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# FABRIC DEVELOPMENT AND DEFORMATION OF GREENSTONE XENOLITHS IN ARCHAEAN TTG PLUTONS AND REGIONAL IMPLICATIONS FOR THE TECTONIC EVOLUTION OF THE BARBERTON GREENSTONE BELT, SOUTH AFRICA


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by

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## ABSTRACT

Fabric development in Archaean tonalitic-trondhjemitic plutons along the southern margin of the Barberton Greenstone Belt, South Africa, records a progression from early-stage magmatically formed foliations to subsequent high-temperature solid-state deformation during the cooling and ballooning stages of the plutons. Intensely deformed greenstone enclaves within the TTG plutons reflect all stages of this deformation, documenting a complex strain history for the deformed greenstone xenoliths. Despite the largely autochtone nature of TTG plutons along the southern margin of the Barberton Greenstone Belt, no regionally developed fabric within the TTG's reflects the intense deformation and northeasterly trending structural grain of the greenstone belt to the immediate north. This absence of a regional fabric within TTG plutons points to considerable competence contrast between the granitoid basement and greenstone cover-sequence during subsequent deformations. The frequently observed tight infolding of greenstone lithologies into TTG plutons and gneisses is interpreted to reflect this competence contrast. Subhorizontal, mainly NW-directed crustal shortening during later deformation phases parallel to the basement-cover interface, which resulted in intense thrust-and-nappe tectonics in the central Barberton Greenstone Belt, produced regional-scale cuspate-lobate folds, giving the Barberton Greenstone Belt its distinctive arcuate geometry. Considering the shallow depth of the Barberton Greenstone Belt, this basement-cover relationship bears important implications as to the structural development of the greenstone belt.


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# FABRIC DEVELOPMENT AND DEFORMATION OF GREENSTONE XENOLITHS IN ARCHAEAN TTG PLUTONS AND REGIONAL IMPLICATIONS FOR THE TECTONIC EVOLUTION OF THE BARBERTON GREENSTONE BELT, SOUTH AFRICA

## INTRODUCTION

The Archaean Barberton Greenstone Belt (BGB) in the Transvaal Province of South Africa (Fig. 1) is an approximately 120x 50km, northeast-trending belt, containing a voluminous sequence of well-preserved volcanic and sedimentary rocks of the Swaziland Supergroup (Visser et al.,1956; Anhaeusser, 1969, 1981a,b). Surrounded by plutonic rocks, the BGB is easily recognizable on large-scale regional maps by its unusual arcuate outcrop pattern which is caused by the projection of strongly attenuated cusps of greenstone lithologies wedged between tonalite-trondhjemite-granodiorite (TTG) plutons and gneisses. The variably foliated TTG plutons contain numerous deformed greenstone xenoliths of various size which are clearly correlatable with the lower parts of the greenstone sequence exposed in the BGB (e.g. Viljoen and Viljoen, 1969; Anhaeusser, 1978, 1983a,b).

In this paper we describe the deformation, deformation mechanisms and orientations of structural elements within TTG plutons and engulfed greenstone xenoliths south of the BGB. The emplacement and deformation style of the largely autochtone TTG plutons which were emplaced during the very early stages of the tectonic history of the BGB bear important implications as to the subsequent deformation of the greenstone belt and its present geometry and outcrop pattern.

## REGIONAL GEOLOGICAL SETTING IN THE SOUTHERN PARTS OF THE BGB

### Stratigraphy and age relationships

The volcano-sedimentary stratigraphy of the Barberton Greenstone Belt is subject of an ongoing controversy. Two highly divergent views can be distinguished:

1) the classic subdivision of the BGB into three major lithostratigraphic units, assuming a largely intact and structurally uninterrupted $\approx$20 km thick stratigraphy (Viljoen and Viljoen, 1969; Anhaeusser, 1975; Anhaeusser et al., 1983a; Lowe et al., 1985; Lowe, 1991). These units, in their stratigraphical order include: a) the Onverwacht Group, consisting of ultramafic and mafic metavolcanics together with minor felsic pyroclastics and siliceous metasediments; b) the Fig Tree Group, a largely sedimentary succession comprising greywackes, cherts and shales together with felsic pyroclastics; and c) the Moodies Group which consists mainly of coarse-grained sedimentary rocks such as quartzites and conglomerates along with minor siltstones and shales; and

2) the subdivision of the BGB into tectonostratigraphic units, assuming significant structural breaks caused by multiple phases of thrusting and recumbent folding, reducing the original sequence within the BGB to less than 10 km (e.g. Williams and Furnell, 1979; De Wit, 1982, 1991; De Wit et al., 1983, 1987, 1992; DeRonde et al., 1991).

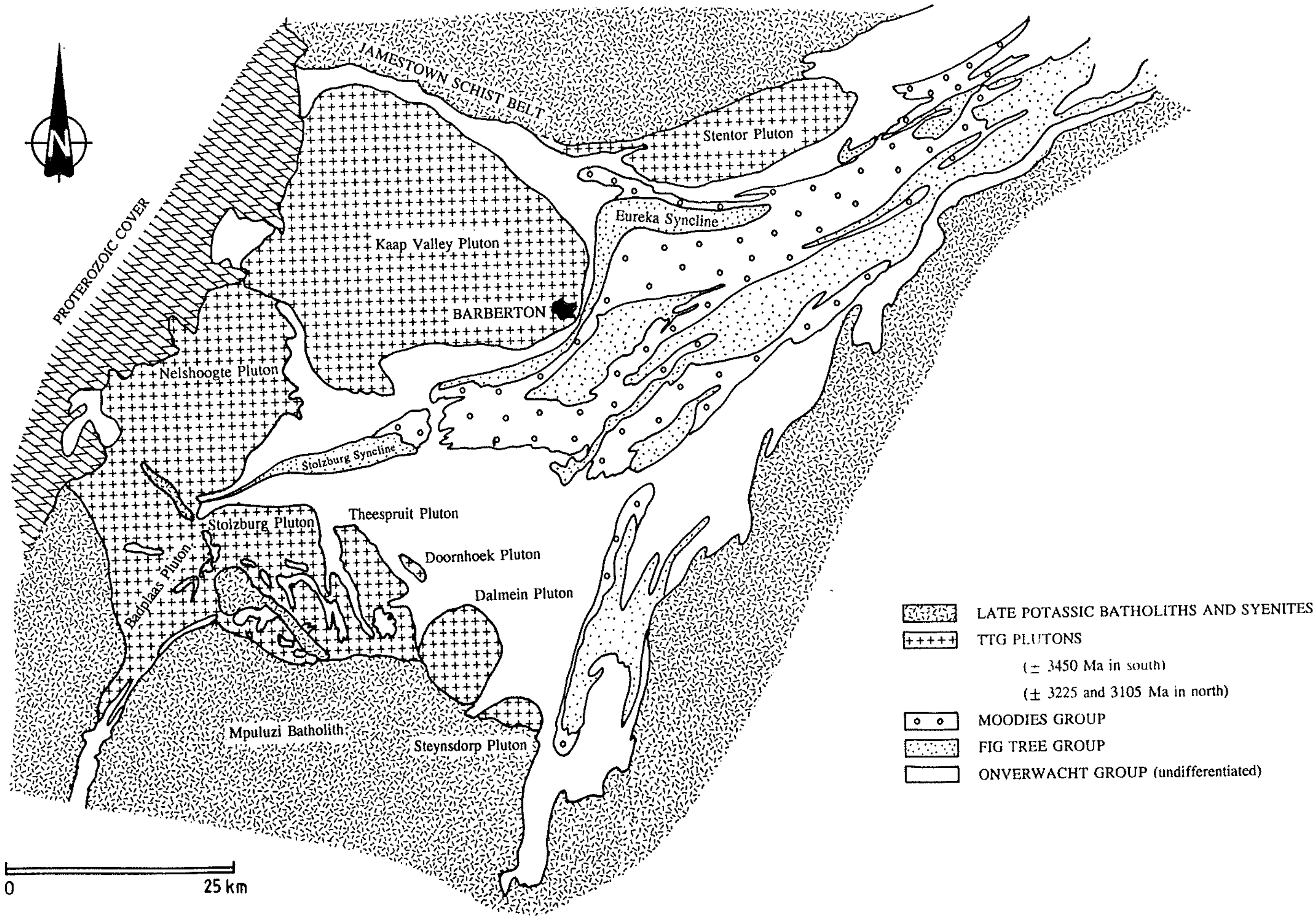



*Figure 1: Simplified geological map of the southern and central parts of the Barberton greenstone belt (modified after Anhaeusser, 1981, 1983).*

The volcano-sedimentary succession of the BGB is surrounded by granitoid plutons of various ages and composition which are in intrusive and/or structural contact with the greenstone sequence (Figs. 1 and 2).

The area south of the Barberton Greenstone Belt, on which this study is focused, is made up of several discrete plutons of the TTG suite (Fig. 2). Regional mapping by Anhaeusser (1981a,b; 1983a,b), as well as the recognition of petrological characteristics by Anhaeusser and Robb (1980) and Robb and Anhaeusser (1983) have established the geometry and outline of individual plutons. These include namely the Badplaas, Stolzburg, Theespruit, Doornhoek, Uitgevonden and Steynsdorp plutons (Figs. 1 and 2). The TTG plutons contain numerous greenstone xenoliths of highly variable proportions (Fig. 2). Lithologies within the greenstone xenoliths are similar to greenstone successions found in the lower parts of the Onverwacht Group (Viljoen and Viljoen, 1969; Anhaeusser, 1978, 1981a,b; 1983a,b). Intrusive into these plutons of the TTG suite are potassium-rich granites and syenites such as the Dalmein pluton, the Boesmanskop and Kees Zyn Doorns syenites, and the Mpuluzi batholith to the south (Figs. 1 and 2).

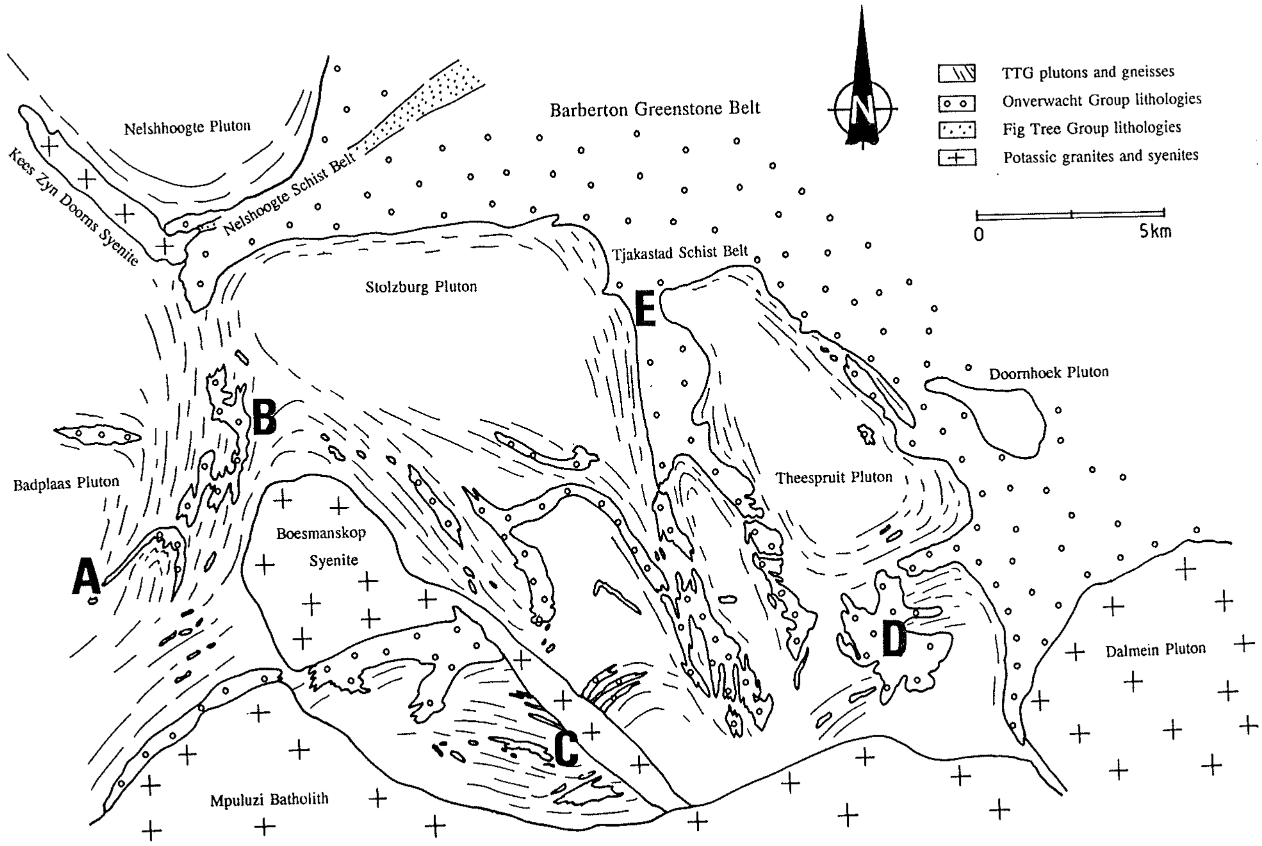



*Figure 2: Simplified geological map of the granite-greenstone terrane along the southern margin of the Barberton greenstone belt (modified after Anhaeusser and Robb, 1980; Robb, 1981b, 1983). Points A-E mark localities discussed in text.*

In recent years, high-precision single zircon dating has constrained the absolute ages and relative age relationships between various intrusions and lithologies within the BGB (e.g. Armstrong et al, 1990; Kröner and Todt, 1987; Kröner et al., 1991, Kamo and Davis, 1991; De Wit et al., 1992; De Ronde and De Wit, in press). Early TTG plutons in the southern part of the BGB, emplaced between 3460 and 3440 Ma, show predominantly intrusive contacts with the mainly ultramafic to mafic metavolcanic rocks of the Onverwacht Group which are locally intercalated with felsic metavolcanics and pyroclastic rocks about 3490 to 3450 Ma old (e.g. Lopez Martinez, 1984; Armstrong et al., 1990; Kamo and Davis, 1991). A gneissic basement predating the ultramafic and mafic metavolcanics of the Onverwacht Group is inferred by gneissic slivers within the Onverwacht Group (De Wit et al., 1983) which yield ages of about 3538 Ma (Armstrong et al., 1990; Kamo and Davis, 1991) as well as approximately 3500 Ma ages for the Steynsdorp pluton in the SE of the Barberton Mountain Land. However, recent investigation of the Steynsdorp pluton by the authors has identified numerous amphibolitic xenoliths within the gneissic banding of the Steynsdorp pluton, indicating the presence of ultramafic, possibly oceanic crustal material, older than the oldest ages obtained from the lowermost Onverwacht Group.

Potassium-rich granites and syenites postdate the emplacement of the TTG plutons by 200 to 300 Ma, yielding ages of 3216 Ma for the Dalmein pluton and 3105 Ma for the Boesmanskop syenite and Mpuluzi batholith, respectively.

**Structure**

The controversy about the stratigraphic succession of the BGB is reflected in the diverging opinions about the tectonic development of the greenstone belt. Early perceptions of the tectonic evolution suggested gravitationally induced vertical tectonics which led to the interpretations of the greenstone succession being infolded between intruding diapirs of the TTG suite (Anhaeusser et al., 1969; Anhaeusser, 1984).

More recent structural studies (e.g. De Wit, 1982, De Wit et al., 1983, Paris, 1984, Tomkinson and King, 1991, and De Ronde, 1991, amongst others), emphasize the significance of horizontal tectonics; namely the formation of thrusts, nappes and recumbent fold structures, which formed along convergent margins in a plate-tectonic environment. Single-zircon dating of these structural events has bracketed these deformation phases, although early deformational events remain controversial and the correlation of deformation phases throughout the belt is problematic (Tomkinson and King, 1991). An early deformation phase ($D_1$, after De Wit, 1982) appears only to have been recognized in the southern parts of the BGB and is believed to represent a phase of low-angle thrusting and recumbent folding, resulting in thrust stacking and duplication of the greenstone succession (De Wit et al., 1983). This deformation probably occurred at $\pm$ 3440 Ma, i.e. at the time of emplacement of the TTG suite in the southern parts of the BGB. Subsequent $D_2$ and $D_3$ events resulted in predominantly NW-verging thrusting and folding, being responsible for the general NE-SW trending structural grain of the greenstone belt (e.g. De Wit et al., 1983; Lamb, 1984; Tomkinson and King, 1991; DeRonde and DeWit, in press). These deformation phases are largely correlated with the emplacement of later TTG plutons and more potassic intrusions and are believed to have occurred between 3227 and 3105 Ma, respectively (Tegtmeyer and Kröner, 1987; Armstrong et al., 1990; Kamo et al., 1990). Late-stage normal and strike-slip faulting affected the BGB during a $D_4$ event (e.g. Robertson, 1989; Tomkinson and King, 1991).

## FABRIC DEVELOPMENT IN TTG PLUTONS

The hornblende tonalites and more leucocratic biotite trondhjemites along the southern margin of the BGB show a variably developed mineral fabric ranging from porphyritic textures, via faintly lineated and foliated textures to a pervasively developed gneissosity associated with a compositional banding. Although this fabric development is highly variable and heterogeneous within a single pluton, there is a tendency for the fabric to become more pronounced towards the margins of the intrusions. This fabric development in TTG's can be identified in the field and can be described as a progression as follows:

1) porphyritic textures dominate in the centres of individual TTG plutons. Minerals, including mainly plagioclase, quartz and biotite or hornblende show no preferred orientation or alignment. Plagioclase is commonly euhedral and zoned; quartz forms an interstitial phase, occasionally defining a weak, subvertical lineation. Biotite and/or hornblende show euhedral to subhedral crystal shapes. Commonly occurring cm- to dm- scale amphibolitic enclaves have typically rounded to slightly ovoid shapes;

2) a faint foliation is produced by the alignment of euhedral plagioclase and subordinate biotite and hornblende. The fabric thus defined shows predominantly subvertical dips and parallels the contacts of individual plutons. Recrystallization of plagioclase along the margins common, and interstitial, partly recrystallized quartz is slightly flattened, imparting a subvertical mineral lineation. Mafic enclaves show moderately flattened outlines aligned in the plane of the foliation;

3) strongly aligned plagioclase laths, together with quartz and biotite/hornblende, lead progressively to a well developed, steep to subvertically inclined mineral fabric. Anhedral plagioclase is largely recrystallized. Interstitial quartz is undulose and strongly flattened and is, together with the mafic minerals, wrapped around plagioclase crystals. Small amphibolitic enclaves are flattened within the foliation and strongly stretched parallel to the steeply inclined mineral lineation, resulting in an overall prolate shape. Finely brecciated material occurs as thin mm- to cm- wide zones subparallel to the gneissose foliation which show persistent strike extents of, in places, several tens of meters; and

4) a pervasively developed foliation together with a compositional banding locally imparts a well-developed gneissosity onto TTG plutons. Plagioclase is pervasively recrystallized. Quartz is finely recrystallized and strongly undulose. Commonly occurring ribbon aggregates of quartz define a steep to moderately inclined lineation. Biotite is strongly bent and wrapped around quartz-plagioclase aggregates. Refolding and crenulation of the gneissosity and the compositional banding is locally intensely developed.

The mineral fabric and\or gneissosity of the TTG plutons frequently describe concentric patterns which are subparallel to the margins of the plutons (Fig. 2). The generally steeply inclined planar fabric (e.g. the Theespruit pluton) shows a somewhat scattered distribution pattern in a lower hemisphere equal area projection (Fig. 3) which deviates from an ideal great circle, rather showing a small circle distribution, indicating the conical shape of the pluton. Despite the concentric foliation pattern within the Theespruit pluton, only northerly dipping mineral fabrics are developed throughout the intrusion, which, together with the predominantly northwesterly plunging mineral lineation, might indicate an overall steep, northwesterly plunge of the TTG pluton. Although heterogeneously developed within individual intrusions, this concentric foliation pattern is a characteristic in most of the TTG plutons (Fig. 2; Anhaeusser, 1981a,b; 1983a; Robb and Anhaeusser, 1983).

## DEFORMATION OF GREENSTONE XENOLITHS

The tonalitic-trondhjemitic granitoids and gneisses south of the Barberton Greenstone Belt are characterized by numerous, commonly steeply inclined greenstone xenoliths ranging in size from minute enclaves to rafts of several kilometers strikelength and width, respectively (Anhaeusser, 1980, 1981b, 1983a,b). Greenstone xenoliths or trains of greenstone enclaves are commonly aligned parallel to the margins of the TTG plutons as well as the internal fabric of the intrusions, often outlining the geometry of individual plutons and, as such, giving a somewhat scattered outcrop pattern on a regional scale (Fig. 2). Interaction between the intruding plutons and greenstones has led to the development of an amphibolite-grade contact metamorphic mineral assemblage within the greenstone xenoliths (Anhaeusser, 1969, 1983b). Furthermore, margins of greenstone remnants are frequently characterized by

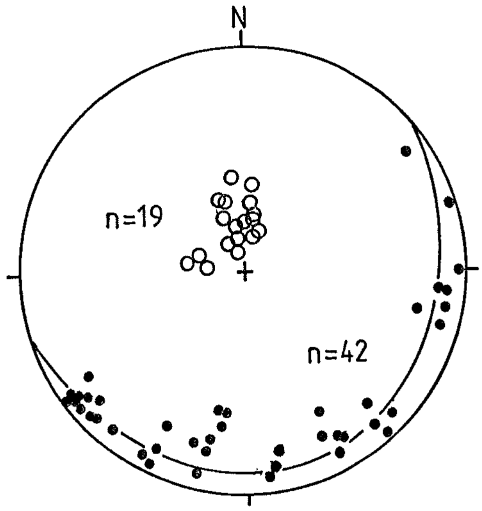



*Figure 3: Lower hemisphere equal area projection of poles to the foliation (full circles) and mineral lineations (open circles) in the Theespruit pluton. Poles to the foliation define a small circle distribution, possibly reflecting the conical shape of the pluton.*

contact migmatites and the onset of partial melting (Anhaeusser and Robb, 1980; Robb, 1981a,b; 1983; Robb and Anhaeusser, 1983).

Whereas in past studies geochemical and petrological aspects of TTG/greenstone interaction have been considered, in this paper we deal with the deformation and deformational features observed within greenstone xenoliths. In addition to a regional reconnaissance, a structural analysis of five selected greenstone remnants in the granite-greenstone terrane (Fig. 2, points A-E) was undertaken. This investigation was carried out in order to establish the orientation of structural elements and the deformational style with respect to TTG plutons as well as the relation to regional deformational events in the Barberton Greenstone Belt.

**Batavia**

Regional mapping by Anhaeusser (1981a,b; 1983b) has identified numerous large greenstone xenoliths along the eastern margin of the Badplaas Pluton on the farm Batavia (Fig. 2). The train of steeply dipping xenoliths follows a curvilinear trend, showing northeasterly trends in the south and more northerly trends in the north (Fig. 2).

In this investigation, two areas have been examined in detail (points A and B, Fig. 2). Detailed geochemical and petrological descriptions of these outcrops were presented by Robb (1981a,b; 1983).

*Batavia fold structure*

The greenstone lithologies of this area outline a prominent fold structure easily

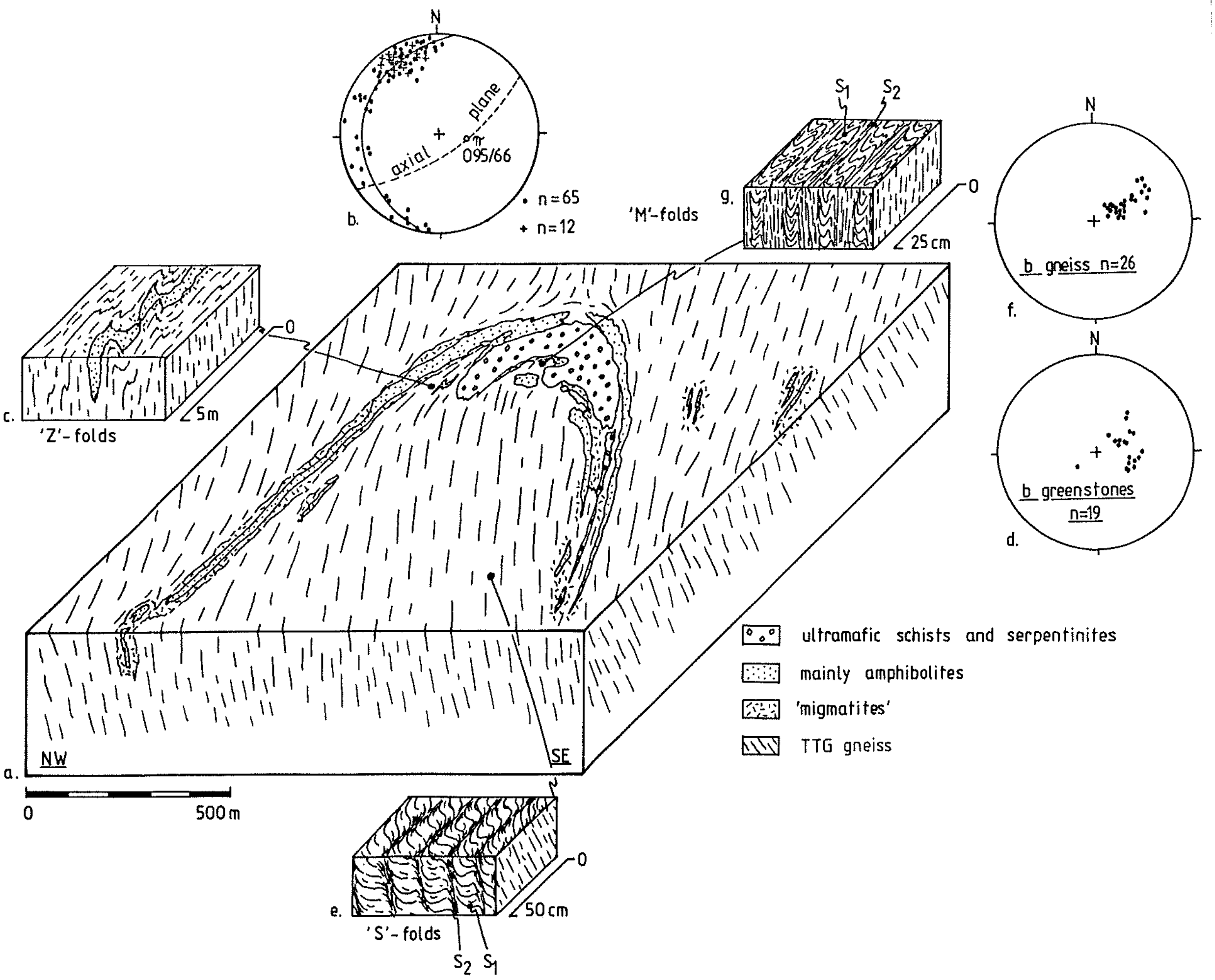



*Figure 4a: Schematic illustration of structural relationships in the Batavia fold structure.*
*b: Lower hemisphere equal area projection of poles to greenstone lithologies (full circles) and axial planar foliation (crosses) outlining easterly plunging, north-westerly verging fold.*
*c: Parasitic folds showing 'Z'-fold symmetry in gneiss and in greenstones on the northwestern limb of the Batavia fold.*
*d: Lower hemisphere equal area projection of poles to fold axes of minor folds in greenstones.*
*e: Crenulation of the tonalitic-trondhjemitic gneissosity on the southeastern limb of the Batavia fold, showing 'S'-fold symmetry.*
*f: Lower hemisphere equal area projection of poles to minor folds in tonalitic-trondhjemitic gneisses.*
*g: Intense crenulation of the tonalitic-trondhjemitic gneissosity in the hinge of the Batavia fold producing minor 'M' folds.*

recognizable on regional maps (Figs. 1 and 2). Lithologies within the greenstone remnant comprise amphibolites, serpentinites, ultramafic and mafic schists and minor ferruginous chert bands. The structure outlined by the outcrops of greenstone lithologies defines a tight, steep easterly plunging, northwesterly verging, overturned fold (Fig. 4a,b). The hinge of the fold is markedly thickened, comprising predominantly outcrops of serpentinitic ultramafic lithologies. The moderate-to-steep southeasterly dipping limbs of the fold are strongly attenuated and are predominantly made up of amphibolites and talc-carbonate schists. Parasitic, easterly plunging dm- to m- scale 'Z'- and 'S'- folds are evident on the northwestern and southeastern fold limb, respectively (Fig. 4c,d). Chevron-type 'M'- folds are commonly developed in serpentinites in the hinge zone of the fold, but extensive soil creep in this area hindered the collection of structural data and possibly accounts for the fairly wide scatter of minor fold plunges in Figure 4d.

The trondhjemites in this part of the Badplaas Pluton display a well-developed gneissosity and compositional banding (Fig. 4a). The regional trend of the steep southeasterly dipping trondhjemitic gneisses is approximately 035-040° and swings around to more northerly trends north of the fold structure (Fig. 2). This gneissosity and compositional banding of the trondhjemitic gneisses is locally intensely refolded. Folding is frequently expressed as a cm- to dm- scale crenulation of the gneissosity (Fig. 4c,e). Minor folds thus produced show a pronounced symmetry with respect to the large-scale fold structure defined by the greenstone lithologies, exhibiting northeasterly plunging 'Z'- and 'S'- folds on the northwestern and southeastern limb, respectively (Fig. 4c,e,f). Intense crenulation and folding of the gneissosity in the hinge of the Batavia fold structure led to the development of cm- to m- scale 'M'- folds (Fig. 4g) which plunge northeasterly. The crenulation cleavage ($S_2$, Fig. 4e,g) which refolds the gneissosity of the trondhjemitic gneisses ($S_1$) is axial planar to the large-scale fold structure (Fig. 4b).

*Batavia North*

Northerly trending greenstone xenoliths of area B (Fig. 2) comprise similar lithologies as the Batavia fold structure to the immediate south, including mainly amphibolites, serpentinites, mafic and ultramafic schists and minor cherts. Migmatization has particularly affected amphibolitic lithologies along the margins of the greenstone lithologies producing stromatic, ophthalmitic, phlebitic and complexly folded schlieren structures (after Mehnert, 1967; Robb, 1981a,b; 1983). A well-developed gneissosity and compositional banding within engulfing trondhjemitic gneisses trends northerly, showing steep easterly dips (Fig. 5a,b), parallel to the greenstone enclave.

Folding within greenstone lithologies is most easily recognized in amphibolites and stromatic amphibolitic migmatites as the stromatic banding within amphibolites has been deformed into upright to moderately inclined west-verging, open to tight folds (Fig. 5a). Folding resulted invariably in the development of non-cylindrical, periclinal or domical folds. This type of folding finds its expression in the wide spread of fold plunges (Fig. 5c). Axial planes, however, show predominantly northerly to northeasterly trends, subparallel to the gneissosity in adjacent gneisses. Original layering features in ultramafic talcose schists have been almost entirely obliterated by a northerly trending, steep-to-moderate, easterly dipping foliation (Fig. 5a,b). This schistosity is subparallel to the gneissose fabric in the adjacent trondhjemitic gneisses and is axial planar to folds in amphibolites (Fig. 4b).

Folding has, in places, also affected the northerly trending gneissosity (Fig. 6). Both, greenstone enclaves and the gneissosity of the granitoid have been deformed into non-cylindrical, generally northerly trending folds (Fig. 6). Where migmatization has reached

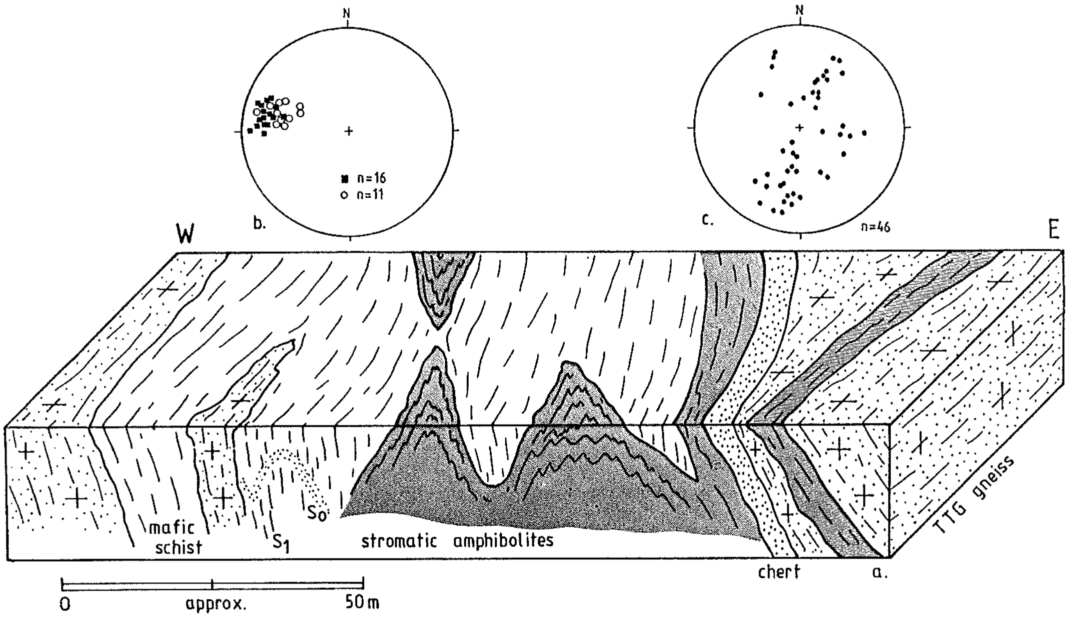



*Figure 5a: Schematic cross-section through the northern termination of a prominent greenstone xenolith at Batavia North (Locality B, Fig. 2). Note the obliteration of the primary layering ($S_o$) in talc-carbonate schists by a secondary schistosity as well as the non-cylindrical folding, producing doubly plunging folds.*

*b: Lower hemisphere equal area projection of poles to the TTG gneissosity (full squares) and poles to the schistosity (open circles) in talc-carbonate schists.*

*c: Lower hemisphere equal area projection of fold axes at Batavia North. Note the wide scatter of fold axes around NNE trends, reflecting the predominance of periclinal and domical folds.*

more advanced stages, i.e. where greenstone xenoliths have been strongly dismembered and the ratio of anatectic leucosome (Robb, 1983) to amphibolitic restite increases, folding is highly irregular, showing doubly plunging, domical, often convolute folds with variable trends of axial traces (Fig. 7).

**Weergevonden**

A west-northwesterly trending, northerly dipping train of greenstone xenoliths is exposed on the farm Weergevonden (Fig. 2, point C). At this locality, the greenstone enclaves consist mainly of felsic schist and minor amphibolites which allows a correlation with the Theespruit Formation of the lower Onverwacht Group (Anhaeusser, 1978; Robb, 1981a,b). A cross-section along a road-cut (Fig. 8a) illustrates the intrusive relationships between tonalitic granitoids and moderate northerly to northeasterly dipping greenstone lithologies. Porphyritic and/or gneissose tonalites interfinger with the greenstones and occur as veinlets subparallel to the foliation of the greenstones. With increasing granitic material, xenoliths of felsic schist and amphibolites are wedged-off and incorporated but fragments

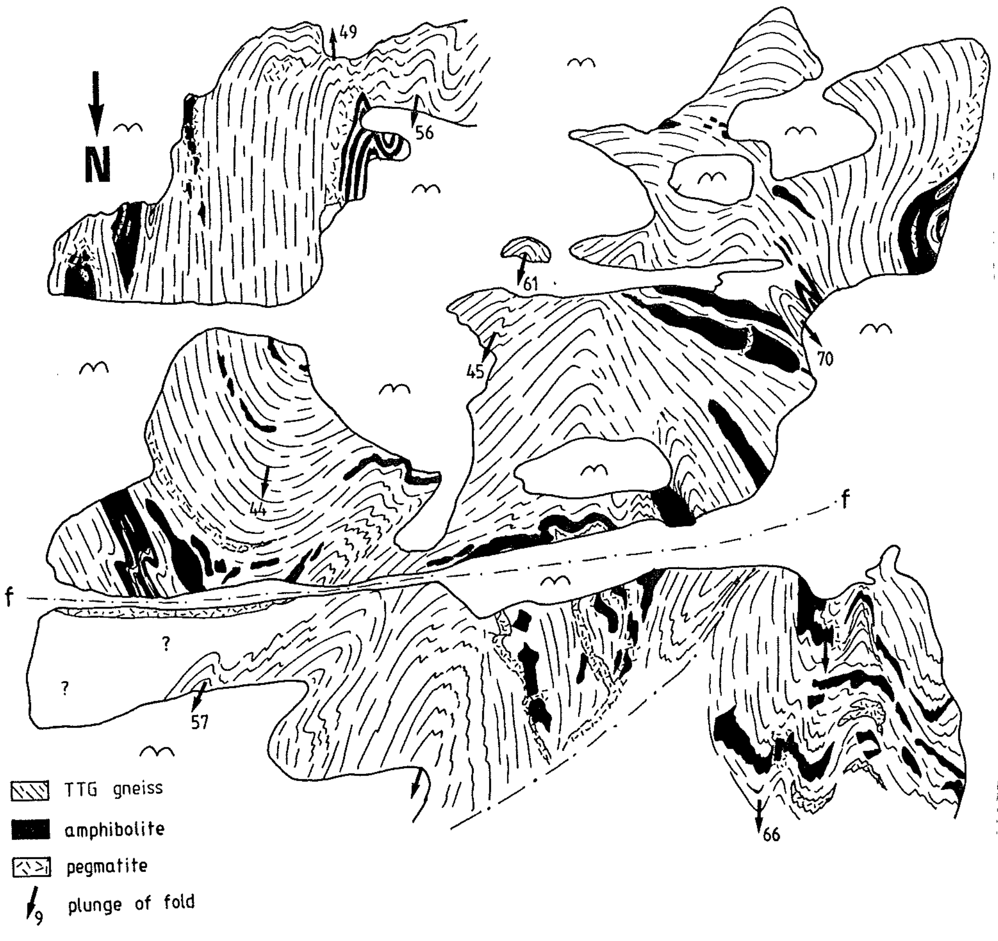



*Figure 6: Sketch map of a gneiss pavement at Batavia North illustrating the folding of the tonalitic gneissosity together with amphibolitic fragments. Although showing variable plunges, fold axes have predominantly northerly plunges parallel to the strike of the engulfing gneissosity and the greenstone xenoliths, respectively.*

retain their moderate northerly dips (Fig. 8a, around 100m, 140m, and 190m). A northerly dipping gneissosity in the intrusive tonalites is variably developed and is parallel to the intrusive contacts as well as the schistosity within greenstones. This tonalitic gneissosity is frequently folded together with the schistosity in felsic schists and amphibolites. An examination of folds in this road-cut (Fig. 8a, around 70m, 170m, 200-220m) shows they are moderately inclined to recumbent and verge invariably to the south. The type of folding can be examined in river bed exposures immediately east of the road-cut (see also Robb, 1981a,b). Folds are frequently of periclinal or domical shapes and, as such, show easterly as well as westerly plunges although moderate easterly plunges dominate (Fig. 8b). Axial planes trend easterly, parallel to the overall strike extent of the greenstone xenoliths. Where felsic schists and tonalitic material are in contact, the less competent schistose material forms tightly pinched cusps along the interface with the tonalitic granitoids (Fig. 8a, between 222 and 245m).

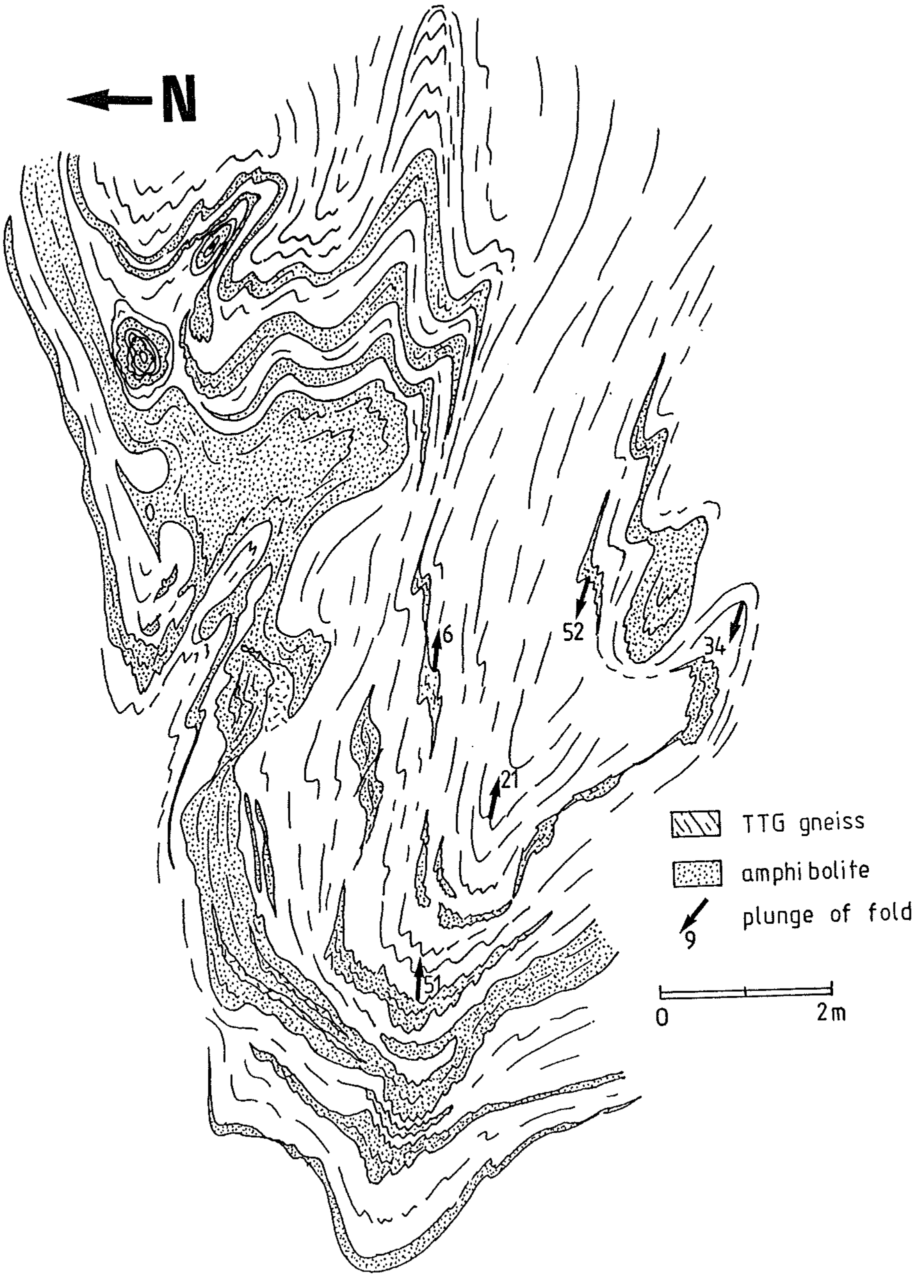



*Figure 7: Complexly folded stromatic amphibolite at Batavia North.*

The southern contact between the greenstone xenoliths and tonalitic gneisses is characterized by intense migmatite development and high strain fabrics in both the greenstones as well as the tonalites which show a subparallel, pervasively developed planar and linear fabric (Fig. 9a). Minor 'S'- and 'Z'- fold symmetries that are developed within the greenstones possibly indicate tight to isoclinal folding of the predominantly felsic schists. Sheath folds (Fig. 9b), which are locally developed within the highly strained felsic schists and amphibolites, probably represent amplified periclinal folds, the latter being developed in the lower strained parts of the greenstone xenolith. Tonalitic apophyses within the greenstones show pinch-and-swell and boudinage structures; the intermediate boudin axes trend east, parallel to the schistosity.

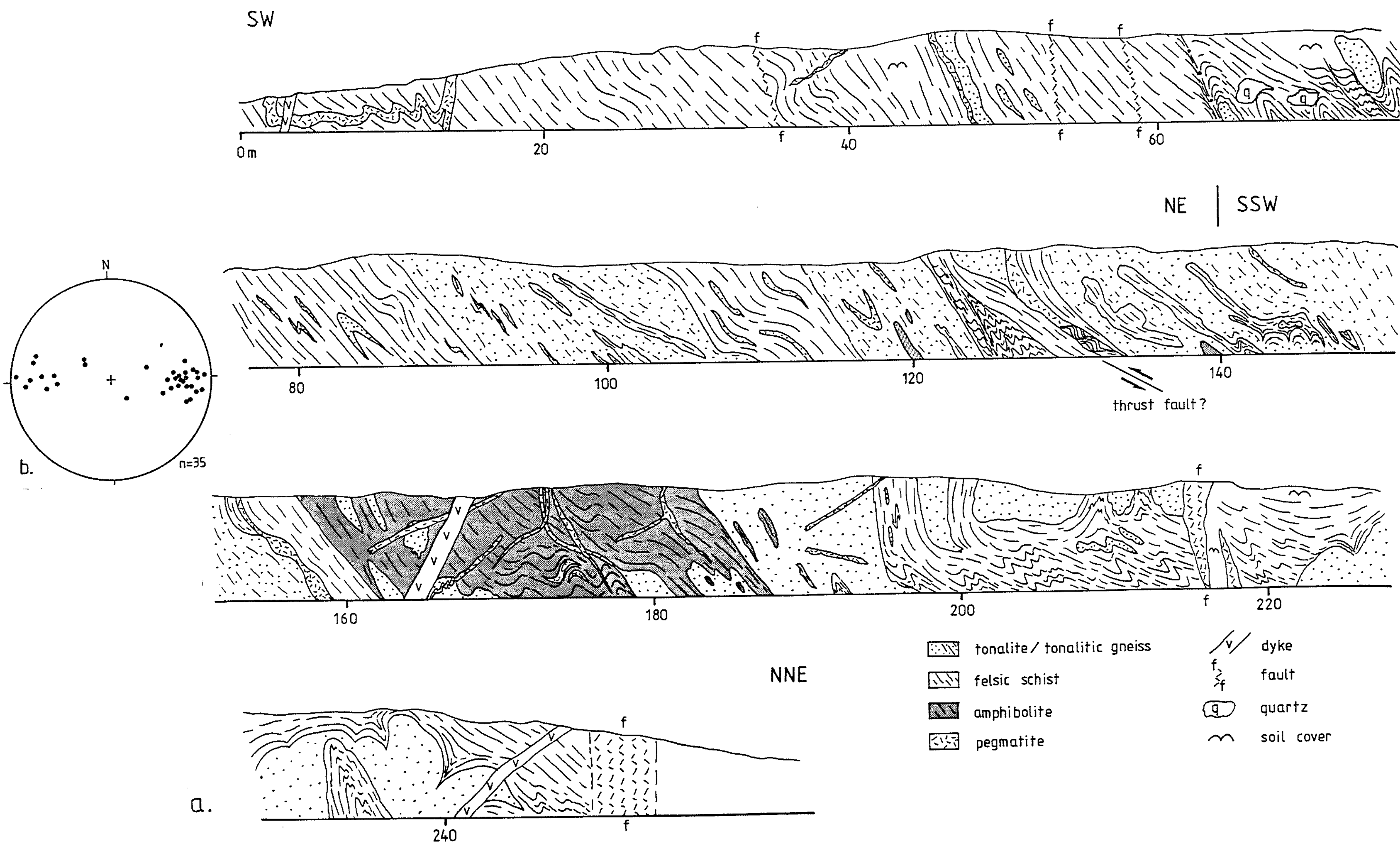



*Figure 8a: Simplified cross-section through the central parts of the Weergevonden greenstone xenolith along a road-cut (Badplaas-Lochiel road).*
*b: Lower hemisphere equal area projection of fold axes taken immediately east of the cross-section. The scatter of fold plunges illustrates the predominantly periclinal fold geometries.*

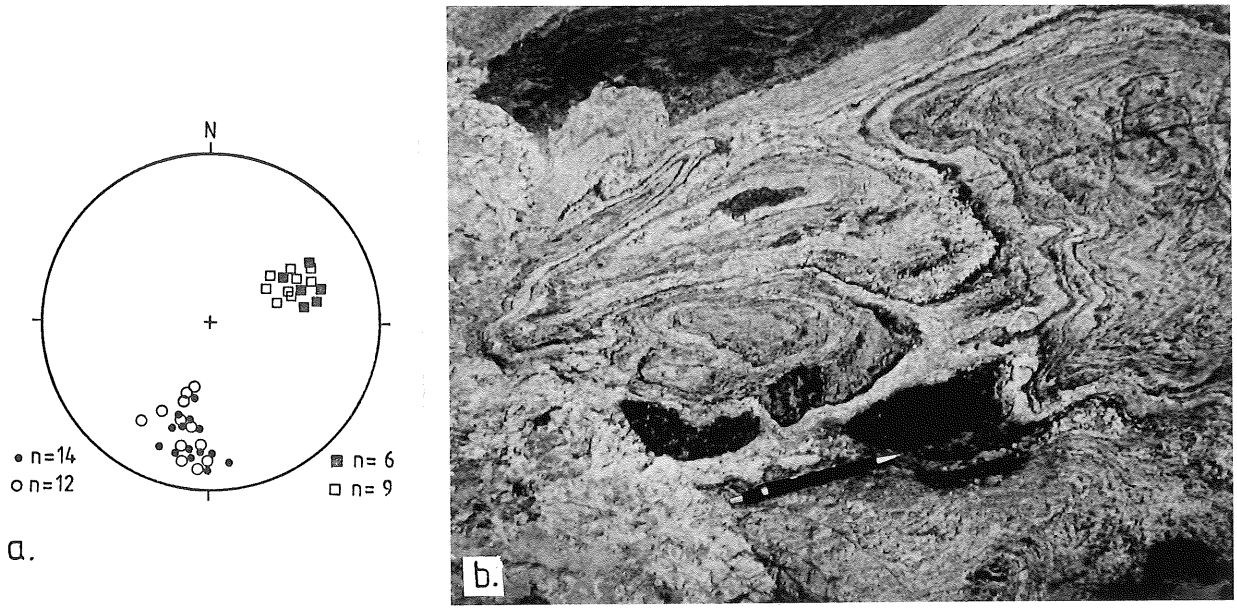



*Figure 9a: Lower hemisphere equal area projection of poles to the gneissosity in tonalitic gneisses (full circles), schistosity in felsic schist (open circles) and lineations in tonalitic gneisses (full squares) together with lineations in felsic schists (open squares) along the southern margin of the Weergevonden greenstone enclave.*
*b: Oblique plan view of sheath fold development along the strongly migmatized southern margin of the Weergevonden greenstone xenolith.*

**Uitgevonden**

A prominent greenstone xenolith on the farm Uitgevonden (Fig. 2, point D) comprises mainly amphibolites which are interlayered with serpentinites. A steep southeasterly dipping, northeasterly trending gneissosity of the well-foliated tonalitic intrusion is parallel to the contacts with the subvertical greenstone enclave (Fig. 10a,b). Intensely folded amphibolites characterize the contact between the tonalitic gneisses and greenstones (Fig. 10a), but deformation decreases away from the contact. Folds within the amphibolites show steep southerly to southeasterly plunges, parallel to a well-developed quartz-plagioclase mineral lineation in adjacent gneisses (Fig. 10b). The gneissosity of the gneisses is approximately axial planar to folds in amphibolites. Refolded boudinaged leucosome veins, leucosomes folded together with the foliation within amphibolites, and leucosomes which partly cross-cut but are also affected by the folding in amphibolites document the syntectonic migmatization of the greenstone lithologies (Fig. 10a).

The finite strain recorded in this part of the greenstone xenolith can be deduced from outcrops illustrating the multiphase generation and\or intrusion and subsequent deformation of granitic (sensu lato) veins in amphibolitic greenstones (Fig. 11). Intrusive tonalitic and\or granitic (anatectic ?) veinlets can be shown to be boudinaged parallel or subparallel to the foliation within amphibolites. The same veins are intensely folded when occurring normal or subnormal to the amphibolitic foliation. The multiple and highly complex cross-cutting relationships between leucocratic veins as well as the decrease in the intensity of deformation associated with later veinlets indicate a protracted time of deformation. The orientation of the finite strain ellipse, determined from the orientation of boudins, pinch-and-swell structures, folds and axial planar foliations is parallel to the amphibolitic foliation and engulfing gneissosity of the Uitgevonden pluton respectively (Fig. 11).

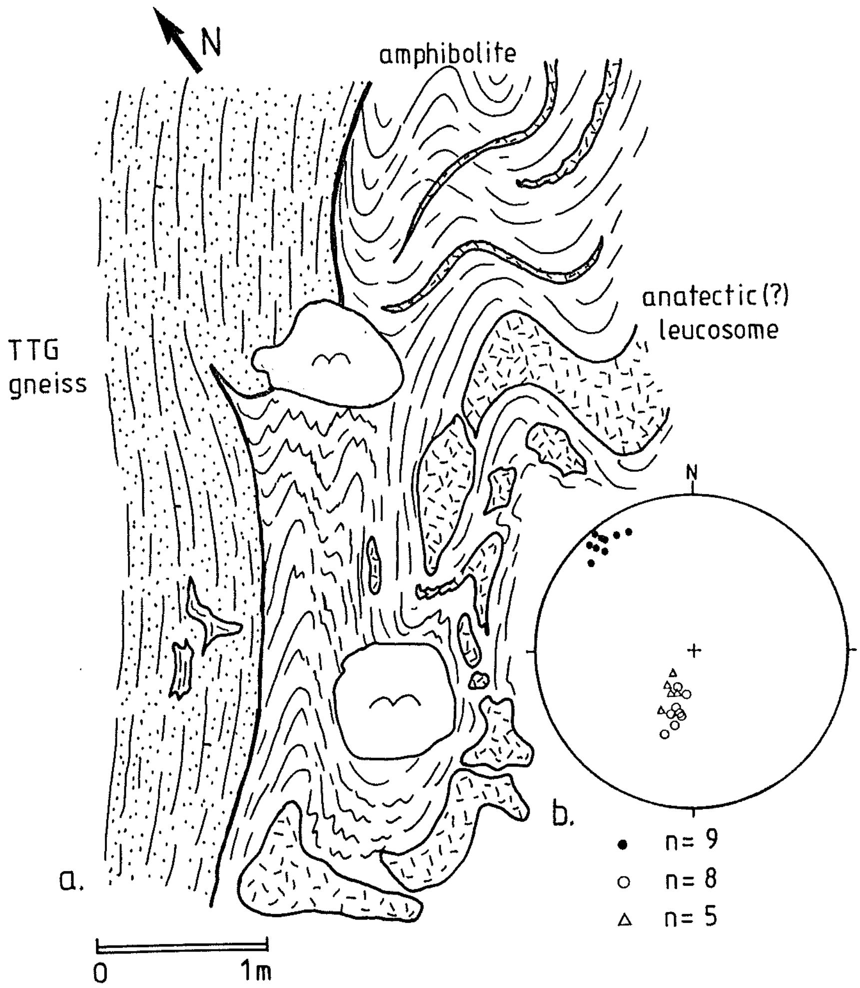



*Figure 10a: Sketch map of the intense folding developed along the contact between tonalitic-trondhjemitic gneisses and amphibolitic greenstones at Uitgevonden (locality D, Fig. 2).*

*b: Lower hemisphere equal area projection illustrating the subparallelism of mineral lineations in tonalitic gneiss (open circles) and fold axes in amphibolites (open triangles). Full circles represent poles to the gneissosity in the tonalitic gneiss which is approximately axial planar to folds in amphibolites.*

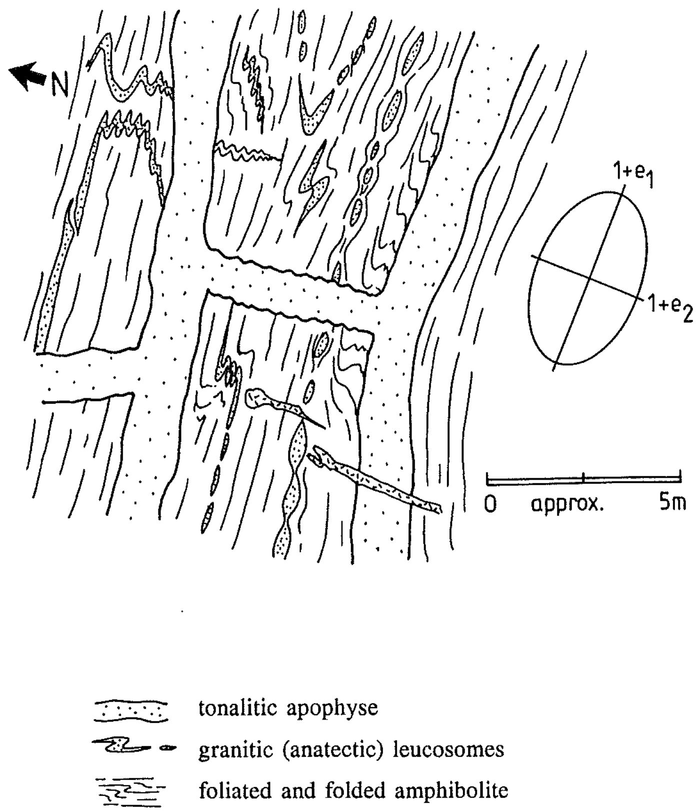



*Figure 11: Composite sketch of the structural relationship between folded and boudinaged granitic veinlets and tonalitic apophyses outlining the finite strain ellipse; compiled from river pavement, Uitgevonden locality (point D, Fig. 2).*

## Tjakastad Schist Belt

The Tjakastad Schist Belt represents a N-S trending outlier of the BGB, sandwiched between the Stolzburg pluton in the west and Theespruit pluton in the east (Fig. 2, point E). The northern part of the Tjakastad Schist Belt consist mainly of felsic schist with minor amphibolites, serpentinites, and talc-carbonate schists (Fig. 12a). The occurrence of prominent units of felsic schist characterizes the Theespruit Formation (Viljoen and Viljoen, 1969). The schists in the Tjakastad Schist Belt comprise fine-grained lithologies, which probably represent meta-tuffs, as well as coarse, agglomeratic varieties. Structurally, the most prominent feature within the schists of the Theespruit Formation in the Tjakastad Schist Belt is a pervasively developed, northerly trending schistosity, parallel to the contacts with the Stolzburg and Theespruit plutons, which is associated with a steep to subvertically plunging mineral (and fragment) stretching lineation (Fig. 12b). The alignment of contact-metamorphic garnet parallel to the subvertical lineation in the amphibolite-grade greenstones suggests a syntectonic growth of metamorphic minerals in the contact aureole of the Theespruit pluton underlining the diapiric nature of the TTG plutons. Within the felsic schists, steeply plunging, isoclinal, upright folds lie within the foliation and are possibly

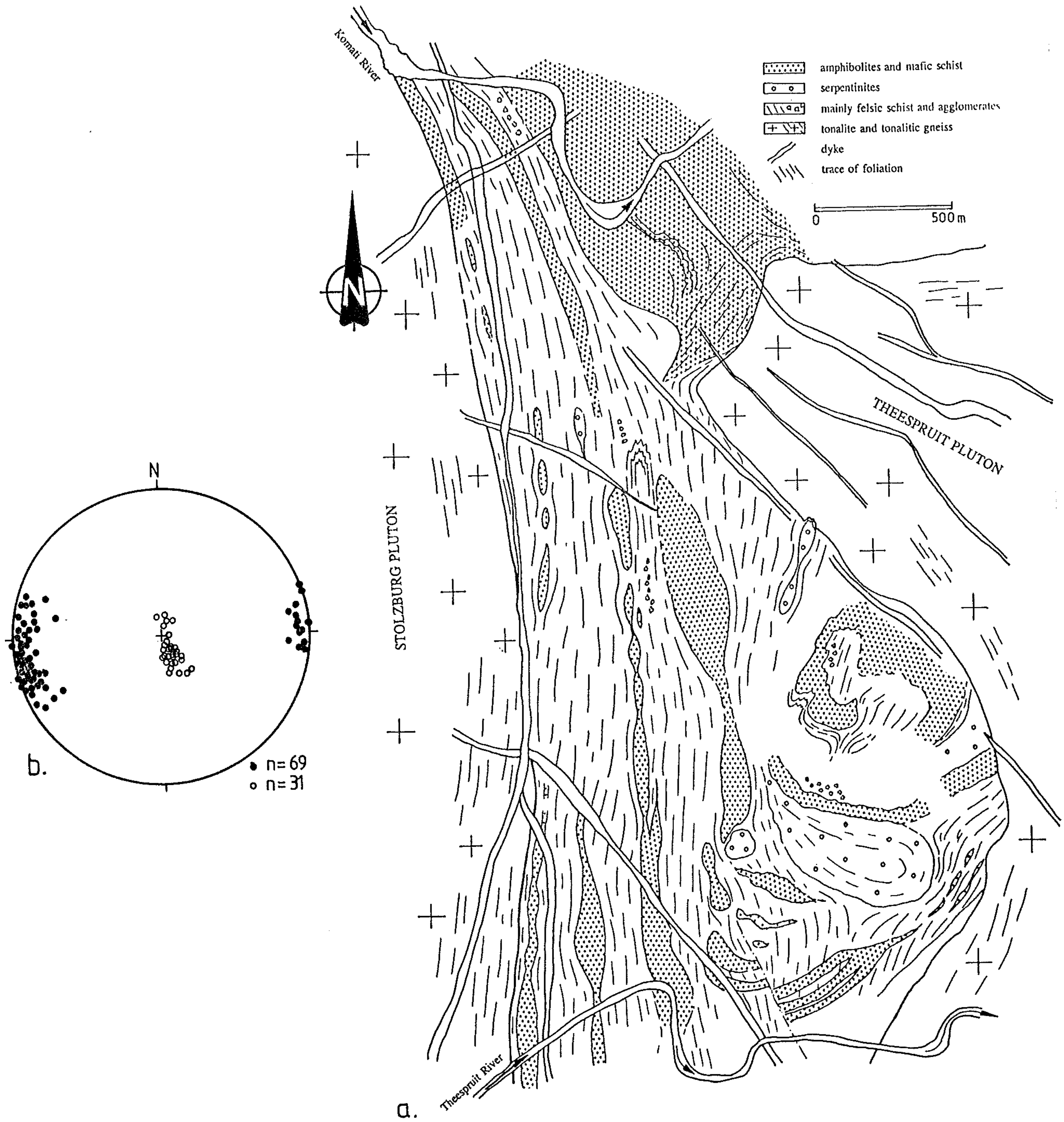



*Figure 12a: Simplified geological map of the Tjakastad Schist Belt. Note the pervasively developed schistosity in felsic schists parallel to the contacts of the adjacent Stolzburg and Theespruit plutons and the boudinage of competent amphibolitic units where parallel to the schistosity.*

*b: Lower hemisphere equal area projection to poles of the predominant northerly trending schistosity (full circles) and mineral and clast stretching lineation (open circles) in felsic schists and agglomerates of the Tjakastad Schist Belt.*

responsible for the partly duplicated and unusually thick sequence of felsic schists in this area. Poorly foliated, massive amphibolitic and ultramafic serpentinitic units interlayered with the felsic schists are commonly boudinaged where they occur located between the Stolzburg and Theespruit plutons, but revert to being continuous units to the north, where they are in direct contact with the greenschist-facies sequence of the main body of the BGB (Fig. 12).

The central parts of the Tjakastad Schist Belt are dominated by a large-scale fold structure, outlined by the closure of lithological units north of the Theespruit River (Fig. 12a). In this part of the Tjakastad Schist Belt the northerly trending schistosity, which is subparallel to the lithological bedding in the northern part of the schist belt, is orientated at high angles to the lithologies, and is approximately axial planar to the fold structure referred to above. This schistosity is refracted and wrapped around more competent units such as serpentinites (Fig. 12a). In felsic and mafic schist, however, the intensity of the subvertical foliation obliterates any primary layering on an outcrop scale and original compositional layering and/or bedding is only evidenced by the trend of prominent lithological units (Fig. 12a). The actual plunge of the northerly to northeasterly trending fold structure is difficult to establish but appears to be at moderate angles to the northeast.

## DISCUSSION

Mineral fabrics and gneissosities recorded in TTG plutons frequently describe concentric patterns, reflecting the elliptical shapes of individual plutons and/or contacts between TTG plutons and greenstones. No regionally consistent gneissosity of mineral fabric is evident in the TTG plutons.

Subtle foliations and linear fabrics, which are expressed by an alignment of primary igneous, euhedral plagioclase, biotite and/or hornblende with interstitial quartz, are likely to reflect a mineral fabric formed by magmatic flow (e.g. Berger and Pitcher, 1970; Castro, 1987; Vernon et al., 1983; Paterson et al., 1989). Minerals show little sign of plastic deformation and their preferred orientation appears to be largely the result of the rotation and alignment of primary igneous minerals in the presence of a melt phase, i.e. in a magma. The development of more pronounced planar and linear fabrics in TTG's is associated with the progressive recrystallization of euhedral igneous minerals and the obliteration of igneous textures and grain boundary contacts. Marginal and ultimately pervasive recrystallization and grain refinement of plagioclase, deformed biotite crystals and strongly undulose, recrystallized quartz or quartz-ribbons are indicative of a solid-state deformation (Holder, 1981; Bateman, 1985; Paterson et al., 1989). This fabric is likely to have developed in the absence of a melt phase, probably during the cooling and ballooning stages of the plutons. Subsolidus deformation is, furthermore, strongly suggested by the refolding and crenulation of the earlier-formed gneissosity and deformation of greenstone xenoliths contained within the gneissose foliation. The subparallelism, co-axial refolding and gradational transitions between these various fabrics suggest a continuum between early-stage magmatic processes during the ascent of the granitoids and later high-temperature solid-state processes operating during the cooling of the TTG plutons. Finely brecciated, narrow, subvertically dipping zones subparallel to the contacts of the plutons are indicative of a late-stage, low-temperature, brittle deformation along the margins of the TTG plutons.

Subvertically inclined greenstone xenoliths which are commonly concentrated and aligned along the margins of plutons show an intense internal deformation. The orientation and vergence of structural elements within greenstone xenoliths is clearly related to the fabric development within the TTG plutons and the relative position of xenoliths within individual plutons. This is evidenced by the co-axiality of structural elements within greenstone enclaves and tonalitic gneisses and includes 1) the orientation of the schistosity and mineral lineation in greenstone xenoliths subparallel to the gneissose foliation and mineral lineation in the engulfing gneisses; 2) the overprinting of original layering in ultramafic schists by a secondary schistosity which is parallel to the gneissosity in adjacent tonalitic gneisses; 3) the gneissosity of adjacent tonalitic gneisses which is commonly axial planar to folds within enclosed greenstone xenoliths; and 4) the orientation of intermediate boudin axes of syntectonic veins as well as more competent greenstone lithologies within greenstone xenoliths which is frequently parallel to the trend of the gneissosity of the enclosing gneisses. This subparallelism of structural elements within greenstone xenoliths and engulfing TTG gneisses makes it unlikely that the deformation observed in greenstone xenoliths is inherited, i.e. represents a deformation phase formed prior to the intrusions of the TTG plutons. It rather suggests that fabric development in TTG plutons occurred together with the deformation in the greenstone xenoliths. In fact, it suggests that the gneissosity-forming event which occurred during cooling and ballooning of the TTG plutons caused the complex deformation in the enclosed xenoliths.

The structural development and the orientation of structural elements within greenstone xenoliths as well as the refolding and crenulation of earlier-formed gneissosities indicate a complex type of strain during cooling and ballooning of the plutons. Boudinage and pinch-and-swell structures of competent syntectonic veins, tonalitic-trondhjemitic apophyses or competent greenstone lithologies indicate a flattening strain normal to individual greenstone xenoliths, greenstone outliers (e.g. Tjakastad Schist Belt) and the gneissosity in the TTG granitoids respectively. Flattening strains are commonly reported for ballooning plutons along their margins and within the contact aureoles of the intrusions (e.g. Bateman, 1985; Clarke, 1992). However, the intense folding and fabric development within greenstone xenoliths as well as the co-axial refolding and crenulation of the earlier-formed gneissosity are indicative of a component of non-coaxial deformation, namely heterogeneous simple shear subparallel to the margins of the plutons.

In summary, fabric development in TTG plutons and the deformation of greenstone enclaves illustrate the progression from the initial intrusion, diapiric ascent, magmatic flow, and alignment of crystals and country-rock inclusions (i.e. greenstone xenoliths) to subsequent cooling, ballooning, and solid-state deformation. From this progression, the following sequence of events can be deduced:

1) The intrusion of tonalitic-trondhjemitic granitoids into the pre-existing greenstone sequence of the lower Onverwacht Group at about 3460 to 3440 Ma prised-off and incorporated country-rock xenoliths (i.e. greenstone lithologies of the lower Onverwacht Group). The alignment of primary igneous minerals during diapiric ascent, which produced an early magmatic foliation, as well as the alignment of greenstone xenoliths parallel to magmatic flow lines (i.e. the margins of TTG plutons), outlines the elliptical geometry of the intrusions. Incompletely separated and incorporated greenstone lithologies are wedged

between individual, plutons but are still connected to the overall greenstone sequence within the belt (e.g. Tjakastad Schist Belt, Jamestown Schist Belt, Nelshoogte Schist Belt, etc. (Figs. 1 and 2)); and

2) a pronounced to locally pervasive gneissosity is indicative of a high-temperature solid-state deformation during the cooling and ballooning stages of the TTG plutons. Greenstone xenoliths respond to this fabric development in the engulfing granitoids by intense internal folding, shearing and boudinage. The coeval development of the gneissosity in the granitoids and the deformation in greenstone xenoliths is evidenced by the co-axiality of structural elements in the greenstone enclaves and the gneissosity of the engulfing TTG plutons. Greenstone xenoliths that were not perfectly aligned with the margins of plutons during the early stages of magmatic flow are folded as in their entirety, the gneissosity in adjacent TTG gneisses being approximately axial planar (e.g. Batavia fold structure, Fig. 4a).

## REGIONAL IMPLICATIONS

Clearly intrusive contacts of most of the southern TTG plutons (with the exception of the Steynsdorp pluton) with the lower Onverwacht Group testify to the largely autochtone nature of the plutons with respect to the BGB. Single-zircon ages of 3460-3440 Ma for the intrusions underscore the fact that the plutons have experienced all deformational events proposed for the BGB. However, the absence of a regionally consistent fabric in the TTG plutons and the lack of evidence of any deformation features within the TTG's that could be related to the intense deformation in the central parts of the BGB is evidence of considerable competence contrasts between the granitoid basement and the volcano-sedimentary succession of the BGB during subsequent deformational phases.

Contacts between the TTG plutons and greenstone lithologies are frequently characterized by strongly attenuated, synformal cusps of greenstone material which project into the tonalitic-trondhjemitic gneisses giving the BGB its characteristic arcuate geometry (Fig. 1). Synformal infolding of greenstone lithologies is frequently associated with the development of a subvertically dipping axial planar schisosity (Fig. 11b; Jamestown Schist Belt: Anhaeusser (1972); Stolzburg Syncline: Reimer, 1967; De Wit et al., 1983). The progressive development of this schistosity can lead to a transposed and even mylonitic fabric which is developed parallel to the limbs of the fold structures where the greenstone material is wedged between the tonalitic-trondhjemitic basement (Anhaeusser, 1972; Fripp et al., 1980; De Wit et al., 1983). Where preserved, secondary folds show moderate-to-shallow plunges subparallel to the plunge of the large-scale synforms which, in places, can be almost at right angles to the general NE-SW grain of the greenstone belt (Anhaeusser, 1972). The characteristic tightening and pinching of synforms with depth from open fold shapes to isoclinal shapes following the down-dip of the axial plane is also documented by Lamb (1984) for greenstone sequences in the southeastern parts of the BGB in northwestern Swaziland.

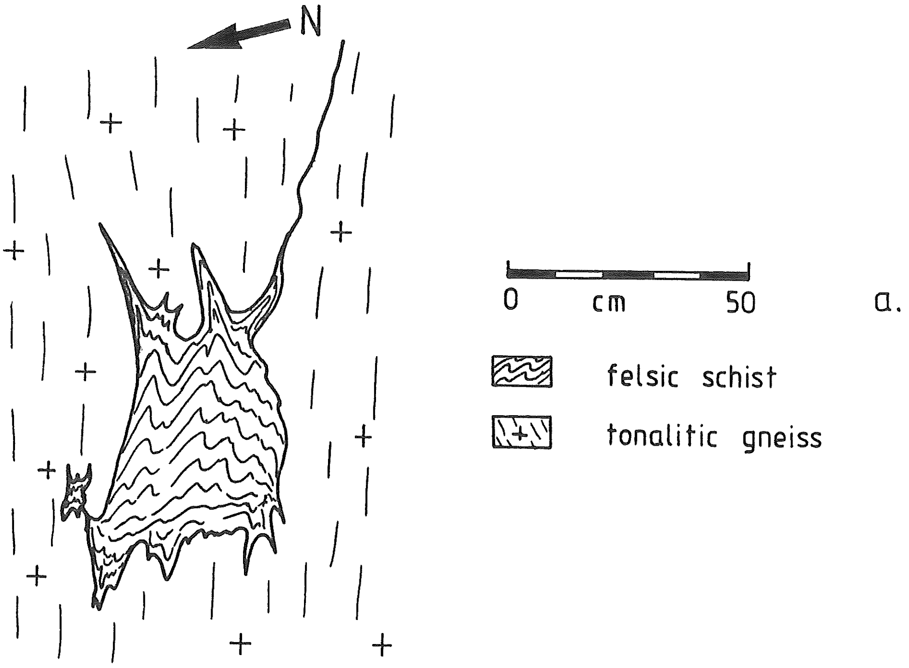
The alternation of rounded and sharp-crested folds along an interface which separates two materials of distinctly different competences is generally believed to be the result of shortening parallel to this interface. Folds developed in such a manner are termed cuspate-lobate folds or mullions (e.g. Wilson, 1953; Ramsay, 1967; Ramsay and Huber, 1987;

Smith, 1975, 1977; Soukoutis, 1987, 1990). The incompetent material tends to form tight synforms with large amplitude to wavelength ratios giving rise to the typically pinched appearance of the synforms which separate broad, rounded antiforms of competent material showing low amplitude to wavelength ratios. Progressive or repeated deformation amplifies the cusp-like synformal structures to give highly attenuated flame structures protruding into the more competent material. Cuspate-lobate folds are described for a wide variety of scales ranging from outcrop scales (Figs. 13a,b and 8a;) (e.g. Fripp, 1980; Anhaeusser, 1984; Jackson, 1984; Cosgrove, 1980) to "basement-cover" relationships on regional scales. In fact, regional-scale cuspate-lobate relationships between a competent, crystalline, often granitoid "basement" and an incompetent sedimentary or volcano-sedimentary "cover" succession have been demonstrated for many orogenic zones such as the Western Alps and the Jura Mountains (e.g. Heim, 1921; Ramsay, 1963, 1967) or the Zimbabwean Craton (Ramsay, 1967; Snowden, 1984).

We conclude that the tight synformal infolding of greenstone material into enclosing TTG granitoids which results in the characteristic arcuate geometry of the Barberton greenstone belt (Fig. 1) is the result of a regional-scale "cuspate-lobate" relationship between competent basement granitoids and a less competent greenstone cover succession. The initial geometry of the BGB is strongly influenced by the intrusion of TTG plutons which show intensely deformed and metamorphosed contact aureoles (Anhaeusser, 1969, 1981a,b; 1983a; Cloete, 1991). Repeated, predominantly NW-verging thrusting and folding, i.e. compressional tectonics during $D_2$ and $D_3$ (e.g. De Ronde and De Wit, in press) led to subhorizontal shortening parallel to the basement (granitoid) - cover (greenstone) interface, resulting in the tight infolding of greenstone sequences into the competent TTG basement.

This model bears further important implications as to the structural development and the present day geometry of the BGB as a whole. Considering the geophysical results of De Beer et al. (1988) which suggest a maximum depth of the BGB of not more than 7 km, competence contrasts during subsequent deformational phases between a granitoid basement and a volcano-sedimentary cover sequence are likely to be reflected in the BGB. Due to the primarily irregular interface between the diapir-shaped basement granitoids and the cover succession, complex strain patterns and fold interferences are to be expected even during a single deformational event. The refolding and progressive arcuation and tightening of earlier fold structures along the margins of a TTG pluton, which is associated with the development of an intense transsecting schistosity parallel to the margins of the pluton, has been documented by Tomkinson and King (1991) for the Eureka Syncline (Fig. 1) (see also Ramsay, 1963a; Anhaeusser, 1964, 1969). This underlines the significance of the proximity and geometry of basement rocks for the resulting fold geometry and structural development of the greenstone sequence. Prominent synformal structures which dominate over antiformal structures (e.g. Viljoen and Viljoen, 1969, Anhaeusser, 1983a; Lowe, 1991; Tomkinson and King, 1991) could represent the surface expression of tightly pinched synforms in depth at the actual contact between a granitoid basement and a greenstone cover.

Considerable competence contrasts between basement granitoids and the volcano-sedimentary cover is, furthermore, suggested by the emplacement pattern of syndeformational intrusions. The northwesterly trending intrusions of the Boesmanskop and Kees Zyn Doorns syenites in the south of the BGB (Fig. 2) yield ages of 3107 (e.g. Kamo and Davis, 1991)



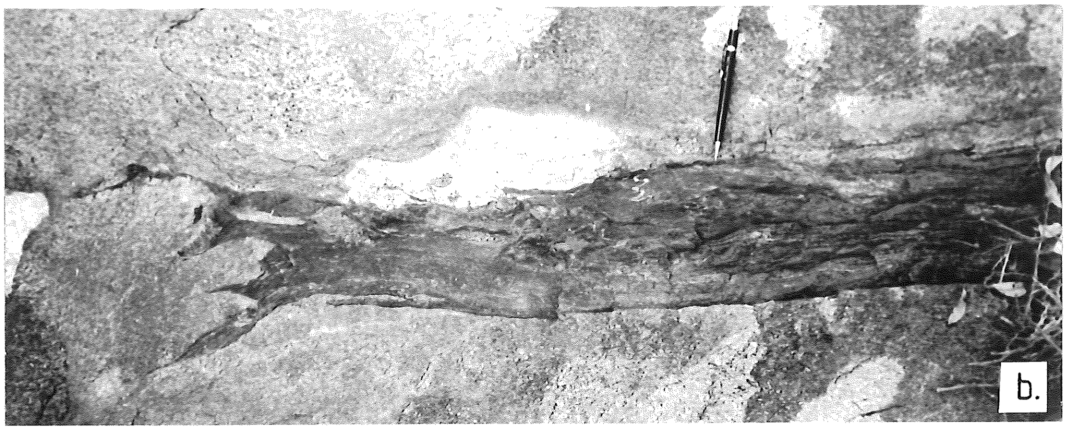




*Figure 13a: Sketch of enclave of felsic schist in tonalitic gneiss. The felsic schist displays cusp-like forms against the lobate tonalitic gneiss. Note that the folding within the xenolith is unlikely to be inherited from an earlier deformation event, as the gneissosity in the adjacent TTG is axial planar to folds within the xenolith (i.e. the folding within the xenolith as well as the formation of the gneissosity appear to be coeval as a result of approximately N-S directed shortening strain); Weergevonden locality (Fig. 2, locality C).*

*b: Amphibolitic xenolith in tonalitic gneiss showing cuspate-lobate forms along the margins. The incompetent amphibolite forms cusp-like flame-structures protruding into the tonalitic gneiss as a result of shortening normal to the amphibolitic xenolith; note the ptygmatically folded vein along the upper margin of the amphibolitic xenolith, indicating the shortening normal to the xenolith; locality is situated at southern margin of the Theespruit pluton.*

and, as such, are largely contemporaneous with the NW-directed $D_3$ deformation phase (e.g. De Ronde and De Wit, 1993). The pronounced linear trend of the syenites parallel to the proposed shortening direction (NW-SE) possibly indicates a brittle behaviour of the granitoid basement during intense folding and thrusting of the cover sequence in which dilation of the intrusions was easiest to achieve parallel to the compressive stress. Northwesterly trending dykes as well as NW-SE trending prominent fault or fracture zones which are characterized by thermal springs (Anhaeusser et al., 1983b) can also be interpreted as being part of this stress pattern, although exact ages of the timing of dykes and fault zones are unknown.

## CONCLUSIONS

1) Fabric development in the 3460-3440 Ma old TTG plutons along the southern margin of the BGB records the progression from an early-stage magmatic foliation to a high temperature solid-state deformation during cooling and ballooning of the tonalitic diapirs.

2) The deformation observed in ultramafic and mafic greenstone enclaves within the TTG plutons suggests that the deformation of xenoliths occurred together with the gneissosity-forming event in the TTG plutons. An alignment of greenstone enclaves during the magmatic stages of the plutons was succeded by the intense folding and fabric development accompanying the solid-state deformation of the plutons during cooling and ballooning.

3) The strain recorded in deformed xenoliths is a combination of a pure flattening strain subnormal to the mafic enclaves and a heterogeneous simple shear parallel to the margins of xenoliths and the contacts of plutons, respectively.

4) Despite their largely autochtonous nature, the TTG plutons and enclosed xenoliths show no regionally consistent fabric reflecting the NE-SW structural grain of the BGB to the immediate north of the study area. This points to considerable competence contrasts between the granitoid basement and the volcano-sedimentary greenstone cover during subsequent deformations.

5) The tight synformal infolding of greenstone lithologies into TTG plutons along the margins of the greenstone gelt, giving the BGB its characteristic arcuate geometry, is interpreted to reflect the competence contrast between a granitoid basement and a greenstone cover. Subhorizontal shortening associated with subsequent deformational phases ($D_2$ and $D_3$) parallel to the basement-cover interface results in the development of regional-scale cuspate-lobate folds.

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