodies sedimentary rocks, the present boundary between the two sedimentary realms (Northern and Southern Facies) coinciding with a major strike-slip fault system (the Saddleback-Inyoka fault zone, Fig. 2A) occurring in the northern half of the Barberton greenstone belt (Visser, 1956; Heinrichs and Reimer, 1977; Eriksson, 1980; Lowe et al., 1999; Heubeck and Lowe, 1999). Subsequent workers came to regard this transitional zone as representing an accretionary convergent domain involving arc- and trench-related processes and culminating in arc amalgamation and suturing (De Wit, 1991; De Ronde and De Wit, 1994; De Ronde and Kamo, 2000; Lowe, 1999).

While the author is in agreement that some form of collisional tectonic process played a role in juxtaposing the northern and southern facies sediments in the Barberton greenstone belt, the position of the suture remains debatable. In this contribution it is argued that the zone occupied by the layered ultramafic complexes is more appropriate as the locus of suturing or oceanic crustal collision. The convergence of two ancient protocontinental crustal blocks, one from the north and the other from the south, as described earlier, would have counterparts similar to obducted oceanic crust (ophiolite suites) comparable to those occurring in Phanerozoic orogenic suture zones and sutured mélange terranes. The collisional process is likely to have been complex, involving a variety of possible plate, ocean, and continental combinations, as outlined by Dewey and Bird (1970, 1971). Evidence from the Barberton greenstone belt, provided by De Ronde and De Wit (1994) and Lowe (1999), suggests that the granite-greenstone terrane represents a compound crustal block constructed of a number of smaller crustal segments, which amalgamated over a time span ranging over 330–490 m.y. A dramatically shorter time frame of ~3 m.y. was later outlined by De Ronde and Kamo (2000) for what they described as an arc-arc D_2 collisional event in the Weltevreden area southwest of Barberton, which occurred between 3229 and 3227 Ma.

Massive serpentinized ultramafic rocks also occur in the Msauli-Havelock mine areas in the southeastern part of the Barberton greenstone belt, adjacent to the Swaziland border (Büttner, 1984; Barton, 1986). These ultramafic rocks, which are hosts to major chrysotile asbestos deposits, occur in a linear, faulted zone that can be traced for ~15 km and may also reflect a zone of collisional suturing within the greenstone belt of smaller crustal segments of the type outlined above by Lowe (1999).

Precise dating techniques now clearly identify an older southern crustal domain (>3445 Ma) from a younger (ca. 3227 Ma) northern domain (Kamo and Davis, 1994). It is suggested that the ultramafic-mafic (ophirag) wedge separating these two crustal blocks reflects a consuming margin along and into which were emplaced TTG granitoids at ca. 3227 Ma following subduction-related arclike volcanism. Figure 3 indicates schematically the possible nature of the collisional interface, with the Fig Tree and Moodies sediments as well as earlier calc-alkaline volcanic rocks (Upper Onverwacht lithologies) occurring to the south and representing products of the subduction event. This could imply that the poorly time-constrained ultramafic-mafic zone in the north as well as the Onverwacht type-locality komatiitic assemblages on the southern side of the Barberton greenstone belt may be part of the same oceanic crust and lithosphere upon which the later arclike events of volcanism and magmatism developed.

MURCHISON GREENSTONE BELT

A number of ultramafic-mafic bodies south of the Murchison greenstone belt (Fig. 4) were first recorded by Hall (1912) in the Ofcolaco-Mica-Phalaborwa region. They include massive bodies of serpentinite, amphibolite, and gabbro as well as schistose

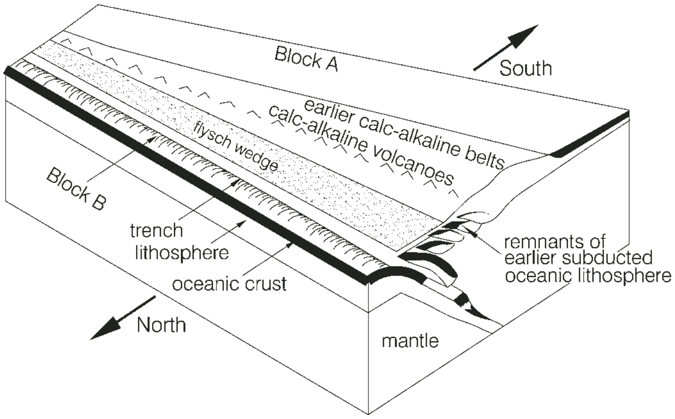

Figure 3. Schematic block diagram (after Dewey and Bird, 1971) showing the collisional interface or suture zone along which the oceanic crust and ultramafic complexes (ophirags) were emplaced on the northern flank of the Barberton greenstone belt. Fig Tree and Moodies sediments (the flysch wedge) and calc-alkaline, arclike volcanics (Upper Onverwacht Group) occupy the area to the south on amalgamated crustal block A. Oceanic crust subducted along the trench is believed to have generated tonalite-trondhjemite-granodiorite (TTG) magmas, which led to the intrusion of the Kaap Valley, Nelshoogte, and Stentor granitoid plutons (Fig. 2A).

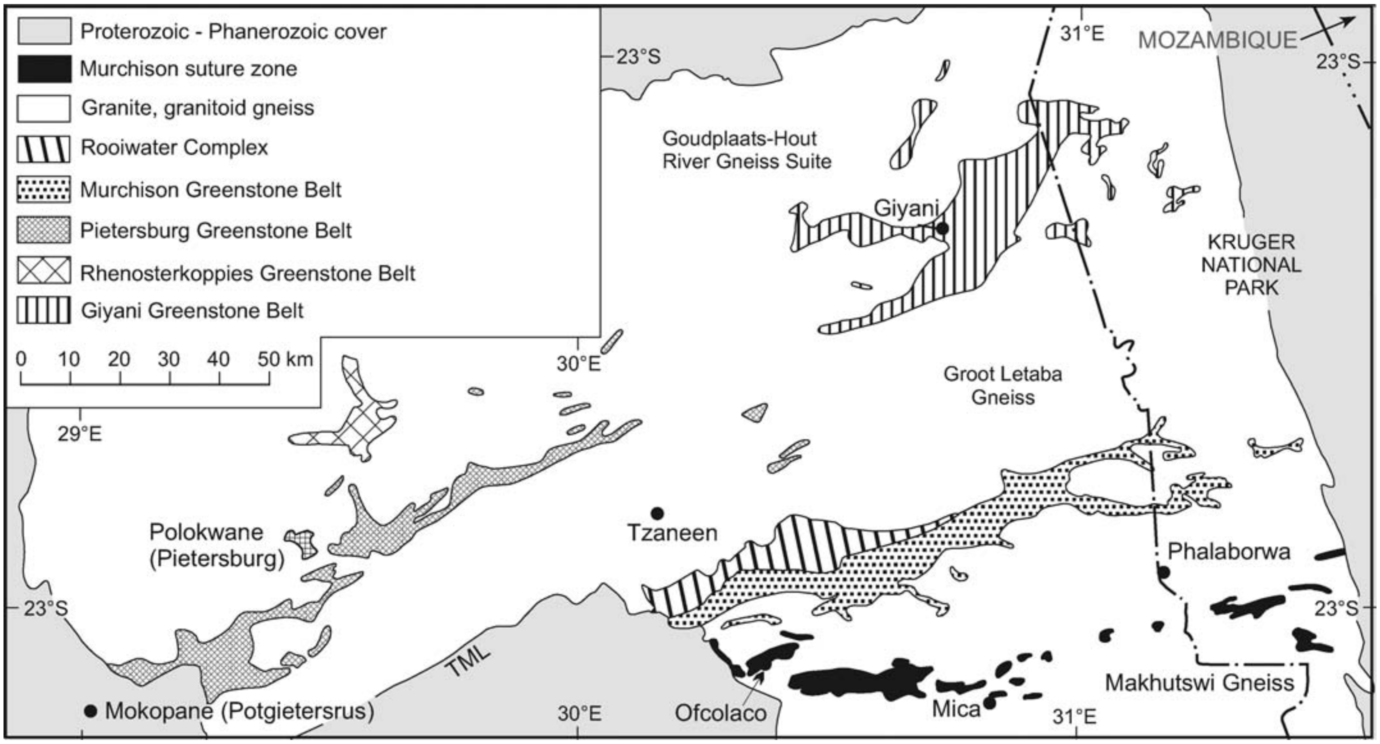

Figure 4. Simplified geological map of the northeastern sector of the Kaapvaal Craton showing the location of the Pietersburg, Giyani (Sutherland), and Murchison greenstone belts and surrounding granitoid basement. The distribution of numerous serpentinized ultramafic-mafic bodies, intruded by granites and pegmatites and discussed in this paper, is shown in a zone south of the Murchison greenstone belt in the vicinity of Ofcolaco, Mica, and Phalaborwa. The Thabazimbi-Murchison Lineament (TML) is shown extending west-southwest along the northeast-southwest projection of the Murchison greenstone belt.

rocks, including hornblende, talc, and chlorite schists. Exposures are generally poor, but these rocks can be traced sporadically from beneath the Neoarchean Wolkberg Group formations of the Transvaal Drakensberg Escarpment in the west toward Phalaborwa and the Kruger National Park in the east—a distance of ~120 km (see 1:250,000 map sheets, 2430 Pilgrim's Rest; Walraven, 1986; and 2330 Tzaneen; Brandl, 1985). The largest bodies occur in the west near Ofcolaco and north of the Makhutswi River east of Alsace. A few of the larger bodies also occur in the east in the Kruger National Park, north of the Olifants River (Walraven, 1986). Between these localities, from just west of Mica to the region south of Phalaborwa, the bodies have been dismembered by intrusive granitoid rocks, including numerous pegmatites of the Selati Line–Olifants River Mica Field (Hall, 1912; Robb and Robb, 1986).

Reconnaissance investigations by the author suggest that the ultramafic occurrences south of the Murchison greenstone belt (Fig. 4) are lithologically similar to the layered ultramafic complexes described above in the Barberton area and those discussed later in the Johannesburg Dome. Their age has not been determined precisely, but they are intruded by granitoid rocks ranging in age from 2700 to 3330 Ma (Poujol et al., 2003), including U-Pb zircon results pointing to a minimum age of 2850 Ma for the pegmatites (Poujol and Robb, 1999).

Together with the Barberton ultramafic-mafic complexes and those on the Johannesburg Dome, the occurrences of serpentinized ultramafic rocks in the Ofcolaco-Mica-Phalaborwa region constitute the largest development of this rock association on the Kaapvaal Craton. These rocks, like their counterparts described earlier, may represent ophiolite-type (ophirag) remnants dispersed along a suture (or oceanic collisional zone) separating two older crustal remnants located north and south of the Murchison greenstone belt.

In the north and northwest are vestiges of the ca. 3282–3333 Ma (Kröner et al., 2000; Brandl and Kröner, 1993) Goudplaats-Hout River Gneiss Suite. These gneisses are located northwest of the Pietersburg and Giyani (Sutherland) greenstone belts (Fig. 4) and south of the Southern Marginal Zone of the Limpopo Belt (i.e., south of the Hout River Shear Zone—HRSZ, Fig. 1). They are pervaded by younger granitoid rocks, emplaced at around 2900 Ma, which were formed during a major magmatic phase involving dehydration melting of amphibolite and biotite-gneiss protoliths (Du Toit et al., 1983). The granitoid rocks in the terrane further to the northeast, occurring between the Murchison and Pietersburg-Giyani greenstone belts, are grouped together under the term Groot Letaba Gneiss (Fig. 4). These gneisses are virtually identical to the Goudplaats-Hout River gneisses and have only recently been distinguished on geochronological grounds. The oldest gneiss from the area south of the Giyani greenstone belt yielded a single zircon Pb-Pb age of 3171 ± 6 Ma (Brandl and Kröner, 1993). Younger ages (ca. 2853–2886 Ma) were obtained from tonalitic and trondhjemitic gneisses and discordant leucogneisses east of Polokwane (Pietersburg) and near the northeastern end of the Pietersburg greenstone belt (Brandl and Kröner, 1993; Kröner et al., 2000).

South of the Murchison greenstone belt more gneisses occur, among which is the Makhutswi Gneiss that extends for some 50 km southward before merging with the Klaserie Gneiss. The Klaserie Gneiss, in turn, adjoins the granitoid terrane that extends to the Nelspruit region north of the Barberton greenstone belt described earlier. The Makhutswi Gneiss has tonalitic to granodioritic compositions and has yielded an age of 3228 ± 12 Ma (Poujol et al., 1996) close to the Murchison greenstone belt. Younger intrusive granitoids in the Makhutswi terrane vary between 3112 ± 5 and 3078 ± 6 Ma (Brandl and Kröner, 1993). Rocks of approximately similar age to those reported near the eastern end of the Pietersburg greenstone belt occur south of the Murchison greenstone belt and include pegmatites and undeformed porphyritic granite yielding ages of 2848 ± 58 and 2820 ± 38 Ma, respectively (Poujol and Robb, 1999; Poujol, 2001). The pegmatites in the Mica area, ~30 km south of the Murchison belt, intrude the Makhutswi tonalitic and trondhjemitic gneisses as well as numerous greenstone remnants comprising mainly serpentinites, talc and talc-chlorite schists, and amphibolites (Hall, 1912; Walraven, 1986; Robb and Robb, 1986). The Union Mine pegmatite, dated at 2912 ± 2.6 Ma (Kruger et al., 1998), and an additional pegmatite from the Olifants River Mica Field, dated at 2848 ± 58 Ma (Poujol and Robb, 1999), provide a minimum age for the ultramafic-mafic remnants, here postulated to represent oceanic crustal rocks.

Murchison Tectonic History

The geotectonic history of the northeastern sector of the Kaapvaal Craton is relatively poorly understood, due in part to the restricted exposure (Viljoen et al., 1993) and the paucity of detailed geological and geochronological data (Poujol et al., 2003). Exceptions include the Murchison and Giyani greenstone belts, which give rise to low ranges of hills that have been exploited for gold, antimony, copper-zinc, titaniferous magnetite, and pegmatite mineralization (Hall, 1912; Van Eeden et al., 1939; Viljoen et al., 1978; Vearncombe et al., 1992; Ward and Wilson, 1998). The concept of Archean plate tectonics in the Murchison area was first mooted by Vearncombe (1991), who maintained that the Murchison greenstone belt formed part of an exhumed volcanic island arc sequence. As modern island arcs are developed above or close to subduction zones, this suggests that the Murchison belt may once have formed in a collisional oceanic tectonic regime. Vearncombe (1991) did not identify a suture zone nor was any detailed subduction configuration provided, but he maintained that the Rooiwater Complex (a layered mafic igneous body with lithologies similar to the Bushveld Complex; Fig. 4) represented a subvolcanic magma chamber overlain by calc-alkaline felsic volcanic rocks of the Rubbervale Formation. Subsequent U-Pb isotopic studies have shown, however, that the Rubbervale Formation (2971 ± 10 Ma) is at least 200 m.y. older than the Rooiwater Complex (2740 ± 4 Ma; Poujol et al., 1996), suggesting that the latter complex is unrelated to the island arc evolutionary model proposed by Vearncombe (1991).

If a volcanic arc model is, however, accepted for the Murchison region as a whole, the suggestion offered here is that two protocontinental blocks (the northern and southern gneiss terranes described earlier) converged in post-Rubbervale Formation times (ca. 2971 Ma) entrapping part of the Murchison volcanic arc as well as some of the mafic-ultramafic oceanic crust in a suture zone to the south of the main Murchison greenstone belt. This "ophiolite-like" oceanic crust was then dismembered and transformed into a variety of mafic and ultramafic schists and massive serpentinite and amphibolite remnants (ophirags) by pegmatites intruded along the Olifants River Mica Field between ca. 2848 and 2912 Ma.

JOHANNESBURG DOME

Studies undertaken on the Johannesburg Dome have led to the recognition of a variety of Archean granitoid rocks (Anhaeusser, 1973a) as well as a suite of mafic and ultramafic rocks analogous to the komatiitic lavas and layered ultramafic complexes encountered in the Barberton greenstone belt. The mafic and ultramafic rocks are exposed intermittently within a WNW-ESE–trending zone across the southern portion of the Johannesburg Dome, extending from beyond Muldersdrif in the west (Anhaeusser, 1977, 1978, 1992) to the Edenvale-Modderfontein area in the east (Anhaeusser, 1973a, 2004; Chaumba, 1992), a distance of ~50 km (Fig. 5). With the exception of the Barberton greenstone belt and the Ofcolaco-Mica area described earlier, the mafic-ultramafic rocks on the Johannesburg Dome represent the largest development of serpentinized ultramafic rocks on the Kaapvaal Craton.

The principal rock types in the ultramafic complexes in the Johannesburg Dome include serpentinized dunite, harzburgite, lherzolite, ortho- and clinopyroxenite, and gabbro (Anhaeusser, 2004). Pillow basalts and ultramafic lava sequences of komatiitic affinity have also been reported from localities in the Muldersdrif area (Anhaeusser, 1977, 1978). In places, the serpentinites contain significant quantities of Cr (up to 5335 ppm) and Ni (up to 2240 ppm), which may account for the presence of detrital chromites and high nickel values found in the conglomerates and shales of the Witwatersrand Supergroup to the south, dated at ca. 2970–2780 Ma (Robb and Robb, 1998).

The mafic-ultramafic assemblages on the Johannesburg Dome have previously been regarded as remnants of ancient greenstone belts, but the absence of other typical greenstone lithologies (viz., chert, banded iron formation, jaspilite, felsic

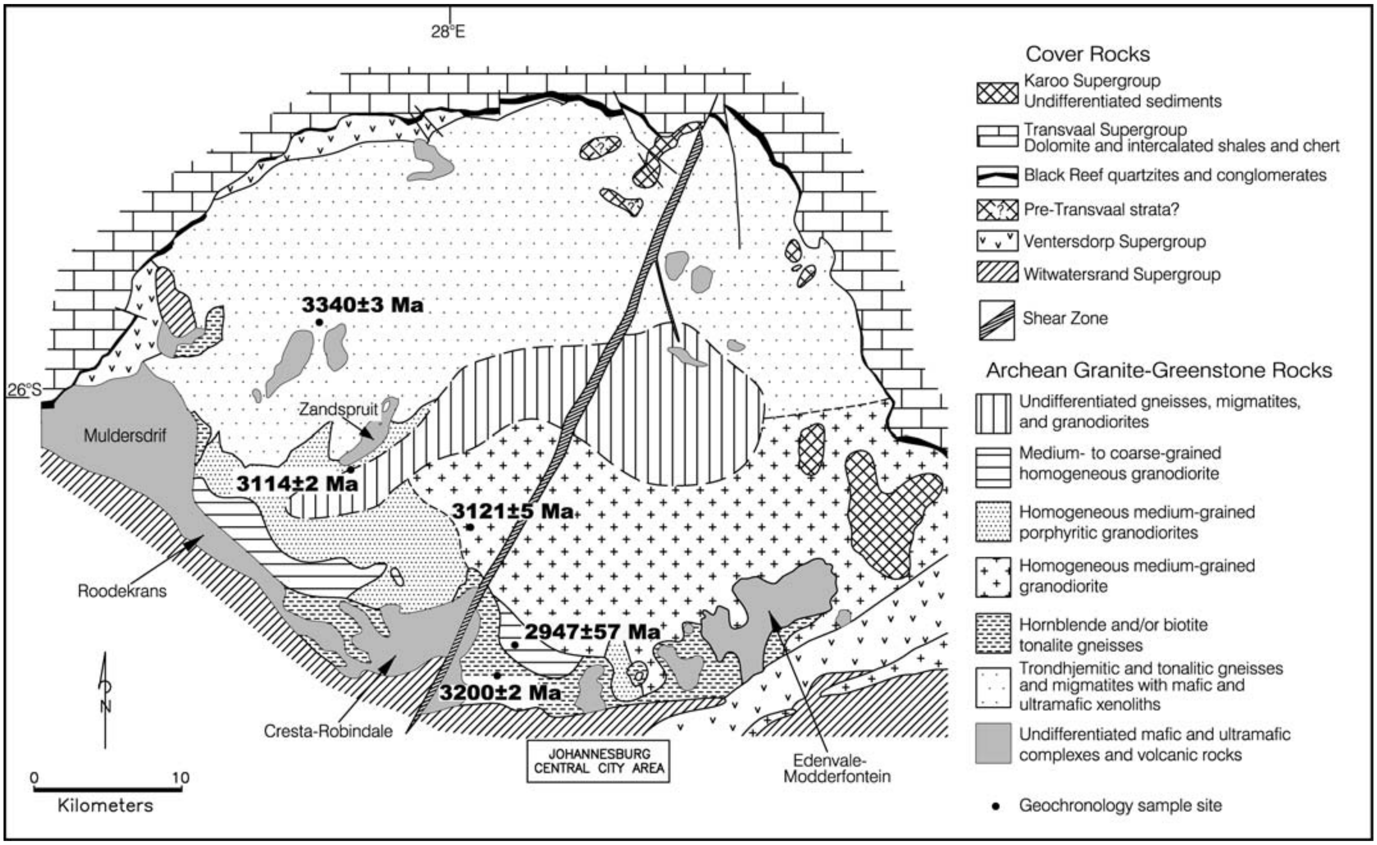

Figure 5. Simplified geological map of the Johannesburg Dome showing the distribution and ages of the various granitoid rocks and the location of Archean ultramafic-mafic complexes that define the position of a possible WNW-ESE–trending, linear suture zone along the southern margin of the dome (after Anhaeusser, 1973a).

volcanoclastic rocks) suggests that these rocks may be more closely allied to upper mantle or oceanic crustal rocks.

Progressive urban development in recent years north of Johannesburg, Roodepoort, and Edenvale has resulted in the destruction of most of the key areas of greenstone exposure on the Johannesburg Dome. The best-preserved, most continuous exposures of mafic-ultramafic rocks occur in the west where the layered successions of the Muldersdrif Ultramafic Complex (Anhaeusser, 1978) form a series of low, WNW-ESE–trending ridges and valleys (Fig. 6). The complex comprises a number of cyclic units consisting of serpentinized dunite, harzburgite, wehrlite, lherzolite, and Mg-rich ortho- and clinopyroxenite cumulate rocks. The cyclic units are terminated by thin (<1-m-wide) medium- to fine-grained metagabbroic layers, which also provide marker horizons delineating chrysotile asbestos fiber development. The rocks of the layered complex have been extensively deformed with superimposed fold events having produced a complex outcrop pattern of interference fold structures (Anhaeusser, 1976a, 1986).

Southeast of the Muldersdrif Ultramafic Complex in the Roodekrans-Ruimsig area, rocks of the Roodekrans Ultramafic Complex form a layered succession largely deformed and altered to talc, talc-chlorite, and talc-tremolite schists. Massive serpentinite layers and pods are present in places and a prominent northeast-trending, pre-Witwatersrand Supergroup cleavage is developed oblique to the layering and to the earlier-formed schistosity, testifying to a complex tectonic history for the rocks in the region (Anhaeusser, 2004).

Ultramafic rock exposures also occur ~5 km northeast of Roodekrans where they occur as remnants of the Zandspruit Ultramafic Complex that crops out discontinuously over a distance of ~4 km (Anhaeusser, 1992). The succession, consisting of alternating, cyclically repetitive, cumulate layers of serpentinized dunite, harzburgite, and metapyroxenite, dips to the southeast at shallow angles (10°–30°) and is surrounded by intrusive porphyritic granodiorites.

In the northwestern suburbs of Johannesburg, massive and schistose ultramafic-mafic rocks, referred to by Anhaeusser (2004) as the Cresta-Robindale complexes, are sporadically exposed over a distance of 10 km. These bodies, consisting predominantly of serpentinized and metamorphosed dunite, harzburgite, ortho- and clinopyroxenite, and minor gabbro, are intruded by hornblende-biotite tonalitic gneiss. Likewise, in the northeastern suburbs on the southeastern edge of the Johannesburg Dome, the Edenvale-Modderfontein Complex (Chaumba, 1992; Anhaeusser, 2004) consists predominantly of east-west–

Figure 6. Oblique aerial photograph, looking west, of part of the Muldersdrif Ultramafic Complex in the southwestern sector of the Johannesburg Dome. The WNW-ESE–trending ridges seen in the photograph consist predominantly of folded, sheared, and altered serpentinized dunite, harzburgite, and pyroxenite.

and northeast-southwest–trending massive and schistose serpentinite (including talc-chlorite and talc-carbonate schists) and pyroxenite layers that are extensively uralitized and steatized (tremolite-actinolite schists). Cyclical layering is again evident, with upward of 14 cyclical units having been identified by Chaumba (1992). Trondhjemitic gneisses and late-stage pegmatites intrude the ultramafic-mafic rocks, but exposures are limited due to the advancement of housing and industrial development in the area.

Johannesburg Dome Geochronology

Recent geochronological investigations have contributed to a fuller understanding of the complex geological and tectonic evolution of events in the Johannesburg Dome. U-Pb zircon dating has yielded ages of 3340 ± 3.3 Ma for trondhjemitic gneisses on the northern half of the dome and an age of 3200 ± 2 Ma for tonalitic gneisses on the southern rim (Poujol and Anhaeusser, 2001). Ages ranging between 3121.2 ± 5 and 2947 ± 57 Ma were determined for K-enriched granodiorites and pegmatites in the south-central parts of the dome (Barton et al., 1999; Poujol and Anhaeusser, 2001). Sediments of the Witwatersrand Basin were deposited unconformably on this basement after ca. 3074 Ma, the age of the upper lava sequence of the Dominion Group (Armstrong et al., 1991), which underlies the Witwatersrand Supergroup ~120 km southwest of the Johannesburg Dome.

The ages of the ultramafic-mafic rocks in the dome have not yet been determined directly because of their unsuitability for dating purposes, but their relationships with intrusive granitoids on the dome provide important age constraints. In the west, the Muldersdrif, Roodekrans, and Zandspruit complexes are intruded by porphyritic granodiorites dated at ca. 3114 Ma (Poujol and Anhaeusser, 2001). The Roodekrans Complex is also partly overlain by ca. 2914 Ma (or older) sediments of the West Rand Group of the Witwatersrand Supergroup (Robb and Robb, 1998). In the Cresta-Robindale area the ultramafic complexes are intruded by hornblende-biotite gneisses that have yielded U-Pb zircon ages of ca. 3200 Ma (Anhaeusser and Burger, 1982; Poujol and Anhaeusser, 2001). Similarly, the Edenvale-Modderfontein Complex has been intruded by biotite-trondhjemite gneisses, which are petrologically and geochemically identical to the ca. 3340 Ma gneisses dated on the northwestern side of the dome by Poujol and Anhaeusser (2001). Thus, although there are no direct ages for the ultramafic-mafic rocks of the Johannesburg Dome, there is evidence that they at least predate the early stages of Witwatersrand deposition (at ca. 2914 Ma) and that they also clearly predate the ca. 3200 Ma tonalitic gneisses. They may equally well be older than the ca. 3340 Ma trondhjemitic granitoids in the northwest (Fig. 5), but no direct contact relationships with these rocks have been recorded.

Johannesburg Dome Tectonic History

Petrological and geochemical studies have demonstrated that the TTG granitoids on the dome have characteristics similar to Archean TTG granitoids interpreted as having evolved in a tectono-magmatic setting analogous to that found in modern-day volcanic-arc environments (Anhaeusser, 1999). As discussed elsewhere in this contribution, Phanerozoic plate-tectonic models involving collisional tectonics commonly show suture zones defined by the preservation of slivers of oceanic lithosphere (ophiolites and ophirags), which formerly separated continental masses (Kearey and Vine, 1995). A reassessment of the Archean basement in the Johannesburg Dome therefore suggests that the ultramafic-mafic exposures described above may represent the locus of collision of two protocontinental blocks, thereby constituting a Paleoarchean suture zone. A possible scenario for the Johannesburg Dome, in pre-Witwatersrand times, envisages an ancient trondhjemitic gneiss-migmatite terrane (ca. 3340 Ma) in the north colliding with another crustal fragment (now hidden beneath the Witwatersrand Basin) in the south. The collision event may correspond with the emplacement, at ca. 3200 Ma, of hornblende tonalite gneisses along the southern margin of the dome, which resulted in the fragmentation of the oceanic lithosphere trapped between the colliding microplates. Subsequent plutonism due to partial melting of the crust of the microcontinent and possibly resulting from overthickening during or after collision (as described by Dewey and Kidd, 1974) thereafter produced the ca. 3121–2947 Ma intrusive granodioritic to granitic rocks on the dome. Further support for this crust-mantle melting interaction, and hence a significant orogenic event, may be linked to a suite of foliated, Mg-tholeiitic basaltic to calc-alkaline lamprophyric dykes emplaced on the Johannesburg Dome at ca. 3120 Ma (Prevec et al., 2004).

The crustal block buried beneath the Witwatersrand Basin probably manifests itself in the ~45-km-wide Archean crystalline basement core of the Vredefort Dome exposed some 120 km SSW of the Johannesburg Dome. Extreme uplift, associated with the Vredefort impact event at 2023 ± 4 Ma (Kamo et al., 1996), has exposed polydeformed high-grade tonalite-trondhjemite-granodiorite (TTG) gneisses, migmatites, and late-tectonic intrusive granitoids metamorphosed to upper amphibolite- to granulite-facies conditions (Hart et al., 1999; Gibson and Reimold, 2001; Lana, 2003; Lana et al., 2004). Isotopic studies carried out on various lithologies in the core of the Vredefort Dome have been summarized by Gibson and Reimold (2001) and Lana (2003). These and more recent results indicate that metamorphism took place at ca. 3100 Ma and that this event postdated most of the TTG–greenstone lithologies identified on the dome. Upper intercept ages obtained from zircons found in these rocks yielded values ranging between 3310 and 3425 Ma (Kamo et al., 1996; Hart et al., 1999). Lana (2003) also reported ca. 3400 Ma zircons from mafic, xenolith-rich enderbitic gneisses. These findings suggest that the Archean basement at Vredefort experienced a protracted and complicated Mesoarchean evolutionary history, much like that found in the other crystalline basement terranes on the Kaapvaal Craton discussed previously.

It is envisaged that the northern and southern blocks outlined above migrated toward one another as a result of oceanic plate consumption and eventually led to continent/continent collision as envisaged by Dewey and Bird (Fig. 15 *in* Dewey and Bird, 1970). The trench zone between the colliding protocontinental blocks was ultimately reduced to a narrow suture from which oceanic crust and accompanying sediments were extruded. Admittedly, this reconstruction is based on circumstantial evidence, but there does not appear to be a readily apparent way to confirm or negate this argument given the lack of exposure.

DISCUSSION

The events that took place not only in the vicinity of the Johannesburg Dome but also north of Barberton and south of Murchison occurred some 3000 m.y. ago or more. Tectonic and other changes including erosion have largely destroyed or removed whatever confirmative evidence that may once have existed (with the possible exception of the Barberton greenstone belt). If the suture concept is correct, the serpentinized ultramafic-mafic rocks preserved in these terrane boundary zones remain as the only acceptable testimony to Archean oceanic plate consumption.

Witwatersrand Basin and Plate Tectonics

Numerous models have been suggested for the origin and evolution of the Witwatersrand Basin located in the central portion of the Kaapvaal Craton (Fig. 1). Prior to the emergence of the theory of plate tectonics in the 1960s, the models employed to explain the genesis of the Witwatersrand Supergroup leaned heavily on taphrogenic or rift-related basin models (Brock and Pretorius, 1964a, 1964b) together with refinements involving intracratonic alluvial plain and lacustrine models (Pretorius, 1976; Myers et al., 1990). Van Biljon (1980) was the first to employ plate-tectonic theory to explain the origin of the Witwatersrand Basin, concluding that it represented an embayment along a subduction zone between two Archean minicontinents. Later, a cratonic foreland model developed in a continental back-arc plate-tectonic setting was proposed (Burke et al., 1985, 1986; Winter, 1987). This was followed by Stanistreet and McCarthy (1991) who introduced the concept of a Wilson cycle for the tectonic evolution of the Witwatersrand triad, which includes the underlying Dominion and overlying Ventersdorp successions. Despite the application of plate-tectonic theory, none of the studies mentioned above provided any details pertaining to the nature of the pre-Witwatersrand basement geology and the influence this may have had on the eventual location and evolution of the Witwatersrand Basin.

Reconstructions of the crustal architecture of the Kaapvaal Craton have led to general agreement among researchers that terrane amalgamation was accomplished by processes akin to but different in scale from those responsible for present-day global plate-tectonic activity. The model that has gained the most support for early Archean crustal accretion suggests that a mosaic of protocontinental subdomains consisting predominantly of nucleated granite-greenstone terranes was welded together by processes similar to those identified as being responsible for Phanerozoic and present-day plate-tectonic activity (Anhaeusser, 1973b, 1999; De Wit et al., 1992; McCourt, 1995; Barley, 1997; Brandl and De Wit, 1997; Myers and Swagers, 1997; Stott, 1997). While the concept of terrane amalgamation in the manner described may be appealing, problems remain in realistically determining the terrane boundaries. Undue speculation as to the shape, size, isotopic characteristics, and boundary relationships of unsubstantiated crustal fragments, some considered exotic or allochthonous and others that may once have formed part of a coherent geological province, suggests that further confirmatory work needs to be undertaken (Mogk et al., 1992).

A number of major crustal features have been identified on the Kaapvaal Craton, many of which display protracted periods of reactivation in post-Archean times (Fig. 1). Some of the larger lineaments include the Palala Shear Zone (Du Plessis and Walraven, 1990; McCourt, 1995), the Hout River Shear Zone (Smit et al., 1992), the Thabazimbi-Murchison Lineament (Du Plessis, 1991; Good and De Wit, 1997), and the Barberton Lineament (Fripp et al., 1980; Van Biljon, 1980), the latter being coincident with the King Fault of Stanistreet et al. (1986). In addition, three major east-northeast–trending, left-lateral wrench-fault systems are located on the northern margin of the Witwatersrand Basin. These strike-slip systems, which came into existence during Witwatersrand times, appear to be of craton-wide scale and are thought to extend eastward at least as far as the Barberton greenstone belt (Van Biljon, 1980; Stanistreet et al., 1986; fig. 1 of Stanistreet and McCarthy, 1991; Fig. 7 herein).

Other lineaments with north-south trends exist elsewhere on the craton (e.g., Colesberg; Corner et al., 1990; Doucouré and De Wit, 2002; Schmitz et al., 2004; Fig. 1 herein) but whether or not all, or some, of these extensive linear features initially constituted Archean terrane boundaries remains debatable. De Wit and Tinker (2004) recently interpreted deep seismic reflection profiles across the Kaapvaal Craton and claim to have recognized four crustal panels (>200 km by 10–20 km) of pre-Ventersdorp age resembling a tectonically stacked series of crustal slivers extending from west to east across the Kimberley and Witwatersrand blocks (Fig. 1). These blocks, also defined on geochronological grounds (Schmitz et al., 2004), are separated by the north-south–trending Colesberg Magnetic Lineament (Corner et al., 1990). This magnetic lineament, it has been conceded by De Wit and Tinker (2004), is not a feature that can be easily linked to an underlying suture in the lower crust and mantle. If a suture zone existed at all it is suggested that it was positioned to the west of the craton boundary, dipping to the west, and indicating east-directed tectonic accretion of the Amalia-Kraaipan terrane across a Witwatersrand basement panel or block.

One clearly identifiable crustal domain boundary is that of the Tugela Terrane of KwaZulu-Natal (Thomas, 1989). Matthews (1972) recognized and interpreted rocks of oceanic affinity, which were thrust northward (obducted) onto the southern flank of the Kaapvaal Craton, as an allochthonous ophiolite complex. Large, dismembered serpentinite bodies (ophirags) occur within and along this zone, which was initially referred to as the Natal Thrust Belt and Natal Nappe Complex by Matthews (1972) and Matthews and Charlesworth (1981). In Figure 1 it is shown as the Tugela Thrust Front. Unlike the inferred suture zones on the Kaapvaal Craton, the Tugela Terrane boundary collision zone separates ca. 3000 Ma Archean cratonic rocks from lithologies of Mesoproterozoic age (ca. 1200–1150 Ma; McCourt et al., 2000). This southern margin of the Kaapvaal Craton has been imaged by seismic profiling (De Wit and Tinker, 2004) and is consistent with the existing geological interpretation originally proposed by Matthews (1972).

Only two of the lineaments on the Kaapvaal Craton (viz., Thabazimbi-Murchison and Barberton) have discernable characteristics linking them to possible intracratonic suturing. In the case of the Thabazimbi-Murchison Lineament the eastern sector exposed in the Archean granite-greenstone basement comprises the highly deformed Murchison greenstone belt, which has been likened to a volcanic arc (Vearncombe, 1991). The Murchison collision zone, as contended, includes both the greenstone belt and the adjacent ultramafic-mafic rocks to the south. The zone of tectonic shortening, which includes the folded, faulted, and sheared granite-greenstones, is ~35–40 km wide. The Mhlapitsi Fold Belt, which represents the westward extension of the earlier-formed Murchison collision zone, is believed to have developed in pre-Bushveld times (Button, 1973). This folded zone, which has been shortened by upward of 35% (Potgieter, 1992), was probably reactivated during the emplacement (at ca. 2060 Ma) of the Bushveld Complex. The full extent of the Thabazimbi-Murchison Lineament, which includes the Mhlapitsi Fold Belt, projects for over 500 km in an ENE-WSW direction across the Kaapvaal Craton and delineates a major intracratonic terrane boundary (McCourt and Vearncombe, 1987; Du Plessis, 1991; Good and De Wit, 1997), the deep structure of which has been supported by seismic anisotropy studies (Vinnik et al., 1995).

The Barberton Lineament was shown by Van Biljon (1980) to strike approximately N60°E in the Barberton region, and it was suggested that if this trend was projected to the southwest beneath the younger Transvaal and Karoo Supergroup cover sequences, it would reemerge in the vicinity of the Witwatersrand Basin (Fig. 7). As was shown by Stanistreet et al. (1986) and Stanistreet and McCarthy (1991), three major, pre-Transvaal, east-northeast–trending wrench fault systems are known to have influenced the northern edge of the Witwatersrand Basin in the Johannesburg vicinity (viz., the Kromdraai, Rietfontein, and Sugarbush fault systems), and these authors presented evidence suggesting that one or more of these fault systems may merge with those in the Barberton region (e.g., the King Fault; Fig. 7). Additional support for a possible geotectonic link between the Johannesburg and Barberton terranes includes the presence of dunite-peridotite-pyroxenite-gabbro rocks beneath the younger cover sequences in the Delmas, Bethal and Carolina areas. These rocks, encountered in borehole intersections,

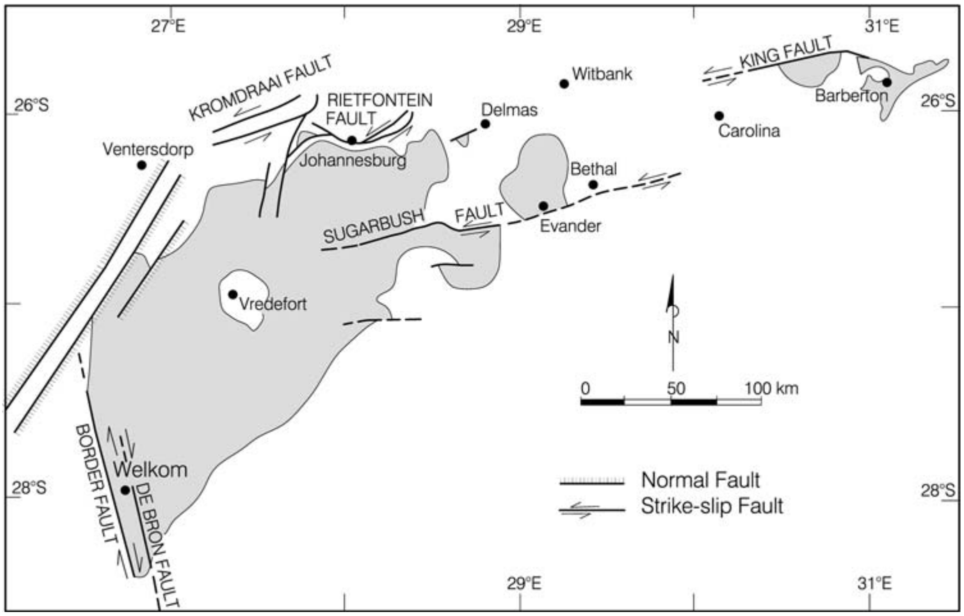

Figure 7. Simplified geological map showing the extent of the Witwatersrand Basin in the central part of the Kaapvaal Craton (gray shaded area south of Johannesburg). Some faults are shown, including the Rietfontein and Sugarbush fault systems, which may extend eastward beneath younger cover toward the Barberton greenstone belt (see text). Diagram modified after Stanistreet et al. (1986) and Stanistreet and McCarthy (1991).

were correlated with Swaziland Supergroup rocks occurring in the Barberton greenstone belt (Ferraz, 1989). If this interpretation is correct it could be argued that the ultramafic-mafic complexes in the Barberton and Johannesburg Dome areas (and the intervening covered areas) may represent components of the same craton-wide suture or terrane boundary.

Equally, it could be argued that the major Rietfontein Fault boundary structure immediately adjacent to the northern margin of the Witwatersrand Basin in the Central Rand area (Myers et al., 1990) owes its position to inherent crustal weaknesses along a pre-Witwatersrand terrane boundary or suture zone. The northern margin of the Witwatersrand Basin may also have been determined or influenced by this terrane boundary. Likewise, the Thabazimbi-Murchison tectonic fault zone could conceivably represent reactivation along a long-lived structure that may once have constituted a suture zone separating Archean crustal blocks developed north and south of the Murchison greenstone belt.

CONCLUDING REMARKS

Proposals have been made suggesting that the Kaapvaal Craton resulted from the amalgamation of a number of Archean protocontinental crustal blocks and that the nucleation of these ancient blocks was accomplished by processes akin to modern-day plate-tectonic activity. Geological and geochemical evidence continues to mount from Archean terranes suggesting that greenstone belt and TTG–granitoid evolution took place in environments not far removed from those seen today in volcanic arc environments (see papers in Kröner, 1981; Condie, 1994; De Wit and Ashwal, 1997). While comparisons between Archean and Phanerozoic geotectonic processes have become increasingly popular, there are differences that still require explanation. Issues such as higher heat flow during the Archean, the absence of high-pressure blueschist facies rocks, and "paired metamorphism," so characteristic of island arcs, together with the absence in Archean terranes of ophiolites (more specifically those not accompanied by sheeted dyke systems, as per the Penrose ophiolite definition) and tectonic mélanges, have been used to dispute direct comparisons. Some would even argue that there is no justification for any analogy between Archean and Phanerozoic tectonics (Hamilton, 1998, 2003; McCall, 2003). The debate continues!

In this contribution the position adopted is one of acceptance of Archean plate-tectonic activity, albeit that this may have taken a modified form from that which is advocated in the theory of uniformitarianism, or the age-old maxim stating that "the present is the key to the past." In an attempt to offer an explanation for the unique development of the massive serpentinite and pyroxenite bodies found in only a few restricted localities on the Kaapvaal Craton, the concept of Archean sutures emerges as a viable possibility for their origin. Their clustering in linear arrays in the Barberton, Murchison, and Johannesburg regions suggests that they may be relics of upper mantle or oceanic crust trapped in Archean plate-tectonic convergent zones separating protocontinental sialic nuclei. Acceptance of plate tectonics during the Archean also acknowledges the presence of ophiolites at this stage in earth history. However, the author only favors the modified form of the ophiolite definition being applied to the Archean (viz., the incompletely developed or dismembered ophiolites referred to by Şengör and Natal'in [2004] as ophirags).

How does one test or verify the existence of fossil suture zones extending as far back in time to the Archean? How also does one attempt to determine the geometric orientation of the subduction zone? At present there is little or no available geophysical profiling across the Kaapvaal Craton ultramafic-mafic zones highlighted in this paper. The great age of these rocks, coupled with the multiplicity of geological and geotectonic events that have occurred on the craton over the past 3 billion years or more, suggest that evidence for the presence of collisional terrane boundaries might have been destroyed as a consequence of the welding process accompanying the intrusion and fragmentation of the suture zone by later granitoid rocks. If, as has been suggested by De Wit et al. (1992), the Kaapvaal Craton is made up of a mosaic of subdomains welded together over a time span extending from ca. 3700–2700 Ma, then the possibility exists that at least some of these terrane boundaries have an identifiable physical presence, as has been proposed in this paper, thereby reducing the degree of speculation concerning their whereabouts. Archean subdomains, defined using lithological and geochronological criteria are recognizable in the Barberton granite-greenstone terrane (Lowe, 1999). By contrast, the scheme outlined by De Wit et al. (1992), whereby the Kaapvaal Craton is envisaged as having been formed by the amalgamation of upward of 12 subdomains, is largely conjectural and has not been adequately proven either in the field or on geophysical grounds.

One final consideration emerging from the suture zone suggestion proposed in this paper concerns the anomalous distribution and amount of gold on the Kaapvaal Craton (particularly that deposited in the Witwatersrand Basin, the outline of which is shown in Fig. 1). It has been calculated that production from the Witwatersrand goldfields, from commencement of mining up to 2002, has amounted to 49,332 tons of gold (Handley, 2004). Potentially, a further 40,000 tons of gold remains to be exploited. This gold occurs in mines located in a "Golden Arc" occupying an area ~8000 km^2 in size out of a total area of ~100,000 km^2 estimated for the greater Witwatersrand Basin.

The origin and source of this gold has been the subject of debate for over 100 yr (Robb and Robb, 1998), and no final solution has yet emerged. Gold production from the Witwatersrand goldfields has mainly been along the northern, northwestern, and western perimeter of the basin, leading to one suggestion that the source may have been from a crescent-shaped, juvenile volcanic arc developed around the northern and western rim of the Kaapvaal Craton (Poujol et al., 2003). However, sedimentological evidence favors the view that the gold may have been derived from a source much closer to the present-day basin edge, leading to the possible link between the Witwatersrand gold mineralization and the suture zones or terrane boundaries postulated in this paper. Likewise, it may not be fortuitous that the main distribution of gold mines and the principal production of gold from the Barberton goldfield has been from localities adjacent to the suture zone suggested in Figure 2B.

If the terrane boundary concept has any validity, the protocontinental collisional events outlined in this paper may have been preceded by ocean-floor consumption and volcanic arc development. Hydrothermal exhalative activity along such zones could have introduced auriferous solutions into the volcanic arc and basin edge formations, which were subsequently eroded and introduced into the fluvial systems as detrital particles that were deposited in the Witwatersrand Basin (Hutchinson and Viljoen, 1988).

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