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MAGMATIC AND STRUCTURAL CHARACTERISTICS OF THE *ca.* 3440 MA THEESPRUIT PLUTON, BARBERTON MOUNTAIN LAND, SOUTH AFRICA

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ABSTRACT. The Archean crust in the Barberton area, on the eastern side of the Kaapvaal Craton, South Africa, consists of a variety of granitic rocks ranging in age from *ca.* 3600 to 2500 Ma. A suite of tonalite-trondhjemite-granodiorite (TTG) intrusions has been divided into an older group (*ca.* 3400 Ma) and a younger group (*ca.* 3200 Ma) and form a set of domal plutons or "cells" that have similar petrological, geochemical, and structural characteristics. The Theespruit Pluton, one of the older trondhjemite cells, dated between 3443 and 3437 Ma, displays a number of unique features that distinguishes it from others in the region. These features include transgressive as well as concordant contact relationships with the enveloping *ca.* 3530 Ma amphibolite-facies metavolcanic rocks of the lower part of the Onverwacht Group (Sandspruit and Theespruit formations) of the Barberton greenstone belt. The trondhjemites further display a variety of textures ranging from homogeneous cumulate rocks to foliated, lineated and banded gneissic granitoids. Amphibolite xenoliths occur commonly throughout the pluton and in many cases show little or no effects of strain, thereby contributing to the interpretation that these rocks represent roof pendants stoped from the overlying supracrustal volcanic rocks. Some xenoliths and pluton contact areas have experienced hydraulic fracturing accompanied by brittle deformation, brecciation and agmatite development. Locally, the breccias have experienced additional transformation to dioritic rocks following assimilation, metasomatism and hybridization resulting from trondhjemite magma injection and late-stage hydrothermal activity in the apical portion of what is interpreted to be a high-level granitic intrusion. At the level exposed, the pluton is geochemically and mineralogically uniform throughout, consisting of plagioclase-quartz-biotite rocks (trondhjemite) with only minor plagioclase-quartz-biotite-hornblende rocks (tonalites, diorites) developed near assimilated amphibolite xenoliths. Views on the emplacement style of the pluton are considered and processes akin to diapirism are favored over alternate views suggesting that the Barberton TTG plutons formed as a consequence of horizontal thrust-accretionary processes.

Key words: Archean plutons, Barberton Diapirism, Assimilation, Cumulate granitoids, Agmatites, Metasomatism, Hybridization.

INTRODUCTION

The granitic terrane surrounding the Barberton greenstone belt (fig. 1) has provided important clues as to the nature and evolutionary development of the early Archean crust of southern Africa. A wide variety of granitoid compositional types are present in the region and range from Eoarchean and Paleoarchean tonalite-trondhjemite-granodiorite gneisses and migmatites (TTG intrusions—*ca.* >3600-3200 Ma) to Mesoarchean granodiorite-monzogranite-syenite-granite (GMS suite—*ca.* 3200-2800 Ma) and Neoarchean high-calcium intrusions (I-type granitoids—*ca.* 2800-2500 Ma).

Studies undertaken on the granitoid rocks in the Barberton and Swaziland regions on the eastern side of the Kaapvaal Craton of southern Africa include details of the *field characteristics* (Visser and others, 1956; Anhaeusser, 1966; 1980; 1981; Viljoen and Viljoen, 1969a; Hunter, 1974; 1979; Glikson, 1979; Anhaeusser and Robb, 1980; 1981; 1983b; Anhaeusser and others, 1983; Kröner and Tegtmeyer, 1994; Robb, 1994; Moyen and others, 2007a; Van Kranendonk and others, 2009; Lana and others, 2010a; 2010b), *geochemistry* (Viljoen and Viljoen, 1969b; Glikson, 1976; Anhaeusser and Robb,

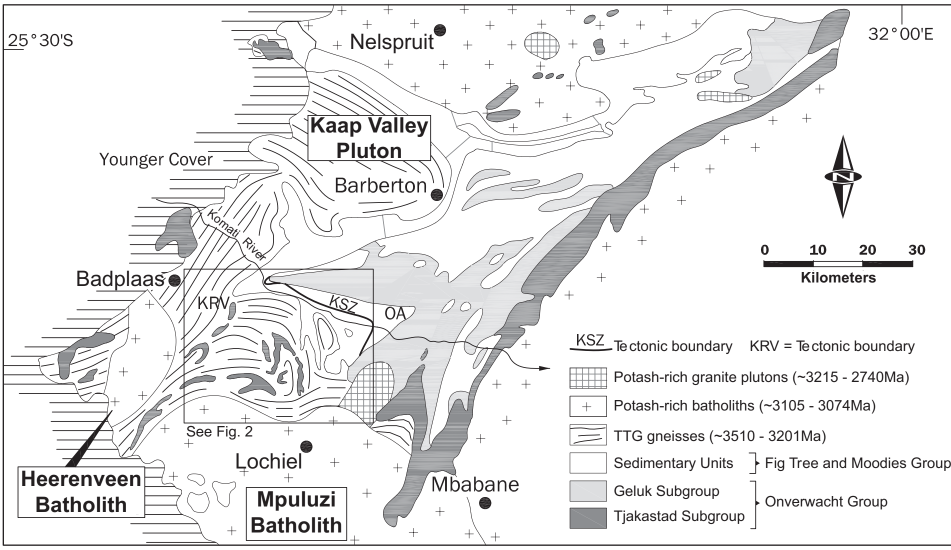

Fig. 1. Map of the Barberton greenstone belt and surrounding granitoid rocks. OA = Onverwacht anticline, KSZ = Komati Schist Zone terrane boundary. KRV = Komati River valley through which flows the Komati River from west to east. The location of fig. 2, which provides details of the granite-greenstone terrane in the vicinity of the Theespruit Pluton, is also indicated.

1980, 1983a, 1983b; Robb, 1981a, 1981b; Robb and Anhaeusser, 1983; Robb and others, 1986; Hunter and others, 1992; Kleinhanns and others, 2003; Yearron, ms, 2003; Clemens and others, 2006, 2010; Moyen and others, 2006, 2007b; Van Kranendonk and others, 2009), *geochronology* (Oosthuyzen, ms, 1970; Kröner and others, 1989; 1991, 1996; Armstrong and others, 1990; Kamo and Davis, 1994; De Ronde and Kamo, 2000; Poujol and others, 2003; Schoene and Bowring, 2007, 2010; Schoene and others, 2008, 2009; Van Kranendonk and others, 2009; Lana and others, 2010b), *structure* (Anhaeusser, 1984; Kisters and Anhaeusser, 1995a, 1995b; Kisters and others, 2003; Belcher and Kisters, 2006), and *metamorphism* (Van Vuren and Cloete, 1995; Dziggel and others, 2002, 2006; Diener and others, 2005; Stevens and Moyen, 2007; Van Kranendonk and others, 2009; Lana and others, 2010a).

Models of crustal evolution determined from the region have found widespread applicability in Archean terranes elsewhere in the world, although there remains debate as to whether early Archean tectonic styles in the Barberton area were dominated by vertical as opposed to horizontal tectonic influences. Early interpretations suggested that the volcano-sedimentary successions of the Barberton greenstone belt were initially tilted and folded due to gravitational influences in an environment where the oceanic-like Eoarchean-Mesoarchean crust was relatively thin and tectonically unsupportive of depositional loading. Extensive granitoid magmatism followed with the emplacement of tonalite-trondhjemite-granodiorite (TTG) diapiric intrusions, which contributed to the thickening and sialic underplating of the earlier-formed crust (Anhaeusser and others, 1969; Viljoen and Viljoen, 1969a, 1969b; Anhaeusser, 1973; 1984). This led to a dome-and-keel configuration of the granite-gneiss terrane in a manner similar to that described in Zimbabwe by Macgregor (1951), which he explained as being formed by polyphase deformation and diapiric intrusion of granitoid batholiths. Minnitt and Anhaeusser (1992) were equally convinced of granitoid diapirism being manifest in the eastern extension of the Murchison greenstone belt 250 km north of the present study area. Emplacement mechanisms for the TTG plutons in the southern part of the Barberton granite-greenstone terrane were illustrated by Kisters and Anhaeusser (1995a) who concluded that "a component of diapirism is suggested by the radially orientated, superimposed flattening and constrictional strains within the plutons as well as in the wall rocks and greenstone xenoliths engulfed by the tonalites-trondhjemites."

Whilst considerable support has been forthcoming for predominantly vertical tectonics and diapir-driven crustal convection for Archean dome-and-keel structures elsewhere (Hickman, 1984; Ramsay, 1989; Jelsma and others, 1993; Collins and others, 1998; Van Kranendonk and others, 2004) some authors have attributed dome-and-keel configurations to cross- or interference-folding (Snowden and Bickle, 1976; Snowden, 1984). Likewise in the Barberton terrane De Wit (1982, 1998) dismissed the vertical tectonics concept and emphasized the role of horizontal thrust-and-nappe tectonics and the allochthonous nature of the Barberton greenstone belt in which granitoid diapirism played no part (De Wit and others, 1983, 1987, 1992).

Recent investigations in Western Australia suggest that both vertical and horizontal tectonic regimes may have played a role in Archean granite-greenstone terranes, and that these may be age-related. Hickman (2004) concluded that the east Pilbara terrane had been subjected to gravity-driven diapiric doming at 3315 Ma, and that the west Pilbara, which exhibits four granitoid complexes formed between 3015 and 2970 Ma, has no diapiric domes. All the deformation in this latter region is attributed to successive episodes of horizontal compression (Hickman and Van Kranendonk, 2004; Sandiford and others, 2004; Van Kranendonk and others, 2004).

In the southwestern Barberton region, Moyen and others (2006) reported metamorphic evidence of subduction-driven tectonic processes reflecting the collision of an older (*ca.* 3445 Ma) Stolzburg gneiss terrane (Stolzburg Pluton) with a younger (*ca.* 3200 Ma) Badplaas terrane (Badplaas Pluton). The older Stolzburg gneiss terrane and associated TTG plutons and infolded septae shown in figure 2 have also been likened to an exhumed core complex of high-grade metamorphic basement rocks (Kisters and others, 2003). This model invokes a continuum of early core-complex formation (pre-3400 Ma) followed by D_2 NW-thrusting and crustal thickening at *ca.* 3230 to 3225 Ma (De Ronde and De Wit, 1994). Core-complex buoyancy occurred relative to the denser overlying supracrustal sequence comprising mainly mafic and ultramafic rocks. A similar exhumed core complex (Steynsdorp core complex) has recently been proposed for the region southeast of the Theespruit Pluton, where Lana and others (2010a) envisaged a further extension of the early crust-forming TTG plutonism at *ca.* 3450 Ma.

Processes of exhumation, according to Marshak and co-workers (1992, 1999), can initiate solid-state diapirism and density inversions, thereby producing basement culminations that are manifest as dome-and-keel patterns in Archean granite-greenstone provinces. Hickman and Van Kranendonk (2004) outlined the characteristic features of diapirs, core complexes and cross-folds and convincingly demonstrated, in the East Pilbara granite-greenstone terrane of Western Australia, that diapiric processes are essentially gravitational responses to the development of an inverted density profile in the upper crust. They further emphasized that diapiric domes are cored by buoyant granitoids as opposed to core complex domes, which are cored by deformed metamorphosed sialic basement of various protoliths of various ages (with prior crustal thickening being due to thrust accretionary assemblages). Support for the exhumation of the Barberton TTG dome-and-keel structures during vertical tectonic movements was presented by Van Kranendonk and others (2009).

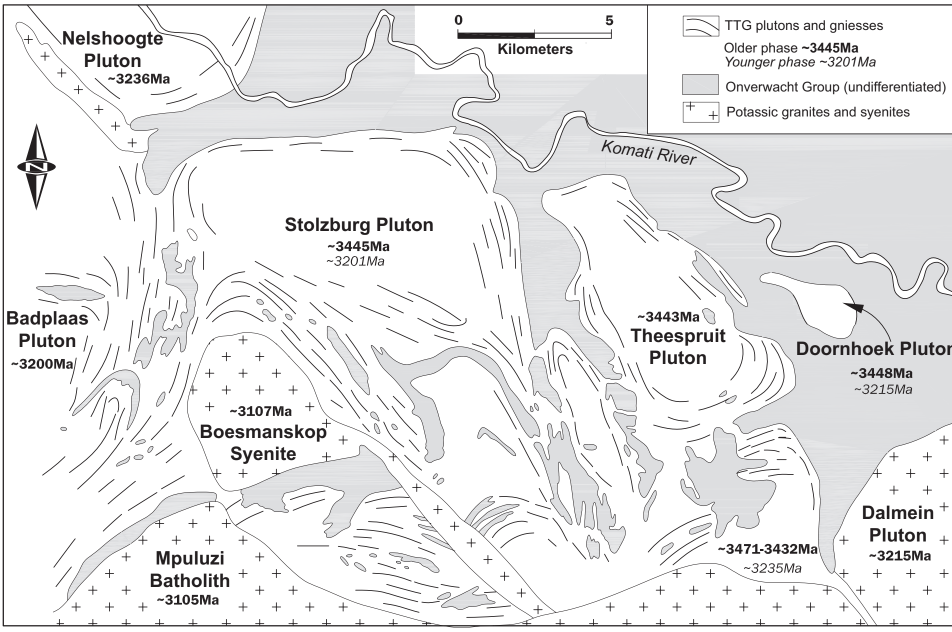

Fig. 2. Map of the granitoid-greenstone terrane in the Komati River valley south of the Barberton greenstone belt, showing the location of the Theespruit Pluton relative to other trondhjemitic gneiss plutons in the region. The zircon crystallization ages of the plutons are shown in bold type and metamorphic titanite ages are italicized.

This paper contributes to the ongoing debate by examining the nature and emplacement style of the Theespruit Pluton (one of a cluster of more than 12 diapiric plutons or granitoid domes flanking the Barberton greenstone belt) that intruded into the lowermost formations of the Barberton greenstone belt in the Komati River valley east of Badplaas (figs. 1 and 2). Also in this region the term "granitoid cell" was introduced by Robb and Anhaeusser (1983) to accommodate a number of intrusive trondhjemite bodies that did not present in the field as identifiable elliptical plutons surrounded by greenstone selvedges like those shown in figure 2. Instead these so-called "cells" were recognized principally in terms of their distinctive geochemical characteristics (Sr content being one), leading to the conclusion that the well-defined plutons incorporate more than single magmatic pulses. Geochronological studies subsequently showed that more than a single age has emerged from many of the plutons dated, confirming that they are manifest as multiple-intrusive bodies comprising at least three tectono-magmatic age groups (*ca.* 3545-3490 Ma; 3490-3420 Ma; and 3255-3225 Ma; Poujol and others, 2003). An alternative explanation suggests that the TTG plutons, depicted in figure 2, may represent a folded trondhjemite sheeted-sill complex deformed into dome-and-keel structures at *ca.* 3240 Ma (Van Kranendonk and others, 2009).

The Theespruit Pluton is the best-exposed granitoid body in the region and exhibits features that suggest it is perhaps unique among the Barberton TTG intrusions. Evidence is presented in this paper highlighting the main characteristics of the pluton and its distinguishing features. It is conceivable, however, that this apparent uniqueness may merely be an artifact of its preservation state and degree of exposure relative to the other plutons in the region.

Regional Geology

The Komati River valley, extending east-southeast of Badplaas for over 60 km (fig. 1), is noted for exceptional exposures of a variety of granitoid rocks which have intruded and dismembered the equally well-exposed volcano-sedimentary components of the lowermost portion (Tjakastad Subgroup, fig. 1) of the Onverwacht Group of the Barberton greenstone belt. The dominant rock types in the approximately 7.5 km-thick, subvertically dipping, northward-younging, Tjakastad sequence include komatiites, komatiitic basalts and felsic volcanic rocks (Viljoen and Viljoen, 1969c; Brandl and others, 2006). The structurally lowermost succession comprises the *ca.* 2135 m-thick Sandspruit Formation, which has not been dated, but consists of amphibolite-facies mafic-ultramafic schists and minor metasedimentary rocks containing detrital zircons ranging in age between *ca.* 3540 and 3521 Ma (Dziggel and others, 2002). A minimum age of 3411 ± 11 Ma is indicated by trondhjemitic gneisses that intrude the Sandspruit rocks. The *ca.* 1890 m-thick Theespruit Formation overlies the Sandspruit Formation, apparently conformably, and is again dominated by amphibolite-facies mafic-ultramafic komatiitic rocks, but is distinguished by a number of metamorphosed felsic lava and tuff interlayers near the top of the succession, at greenschist facies. Recent geochronology (evaporation, SHRIMP II, TIMS, carried out on zircons, and Nd isotopic systematics) yielded an age of *ca.* 3530 Ma for these rocks (Van Kranendonk and others, 2009). The Sandspruit and Theespruit formations are separated from the overlying greenschist-facies, *ca.* 3500 m-thick, Komati Formation, by a broad (600-800 m-wide) ductile extensional shear zone (Komati Schist Zone—fig. 1; De Wit and others, 1983; Kisters and others, 2003; Van Kranendonk and others, 2009). Komatiites and komatiitic basalts make up the bulk of the Komati Formation, which has been dated at between 3490 Ma ($^{40}Ar/^{39}Ar$ ages, Lopez-Martinez and others, 1992) and 3481 Ma (zircon age of Komati Formation tuff, Dann, 2000) and is cut by *ca.* 3470 Ma porphyritic tonalite sills (Kamo and Davis, 1994). These rocks are conformably overlain by younger ultramafic, mafic and felsic volcanic rocks to 3300 Ma (Hooggenoeg, Kromberg and Mendon formations of the Geluk Subgroup) and dominantly sedimentary rocks of the Fig Tree and Moodies Groups, to 3230 Ma (Lowe and Byerly, 1999; Brandl and others, 2006).

TTG plutons were emplaced into the greenstone formations outlined above, as shown diagrammatically in figures 1 and 2. Viljoen and Viljoen (1969a) maintained that the ovoid Theespruit granitoid dome, together with others in the area, occupy the core of the steeply northeast-plunging, asymmetrical, Onverwacht Anticline in the southern part of the Barberton greenstone belt (fig. 1). It is, however, difficult to rationalize the northwest orientation of the Theespruit dome with the northeast plunge of the Onverwacht Anticline, and it is possible that the two are not coeval as these authors may have implied. Instead, as pointed out by Van Kranendonk and others (2009), there may have been an early period of doming prior to the *ca.* 3230 Ma dome-and-keel development as seen today in the area southwest of the Barberton greenstone belt.

Available dating suggests that the TTG plutons in the gneiss terrane east of the 3290 to 3240 Ma Badplaas Pluton, described by Kisters and others (2006), are of approximately the same age (in the range *ca.* 3460-3443 Ma), and coincide with the earlier-mentioned exhumed core complex postulated by Kisters and others (2003).

The Theespruit Pluton, the main topic of this paper, is an oval-shaped, NW-SE orientated body with a long axis measuring 11.5 km and an average width of approximately 4.5 km (fig. 3). It is intruded into undated metavolcanic (predominantly Sandspruit Formation?) rocks in the southwest and south, and *ca.* 3530 Ma Theespruit Formation rocks in the northwest, north, northeast and east (Van

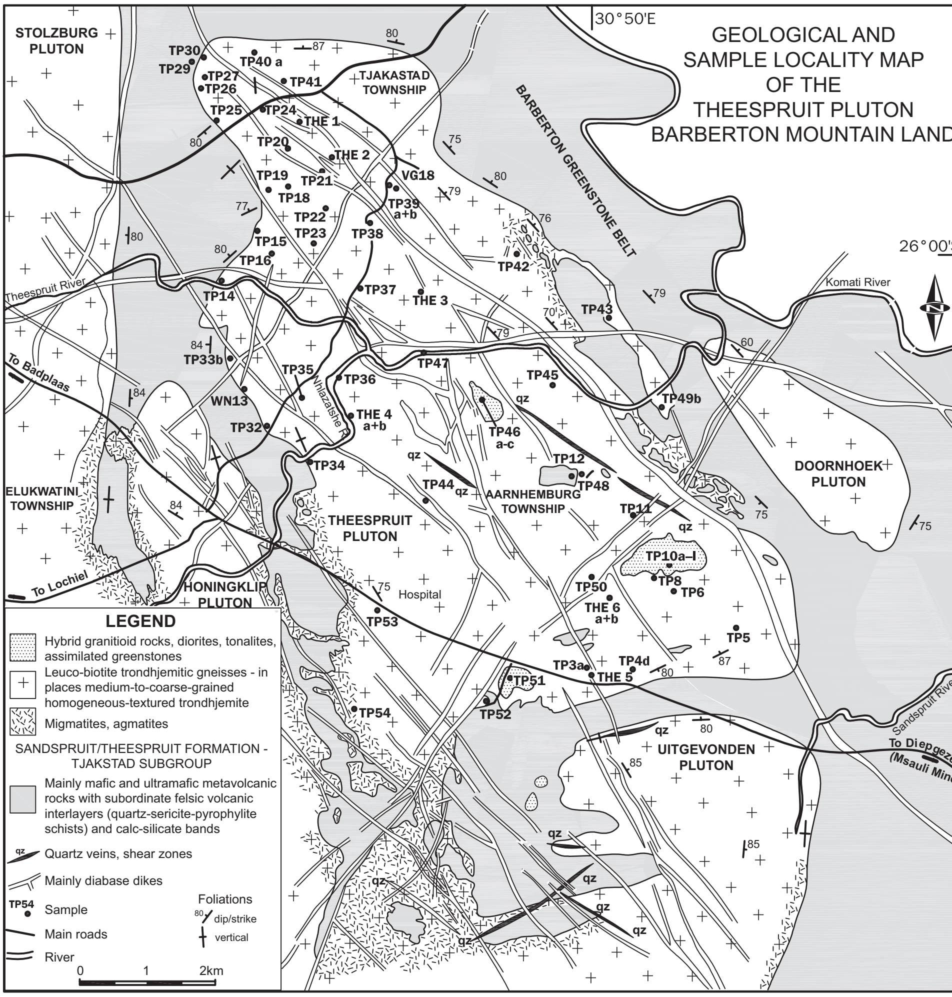

Fig. 3. Geological and sample locality map of the Theespruit Pluton and surrounding areas. The pluton intrudes mafic and ultramafic rocks of the Sandspruit and Theespruit formations (lower Onverwacht Group) and is cut by numerous, predominantly NW-trending, diabase dikes of presumed Proterozoic age (map modified after Anhaeusser, 1981).

Kranendonk and others, 2009). The pluton is also surrounded regionally by other TTG intrusions including the Honingklip and Stolzburg plutons in the west, the Uitgevonden Pluton in the south and the Doornhoek Pluton in the east. The Stolzburg Pluton exhibits an older phase dated at *ca.* 3460 Ma (Kröner and others, 1991; Kamo and Davis, 1994) and a younger phase *ca.* 3201 Ma old (Kamo and Davis, 1994). The Doornhoek Pluton yielded an older single zircon age of *ca.* 3448 Ma and a younger titanite U-Pb age of *ca.* 3215 Ma (Kamo and Davis, 1994). The Honingklip and Uitgevonden plutons, located southeast and south of the Theespruit Pluton, respectively, have not been dated, but the Southern Theespruit gneiss (south of the Uitgevonden Pluton), showed two distinct zircon populations, the older group ranging in age between *ca.* 3471 and 3432 Ma and the younger group yielding an age of *ca.* 3235 Ma (Lana and others, 2010b). Geochronological investigations have thus confirmed that the Komati River valley gneissic terrane, in the area surrounding and including the Theespruit Pluton, consists essentially of two TTG magmatic episodes that occurred approximately 200 Ma apart (namely, an early >3400 Ma event and a later *ca.* 3200 Ma event).

The Theespruit Pluton, dated using a variety of techniques, gave single-zircon U-Pb ages varying only slightly between 3443 and 3437 Ma. These included an U-Pb ID-TIMS age of $3443 + 4/-3$ Ma (Kamo and Davis, 1994), Pb-Pb zircon evaporation ages of 3441 ± 3 and 3437 ± 5 Ma (Kröner and others, 1991, 1992), and an U-Pb SHRIMP age of 3437 ± 6 Ma (Armstrong and others, 1990). No younger Theespruit age was reported by these authors, but as will be shown later, there are cross-cutting granitoid dikes that likely reflect intrusive activity possibly coincident with the *ca.* 3200 Ma phases recorded in both the Stolzburg and Doornhoek plutons and the D_2 compressional tectonic event outlined by De Ronde and De Wit (1994) and Kamo and Davis (1994).

Theespruit Pluton

Field Relationships

The TTG plutons surrounding the Barberton greenstone belt are generally ovoid in shape, vary considerably in size from a few hundred meters to 30 km in diameter, display concordant contacts with the surrounding supracrustal successions, are invariably concentrically foliated, particularly near the pluton margins, and contain xenoliths aligned parallel to the foliation of the gneisses. The plutons and their contained xenoliths commonly display subvertical prolate stretching lineations that are also present in the adjacent greenstones, the latter metamorphosed to amphibolite or upper-greenschist facies schists. Mafic, ultramafic and felsic lavas and tuffs are transformed into a variety of schists, and flattening and extension of features such as pillows, amygdales, spherulites, agglomerate and tuff fragments and clasts is commonplace.

By contrast, the Theespruit Pluton, which is exceptionally well exposed (fig. 4), exhibits a number of features not seen elsewhere in the Barberton granitic terrane, making this intrusion unique with respect to the physical relationships within the pluton itself and with the surrounding country rocks. These features are best illustrated in the accompanying photographs.

The first distinguishing aspect concerns the transgressive nature of the pluton with respect to the adjacent metavolcanic supracrustal sequences. This is particularly evident in the west, northwest and northern parts of the intrusion (Kisters and Anhaeusser, 1995a) where the granitoid rocks embay into lithologies of the Theespruit Formation. This relationship is illustrated in figure 5 (after Diener, ms, 2004; Diener and others, 2005) where the successions on the east side of the Tjakastad schist belt, which separates the Stolzburg and Theespruit plutons (fig. 3), are discordantly truncated by Theespruit trondhjemite. A similar relationship was demonstrated by Viljoen and Viljoen (1969a, 1969c) for the northern sector of the pluton in the vicinity of Tjakastad Township (fig. 3) where northwest-striking komatiites, komatiitic basalts and felsic volcanic rocks of the Theespruit Formation are truncated by an obliquely transgressive contact with the granitoid rocks.

Of particular note is the homogeneous, weakly foliated to undeformed nature of the trondhjemites in areas where the contacts are discordant. The granitic rocks in these areas display cumulate-like textures with equant plagioclase feldspar crystals (fig. 6A). On the northeast and southern contacts the trondhjemites show conformable gneissic fabrics with subvertical foliations and lineations, as well as xenoliths and schlieren aligned parallel to the foliation (figs. 6B and 6C). In the northeast,

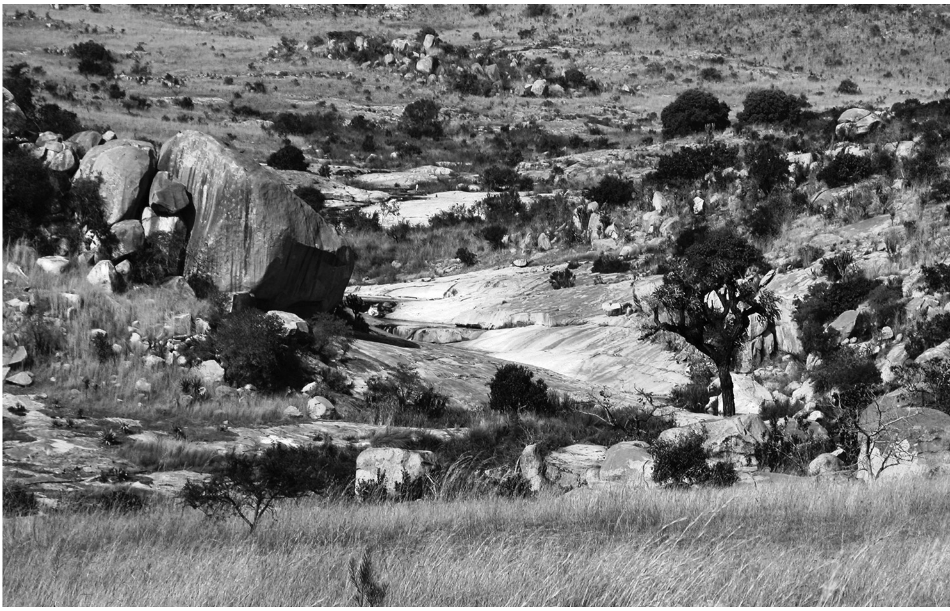

Fig. 4. Trondhjemitic gneiss exposures in and adjacent to the Nhlazatshe River in the central part of the Theespruit Pluton, north of Elukwatini Township (near sample site TP 36, fig. 3).

between the Theespruit and Doornhoek plutons, large rafts of amphibolite have been prized off the adjacent Theespruit Formation (fig. 3). In this sector, migmatites and banded gneisses are developed locally (fig. 6D) and several granitoid phases resembling sheeted sills, as well as multiple vein sets, are displayed on outcropping platforms (figs. 6E and 6F).

On the southwestern side of the pluton in the Nhlazatshe River section between the Theespruit and Honingklip plutons (sample site TP34, fig. 3), granitic rocks abut against black hornblende-garnet amphibolites of the Sandspruit Formation. A spectacular set of anastomosing trondhjemite dikes invade the amphibolites at this locality causing their brittle fragmentation and the development of agmatite breccias (figs. 7A-D). Some fragments prized off the amphibolites occur as mafic schlieren aligned parallel to the intrusive granitoid dikes (fig. 7E), while others occur as mafic schlieren in the foliated trondhjemites only meters from the pluton-greenstone contact (fig. 7F). Additional granite-greenstone relationships are displayed in the river section upstream of site TP34, some examples of which are shown in figure 8. Linear and folded lit-par-lit sheets of trondhjemite injected into amphibolite schistosity planes are shown in figures 8A and 8B. Flattened, stretched and dismembered granitoid veins, occurring as boudinage structures, are common (figs. 8 C-E) and garnets (like those shown in fig. 8F from near sample site TP52) are exposed locally in the amphibolites along the Nhlazatshe River.

Metavolcanic rocks occurring at TTG-greenstone contacts invariably possess strongly schistose textures. This relationship can be seen along the southern contact of the Theespruit Pluton where amphibolite schists occur in a flattened greenstone sliver wedged between the Theespruit and Uitgevonden plutons (fig. 3). However, on the western margin of the pluton, the contact is remarkably different, with well-formed bulbous to slightly flattened pillow structures abutting mildly foliated trondhjemite

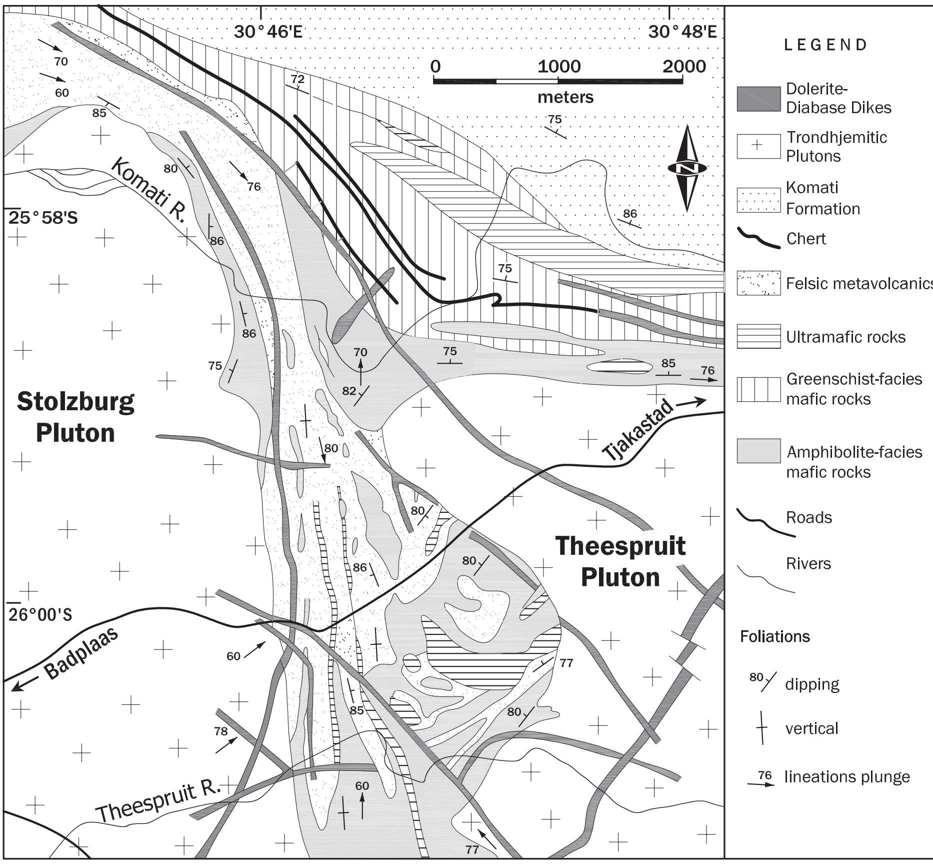

Fig. 5. Geological map of the Tjakastad schist belt wedged between the Stolzburg and Theespruit plutons. The northwest lobe of the Theespruit Pluton displays transgressive relationships with rocks of the Theespruit Formation (map after Diener, ms, 2004).

gneiss. Figure 9A shows this relationship at the Nhlazatshe River section described earlier where intrusive granitoid dikes and agmatites are also present. The amphibolite facies pillow structures, which young to the north, display vesicles and chilled margins that permit recognition of pillow shapes even in exposures affected by agmatite brecciation (figs. 7B, 10E). The manner in which slivers of amphibolite have been prized off the greenstone contact are shown in figure 9A. These slivers survive as flattened amphibolite schlieren aligned parallel to the foliated gneiss (fig. 7F) or as larger xenoliths (fig. 10A).

The Theespruit Pluton contains predominantly amphibolite xenoliths, which are aligned parallel to the foliation in the trondhjemite gneisses and display strong vertical stretching lineations like those in the Tjakastad schist belt (fig. 10F). Whilst some xenoliths might conceivably represent cognate remnants of the trondhjemite protolith, available evidence points to them having being derived directly from neighboring Onverwacht volcanic successions as, in some cases, pillow structures are recognizable even in relatively small remnants (figs. 10A and 10B). Some mafic xenoliths show cuspate margins (figs. 10A-C), indicative of rheology differences during post-emplacement folding. Banded chert xenoliths (fig. 10D), occur in the southern sector

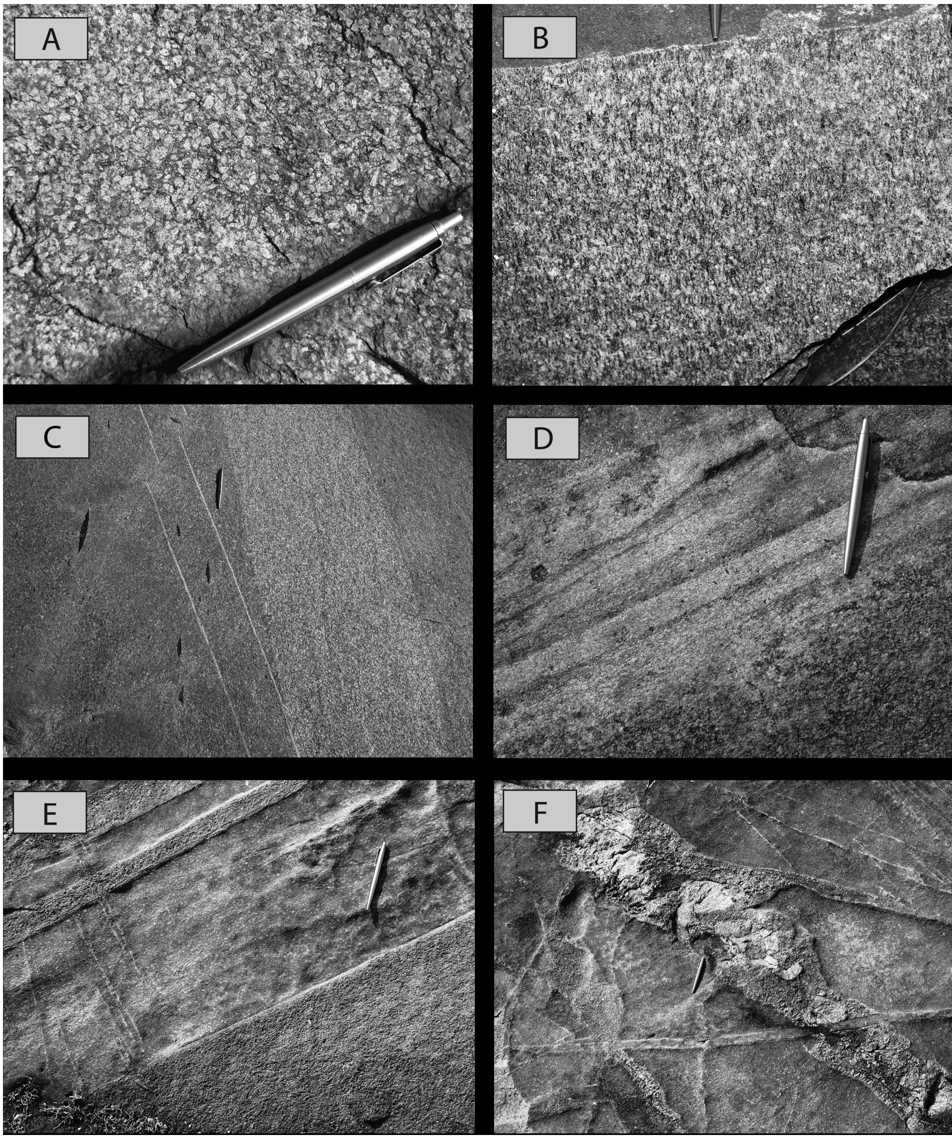

Fig. 6. Granitoid rocks of the Theespruit Pluton (see fig. 3 for localities). (A) Homogeneous, cumulate-textured trondhjemite exposed near sample site TP25, northwest sector of pluton. (B) Foliated biotite-trondhjemite gneiss at site TP3, southeast sector. (C) Two phases of foliated trondjhemitic gneiss and aligned mafic schlieren near site TP42, northeast sector. (D) Banded trondhjemitic gneiss near site TP42. (E) Two phases of trondhjemite, one coarse-grained and foliated, the other with a weakly foliated cumulate texture near site TP42. (F) Rare, coarse-grained, pegmatite dike intruding trondhjemite near site TP42. The pegmatite dike is cut by a later granitoid phase. Pen for scale.

of the pluton northeast and southwest of sample site TP4d (fig. 3) and were probably derived from a chert layer mapped in the greenstone sequence to the south, wedged between the Theespruit and Uitgevonden plutons. Chert remnants are rare, unlike their more refractory amphibolite counterparts.

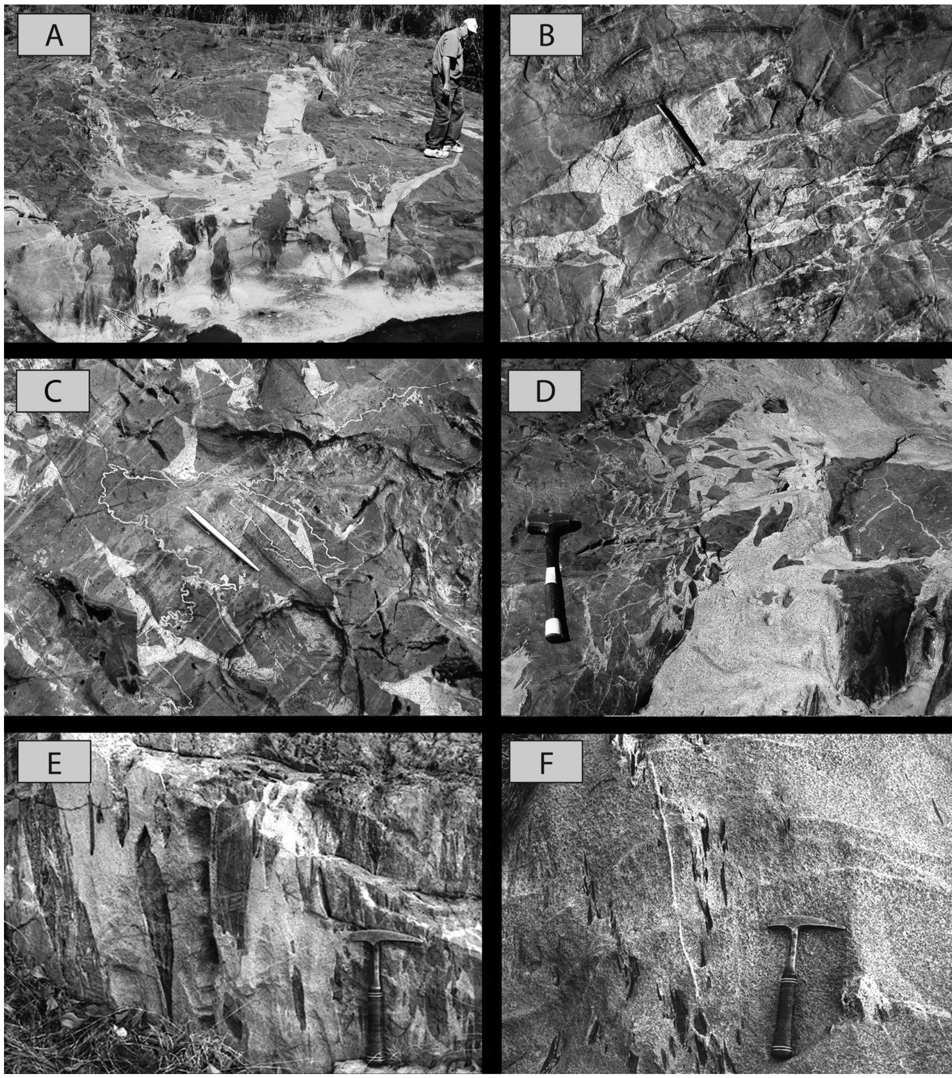

Fig. 7. Granitoid-greenstone relationships at site TP34 adjacent to the Nhlazatshe River (fig. 3). (A) Trondhjemite dikes intruded into and brecciating Sandspruit Formation amphibolite-facies pillow basalts near the Theespruit Pluton contact. (B) Agmatite breccia in pillow lavas (note chill margins above pen). (C) Ptygmatic folds (veins close to pen) in amphibolite. (D) Agmatite brecciation of amphibolite and invasion by trondhjemite dike. (E) Amphibolite schlieren in granitoid dike near Theespruit Pluton contact. (F) Amphibolite schlieren aligned parallel to foliated trondhjemitic gneiss and pluton-greenstone contact. Pen and hammer for scale.

ROOF PENDANTS AND ASSIMILATED OR HYBRIDIZED REMNANTS

A number of relatively large amphibolite xenoliths occur in the central and southeastern sectors of the pluton. The largest of these remnants, situated north of Aarnhemburg Township, is several hundred square meters in extent (fig. 3). Tonalitic granitoid rocks occur in sharp contact with the xenolith on its southern side (fig. 9B) and veins and dikes of tonalitic-trondhjemitic rocks intrude the amphibolitic

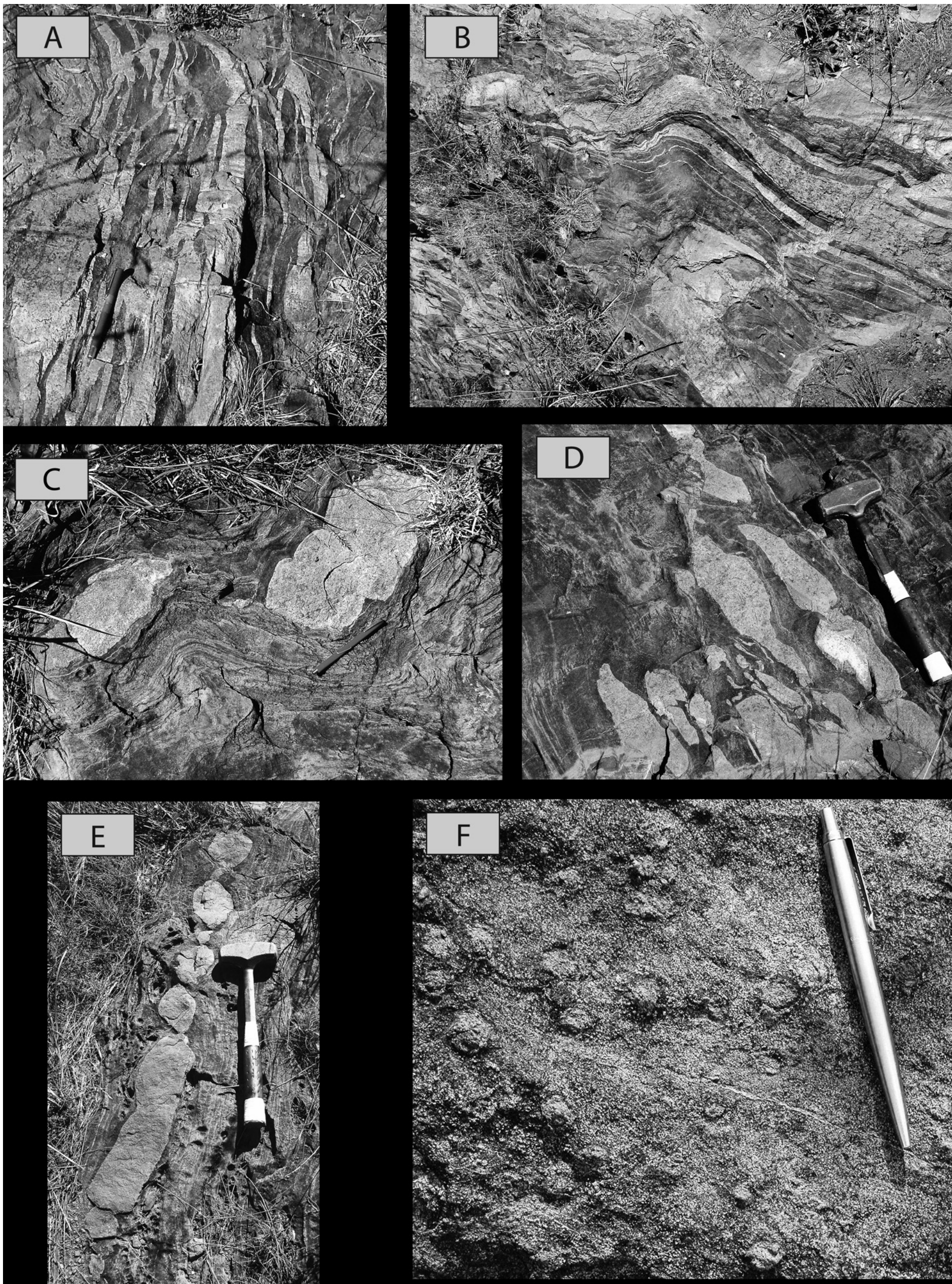

Fig. 8. (A) *Lit-par-lit* veins of trondhjemite intruded into amphibolites of the Sandspruit Formation on the western flank of the Theespruit Pluton near the Nhlazatshe River (fig. 3). (B) Folded layers of amphibolite and trondhjemite at same locality as (A). (C), (D), (E). Boudinaged veins of trondhjemite in Sandspruit Formation amphibolite (as at locality A). (F). Garnets in Sandspruit Formation amphibolite near Theespruit Pluton contact at site TP52. Pen and hammer for scale.

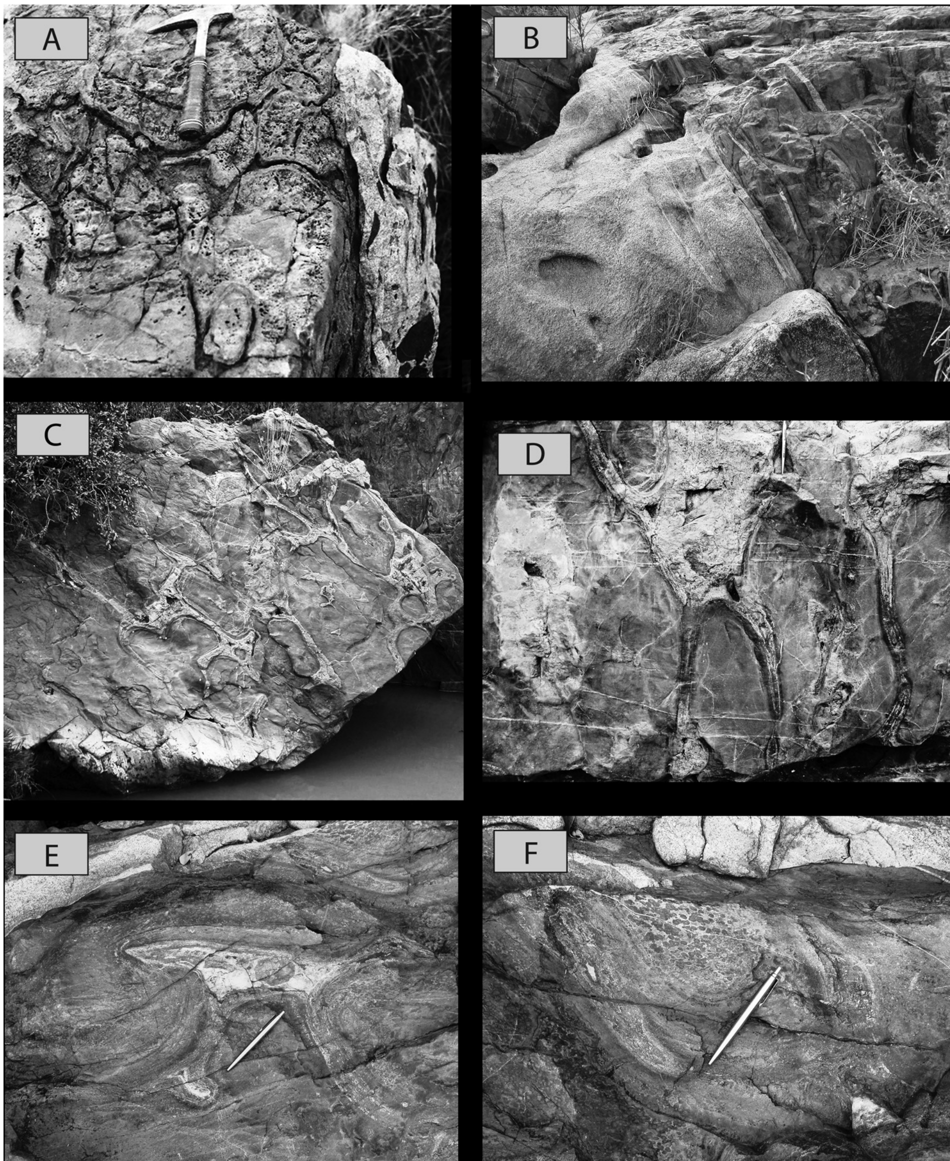

Fig. 9. (A) Theespruit Pluton contact with relatively undeformed Sandspruit Formation pillow lavas at site TP34 (fig. 3) adjacent to the Nhlazatshe River. Note the amphibolite schlieren aligned parallel to the granitoid contact. (B) Sharp contact of tonalitic gneiss and amphibolite xenolith roof pendant at site TP48 (east-central sector of Theespruit Pluton). (C) Bulbous, amphibolite-facies pillow structures showing triple junctions filled with metahyaloclastite and quartz in amphibolite xenolith roof pendant at site TP48. (D) Close-up of pillow structures with chilled margins, metahyaloclastite- and quartz-filled triple junctions and lava drainage cavities. (E) Pillow lava cut by trondhjemite dike and showing quartz-filled triple junction and chilled re-entrant pillow crusts. (F) Trondhjemite dike intruded into amphibolite pillow lavas displaying spherulitic or ocelli immiscibility structures. Pen and hammer for scale.

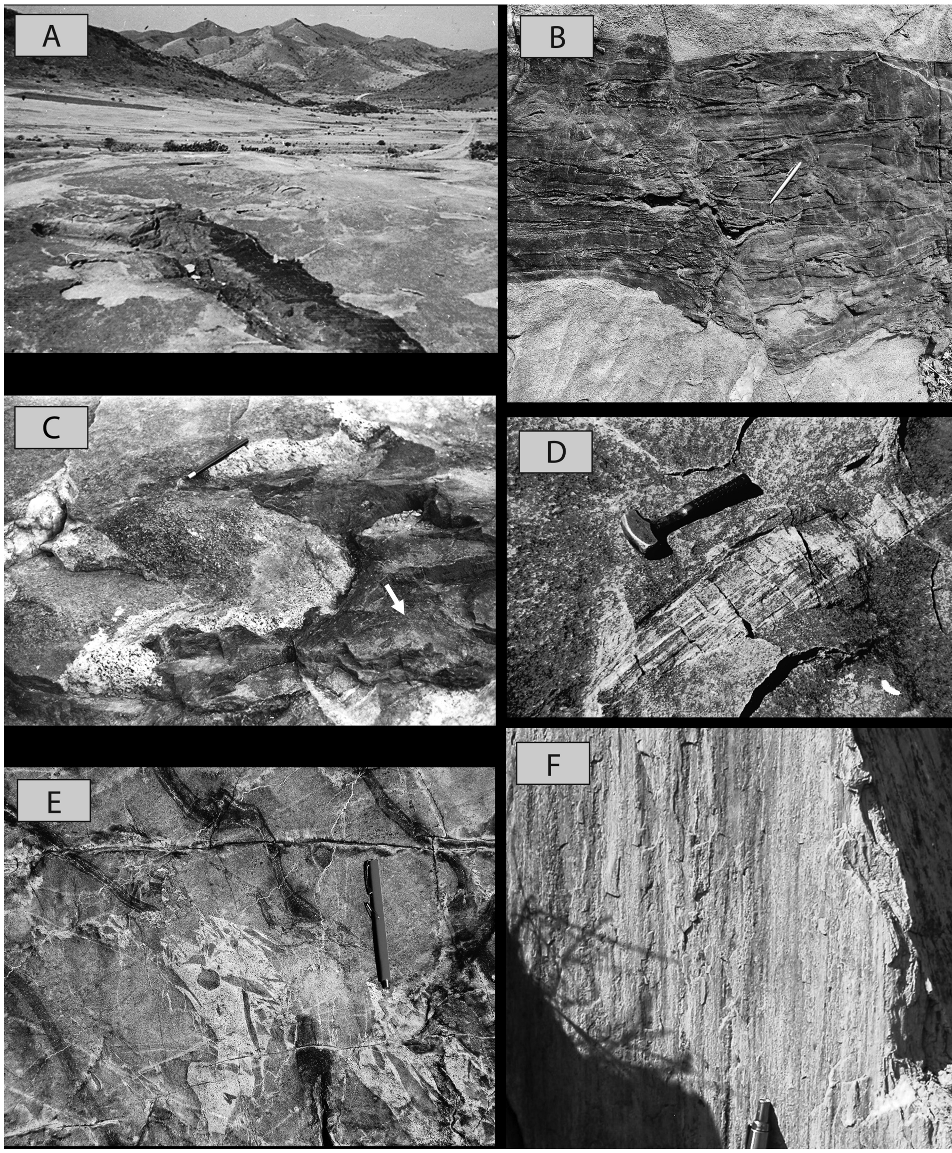

Fig. 10. (A) Amphibolite xenolith orientated parallel to foliated trondhjemite gneiss, southeastern sector of Theespruit Pluton near site TP4d (fig. 3). In the background is the Kromberg Syncline comprised of upper Onverwacht volcanic and sedimentary rocks of the Kromberg Formation. (B) Close-up of amphibolite xenolith (A) showing flattened pillow structures. (C) Amphibolite xenolith with cusp-like features in subvertically foliated trondhjemite gneiss near site THE5 (arrow points to the steeply NE-plunging stretching lineations). (D) Xenolith of rare banded recrystallized chert aligned parallel to foliated trondhjemitic gneiss near (C). (E) Agmatite breccia in amphibolite displaying chilled pillow margins near site TP34. (F) Foliated and lineated quartz-sericite schist in the Tjakastad schist belt between the Stolzburg and Theespruit plutons (fig. 3). Pen and hammer for scale.

metabasalts locally producing agmatites. Spectacular undeformed pillow structures showing chilled margins, interpillow metahyaloclastite, re-entrant features, tri-cuspate pillow intersections, quartz- and carbonate-filled drainage cavities, and spherulitic structures are displayed in the stream section (figs. 9 C-F). The absence of flattening features supports the view that the remnant represents a roof pendant in the crestal part of the pluton where minimal finite strain occurred during emplacement (see also Van Kranendonk and others, 2009).

Locally, some of the roof pendants have been altered and assimilated by granitic magma and hydrothermal fluids migrating through the mafic rocks. This has produced a wide range of hybrid rocks, predominantly of tonalitic to dioritic composition, similar to the products of metamorphism, assimilation and metasomatism reported from the Archean Johannesburg Dome some 300 km to the west (Anhaeusser, 1999).

The largest development of hybrid rocks occurs in the southeastern sector of the Theespruit Pluton (sample site TP10, fig. 3). At this locality, trondhjemites displaying cumulate textures, like those described earlier, envelop and intrude a greenstone xenolith several hundred square meters in extent producing a range of textures and hybridized rocks like those shown in figures 11A–F. Interpretation of the exposures suggests that the mafic xenolith was initially brecciated in a manner similar to the agmatite occurrences described earlier. However, the alteration processes were able to continue as a result of additional magmatic fluids being available at this locality, which infiltrated and metasomatized the breccias. Other mafic fragments showing differing degrees of assimilation and replacement by invading hydrothermal fluids as well as large patches of tonalite-diorite-gabbro, occur at a number of other sites in the pluton (fig. 3). The invading fluids invariably caused sodium metasomatism and resulted in plagioclase megacryst development in the mafic rocks (figs. 11 B, C, E, F).

TTG CHARACTERISTICS

Trondhjemite and Tonalite Mineralogy

The granitoid rocks of the Theespruit Pluton are uniform mineralogically, despite the textural variations encountered locally. Trondjhemite contains roughly equal proportions of quartz and plagioclase (variably sericitized albite-oligoclase), together with biotite locally altered to secondary chlorite. Minor microcline, and accessory amounts of zircon, titanite, apatite, iron and titanium oxides (magnetite-ilmenite), epidote, allanite and leucoxene occur variably throughout the pluton. Hornblende is mainly encountered near assimilated amphibolite xenoliths and in tonalitic phases, but is rare in the trondhjemite.

Trondhjemite and Tonalite Geochemistry

The TTG rocks in the Barberton region have been shown by Yearron (ms, 2003) and Moyen and others (2007b) to be low- to medium-K, metalumious I-type granitoids belonging to a calc-alkaline series (as defined by Chappell and White, 1974; La Bas and others, 1986; Le Maître, 2002). They differ from modern arc-related I-type granitoids in that two distinctive rock types are present, namely leucocratic biotite trondhjemites and hornblende tonalites. These are also temporally and spatially distinct, with the older trondhjemites (*ca.* 3450 Ma) occurring in the east of the region and younger tonalites and trondhjemites (*ca.* 3200 Ma) occurring side by side in separate intrusions in the west (Anhaeusser and Robb, 1981; Anhaeusser and others, 1983; Robb and others, 2006).

A number of regional geochemical studies of granitoid rocks in the Barberton region were undertaken with a view, initially, to characterize the rocks and, subsequently, to probe petrogenetic aspects of the various granitoid events in the region. Geochemical studies by Viljoen and Viljoen (1969a, 1969b) were followed by more detailed geochemical investigations (Glikson, 1976; Anhaeusser and Robb, 1980, 1983b; Robb, 1981a; Robb and Anhaeusser, 1983) leading to a regional geochemical database with numerous analyses of granitoid rocks (Anhaeusser and Robb, 1983a).

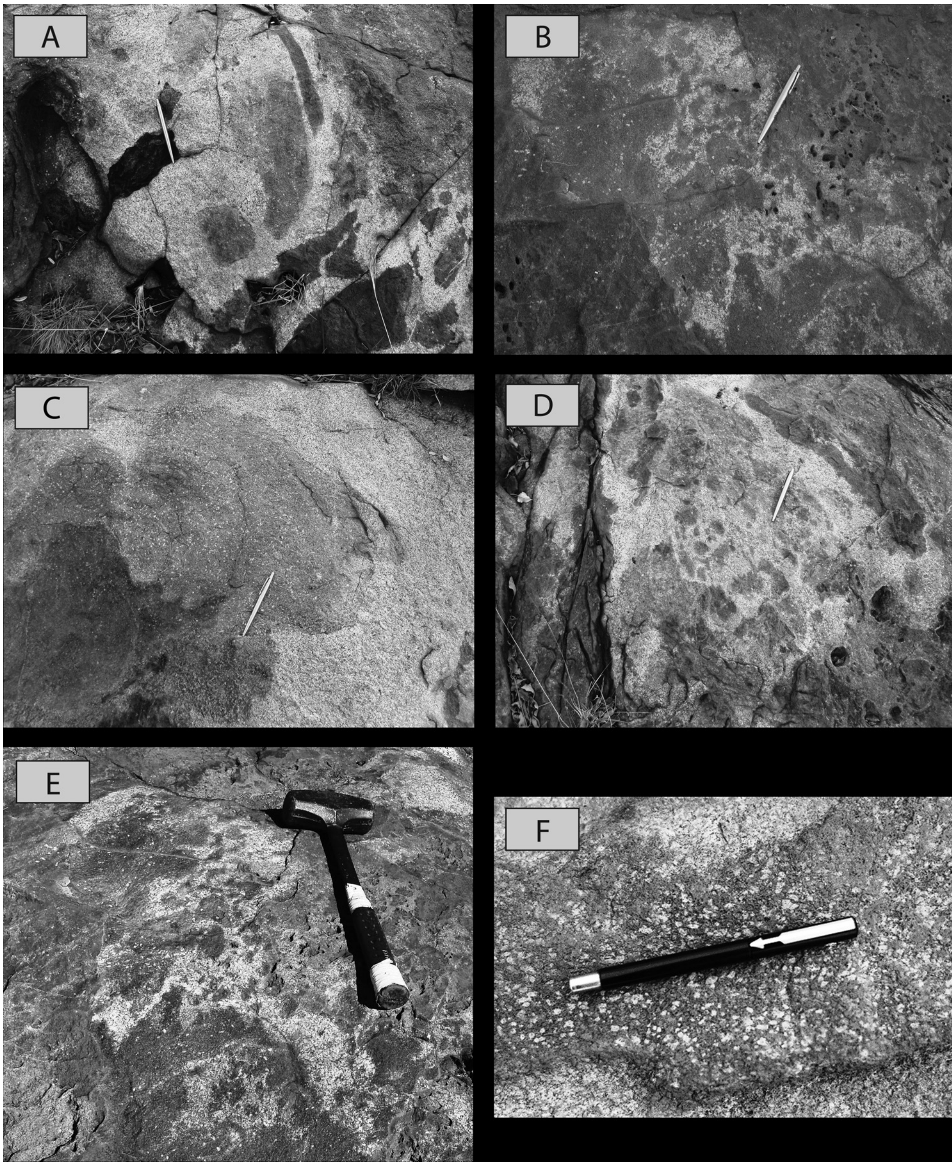

Fig. 11. Hybridized or assimilated greenstone xenoliths at sample site TP10 (southeast sector of Theespruit Pluton). (A) Trondhjemite magma intruded into amphibolite resulting in fragmented remnants showing variable stages of transformation. (B) Assimilated mafic fragments in a hybridized dioritic matrix. (C) Mafic remnants altered to tonalitic-to-dioritic nebulites or granitized skialiths. (D) Patchy fragmentation and assimilation of greenstone xenolith. (E) and (F) hybridized mafic remnants showing equant plagioclase porphyroblast or xenocryst growth resulting from Na-metasomatism associated with the intrusion of trondhjemite magma. Pen and hammer for scale.

The granitoid bodies in the southwest Barberton granitoid terrane reveal recognizable geochemical variations between the plutons, which have been explained in terms of small differences in the degree of partial melting required for their derivation. Robb and Anhaeusser (1983) found the most significant differences in the compositions of the TTGs lay in their Sr contents, the latter being SiO_2 independent. These authors employed the Sr values to fingerprint plutons and granitic "cells" that were not previously recognized, or which were not outlined by enveloping greenstone septae.

REE variations likewise suggested a melt origin at different crustal levels and it was further proposed that the origin of the TTG magmas was not so much linked to compositions in the parental material, but rather a response to differences in P, T, P_{H2O}, and/or crustal depth of specific source regions, with some magmas formed by partial melting under amphibolite facies conditions and others under granulite facies conditions (Robb and Anhaeusser, 1983).

The Theespruit Pluton initially received only cursory geochemical attention and was sparsely sampled with only single analyses (VG18, Viljoen and Viljoen, 1969b; 106, Glikson, 1976) used to classify the pluton into the TTG granitoid series. Subsequent detailed mapping and widespread sampling carried out by the writer, led to over 60 analyses of granitoid rocks, mafic xenoliths and hybrid rocks (TP and WN samples, fig. 3) being added to the database (Anhaeusser and Robb, 1983a). Supplementary studies by Yearron (ms, 2003) contributed an additional 6 new analyses (THE samples). Recent geochemical studies, embracing existing data, and new data acquired using modern analytical techniques, were undertaken by Yearron (ms, 2003) and Moyen and others (2007b). Their work detailing the Barberton TTG geochemistry and petrogenesis is regionally comprehensive and should be consulted for additional information. Magnetic susceptibility studies were also carried out on representative Barberton granitoid rocks, including Theespruit samples. These were found to have low magnetic susceptibilities corresponding to ilmenite-series granitoids reflecting a reducing environment in the granitic source (Ishihara and others, 2002), believed to be lower-crust amphibolites.

In the present study, an attempt was made to determine any discernable variations in the major element geochemistry in different sectors of the Theespruit Pluton. Data from the geochemical database were used to construct major element sector averages (columns 1-3, table 1). These averages can be compared (columns 4 and 5, table 1) with the average composition of the pluton as a whole and the average value determined from analyses by Yearron (ms, 2003). In general the composition of the pluton is relatively homogeneous, the only variations being noted in a few localities where some contamination with country rocks and xenoliths has produced tonalites (quartz-plagioclase-biotite ± hornblende rocks), which have lower SiO_2 and higher TiO_2, Fe_2O_3, MgO and CaO than the predominant trondhjemites (table 2). Barker and Arth (1976) and Barker (1979) provided definitions of trondhjemite and described two suites resulting from differentiation and partial melting, namely, low-Al_2O_3 and high-Al_2O_3 types separated at 15 percent Al_2O_3 and 70 percent SiO_2, respectively. Table 2 shows the Theespruit TTG rocks include both low- and high-Al tonalites, low-to-high Si and Al trondhjemites, and some rare examples of granitoids that fall in the range of low-to-high Si leucogranite or granodiorite. Robb and Anhaeusser (1983) and Moyen and others (2007b) further identified several sub-series of TTGs in the Barberton region on the basis of their distinct geochemical signatures, most notably their Sr contents and their K_2O/Na_2O nature. SiO_2 versus Sr plots showed that the high-Sr sub-series is somewhat more sodium-rich (trondhjemitic) than the low-Sr series (tonalitic). The Al and Sr relationships suggested variations in differentiation and partial melting of the Theespruit source rocks, believed to be amphibolites melted at different crustal depths (Robb and Anhaeusser, 1983; Yearron, ms, 2003; Moyen and others, 2007b), the magma later coalescing to form the pluton which crystallized at *ca.* 3440 Ma.

The concepts of fractional crystallization and processes of segregation of melt and solid during crystallization have not generally been widely applied to deep-seated magmatic granitic rocks. Furthermore, granitic rocks rarely display gravity-segregated

TABLE 1

Major element sector averages

Column	1	2	3	4	5
Number of Samples	25	6	13	44	6
SiO_2	71.17	71.15	70.92	71.08	71.77
TiO_2	0.29	0.28	0.27	0.28	0.19
Al_2O_3	14.71	15.25	15.16	15.04	15.19
Fe_2O_3	2.38	2.6	2.26	2.41	1.55
MnO	0.04	0.45	0.03	0.17	0.03
MgO	1.21	1.19	1.2	1.2	0.74
CaO	2.36	3.15	2.58	2.7	2.18
Na_2O	5.59	5.55	5.82	5.65	5.29
K_2O	2.12	1.88	1.65	1.88	1.91
P_2O_5	0.12	0.12	0.12	0.12	0.06
LOI	0.65	0.71	0.64	0.67	nd
Totals	100.64	102.33	100.66	101.2	98.91
Trace element averages in sectors					
Number of Samples	23	6	12	41	6
Rb	51	53	39	48	6
Sr	566	518	654	580	480
Ba	322	288	338	312	237

Columns: 1. Northwest sector of pluton—NW of Elukwatini—Tjakastad road; 2. North-central sector—north of xenolith TP48; 3. Southern and southeast sector—south of xenolith TP48; 4. Average of Theespruit Pluton (Anhaeusser and Robb, 1983a); 5. Average of Theespruit data from Yearron (ms, 2003).

cumulus-intercumulus textures, although it is noteworthy in this context that primary igneous layering was recorded by Robb and Anhaeusser (1983) in the Doornhoek Pluton to the east of the Theespruit Pluton. Most granites are therefore assumed to

TABLE 2

Selected analyses of tonalites, trondhjemites, and granodiorites

Column	1	2	3	4	5	6	7	8	9
Sample	TP38	TP47	TP45	TP52	THE4A	TP16	TP4D	TP22	THE4B
SiO_2	65.27	66.52	69.87	69.87	70.34	71.3	73.62	70.54	76.05
TiO_2	0.79	0.31	0.31	0.3	0.25	0.23	0.32	0.39	0
Al_2O_3	13.63	17.12	14.77	15.8	16.04	14.08	15.83	14.23	13.89
Fe_2O_3	4.03	2.7	3.26	2.37	2.01	4.16	2.75	2.41	0.53
MnO	0.08	0.04	0.03	0.02	0.03	0.03	0.04	0.04	0.06
MgO	3.8	1.39	1.22	1.09	1.1	0.82	1.49	1.07	0.03
CaO	3.71	3.22	2.64	2.86	2.85	2.19	3.02	1.35	0.42
Na_2O	4.91	6.11	5.68	5.55	5.74	5.97	0.91	5.34	5.09
K_2O	2.3	1.51	1.71	1.2	1.56	1.74	1.6	4.83	3.9
P_2O_5	0.39	0.13	0.12	0.11	0.08	0.08	0.14	0.14	0.02
LOI	0.6	1.32	0.55	0.87	nd	0.72	0.55	0.51	nd
Totals	99.51	100.37	100.16	100.04	99.6	101.32	100.27	100.9	99.8

Columns: 1–2. Low- and high-Al tonalites; 3–7. Low- to high-Si and Al trondhjemites; 8–9. Low, to high-Si leucogranite/granodiorite.

TP analyses—from Barberton granitoid database (Anhaeusser and Robb, 1983a).

THE analyses—from Yearron (ms, 2003).

Table 3

Rare Earth Element analyses of trondhjemite, basalt and diorite

Column	1	2	3	4	5	6	7	8
Sample	TP12	TP26	TP43	THE4A	THE5	106	TP48	TP51
La	9.15	10.8	19.2	11.69	18.1	13	1.75	19.1
Ce	17.4	19.3	33.8	19.82	30.52	25	4.71	42.6
Pr	1.96	2.19	3.57	nd	nd	2.5	0.68	5.46
Nd	7.97	8.28	13.1	9.95	11.45	7.4	3.43	23.7
Sm	1.6	1.5	2.4	1.6	1.71	1.3	1.08	4.86
Eu	0.53	0.47	0.7	0.54	0.49	0.54	0.43	1.62
Gd	1.41	1.24	2.3	1.36	1.54	1.2	1.54	4.68
Tb	0.19	0.17	0.34	0.18	0.22	0.16	0.28	0.67
Dy	1.02	0.9	2.05	nd	nd	0.77	1.91	3.8
Ho	0.19	0.17	0.42	nd	nd	0.15	0.42	0.72
Er	0.51	0.47	1.16	nd	nd	0.39	1.16	1.21
Tm	0.07	0.06	0.17	nd	nd	nd	0.18	0.24
Yb	0.46	0.45	1.15	0.48	0.32	0.28	1.2	1.48
Lu	0.07	0.07	0.17	0.06	0.07	nd	0.18	0.21

REE patterns normalized to chondrite after McDonough and Sun (1995).

Columns: 1–3. Trondhjemites (this study); 4–5. Trondhjemites—data from Yearron (ms, 2003); 6. Trondhjemite—data from Glikson (1976); 7. Amphibolite—high-Mg pillow basalt xenolith (this study); 8. Diorite—(this study).

Analyst: A. Spath—ICP-MS Facility, University of Cape Town.

result from *in situ* equilibrium crystallization, the latter following some fractional crystallization prior to emplacement. In contrast, McCarthy and Hasty (1976) and McCarthy and Robb (1978) suggested, on the basis of Rb, Sr, and Ba trace element data, that many granitoids have a cumulate character resulting from *in situ* fractional crystallization involving inward nucleation of crystals from the margins of a magma chamber. The cumulus textures in the Theespruit Pluton illustrated earlier (fig. 6A) suggest that fractional crystallization was most likely responsible for separating cumulus plagioclase, and to a lesser extent quartz, from a residual intercumulus melt phase.

Rare earth element (REE) data for selected trondhjemites, amphibolite and diorite associated with the Theespruit Pluton are provided in table 3. The REE elements are considered to be relatively immobile during metamorphism and hydrothermal alteration (Rollinson, 1998). Their patterns, shown as chondrite normalized plots in figure 12, permit insight into the mineralogy of the source residuum and are a result of the influence of minerals such as garnet and plagioclase, the latter formed either by melt segregation and fractionation, or as a product of the melting reaction causing depletion of certain REEs. Plots of the Theespruit data show light rare earth (LREE) enrichment and heavy rare earth (HREE) depletion with no Eu anomalies. This relationship applies to all the other TTG plutons in the Barberton region, with the exception of the Doornhoek Pluton, which has a significant negative Eu anomaly (Robb and Anhaeusser, 1983). The HREE depletion most likely indicates their removal from the melt by garnet when it formed as a product of the melt reaction and became a residual mineral. Negative Eu anomalies, as explained by Rollinson (1998), arise from the removal of plagioclase from a melt by crystal fractionation or partial melting; hence the absence of a negative Eu anomaly in the Theespruit Pluton suggests that plagioclase did not fractionate out of the melt, but remained as phenocrysts in the now present cumulate-textured rocks. Extreme enrichment in LREE may be accounted for by the presence of hornblende in the melt. The flat REE pattern of sample

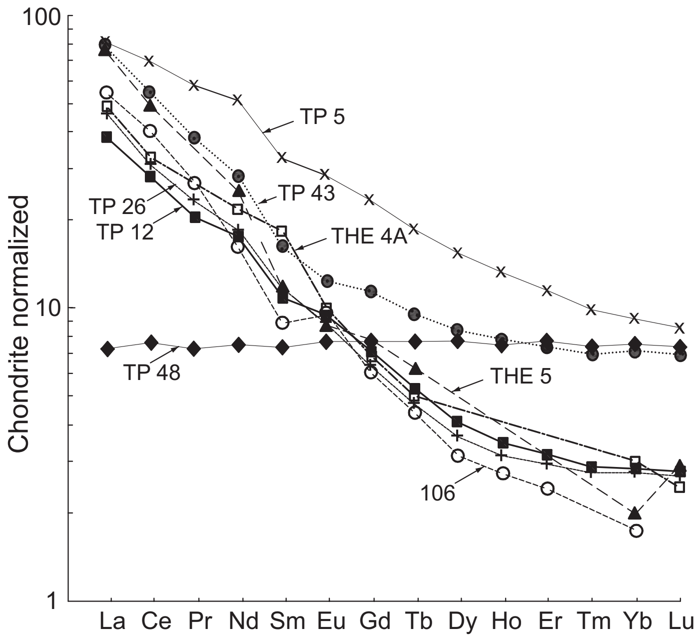

Fig. 12. REE patterns of Theespruit TTGs (normalized to chondrite after McDonough and Sun, 1995). TP samples (ICP-MS, University of Cape Town—analyst A. Spath); THE sample data from Yearron (ms, 2003); sample 106 data from Glikson (1976).

TP48 (fig. 12) is that of the amphibolite xenolith roof pendant described earlier, which is considered to represent a high-Mg pillow basalt from the Theespruit Formation.

Mineralogy of the Hybrid Rocks

The assimilated roof pendants described earlier appear to have undergone successive stages of modification commencing, initially, with the metamorphism of originally mafic volcanic rocks. This resulted in the formation of euhedral to subhedral hornblende crystals with poikiloblastic and interlocking textures and triple junctions. The intrusion of trondhjemitic magma followed, the latter containing large, commonly zoned, highly sericitized plagioclase crystals together with some quartz and intensely chloritized biotite flakes. This plagioclase phenocryst-rich trondhjemite (sample TP10E, table 4) displays a cumulate texture like that shown in figure 6A. A metasomatic overprinting, arising from the permeation through the mafic rocks of a fluid comprising essentially silica + sodium + titanium resulted in the formation of small euhedral twinned and unsericitized plagioclase grains, unaltered biotite, and fine-grained crystalline quartz. Titanium and calcium, mobilized during the metasomatic event, produced secondary titanite around pre-existing Fe-Ti opaque oxides. An U-Pb titanite date from the Stolzburg Pluton at *ca.* 3201 Ma (Kamo and Davis, 1994) suggests this metasomatism is much younger than the pluton emplacement age.

The hornblende growth appears to have been multi-stage. In the least altered hybrid samples examined (TP46C and TP10I, table 4), the hornblende is fine-grained, exhibits interlocking texture, and is not poikiloblastic. In samples displaying more intense hybridization, the hornblende is coarser-grained, having most likely been recrystallized by the heat of the granitic intrusion. The core zones of some of these

TABLE 4

Hybrid or assimilated mafic xenoliths, diorites and high-Mg basalt xenolith

Column	1	2	3	4	5	6	7	8	9	10	11	12	13
Sample	TP10E	TP10A	TP10B	TP10C	TP10D	TP10F	TP10G	TP10I	TP46A	TP46B	TP46C	TP51	TP48
SiO_2	70.4	55.3	54.7	59.6	55.6	53.4	56.4	52.3	56.7	58.2	51.9	57.6	51.43
TiO_2	0.31	1.45	1.49	1.52	1.82	1	1.33	3.13	1.64	1.69	0.57	2.24	0.5
Al_2O_3	15.9	15.5	15.6	15.9	16.6	15.8	16.6	14.5	14.7	15.1	14	14.66	12.65
Fe_2O_3	2.19	8.98	9.14	6.5	8.29	8.63	7.55	12.2	9.87	8.5	9.65	9.06	10.16
MnO	0.01	0.07	0.07	0.07	0.05	0.1	0.05	0.09	0.09	0.11	0.16	0.12	0.19
MgO	0.86	4.7	5.47	4.47	4.57	7.23	4.33	5.7	4.71	4.21	7.02	4.48	10.22
CaO	2.71	6.94	7.53	7.02	6.81	8.2	6.68	7.71	6.52	5.47	12.5	5.5	10.73
Na_2O	4.8	3.9	2.8	3.8	3.4	2.9	3.9	2.6	2.9	3.5	1.7	4.03	1.86
K_2O	1.25	1.05	1.19	0.57	1.18	0.64	0.93	0.6	1	1.14	0.77	1.35	0.56
P_2O_5	0.03	0.2	0.17	0.01	0.1	0.08	0.09	0.25	0.17	0.12	0.02	0.3	0.06
LOI	-	-	-	-	-	-	-	-	-	-	-	1.08	0.79
Totals	98.5	98.09	98.16	99.46	98.42	97.98	97.86	99.08	98.3	98.04	98.29	100.42	99.15

Columns: 1. Trondhjemite immediately adjacent to hybridized rocks (sample site TP10, fig 3); 2–8. Hybridized dioritic xenolith samples—Farm Aarnhemburg 155 IT; 9–11. Hybridized zone of diorites in central sector of pluton, south of Theespruit River; 12. Diorite near south-central margin of Theespruit Pluton; 13. High-Mg pillow basalt altered to hornblende amphibolite, northwest of Aarnhemburg Township.

Analysts: Bergström & Bakker, Johannesburg.

grains are poikiloblastic whereas the grain margins are relatively free of inclusions, suggesting more than one stage of hornblende growth. Crystals with minute inclusions of quartz and feldspar aligned along crystallographic planes may represent diffusion of metasomatic fluids along structural weaknesses in the hornblende. Sample TP10I is characterized by chlorite veinlets and chlorite porphyroblasts, which poikiloblastically enclose pre-existing hornblende crystals, suggesting retrograde metamorphic overprinting at *ca.* 3201 Ma, as pointed out earlier. This sample, containing over 3 percent TiO_2, also differs from others listed in table 4 in that it displays abundant (10-15%) fine-grained subhedral crystals of Fe-Ti oxide (titanomagnetite), which do not appear to be secondary or remobilized.

Titanite does not occur as primary euhedral grains in the trondhjemite collected adjacent to the hybrid rocks (sample TP10E), but it does occur locally as encrustations around pre-existing Fe-Ti oxides in the hybridized samples. From this it is inferred that Ca and Ti have been relatively mobile and were likely introduced into the hybridized rocks together with other hydrothermally derived elements (Si, Al, Na, K). Where titanite is absent other hybrid samples commonly show evidence of remobilized Fe-Ti oxides, which occur as veinlets or stringers in the rock. Chlorite was noted with the Fe-Ti stringers in sample TP10B.

The hybrid samples are also characterized by fractures and veinlets containing late-stage, low-temperature epidote and leucoxene, which would have influenced to some extent the chemistry of the rocks listed in table 4 (particularly Ti, Ca and Fe).

Geochemistry of the Hybrid Rocks

Chemical analyses of samples collected at various sites from the pluton where hybridization or assimilation of mafic xenoliths is presumed to have taken place are listed in table 4. The assimilated xenoliths are thought to have originally been similar compositionally to the high-Mg pillow basalts (sample TP48 in fig. 12). Trondhjemite magma, compositionally like that of sample TP10E immediately adjacent to the dioritic rocks at site TP10 (fig. 3), appears to have reacted with the mafic rocks, producing the range of dioritic rocks such as those shown in figure 11.

A wide compositional range is shown for these rocks, as expected, with the most obvious variations affecting the SiO_2, TiO_2, Fe_2O_3, MgO, CaO and alkali element contents. The possibility of a pre-existing metabasaltic xenolith being assimilated by an invading trondhjemitic magma can be tested using a technique suggested by Langmuir and others (1978). These authors provided a general hyperbolic equation depicting mixing in ratio-ratio plots, and also providing a test for mixing of either two magmas (hybridization) or a magma and a rock (assimilation).

In addition to simple mechanical or physical mixing, suggested in figure 11, one or more other processes may apply, including partial melting of components, differentiation, co-mingling of magmas, and metasomatism due to the presence of an evolved hydrothermal fluid. On a ratio-ratio plot, data broadly consistent with mixing will lie along a hyperbolic curve. To test for the consistency of mixing in the data set, a plot of one of the original ratios versus the ratio of the denominators of the two original ratios should yield a straight line relationship as outlined by Langmuir and others (1978). For the Theespruit data, a plot of Fe_2O_3/SiO_2 versus Na_2O/MgO reveals a good hyperbolic function between the two sets of variables (fig. 13A). The companion plot of Na_2O/MgO versus SiO_2/MgO (fig. 13B) shows a good linear relationship. These results therefore provide added confirmation that some form of mixing between the end-member components (namely, trondhjemite and basalt) has occurred.

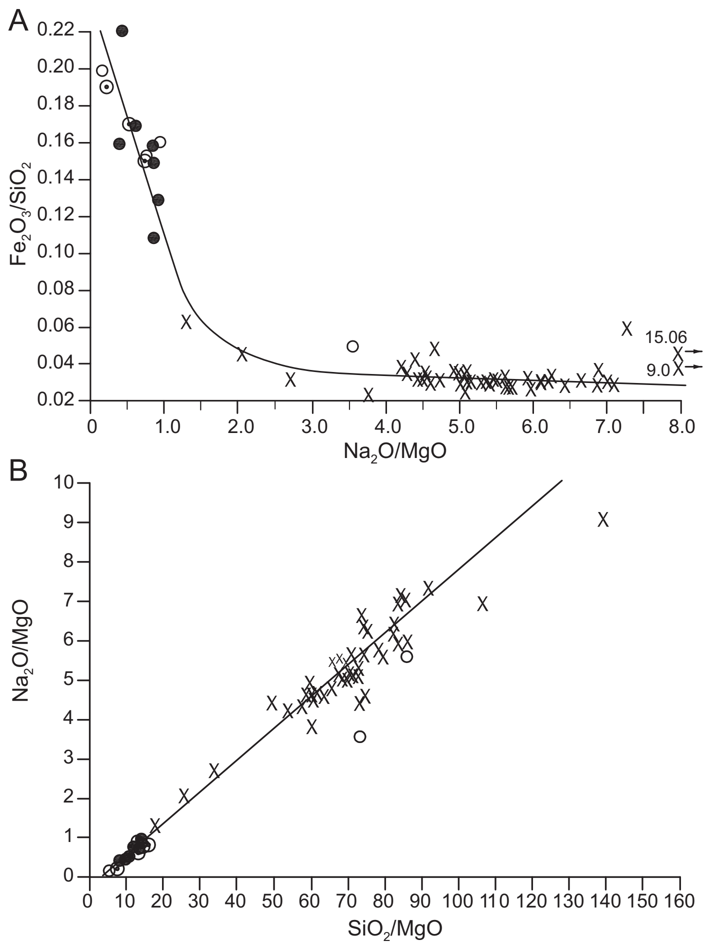

Fig. 13. Ratio/ratio plot (after Langmuir and others, 1978) of (A) Fe_2O_3/SiO_2 versus Na_2O/MgO (hyperbolic function) and (B) Na_2O/MgO versus SiO_2/MgO (linear) plots of the trondhjemites and hybrid rocks of the Theespruit Pluton suggesting mixing between basalt and trondhjemite end-member components. Closed circles: hybrid dioritic xenoliths (columns 2-8, table 4); circles with dots: hybrid diorites (columns 9-11, table 4); X's: Theespruit trondhjemite samples from database; open circles: other Theespruit diorite and trondhjemite samples not listed.

METAMORPHISM

Diener and others (2005) recorded high-*P*, low-*T* peak metamorphic conditions of 7.4 ± 1.0 kbar and 560 ± 20 °C determined for garnet-bearing metasediments and metabasites in the Tjakastad schist belt between the Theespruit and Stolzburg plutons (fig. 3). Earlier, metamorphic investigations undertaken within and adjacent to the Theespruit Pluton were reported by Van Vuren and Cloete (1995). These authors found that amphibolites from the Nhlazatshe River section on the same (western) side of the pluton as that examined by Diener and others (2005) yielded the highest temperatures and pressures in rocks adjacent to the Theespruit Pluton. These included 700 °C recorded by garnet and clinopyroxene and 9 kbar pressure recorded by garnet + hornblende + plagioclase + quartz (sample site TP34, fig. 3).

The above values differed significantly, however, from values obtained on the eastern and southern parts of the Theespruit Pluton (Van Vuren and Cloete, 1995). For example, amphibolites wedged between the Theespruit and Doornhoek plutons gave temperatures ranging from 390 to 440 °C and pressures of 2.6 to 5.4 kbar (near sample site TP49b, fig. 3) and, in the contact aureole in the south, between the Theespruit and Uitgevonden plutons (near sample site THE 5, fig. 3), these authors obtained temperatures ranging between 360 to 415 °C and pressures between 3.0 to 5.0 kbar.

Within the Theespruit Pluton itself, the pillowed garnet-hornblende amphibolites of the roof pendant xenolith (sample site TP48) appear to have crystallized under conditions ranging between 380 to 600 °C and 2 to 3 kbar pressure, while trondhjemite samples, mostly from the area north of the Theespruit River, gave temperatures of between 460 to 480 °C and pressures in the range 2.8 to 5.3 kbar (Van Vuren and Cloete, 1995). Van Kranendonk and others (2009) also reported kyanite overprinting andalusite, indicating anticlockwise *P-T* paths for greenstones flanking the northern part of the pluton.

Interpretation of these widely divergent results remains unclear. However, it seems that they reflect variable *P-T* conditions within the magma body and adjacent country rocks, in which case they may indicate unusual crystallization and emplacement conditions. What does seem to be indicated from the metamorphic studies in the Komati River valley area as a whole is that the supracrustal remnants of the Theespruit and Sandspruit formations were buried at *ca.* 3230 Ma to mid- and lower-crustal depths of 25 to 35 km (Dziggel and others, 2002, 2005; Diener and others, 2005; Moyen and others, 2006). This burial occurred only locally in the most steeply dipping and lineated inter-dome greenstone synclines. The roof pendants do not show this high degree of metamorphism. This is critical in terms of emplacement style and, when combined with kyanite overprinting andalusite mentioned above, indicates that the granitoids were originally emplaced at relatively shallow levels (2-3 kb, or at most <4 kb), but that greenstone synclines developed and were buried deeply thereafter, during dome-and-keel formation. Data from Dziggel and others (2005) show that this latter event occurred at *ca.* 3230 Ma, as argued for by Van Kranendonk and others (2009).

Emplacement Style

Van Kranendonk and others (2009) visualized the Komati River valley plutons, particularly the Stolzburg, Theespruit and Doornhoek plutons, as not being isolated intrusions, but rather as "three domal culminations, or lobes, of a compositionally and geochronologically homogeneous granitic layer separated by infolded, synformal septae of strongly deformed greenstones of the Sandspruit and Theespruit formations." This view may have some substance if this group of plutons can collectively be held responsible for occupying the granitic core, and causing the updoming of the steeply northeast-plunging asymmetrical Onverwacht anticlinal fold structure, as suggested by Viljoen and Viljoen (1969a).

The emplacement features of the TTG plutons in the Komati River valley area were described by Kisters and Anhaeusser (1995a) as being the result of multiple, simultaneously operating processes involving ductile wall-rock deformation, stoping, assimilation and the intrusion of ring dikes. These processes, operating singly, or in various combinations, were regarded as being responsible for the diapir-like concordant to locally discordant contact relationships as well as deformation in adjacent country rocks and xenoliths. Geochronological and metamorphic/structural arguments indicate there are probably two emplacement styles at two different ages: (1) mechanical stoping under relatively shallow crustal levels at *ca.* 3440 Ma, during initial emplacement of the granitic rocks; and (2) ductile shearing and domical reactivation during greenstone sinking and high-grade metamorphism in greenstone septae at *ca.* 3230 Ma.

Like the neighboring Doornhoek Pluton to the northeast (figs. 2 and 3) the Theespruit Pluton appears to have been initially a high-level intrusion relative to others in the Barberton region, as confirmed by the metamorphic data determined by Van Vuren and Cloete (1995). Furthermore, the kyanite overprinting andalusite relationships noted by Van Kranendonk and others (2009) indicate anticlockwise *P-T* paths for greenstones adjacent to the northern part of the pluton. This sets it apart from the other plutons in terms of many of the physical characteristics illustrated earlier. Most other plutons in the region display well-foliated, sheared, concordant relationships, suggesting that these bodies were structurally emplaced into their present positions at a stage subsequent to their total, or near total solidification; that is at *ca.* 3230 Ma. The high-level bodies, by contrast, had a component of discordance due to the intrusion of the primary igneous (*ca.* 3440 Ma) magma, part of which was in solid form, but much of which probably consisted of a semi-consolidated crystal mush. As outlined by Robb (2005), granitic magma may become water-saturated (also referred to as "boiling" or "vapor saturation") as crystallization progresses. In high-level granitic systems, vapor saturation is strongly dependent on pressure, which decreases as a result of upward migration of magma. The process whereby fluid is exsolved from the magma was shown by Burnham (1997) to be also responsible for the release of mechanical energy. Resulting overpressuring in a magma body thus causes brittle failure in the rocks into which the granite intrudes. As discussed by Sibson (1996), overpressuring may arise from metamorphic dewatering in the middle to deep crust, by thermal overpressuring from magmatic intrusion, and by mantle degassing. Suprahydrostatic vertical fluid pressure gradients generally result, but strong lateral hydraulic gradients may also develop, particularly adjacent to magmatic intrusions.

In the case of the Theespruit intrusion, hydrofracturing of the brittle Sandspruit and Theespruit amphibolites above the apical portion of the granite intrusion resulted in the dismemberment of the cover rocks to form roof pendant xenoliths and agmatitic breccias. This occurred during igneous emplacement of the pluton at *ca.* 3440 Ma, the xenoliths interacting with late granitic melts and vapor-saturated fluids to form assimilation or hybridization products. Lateral displacement of the supracrustal rocks likely resulted in ductile flattening and shortening, manifest by the schist belt septae between emergent plutons (Glikson, 1979), and having formed later during reactivation of the dome-and-keel architecture at *ca.* 3230 Ma.

Despite views dismissing diapirism as a viable mechanism of TTG emplacement in the Barberton region, Kisters and Anhaeusser (1995a) argued that the radially orientated superimposed flattening and constrictional strains within the plutons, wall rocks, and greenstone xenoliths in the granitoids, coupled with contact metamorphic aureoles, imply that diapiric emplacement was accommodated by ductile flow, stoping, assimilation, migmatite formation, and banded gneiss development—processes these authors considered far outweighed any horizontal thrust-accretion hypothesis at this stage in the crustal evolution of the Barberton granite-greenstone terrane. The intrusive contact relationships between the Stolzburg and Theespruit plutons and the Sandspruit and Theespruit formations suggest that this crustal section was already assembled at *ca.* 3440 Ma (Kamo and Davis, 1994; Van Kranendonk and others, 2009) and then reactivated at *ca.* 3230 Ma during regional folding and extension. These authors also concluded that the Sandspruit-to-Komati succession was a coherent section as it was collectively intruded by 3470 to 3440 Ma TTG magmas. In other words, the southern granitoid-gneiss terrane, including the Theespruit and Sandspruit formations and the TTG plutons, appears to have behaved as a coherent entity during the *ca.* 3230 Ma mid-to deep-crustal burial and exhumation of the rocks (Kisters and others, 2003; Diener and others, 2005; Van Kranendonk and others, 2009). Later magmatism led to the emplacement of the undeformed, post-tectonic Dalmein Pluton (fig. 2). This potash feldspar-rich, quartz monzonite pluton was intruded east of the Theespruit Pluton at between *ca.* 3216 and 3203 Ma (Kamo and Davis, 1994; Lana and others, 2010b) and marks the culmination of TTG igneous activity in the Komati River valley. This, in turn, was followed by the emplacement of areally extensive potash-rich granodiorite batholiths, such as the Mpuluzi Batholith (fig. 2), at *ca.* 3105 Ma (Kamo and Davis, 1994).

SUMMARY AND CONCLUSIONS

The Theespruit Pluton is one of approximately 12 circular- to ovoid-shaped, *ca.* 3550 to 3200 Ma, TTG plutons located on the western and southern side of the Barberton greenstone belt that are clearly defined by encircling amphibolite or upper greenschist facies ultramafic, mafic and felsic volcanic rocks. Other plutons or "cells" exist in the region that have been identified geochemically on the basis of their Sr contents (Robb and Anhaeusser, 1983). All plutons, with the exception of the Kaap Valley tonalite pluton west of Barberton (fig. 1), consist of trondhjemitic granitoids and all display a common structural style with generally concordant contacts, variably foliated and lineated gneissic fabrics, and variably sized deformed greenstone xenoliths. There is a total absence of regionally pervasive linear fabrics across the granitic terrane, each pluton instead exhibiting its own unique concentric-style gneissosity and, locally, compositional banding near pluton margins (Viljoen and Viljoen, 1969a; Robb and Anhaeusser, 1983; Anhaeusser, 1984; Kisters and Anhaeusser, 1995a).

A number of individualistic features sets the Theespruit Pluton apart from the other granitic intrusions in the Barberton terrane. These include: (1) both concordant and discordant contact relationships with the surrounding supracrustal greenstones; (2) the presence of strongly tectonized as well as undeformed greenstone xenoliths representing roof pendants stoped from the supracrustal Onverwacht volcanic succession; (3) areas where mafic xenoliths have been variably assimilated by trondhjemite magma resulting in the production of a range of hybrid dioritic rocks; (4) evidence, in the assimilated rocks, of the influences of sodium and titanium metasomatism; (5) the presence of cumulate-like textures in the granitoids resulting from plagioclase phenocryst formation following fractional crystallization; (6) the "explosive" intrusion of trondhjemite magma into brittle garnet-amphibolite contact wall rocks as well as xenoliths, expressed as hydrofracturing, brecciation, granitoid intrusion and agmatite development; and (7) evidence of heterogeneous and low-to-minimal strain being imposed on flanking country rocks during pluton emplacement, suggesting that the granitoid body represents a high-level intrusion.

Geochemical data show that the pluton is a compositionally uniform, plagioclase-quartz-biotite trondhjemite with only locally developed tonalites and diorites resulting from the addition of hornblende derived from assimilated amphibolite wall rocks and xenoliths. More than one granitic phase is evident locally, the later phase probably being associated with magmatic activity in the region that led to the emplacement of the *ca.* 3230 Ma trondhjemites in the west (Nelshoogte and Badplaas plutons; Kisters and others, 2006; Belcher and others, 2009—fig. 2). A consensus view is that the source rocks of the trondhjemites was most likely an enriched Archean MORB-type parent, compositionally similar to the basalts occurring in the lower part of the Onverwacht volcanic succession (Robb and Anhaeusser, 1983; Clemens and others, 2006; Moyen and others, 2007b; Smithies and others, 2009).

The style of emplacement of the Theespruit Pluton remains debatable. If, as has been suggested by Clemens and Mawer (1992) and Clemens (1998), granitic magmas ascend tens of kilometers from their source terranes to upper crustal emplacement levels via propagating fractures, in the form of dikes, there appears to be no present-day surface expression in the Barberton granite-greenstone terrane in support of such a fracture-related process. Rather, despite erudite thermal and mechanical objections to diapiric magma emplacement posed by these authors, the overwhelming consensus is that the process of diapirism *did* have a role to play in Archean granitic terranes (Anhaeusser, 1984; Hickman, 1984; Van Kranendonk, 2004; Van Kranendonk and others, 2004, 2009). In an attempt to address one of the main areas of contention—that of how space is made available during pluton emplacement—Paterson and Fowler (1993) concluded that the suggested models of diapirism were too simplistic and essentially too superficial. Instead, it was argued by these authors, the ascent and emplacement of magmas require *multiple* near- and far-field material transfer processes (MTPs). These MTPs will vary with depth, distance from pluton, and time, and they will depend on temperature, bulk composition of the magma and wall rocks, fluids present, magma and wall-rock viscosities, anisotropy of the wall rocks and other factors—in short, a complex set of variables given only cursory attention in most diapiric modeling arguments. A process akin to circuitous recycling or crustal convection (Weinberg, 1997) of material from the aureoles of plutons towards the source of magma generation is implicit in the Paterson and Fowler (1993) scenario—as described for models of partial convective overturn of the upper and middle crust (Collins and others, 1998; Van Kranendonk and others, 2004, 2007).

In conclusion there are four main components of granite emplacement recorded by the Theespruit Pluton: (1) high-level brittle stoping at *ca.* 3440 Ma; (2) a secondary, ductile process, during greenstone subsidence, when greenstone septae were metamorphosed to high-*P* conditions and steep lineations were formed; (3) this reactivation stage was accompanied by granitoid metasomatism, involving Si, Na, and Ti, probably at *ca.* 3200 Ma, as determined by U-Pb dating in the general vicinity of the pluton; and (4) the trondhjemitic magma originated, not as a subducted slab source, but by infracrustal melting processes at granulite to amphibolite facies conditions.

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