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by

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ABSTRACT

An extensive greenstone terrane, termed the Greenlands Greenstone Complex, is exposed in the southeastern sector of the core of the Vredefort Structure. A second, smaller and less exposed greenstone occurrence is known from the western margin of the core. Both areas have been mapped in lithological and structural detail. Furthermore, several isolated exposures of basement gneiss were also mapped. Deformation styles, in the form of shear zones, mylonite zones, kinkbanding, and fracturing, as well as pseudotachylite and shatter cone occurrences, have been recorded. Chemically, the altered mafic-to-ultramafic greenstones resemble typical komatiitic and basaltic komatiitic-tholeiitic lavas of well-studied greenstone belts, such as the Barberton Mountain Land. The limited chronological data available suggest an age in excess of 3.35 Ga for this Complex which is intruded by at least three different populations of younger mafic dykes and sills, as well as bodies of alkali granite and feldspar porphyry. A spodumene-rich pegmatite also intrudes the Complex and contains in excess of 1 wt% lithium.

Although northeasterly and northwesterly trending shear and mylonite zones were observed in both the gneissic and greenstone terranes, it was found that conjugate shear zones are predominantly developed in the gneissic basement, whereas mylonitic zones are more prominent in the greenstones.

In the absence of any exposed contacts between the greenstones and the enveloping gneisses it is not possible to state with certainty what the relationship is between these lithologies. The authors favour the possibility that the greenstone terrane represents a large xenolith in the gneissic basement - this in preference to the hypothesis that these two terranes were tectonically juxtaposed. The presence of the South East Boundary Fault, as proposed in earlier literature, could not be confirmed in this study.

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INTRODUCTION

The Greenlands Greenstone Complex is located in the southeastern quadrant of the Vredefort Dome (Fig. 1). To the east and southeast of this greenstone remnant are three isolated exposures of ferruginous shales and orthoquartzites of the Orange Grove Formation of the Lower Witwatersrand Supergroup. These outcrops represent the best exposures of the collar rocks around the southeastern perimeter of the Vredefort dome.

A second, very much smaller, greenstone remnant comprising weathered talc- and actinolite-schists is exposed on the farm Wittekopjes 169 about 16 km south of the town of Vredefort. Remnants of these greenstones can be studied in several shallow prospecting trenches dating from the 1890s.

The Greenlands Greenstone Complex is shown on the geological map of the Vredefort area compiled by Nel (1927), but until recently this remnant received little attention. Some gold exploration took place in this part of the dome around the end of the previous century (Hall and Molengraaff, 1925) and a number of exploration trenches were excavated at that time, largely in silica-enriched schist and in granite or pegmatite intrusions that resemble quartz veins.

The controversy as to whether the Vredefort Dome (also referred to as the Vredefort Structure) was formed by asteroid impact or by cryptovolcanic processes has in recent years been further compounded by the proposal that tectonic processes might have played a major role in forming and/or developing the Vredefort Structure (for example, Reimold et al., 1990a, b; Colliston and Reimold, 1990, 1992; Reimold and Colliston, 1992; Hart et al., 1991). The recognition of tectonic activity prior to and during the evolution of the Vredefort Dome is derived largely from recent detailed structural mapping and studies of the pseudotachylites associated with the core of the Vredefort Structure. These studies have highlighted the need for further comprehensive structural geological analysis as, to date, only about 10% of the dome has been mapped in detail. The Greenlands Greenstone Complex and associated granitoid terrane in the southern portion of the dome were selected to complement the existing data base on the Broodkop Shear Zone (Colliston and Reimold, 1990) and to complete the mapping of the southern part of the Archaean core of the dome.

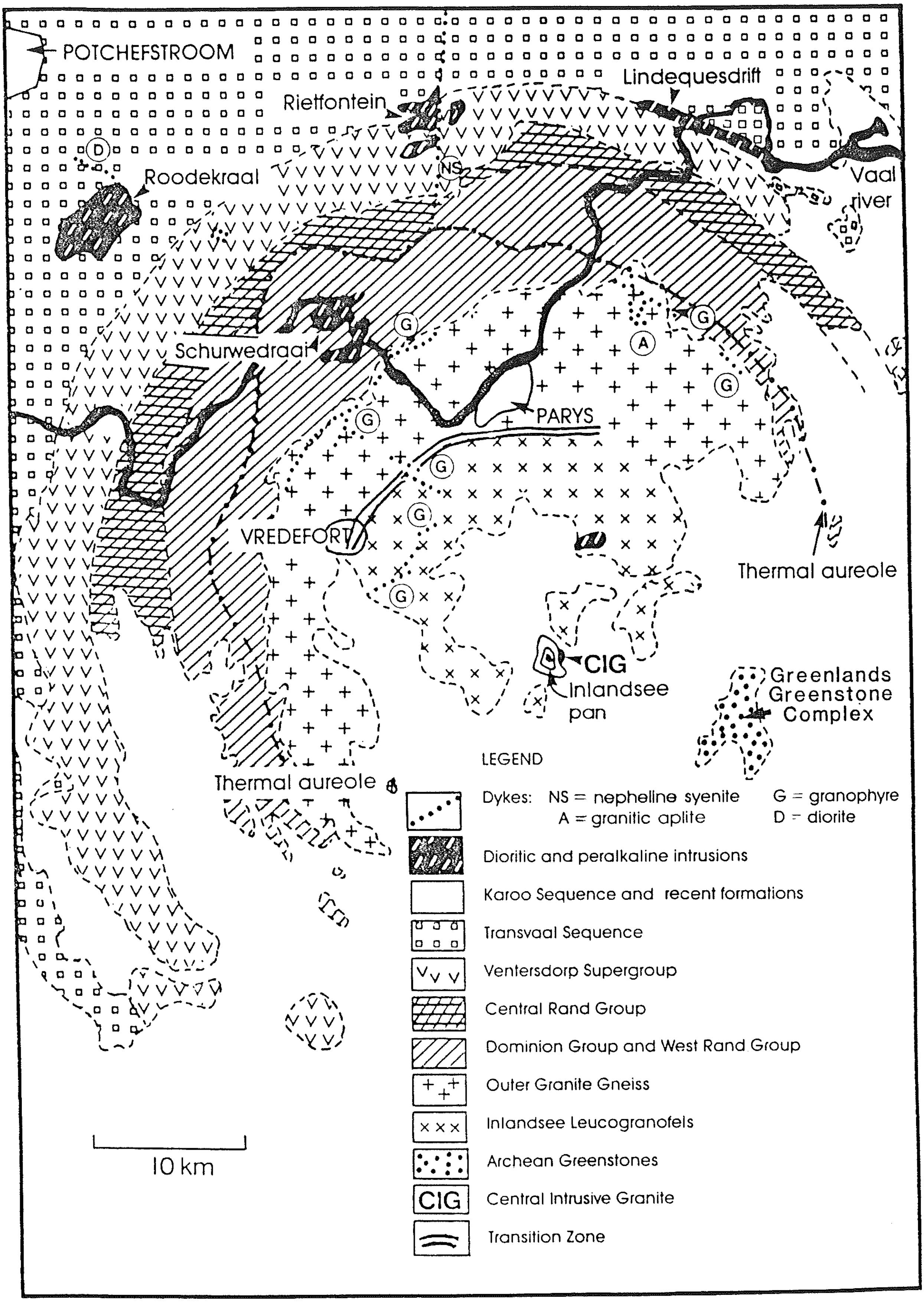


Figure 1: Simplified geological map of the Vredefort Dome, showing the locality of the Greenlands Greenstone Complex. (Modified after Bisschoff, 1988 and Reimold, 1991).

The results of earlier studies of this region (for example, Sawyer, 1903) are summarized by Hall and Molengraaff (1925) and Nel (1927) who emphasized the similarity between the greenstone lithologies at Greenlands and the Barberton Mountain Land in the eastern Transvaal. Nel (1927) pointed out that the granites and pegmatites are intrusive into the mafic and ultramafic rocks, and accordingly classified them as members of the 'Swaziland System' (Swazian - SACS, 1980). Nel also concluded that the Greenlands greenstones and the mafic or ultramafic xenoliths observed within the Archaean granite-gneiss found throughout the core of the Vredefort Dome, including the Steynskraal Metamorphic Zone (Stepto, 1990), were apparently unrelated.

According to Nel (1927) the "types of gold deposit in the ancient schists on Blaauwboschpoort 13 and adjoining farms are similar to the occurrences met with in the Jamestown series of the Barberton District" and he described these occurrences as impregnated schists or quartzose reefs, where mineralization is generally in the form of pyrite. It was assumed that the gold was introduced by the "Old Granite", the Archaean granite-gneiss of the Vredefort core (Fig. 1). Nel further reported that, in places, several gold- and silver-rich lodes were opened up around 1889 by the Blaauwboschpoort Gold Mining Co. Ltd., but the sporadic nature of the mineralization did not allow profitable exploitation.

Willemse (1937) recorded an occurrence of andalusite hornfels on the farm Avondale 6, that was also alleged to have been prospected for gold.

The only previously documented structural data for the Greenlands area were provided by Hall and Molengraaff (1925) who discussed the general strike and dip orientation of the greenstones, the granite gneisses, and the schists in the western greenstone remnant on the farm Wittekopjes 169. Besides these early reports, attention was given to this region by Bisschoff and Bisschoff (1988) who described the lithium-bearing pegmatites from farms Benshoop 74 and Avondale 6 (Fig. 2). Hart et al. (1990) proposed that the Vredefort Structure was intersected, in the vicinity of the north-northwestern margin of the Greenlands Greenstone Complex, by a northeast-southwest trending, vertically dipping shear zone, which they termed the South East Boundary Fault. They suggested that the terrane to the southeast of this fault, including the greenstone remnant, had been uplifted and juxtaposed to an originally relatively higher crustal level.

This report describes the geology and structure of the Greenlands Complex and surrounding granite-gneiss terrane. In addition, chemical analyses of volcanic and intrusive rocks of the greenstone complex are presented and discussed.

REGIONAL GEOLOGY

The crystalline basement in the southeastern quadrant of the Vredefort Dome (Fig. 1) is largely overlain by a thin veneer of Ecca Group shales and sandstones. In the wider environs of the greenstone terrane (especially south of the map area around the town of Koppies and to the south and southeast of the Greenlands Complex), Karoo intrusives are exposed, forming up to several metres wide and 50 - > 100 m long ridges. Small, but economic concentrations of bentonite are locally developed in palaeotopographic lows at the base of the Karoo strata. The contact between the basement gneisses and the Lower Witwatersrand rocks of the collar is completely obscured by Ecca shales.

LOCAL GEOLOGY

The results of detailed lithological and structural mapping are shown in the map of Figure 2. In the following the various rock types encountered, their characteristics, and relationships will be described:

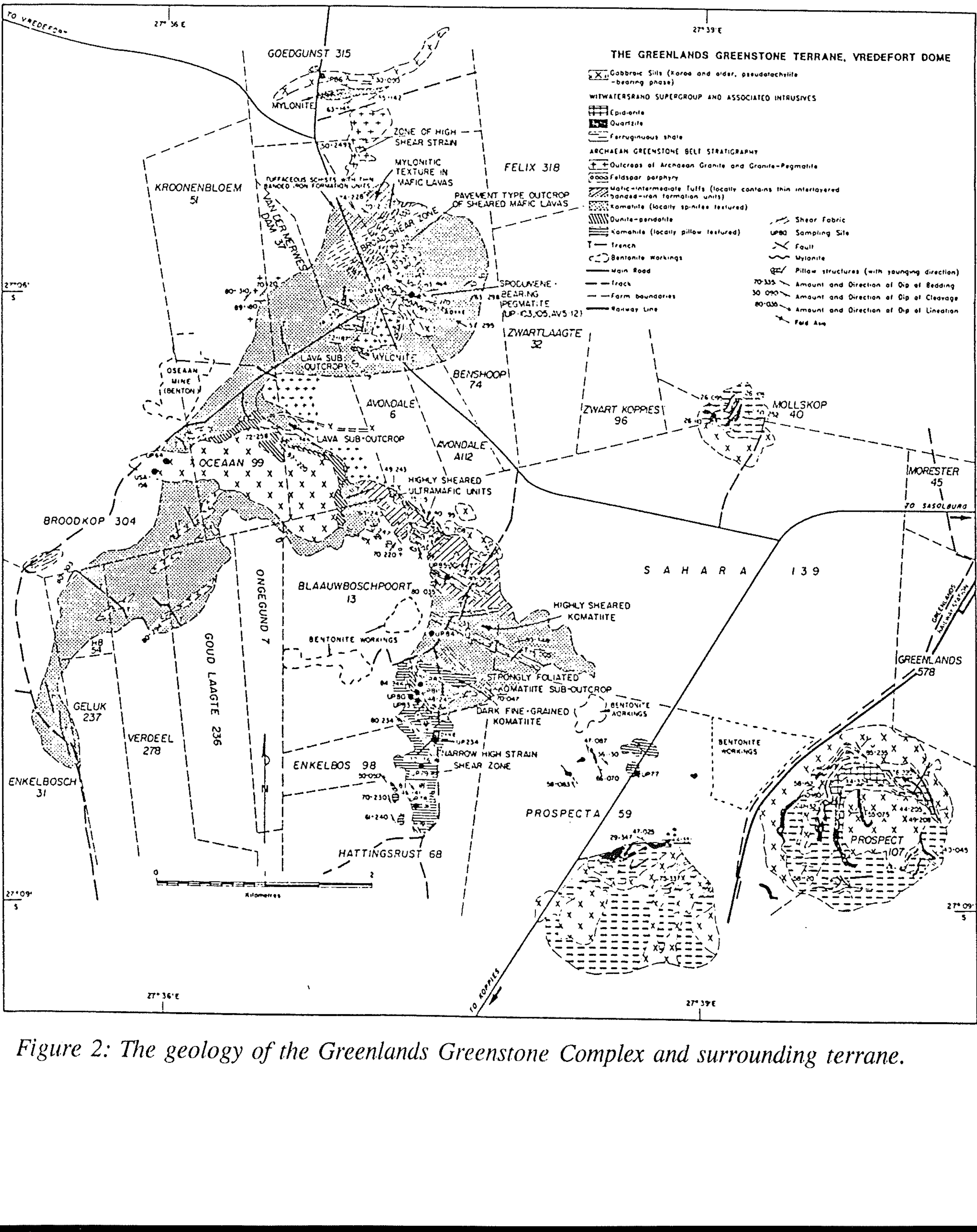


Figure 2: The geology of the Greenlands Greenstone Complex and surrounding terrane.

Metavolcanic Rocks

The Greenlands Greenstone Complex is composed principally of metavolcanic rocks having high magnesian tholeiitic to komatiitic basaltic or komatiitic affinity. Four texturally distinctive varieties have been identified:

1. a medium- to coarse-grained type;
2. a dark-green, very fine-grained type;
3. a pillowed variety, and
4. a spinifex-textured type.

The medium- to coarse-grained komatiitic basalts occur throughout the Greenlands Complex and usually occur as ankle-high outcrops consisting of massive khaki-green amphibolite (Fig. 3). No indication of layering or of other volcanic textures was observed. Some of the better exposures are found in the numerous trenches and on waste-heaps alongside such excavations.

Thin sections of these rocks display a variety of textures and mineral compositions. The main mineral constituents are chlorite, amphibole, and magnetite, with minor amounts of talc and carbonate. The rocks consist mainly of a chlorite-rich groundmass with small, evenly distributed grains of magnetite and subordinate talc. Prismatic and acicular laths or needles of tremolite or actinolite of various sizes are randomly distributed in this groundmass (Fig. 4). Changes in colour and texture of the metavolcanics are due to variations in the size of the amphibole crystals and in the relative proportions of chlorite and amphibole.

Dark-green, fine-grained komatiitic basalt found on the farms Blaauwboschpoort 13 and Sahara 139 (Fig. 2) occurs in outcrops similar to those of the coarser-grained variety. The darker green colour and finer texture is due to the predominance of chlorite over amphibole in these rocks. Volcanic textures are more common amongst the fine-grained varieties. Metavolcanics comprising alternating layers of coarser and finer-grained metabasalts containing spherulites of about 1 cm diameter were mapped in isolated outcrops on the farms Oceaan 99 and Sahara 139 (Figs. 2 and 5). In places these spherulites have been moderately flattened in a roughly east-west direction (Fig. 6). Flow-banding and disrupted pillow lava with vesicular palagonite occur in the komatiitic basalt sequence on farm Oceaan 99 (Fig. 7).

Compound lava flows consisting of pillowed komatiitic basalt and associated hyaloclastic deposits were discovered on the farm Hattingsrust 68. The pillow lavas are weakly flattened and generally oval in shape. The largest pillow structure measures about 80 cm in length and 60 cm in width. No obvious "way-up" indicators could be identified, but the characteristic tricuspate intersections between pillows and the finer-grained texture of the rim around individual pillow structures are well preserved (Fig. 8). Smaller pillows with 20-50 cm diameters are also present in the area and, significantly, display well-developed and -preserved shatter cones (Fig. 9). The larger, striated surfaces of such shatter cones are more or less parallel to the orientation of the pervasive foliation (that is, apical axes lie in the foliation plane), which at this locality trends approximately northwest-southeast.

Figure 3: *The rough surface texture of coarse-grained komatiitic basalt on Farm Enkelbos 98, caused by aggregates of amphibole laths.*

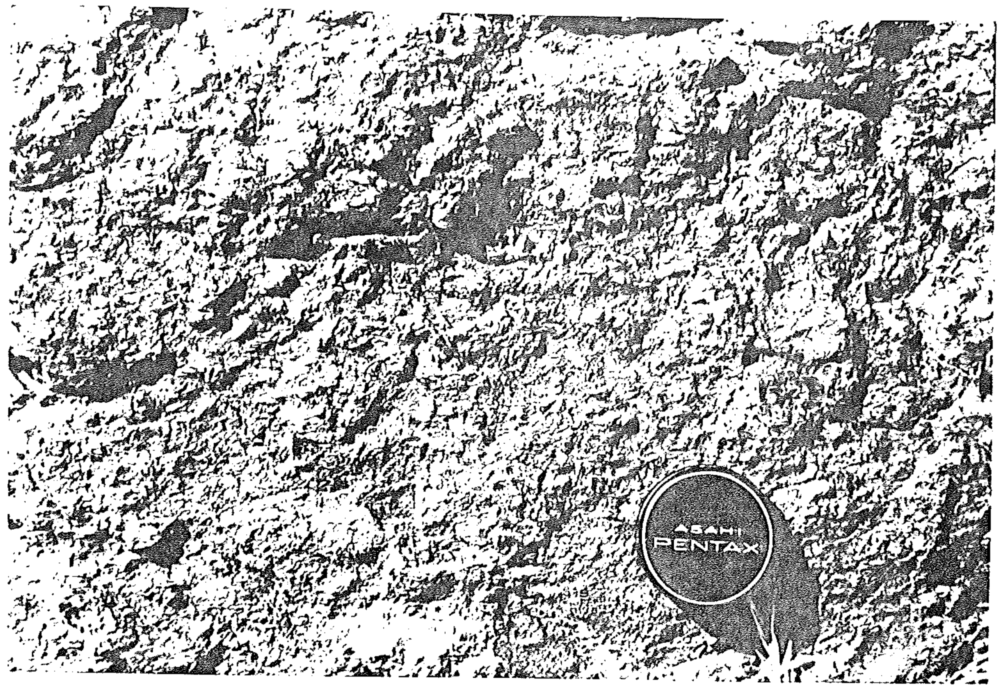


Figure 4: *Prismatic and acicular tremolite and actinolite laths in a chlorite-rich groundmass also containing minor talc and magnetite. Parallel nicols, 3.4mm wide.*

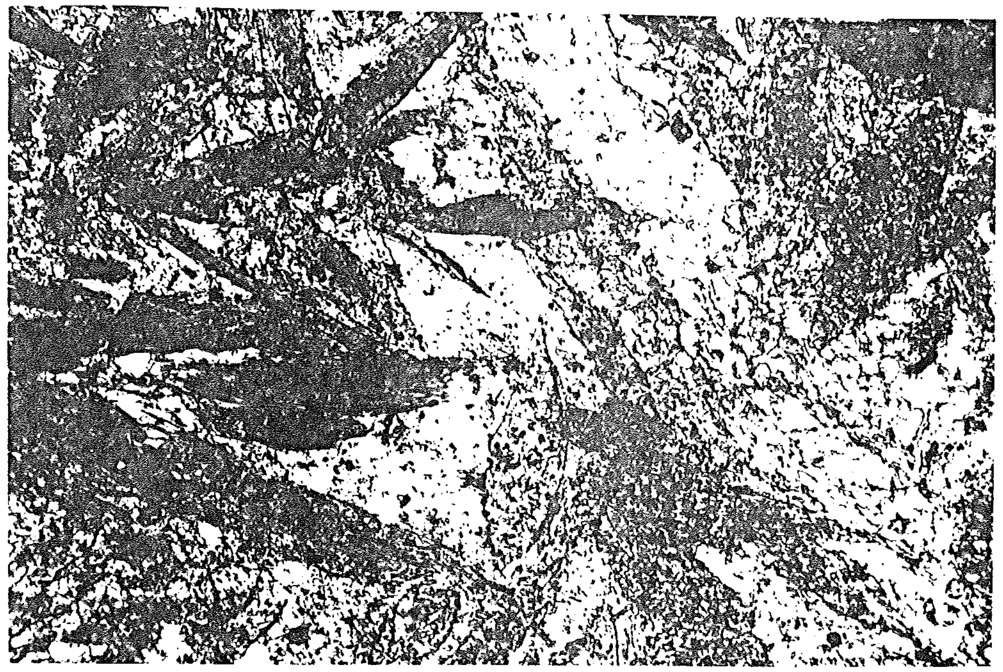
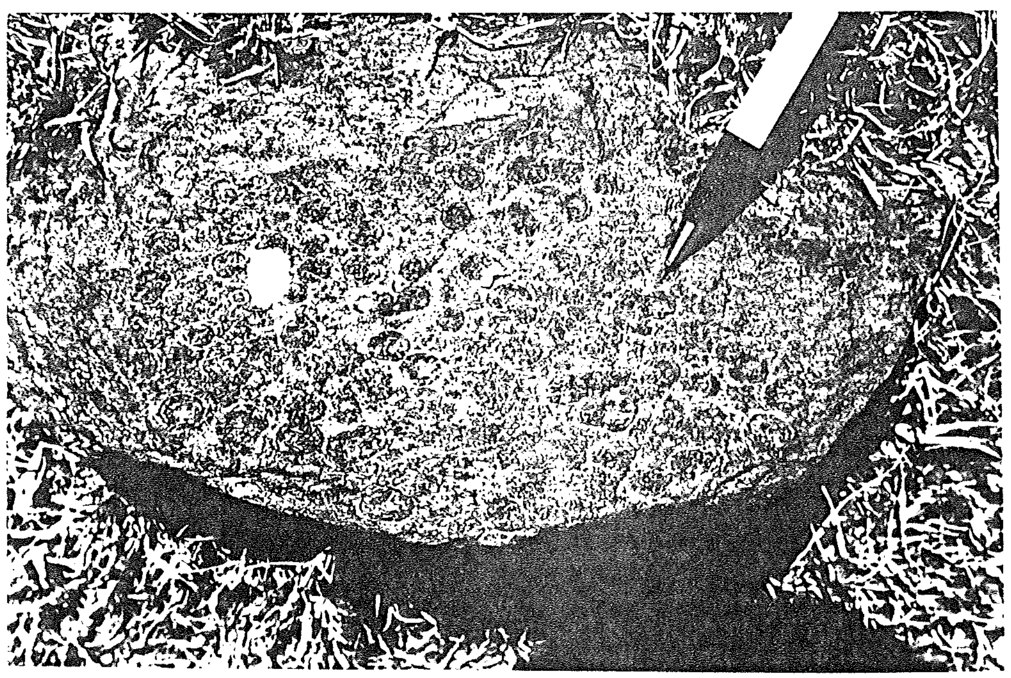


Figure 5: *Undeformed spherulites, about 1cm in diameter, in fine-grained komatiitic basalt matrix (Blaauwboschpoort 13).*



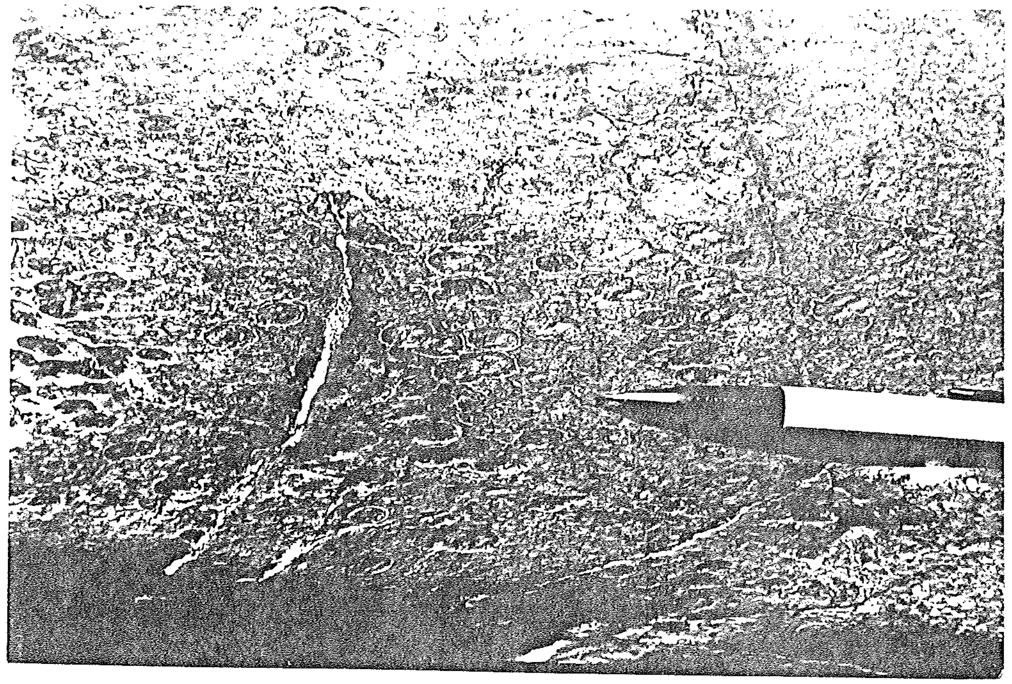


Figure 6: *Roughly east-west flattened spherulites in fine-grained komatiitic basalt. The orientation of the strain ellipse indicates principal strain along a north-northeast to south-southwest orientation (Blaauwboschpoort 13).*

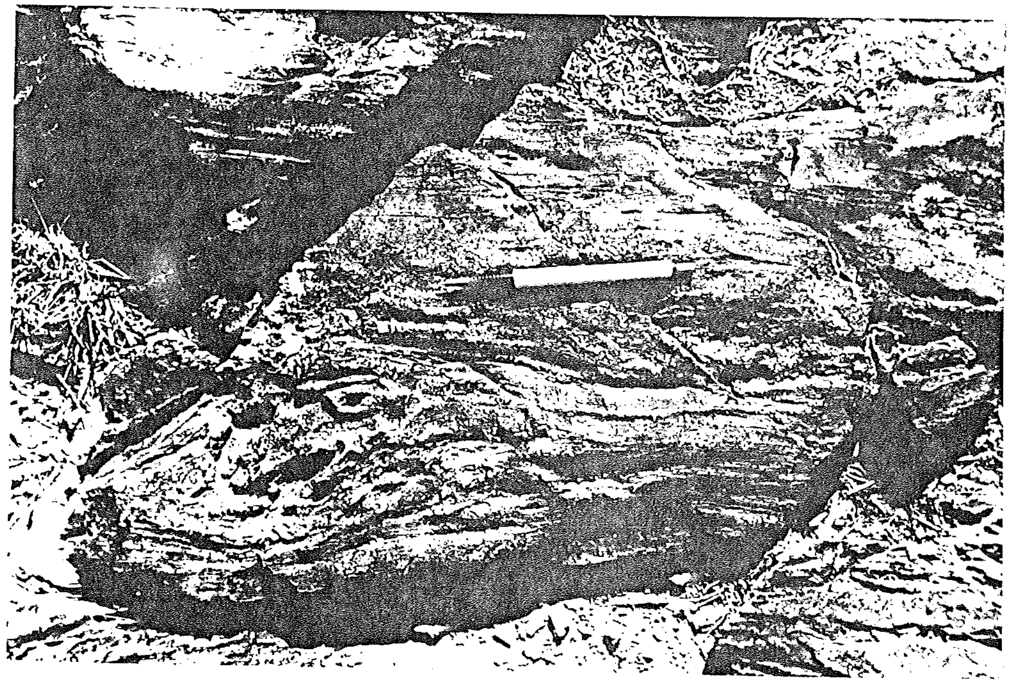


Figure 7: *Flow-banded komatiitic basalt and vesicular siliceous palagonite in the metavolcanic sequence on Farm Ocean 99.*

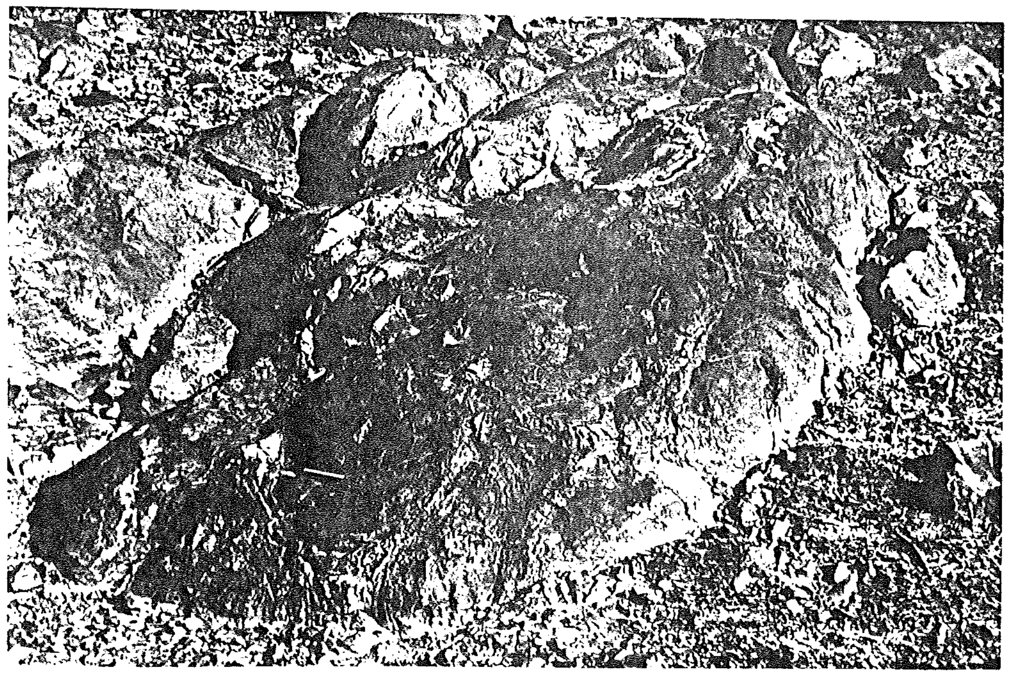


Figure 8: *Well-developed pillow structures with tricuspate intersections in high magnesian metabasaltic lavas on Farm Hattingsrust 68. (Chemical composition of these lavas: see samples UP78 and UP79, Table 1). Pen for scale: ca 14cm long.*

In the eastern and central portion of the farm Blaauwboschpoort 13 the metabasaltic lavas have been extensively sheared and hydrothermally altered. They now consist mainly of strongly foliated quartz-chlorite schists. Exposures along the extreme northeastern flank of the greenstone complex on this farm consist of strongly foliated and sheared, alternating units of komatiitic basaltic lavas and serpentinized ultramafic rocks. The units of metabasalt are up to several metres thick, whereas the serpentinite layers rarely exceed 20 cm in thickness.

Spinifex-textured komatiite (Fig. 10) is developed on the farms Enkelbos 98 and Blaauwboschpoort 13 and occurs in a layered succession of komatiite and dense, bluish serpentinized ultramafic rock. The chemical compositions of these ultramafic rocks suggest the original existence of peridotitic lavas, but these could not be identified in the field. In thin section the ultramafic rocks consist primarily of talc and chlorite with subordinate amounts of magnetite and carbonate.

A fine-grained serpentinized hornfels is developed along the contact of a large, sill-like diabase body in the central portion (farm Oceaan 99 and adjoining farms) of the greenstone complex. These rocks are best developed along the northern flank of the sill and form a zone up to 200 m wide, beyond which they give way to fine- to medium-grained komatiite. Igneous banding in these rocks is cut by a strong, superimposed cleavage, which is oblique to the banding (Fig. 11). The distribution of the hornfels strongly suggests that it is the product of contact metamorphism on the lavas surrounding the intrusive sill. The absence of similar hornfels from the southern and southwestern contact of the sill may indicate that the fine-grained serpentinite along the northern contact is part of the underlying komatiitic sequence.

Mafic-to-Intermediate Tuffaceous Units

The northwesterly trending belt of greenstone rocks in the northwestern corner of farm Blaauwboschpoort 13 is composed of highly sheared and strongly foliated schists. Some of these schists can be identified as basaltic lavas which have developed a schistose texture similar to that in other greenstone belts (e.g., the Murchison Range - Viljoen et al., 1978).

Steeply dipping units of finely cleaved, light-green quartz-sericite-chlorite schists are also developed in this portion of the greenstone sequence. Both the composition and the finely cleaved character of these schists suggest that they originally may have been tuffaceous units, even though no other volcaniclastic textures are preserved. The composition and texture of these schists helped preserve evidence of late tectonic events. This is seen in the form of conjugate and chevron folds (Figs. 12 and 13).

Figure 9: *Shatter cones preserved in small-pillow (20-50cm) metabasaltic lavas on Hattingsrust 68. Multi-striated joint surfaces (MSJS - Nicolaysen and Reimold, 1987) are preferentially developed parallel to the foliation direction (NW-SE) in the lavas. Pen length about 14cm.*

Figure 10: *Randomly oriented bundles of chlorite, talc, and tremolite in spinifex-textured komatiite from Enkelbos 98.*

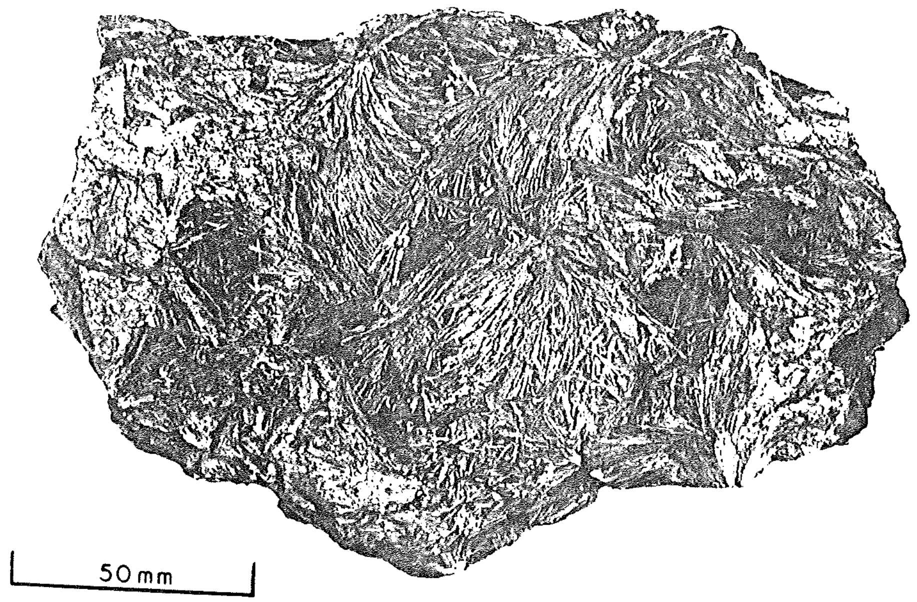
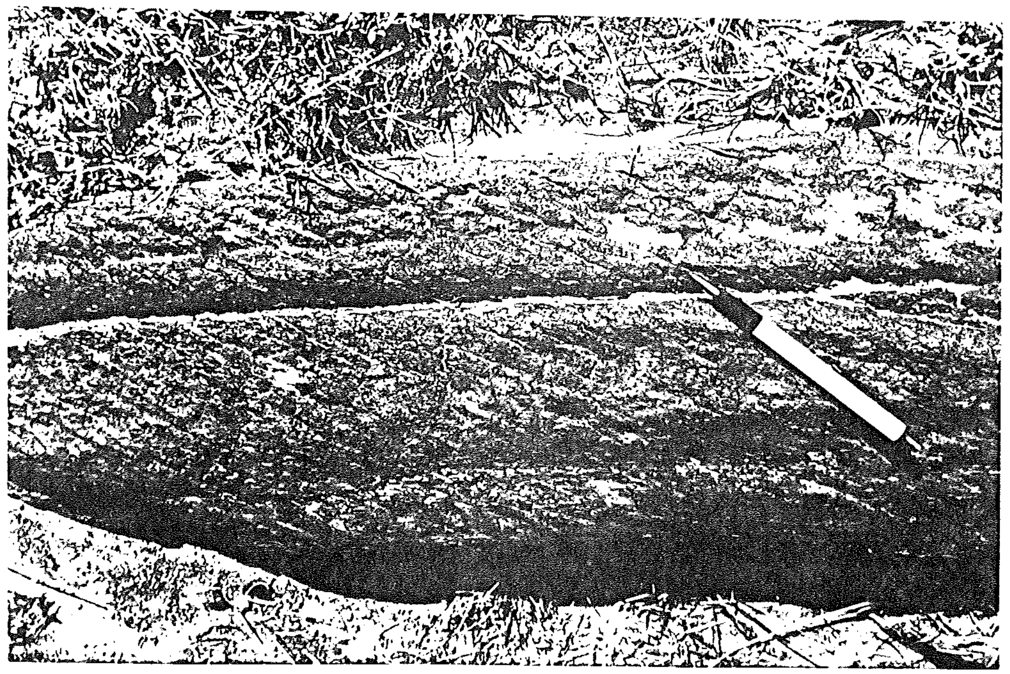


Figure 11: *Igneous layering (horizontal) in fine-grained serpentinized hornfels with superimposed penetrative cleavage near the contact of a large sill-like diabase intrusive (Farm Oceaan 99).*



On farm Avondale 6 several up to 2m wide occurrences of highly sheared "hornfels-like" amphibolitic or more felsic rocks are exposed. In between these layers thin bands of banded iron formation can be observed.

Feldspar Porphyry

Two dykes of leucocratic feldspar porphyry were located in the central portion of farm Avondale A112 and the eastern portion of the farm Blaauwboschpoort 13. Suboutcrop of feldspar porphyry is also found along the northern flank of the intrusive dyke on Goedgunst 315 (Fig. 2), where small remnants of feldspar porphyry scree are scattered over a wide area. The dykes have a characteristic waxy appearance, being pale yellow to light orange on weathered surfaces and consisting of a fine-grained leucocratic quartzo- feldspathic groundmass containing feldspar phenocrysts up to 1-2 mm in diameter. The dykes are fairly short (up to 30 m in length) and up to several metres wide. Their orientation is generally east-west.

Diabase Sills and Intrusives

The Greenlands Greenstone Complex is cut by a number of diabase dykes and sills of tholeiitic composition. These intrusives are more resistant to weathering than the surrounding metavolcanics and usually form positive features on the otherwise gently undulating topography. The sill-like intrusive on the southern boundary of Blaauwboschpoort 13 is conformable with the dip of the layered ultramafic units that it intrudes. Elsewhere the dyke-like intrusives are discordant.

A larger mafic sill (about 2 km long and 1.5 km wide) crosses the farms Broodkop 304, Oceaan 99, and Van der Merwes Dam 37. This diabase intrusive consists of about 50-60 vol% plagioclase, up to 30 vol% orthopyroxene and clinopyroxene (in approximately equal proportions), up to 15 vol% amphibole, and a small amount of magnetite. These minerals collectively form a subophitic texture. Locally, pyroxene has been converted to amphibole, but it is not clear whether this occurred during the end-phase of crystallization or represents a later metamorphic transformation. The rock is very fresh with only slight sericitisation of the feldspar. Mineralogically, this rock type is very similar to that of other gabbroic or dioritic intrusives into the Vredefort Dome, such as the Anna's Rust Sill or the elongated, southwest-northeast trending mafic intrusive mapped by Nel (1927) near the town of Vredefort (termed the Vredefort Mafic Complex - Pybus, 1994), which are also chemically similar (cf. chapter on Geochemistry). The Anna's Rust Sill does not contain any amphibole, but samples from the Vredefort Mafic Complex may contain several volume percent of amphibole and is texturally very similar to the Oceaan diabase. Neither of these intrusives is cut by pseudotachylite, whereas Nel (1927) indicated a pseudotachylite find in the body on Oceaan 99. In the course of this study only a few pieces of pseudotachylite float could be observed within the area covered by this diabase complex, and these samples all exhibited mainly granitic inclusions and most likely are derived from the surrounding granite-gneisses.

A sill-like intrusive on farm Goedgunst 315 has a brownish weathered surface which is slightly pitted due to the preferential weathering of pyroxene grains. Dark-grey to black surfaces of freshly broken rock have an ophitic textural appearance. In thin section this rock consists of euhedral to subhedral plagioclase grains in an augite-magnetite-rich groundmass. Some smaller plagioclase crystals are poikilitically enclosed in large irregular augite grains (Fig. 14).

A small intrusive body (AV-4, Figure 2) is located just to the northeast of the lithium pegmatite occurrence on farm Benshoop 74. Exposures are limited to an accumulation of partially buried boulders at the sampling site AV-4, and to a small patch of apparently autochthonous material at the northeastern edge of the pegmatite body. This gabbroic rock consists of approximately 60 vol% plagioclase, 30 vol% pyroxene, and at maximum of 10 vol% amphibole and some magnetite. A single olivine grain was observed in a thin section. The texture of this rock is subophitic to ophitic, and the amphibole occurs in similar fashion to that of the Oceaan sill.

A narrow, only up to 7 m wide, but some 100 m long, dyke of a very fine-grained mafic intrusive (UP-234) was mapped on farm Blaauwboschpoort 13. This intrusive strikes roughly north-south. At the ends of the dyke the exposures pinch out and disappear beneath soil cover. This rock consists of partially saussuritized plagioclase together with amphibole, but remnant pyroxene crystals suggest an original feldspar-pyroxene mineralogy. Minor phases include biotite and magnetite, at up to 5 vol%, respectively. The microtexture in this dyke is subophitic, with needle- and lath-like mineral shapes being dominant.

Radiometric ages for these intrusives have not yet been determined. These occurrences, with exception of the diabase complex, are characterised by an absence of strong foliation and by the presence of thin pseudotachylite veinlets. Accordingly, they are clearly younger than any foliated lithology in this area, but older than the abundant Palaeozoic Karoo age intrusives of the Vredefort Dome of similar texture (cf. also section on Geochemistry). They are also older than the approximately 1.05 Ga Anna's Rust Sill-type intrusives described by Pybus et al. (1994).

Granites, Pegmatites and Alkali Granites

In addition to the greenstone sequences, there are a number of small granitoid intrusions exposed within and around the Greenlands Greenstone Complex. The largest outcrops of such rocks occur on the farms Goedgunst 315 and Van der Merwe's Dam 37. The significance of the structural features of the migmatite complex and the shear zone on Broodkop 304 have previously been described (Colliston and Reimold, 1990).

Leucocratic pegmatites, consisting of approximately equal amounts of quartz and feldspar with subordinate muscovite, occur on Van der Merwe's Dam 37, and as numerous dykes on the farms Oceaan 99, Broodkop 304, Goudlaagte 236, Verdeelt 78, Avondale A112, and Benshoop 74 (Fig. 2). An occurrence of spodumene-bearing pegmatite was identified by Bisschoff and Bisschoff (1988) on farms Avondale 6 and Benshoop 74. These authors did not record the presence of numerous, up to 2 cm wide, generally anastamozing

Figure 12: *Upright kinkbands, oblique to the regional foliation, in mafic-to-intermediate tuffaceous schists from the northeast corner of Blaauwboschpoort 13.*

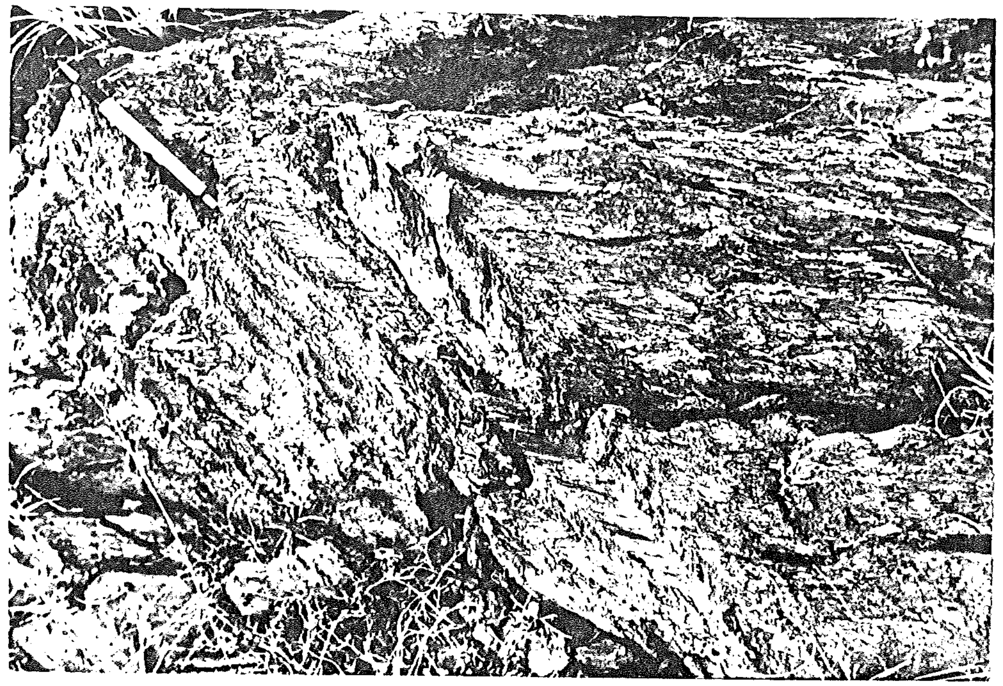


Figure 13: *Chevron folds in mafic-to-intermediate tuffaceous schists from Blaauwboschpoort 13.*

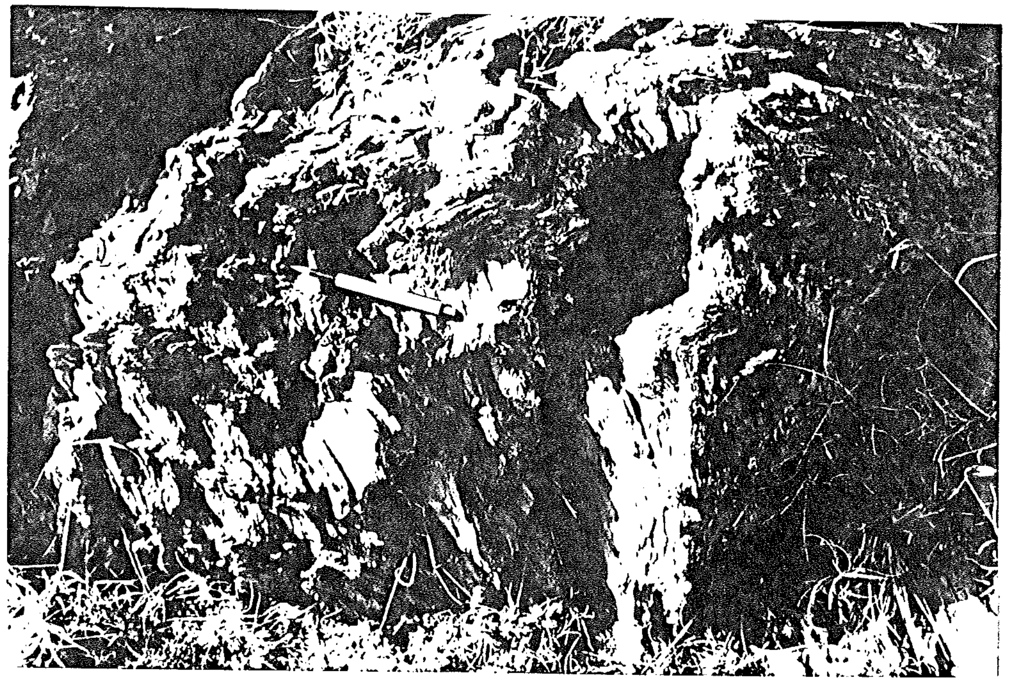
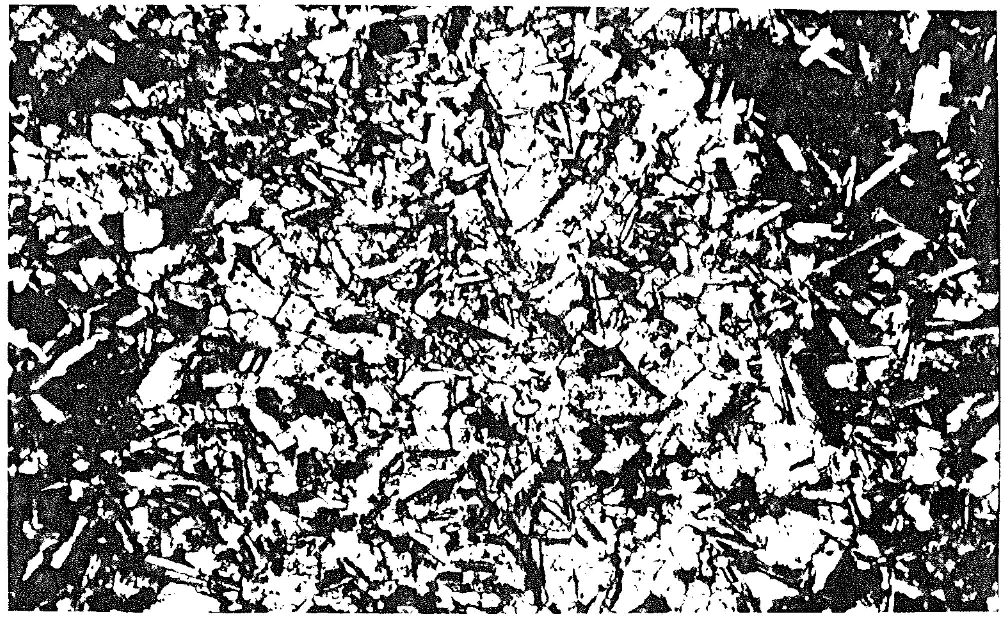


Figure 14: *Large irregular augite grain (lighter area) with smaller, poikilitically enclosed, plagioclase crystals. Sample UP-86, crossed nicols, width of view = 3.5mm.*



and short pseudotachylite veinlets. Interestingly the Li content in this pegmatite ranges from 0.25 to 1.29 wt%. An alkali feldspar-rich pegmatite was encountered on farm Avondale A112.

The granitic rocks on Goedgunst 315 are gneisses of possibly tonalitic or trondhjemitic composition. They have been strongly sheared and intruded by later pegmatitic phases. Highly sheared pegmatitic granites, with quartz ribbons indicating the development of protomylonite, were mapped along the northwestern flank of the greenstone complex on the farms Kronenbloem 51 and Van der Merwes Dam 37. These outcrops appear to form part of a large and continuous northeasterly trending shear zone, of which the Broodkop Shear Zone probably forms part (cf. discussion of South East Boundary Fault).

Witwatersrand Supergroup Strata and Associated Intrusives

Three major outcrops of Lower Witwatersrand strata are found on the eastern side of the Greenlands Greenstone Complex (Fig. 2). The two southernmost outcrops form the so-called Tweeling Koppies (Twin hills) on the farms Prospect A59 and Prospect 107, to the south and southwest of the Greenlands railway siding. The third outcrop, known as Mollskop, occurs to the northwest of the Greenlands siding and is the promontory on which the boundaries of four contiguous farms converge (Fig. 2).

In each of these windows of Witwatersrand strata, in otherwise Karoo- or alluvium-covered terrane, orthoquartzites of the Orange Grove Formation are found interbedded with ferruginous shales. In addition, younger intrusive dykes and sheets of gabbroic composition are found in all these packages, with epidiorite being part of the intrusive assemblage found in the larger and most easterly of these Witwatersrand outliers.

A significant feature of these exposures of Lower Witwatersrand strata is that they are structurally atypical of the collar rocks found along the northern and eastern perimeter of the Vredefort Dome. Elsewhere the collar rocks are steeply dipping to overturned and are more or less parallel to the contact with the granitic gneiss core. In the Greenlands area, however, the Witwatersrand strata are not parallel to the projected perimeter of the Vredefort Dome (contrary to statements by Martini, 1991). It has been suggested in the past (Borchers, 1961; Pretorius et al., 1986) that this configuration is the result of complex faulting in this part of the Vredefort structure. In the absence of published drilling or reflection seismic information, it is also possible to speculate that this unusual deformation style could be a function of the composition of this portion of the basin floor, onto which the Witwatersrand strata were originally deposited. There is no evidence to suggest that the Greenlands Greenstone Complex does not constitute the floor of the Witwatersrand Basin in this portion of the dome. It is possible that the deformation in the overlying strata is a reflection of the response of greenstone material to the dynamic processes that formed the dome.

The presence of shatter cones, multipli-striated joint surfaces (MSJS - Nicolaysen and Reimold, 1987), and pseudotachylite veins in the metavolcanic rocks of the greenstone complex (Figs. 9 and 15) indicates that they are well within the domain of Vredefort dynamic deformation. Although no shatter cones were found in the shale members of the Witwatersrand strata, a single pavement, measuring some 4 m x 2 m, with numerous closely spaced shatter cones and multi-striated joint surfaces was located in the quartzite on Tweeling Koppies on farm Prospect A59 (Fig. 16).

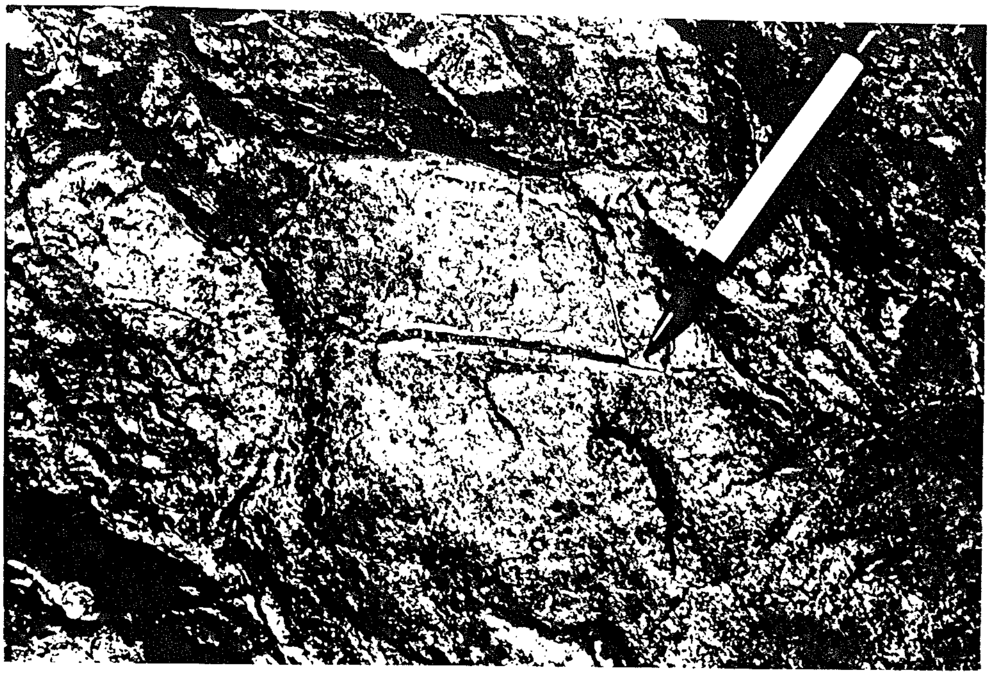


Figure 15: Pseudotachylite veinlet in komatiitic lava on Blaauwboschpoort 13.

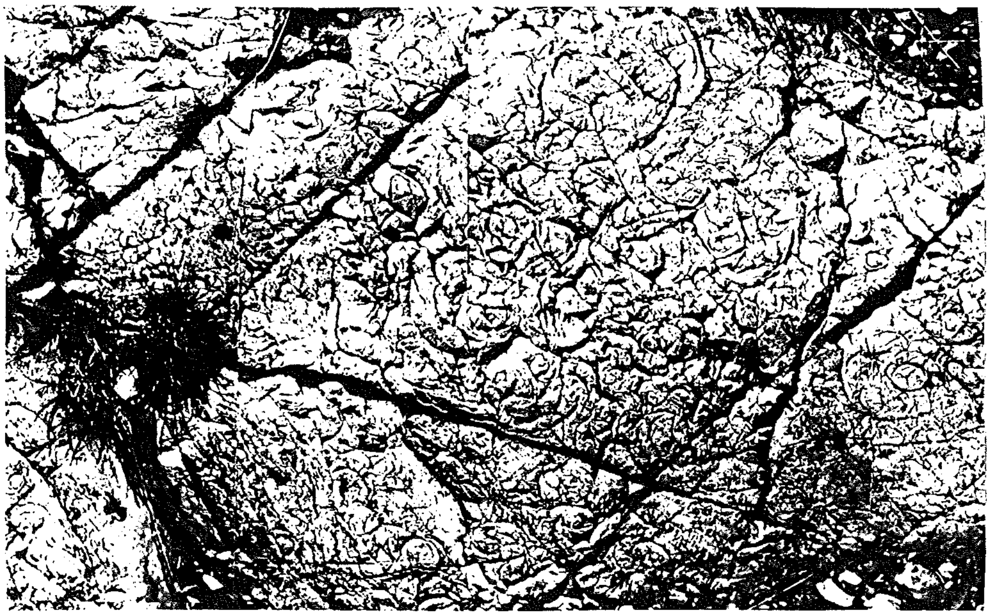


Figure 16: Numerous closely spaced shatter cones and multi-striated joint surfaces on a pavement exposure of Orange Grove Quartzite on farm Prospect A59. Area shown is approximately 1m wide. View towards the south-southeast.

A few strongly fractured outcrops of orthoquartzite occur about 1 km north of Tweeling Koppies, but none of these exposures is larger than a few square metres. According to Nel (1927) this orthoquartzite also belongs to the Orange Grove Formation.

SOME PETROGRAPHIC OBSERVATIONS

Typical samples, representing the different lithological types of mafic intrusives in the Greenlands Greenstone Complex, were studied petrographically with regard to texture, alteration, and microdeformation. Sampling localities for these and other samples analysed for their chemical composition are shown in Figure 2.

Sample UP-78 (fine-grained komatiitic basalt) is transected by a number of microfaults, the widest of ($< 200\ \mu m$) which contains an extremely fine-grained fault rock type. It resembles altered pseudotachylite, but because of the alteration the original lithology cannot be positively identified.

UP-81 represents an intersertally textured actinolite schist. Primary phenocrysts can no longer be observed. Most amphibole laths or needles display well-developed cleavage as the only evidence of brittle deformation.

UP-82, a talc-chlorite schist from the contact between the komatiitic and tholeiitic rocks on farm Blaauwboschpoort 13, contains a number of relatively fresh relic hornblende phenocrysts in the clay mineral matrix. Most of these show significant intragranular fracturing, and some contain near-planar fluid inclusion trails orientated approximately perpendicular to (001).

UP-84, a fine-grained chlorite-talc schist, consists of a silica-rich clay mineral matrix and scattered, up to 0.5 mm wide and 4 mm long, amphibole phenocrysts. The matrix is silica-impregnated, and the sample is cut by an up to 1 mm wide quartz veinlet with chert-like microtexture.

Several interesting observations were made in the GGB sample series, which were derived from several trenches in the komatiitic lava succession.

Sample GGB-1 is a partially silicified actinolite-schist that is also transected by several $>$ 1 mm wide quartz veins. The quartz-rich, cherty-textured parts are rich in secondary opaque minerals, mainly pyrite and some chalcopyrite. Additional ore minerals identified include sphalerite and traces of galena and hematite. The overall sample appears very fresh (no late alteration). The amphibole does not display any microdeformation effects, besides intricate intragranular fracturing. The fine-grained quartz crystals in the matrix and quartz vein appear completely unstrained.

Samples GGB-2 and -5 are very similar to GGB-1, but the schist component consists largely of talc and chlorite, with less silica. GGB-2 contains a quartz band with several crystals that are transected by completely annealed (stringers of elongated quartz crystallites) "features" that are reminiscent of the annealed "planar features" so abundant in the lithologies of the core and collar of the Vredefort Dome. This sample is also transected by a series of late fractures that acted as nuclei for even later alteration (deposits of finest-grained clay minerals). GGB-5 is somewhat distinct in its even finer-grained texture and very finely disseminated ore mineral component.

Sample GGB-3 is a well-laminated, fine-grained talc-schist with up to > 1 cm angular clasts of quartzitic composition. These fragments contain two generations of quartz: an older, medium-grained phase that can be recognized by its brecciated nature (all fragments from one grain still exhibit mutual extinction), and a younger phase that serves as fine-grained, mosaic-textured cement for the brecciated variety. These assemblages, in turn, have been brecciated during the shearing event that caused the strong foliation of the schist, as suggested by the alignment of the quartzitic clasts with their long axes parallel to the foliation orientation. No post-shearing deformation is indicated.

Three relatively late intrusives into the greenstone complex were sampled for chemical analysis (Table 1): the diabase sill on farm Oceaan 99 and adjoining farms (sample USA-156), a tholeiitic intrusion in the central part of farm Blaauwboschpoort 13 (UP-85), and the intrusive on farm Goedgunst 315 (sample UP-86). Sample USA-156 displays some intragranular fracturing in plagioclase and hornblende, but lacks any intergranular deformation. Specimen UP-85 has a medium- to coarse-grained (up to 3 mm long and 1 mm wide plagioclase crystals) subophitic texture formed by hornblende and plagioclase and little interstitial magnetite. The sample is strongly altered (strong chloritization of hornblende and less pronounced saussuritization of plagioclase). Microdeformation is not significant and is restricted to local intragranular fracturing. Several brittle magnetite grains have been brecciated, but without significant indication of subgrain rotation or displacement. Sample UP-86 shows typical Karoo dolerite texture with large pyroxene crystals poikilitically enclosing finer-grained plagioclase laths. These, up to > 4 mm wide, often subrounded aggregates are set into a finer-grained matrix enriched in fine-grained magnetite. The sample is very fresh and does not show any microdeformation besides occasional intragranular fracturing.

Neither samples AV-4, from a small body on Benshoop 74, nor UP-234, from the long, narrow dyke on Blaauwboschpoort 13, revealed any microdeformation. UP-234 is strongly altered, (saussuritized plagioclase, incipient chloritization of amphibole). In AV-4 plagioclase is rather fresh, but some pyroxene is rimmed by amphibole. Other pyroxene grains are altered from the core outwards, forming uralite, similar to the alteration observed in the Anna's Rust Sill and other related complexes.

GEOCHEMISTRY

The chemical characteristics of some of the mafic and ultramafic metavolcanics, as well as the principal mafic intrusive rock types found within the Greenlands Greenstone Complex have been investigated. Both major and trace element abundances for these rocks are listed in Table 1. The chemical compositions of the Greenlands rock types are compared with well-defined komatiitic and tholeiitic volcanic rock types described from the Barberton Mountain Land by Viljoen and Viljoen (1982) and Smith and Erlank (1982).

TABLE 1

Major (in wt%) and trace element (in ppm) data for mafic and ultramafic rocks from the Greenlands Greenstone Remnant.

Sample	UP77	UP78	UP79	UP80	UP81	UP82	UP84	UP85	UP86a	UP86b	GGB1	GGB2	GGB3	GGB4	GGB5	UP64	USA156	UP234	AV4	BLK-Bulk*
SiO_2	54.25	53.40	52.57	52.02	40.20	41.22	53.18	49.16	51.23	50.91	71.28	75.87	46.44	64.96	64.50	51.48	50.19	51.47	50.22	51.25
TiO_2	0.25	0.24	0.24	0.84	0.08	0.09	0.25	1.21	1.02	0.96	0.13	0.13	0.22	0.26	0.06	1.25	1.61	2.19	2.11	0.86
Al_2O_3	13.69	12.82	12.48	11.18	5.78	4.56	13.52	15.49	15.22	15.04	6.09	6.36	12.70	10.62	6.36	15.28	15.11	13.17	13.00	15.62
Fe_2O_3	9.18	8.86	8.86	11.79	7.38	7.65	9.05	12.68	11.10	11.57	9.52	6.37	13.36	8.27	7.71	12.62	14.00	15.91	15.93	10.75
MnO	0.15	0.14	0.17	0.19	0.12	0.13	0.14	0.18	0.17	0.17	0.04	0.03	0.13	0.03	0.15	0.18	0.19	0.20	0.22	0.16
MgO	11.05	12.48	13.03	9.49	31.92	32.37	11.94	7.06	7.40	7.47	0.59	1.55	9.81	1.68	10.58	6.76	6.44	4.23	5.25	7.58
CaO	7.97	8.68	9.31	10.77	2.72	2.63	7.61	10.60	10.42	10.29	0.84	0.67	0.54	3.38	7.77	10.12	9.42	7.51	8.81	10.79
Na_2O	1.43	1.24	1.06	2.29	bd	bd	0.45	1.71	1.54	2.19	1.86	1.85	0.97	2.23	0.65	2.10	2.20	1.95	2.99	2.31
K_2O	0.14	0.09	0.10	0.12	0.03	0.03	0.11	0.28	0.67	0.61	0.25	0.14	0.35	0.26	0.16	0.57	0.74	1.40	1.35	0.54
P_2O_5	0.02	0.03	0.03	0.09	0.01	0.02	0.02	0.13	0.15	0.17	0.02	0.03	0.06	0.01	0.03	0.14	0.16	0.48	0.53	0.13
LOI	2.30	2.56	2.47	0.70	11.09	10.86	3.17	0.70	0.24	0.36	8.24	5.21	3.73	6.94	1.47	0.09	0.36	1.32	0.24	-
TOTAL	100.43	100.54	100.22	99.48	99.33	99.56	99.44	99.20	99.16	99.74	98.87	98.22	98.32	98.63	99.44	100.59	100.42	99.83	100.65	99.99
Ba	336	17	19	61	6.5	140	62	131.5	199	195	19.5	26	15	16	7	188	234	543	387	152
Rb	2	bd	1	6	bd	bd	0.5	13.5	17	23	32	120	109	66.5	45	36	45	78	71	9
Sr	56	51	43	107	36	20.5	62	149	205	206	67	51.5	102.5	99	32	183	172	177	195	185
Y	11	10	11	20	3	7	11	24	24.5	24	4.5	4.5	11.5	6	6	26	31	50	48	22
Zr	27	28	27	76	17	19	27	86	96	95	19	16	24	29	8	104	126	305	293	76
Nb	2.5	2	2	4	2	2	2	5.5	7	7	2	2	1	2	2	7	8	17	14.5	4
V	235	231	231	315	92	83	220	234	253	244	112	110	227	156	111	253	314	333	289	232
Cr	867	1064	1122	738	2753	2463	1070	259	387	363	1905	1169	2279	2144	477	176	108	45	98.5	384
Co	41	42	46	48	71	71	45.5	44	38	35	281	157	226	112	87	39	51	46	46	53
Ni	137	21	218	221	1550	1766	206.5	130	103	105	538	504	575	669	138	100	108	60	63	107
Cu	bd	59	22	39	bd	3.5	10.5	72	89	81	325	370	1552	258	729	89	122.5	79	67	96
Zn	42.5	57	47	63	45	51	72	91.5	83	84	33	15	32	29	34	86	124	133	94	76

bd = below detection limits.

* Marsh and Eales (1984).

Ultramafic Komatiite

Two analyses of ultramafic rocks (UP-81 and UP-82) from the farm Blaauwbosch-poort 13 (Fig. 2) are presented in Table 1. The overall chemical character of these now altered volcanic rocks is comparable to the composition of komatiitic peridotites in the Lower Ultramafic Unit of the Onverwacht Group of the Barberton Greenstone Belt (Viljoen et al., 1982). In detail, the Greenlands ultramafic lavas are chemically similar to the Sandspruit-Komati-type lavas with regard to their MgO contents, but they are slightly enriched in Al_2O_3 (Fig. 17) and depleted in TiO_2 and CaO (Figs. 18 and 19). These depletions are likely to be the result of a somewhat higher degree of alteration of the Greenlands samples in comparison with the Barberton sample suite. The slight enrichment in Al_2O_3 may be a reflection of somewhat different primary compositions of the volcanics in the two regions and probably of inhomogeneous mantle conditions at the time of extrusion.

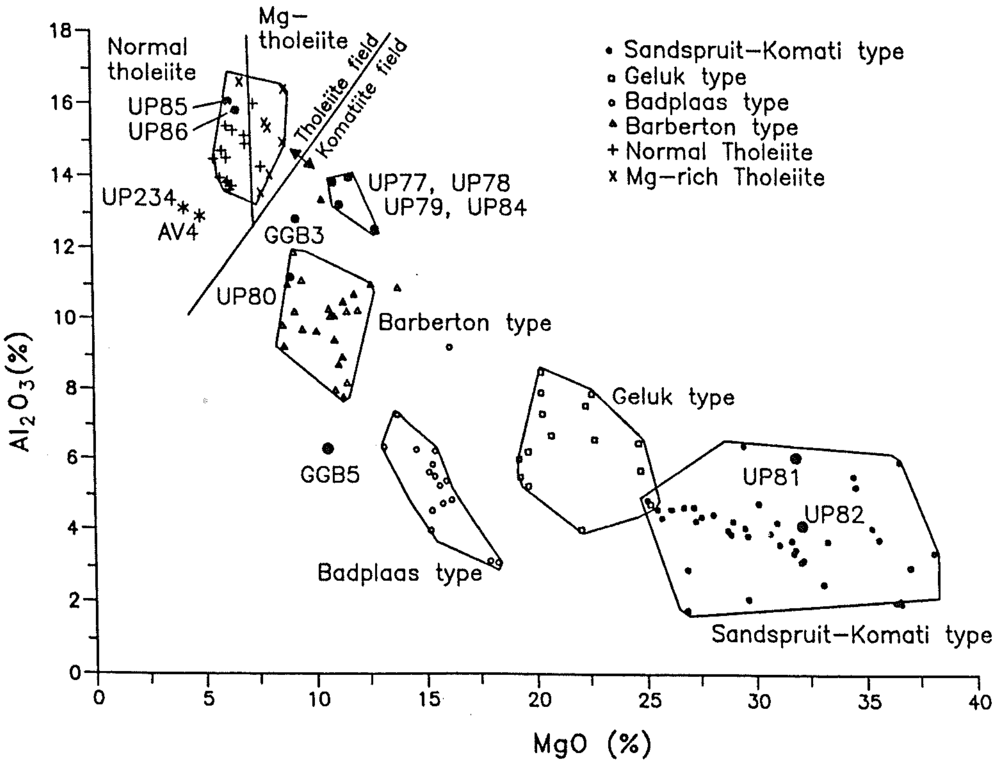


Figure 17: A plot of Al_2O_3 versus MgO for tholeiitic and komatiitic rocks from the Greenlands Greenstone Complex, in comparison with data for well-established tholeiite and komatiite types from the Barberton Mountain Land (after Viljoen et al., 1982). Note the enrichment of Al_2O_3 in the Greenlands komatiitic rocks.

Komatiitic Basalts

Volcanic rocks of komatiitic basalt affinity are the most widespread lithology in the Greenlands Greenlands Complex. In all, ten samples approximating komatiitic basalt composition were analyzed from this area. The freshest specimens were found amongst the pillowed basalts on the farms Prospect A59 (sample UP-77), Hattingsrust 68 (UP-78,

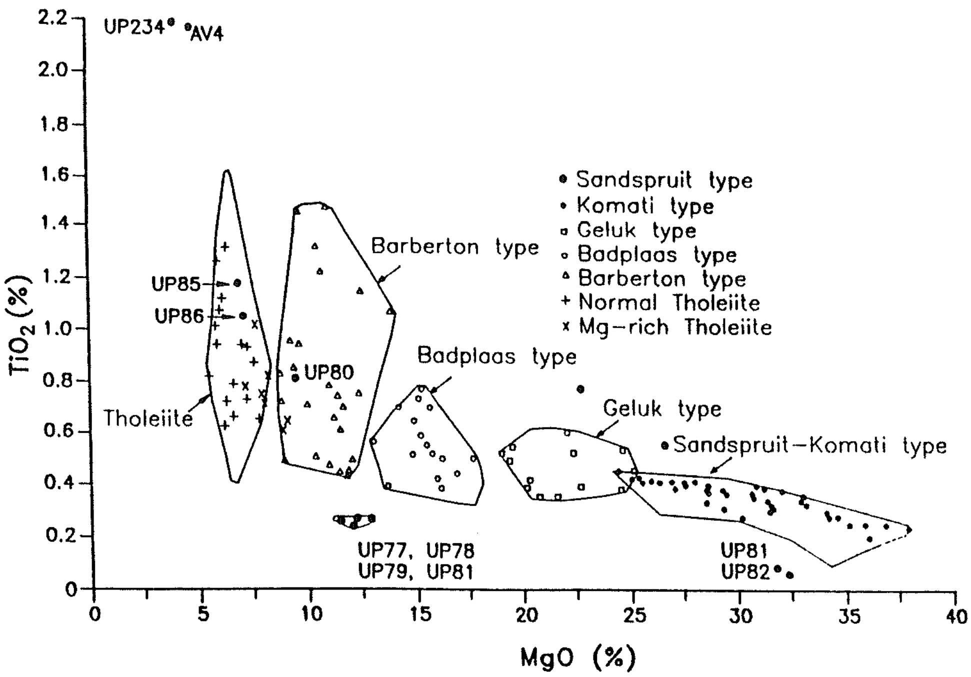


Figure 18: A plot of TiO_2 versus MgO for Greenlands and Barberton tholeiitic and komatiitic rocks (after Viljoen et al., 1982). Greenlands komatiites are relatively depleted in TiO_2.

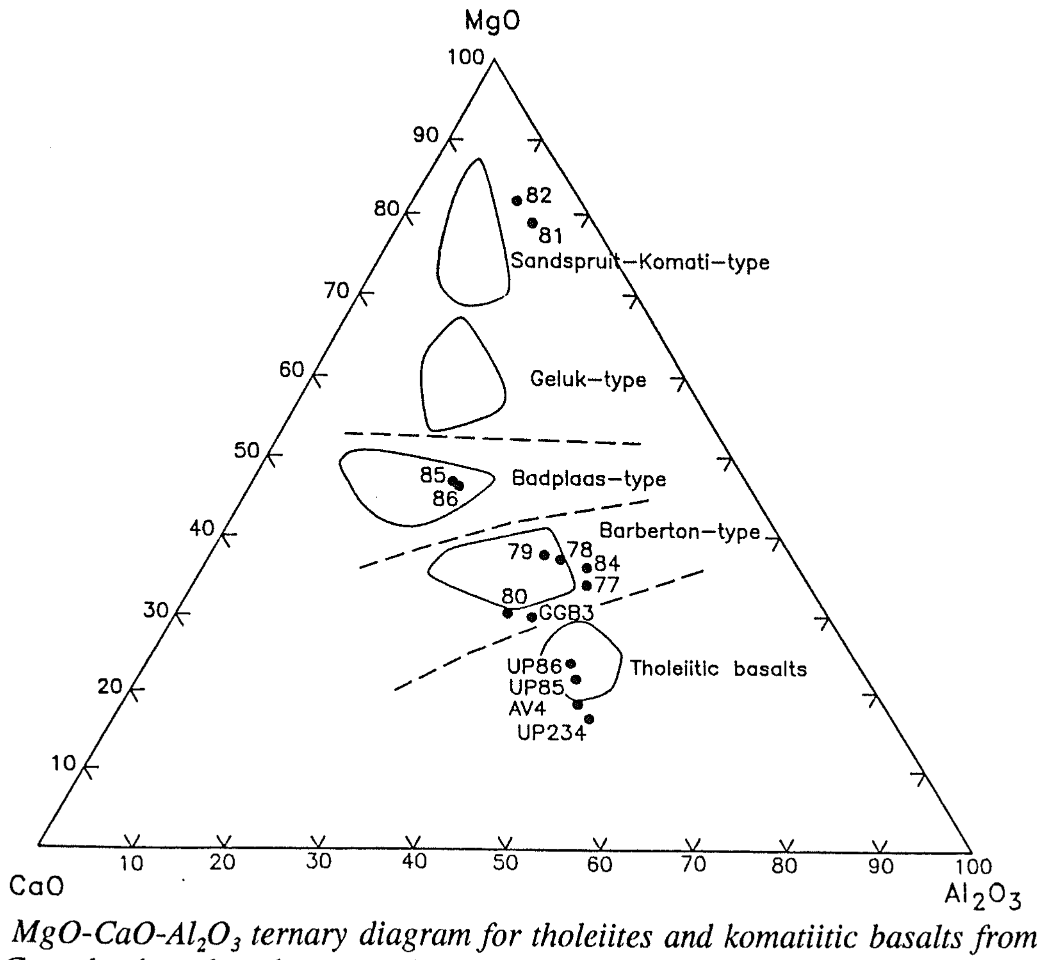


Figure 19: MgO-CaO-Al_2O_3 ternary diagram for tholeiites and komatiitic basalts from the Greenlands and Barberton regions (after Viljoen et al., 1982), showing similarities with the respective komatiitic groups.

UP-79), and Blaauwboschpoort 13 (UP-80). Of the five samples of altered komatiitic basalt collected from the old gold mine workings on Avondale A112 (samples GGB1-GGB5) only two, namely GGB3 and GGB5, were sufficiently unaltered to yield representative analyses. Samples GGB1, GGB2, and GGB4 all contained excessive amounts of hydrous mineral phases, as reflected by the comparatively high 'loss on ignition' values. Analyses GGB1 and GGB2 also have abnormally high SiO_2 concentrations, probably due to late-stage silicification.

In all binary and ternary diagrams (Fig. 17 - 20) used to characterize the komatiitic basalts, samples UP-77, UP-78, UP-79, and UP-84 constitute a fairly tightly clustered group, whereas GGB3, GGB5, and UP-80 are more scattered. In general, the Greenlands komatiitic basalts are almost identical to Barberton-type komatiites with regard to their MgO contents, but are relatively enriched in Al_2O_3 and depleted in TiO_2, CaO, and Fe_2O_3 (representing total Fe contents). The interpretation of these effects would be the same as that offered for the anomalous chemical properties of the Greenlands ultramafic komatiites.

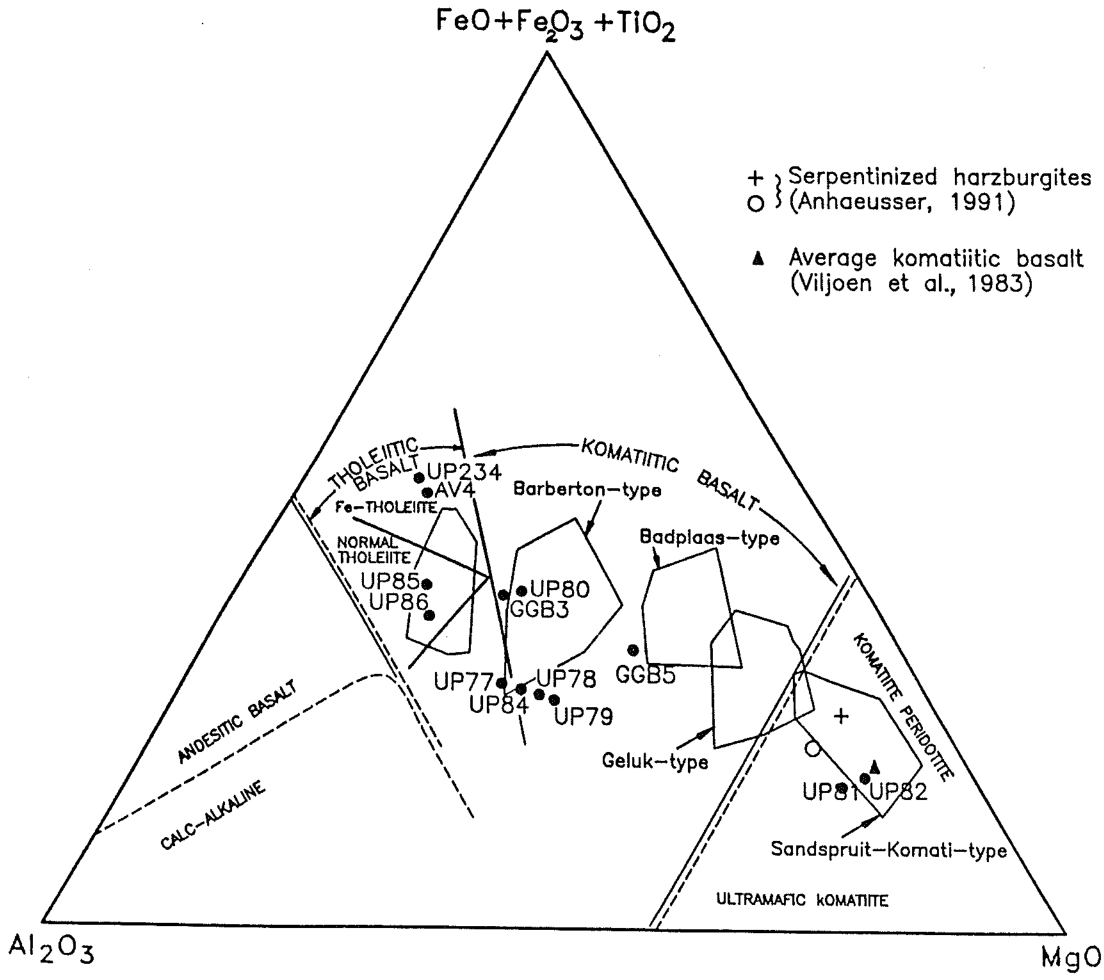


Figure 20: Comparison of tholeiitic and komatiitic rocks from the Greenlands Greenstone Complex with similar rock types from the Barberton Mountain Land, in terms of $(FeO+Fe_2O_3+TiO_2)$-Al_2O_3-MgO variations (after Viljoen et al., 1982).

Tholeiitic Intrusives

Dyke- and sill-like intrusives, which on the basis of their occasional pseudotachylite veining are regarded as being older than Karoo dolerite, were sampled for chemical analysis (Table 1) on the farms Blaauwboschpoort 13 (sample UP-85) and Goedgunst 315 (UP-86). In Figures 17 - 20 the data for these two samples always lie within the field of normal tholeiitic basalts, even though they are clearly not extrusives. The relationship of these rocks with the surrounding greenstone lithologies, as well as the internal textures, clearly indicate that they are relatively young intrusives, in comparison with the greenstone volcanics, but older than the Karoo age dolerite intrusives. Comparison of analyses UP-85 and -86 with that of the Blaauwkrantz Karoo sill (Marsh and Eales, 1984; cf. BLK-Bulk Table 1) indicates a strong similarity between these rock types. Furthermore, analyses of bona fide Karoo samples from the southern portion of the Vredefort Dome (unpubl. results from the studies by Jackson et al., 1992 and Pybus et al., 1993) for trace element abundances yielded consistently similar results - both with respect to homogeneity of individual bodies and to comparison between samples from different complexes of this region. All these samples compare well with the Lesotho-type lava or dolerite of the Central Karoo Province, as defined chemically by Marsh and Eales (1984). Sample UP-86 coincides with this group.

Jackson et al. (1992) and Pybus et al. (1994) noted, besides the Karoo intrusive suite, an additional gabbroic to dioritic rock type of relatively high Ti content occurring in the area of the Vredefort Dome (the so-called Anna's Rust Sill to the north and east of the town of Parys). A Rb-Sr age of 1054 $\pm$13 Ma for this intrusion was established by Pybus (1994). On the basis of chemical and petrographical data the tholeiitic intrusives from the Greenlands area compare well with this high-Ti type. However, in contrast to the Anna's Rust type, one of the Greenlands intrusives (UP-85) was found to be cut by pseudotachylite. This would indicate that there could be three similar, but not coeval, generations of Ti-enriched intrusives in the Vredefort Dome.

Oceaan Sill

Two analyses of samples from the diabase body on Oceaan 99 and adjoining farms (UP-64 and USA-156) are given in Table 1. These samples are characterized by relatively high Fe and Ti concentrations, that are similar to those of sample UP-85. This sample is, however, distinct in most of its trace element abundances. The relatively high Fe and Ti concentrations of the diabase samples are similar to those of other mafic intrusives in the Vredefort Dome (e.g. the Anna's Rust and Vredefort Mafic Complex types - Pybus, 1994). It remains to be proven whether all three occurrences are part of a single, dome-wide sill.

AV-4/UP-234 Type

These two samples are slightly enriched with regard to incompatible elements, such as Ti, Zr, Y, and Nb, when compared with both the Karoo type, the UP-85 type and the Anna's Rust Sill-type intrusives. An older, evolved, group of Ti-rich intrusives, is, therefore, postulated, but this is based on only a limited amount of data. On the basis of the data available, it appears that AV-4 and UP-234 are chemically similar to a gabbroic dyke exposed just north of the Broodkop Shear Zone (Colliston and Reimold, 1990), which is pervasively transected by pseudotachylite veinlets. This dyke was dated by the Rb-Sr (whole rock and mineral) isotope technique by Reimold et al. (1988) at 1.60 $\pm$ 0.12 Ga and has since been cited as strong evidence for the post-2 Ga formation of pseudotachylitic breccia in the Vredefort Dome (e.g., Reimold et al., 1990b).

CHRONOLOGY

No significant radiometric data have been obtained so far on any of the Greenlands lithologies. A lower age limit for the Archaean greenstone sequence is, however, given by the 3.08 Ga age determined by Hart et al. (1981) for the Outer Granite Gneiss, the outer annulus of granitic gneisses of the core to the Vredefort Dome (Figure 1). This rock type is similar, but not identical (Colliston et al., 1987), to the migmatitic gneisses in the southeastern quadrant of the dome. It should also be noted that it is not certain that this 3.08 Ga age really represents the age of intrusion, as a very similar age of 3.03 Ga was obtained in an ^{40}Ar-^{39}Ar stepheating experiment by Reimold et al. (1992) for a metamorphic amphibole separated from a gneiss sample from the so-called Transition Zone (Fig. 1) between Outer Granite Gneiss and Inlandsee Leucogranofels. Accordingly, the 3.08 Ga age may represent the time of amphibolite facies metamorphism of actually older Outer Granite Gneiss.

Four amphibolitic samples from the Greenlands Greenstone Complex were analysed by Reimold et al. (1988) using the Rb-Sr whole rock technique. They reported the YORK regression result of an errorchron corresponding to an age (errors are 2 sigma) of 3.34 $\pm$ 0.23 Ga (I_{Sr} = 0.7003 -+ 0.0007). Recent regression of these data with the GEODATE (Eglington and Harmer, 1991) data reduction programme yielded an age of 3297 $\pm$ 212 Ma (I_{Sr} = 0.7005 -+ 0.0008; MSWD = 9.9). Data for three amphibole separates from some of these amphibolites resulted in an age of 1.98 +- 0.17 Ga (I_{Sr} = 0.709 -+ 0.001) (Reimold et al., 1988). Recalculated, these values changed to T = 1.92 +- 0.18 (I_{Sr} = 0.7088 -+ 0.0011). These results could be interpreted to indicate formation of the komatiitic-tholeiitic extrusives at around 3.4 Ga ago, which is a very similar time to that determined for the formation of felsic and mafic units of the Barberton Greenstone Belt (3.35 - 3.55 Ga; for example, Armstrong et al., 1990), with significant isotopic resetting at around 2 Ga ago, at the time of the dynamic Vredefort event (Walraven et al., 1990).

The only tholeiitic intrusion from the region of the Greenlands Greenstone Complex, that has been dated so far, is the pseudotachylite-bearing Broodkop dyke dated by Reimold et al. (1988) at 1.60 $\pm$ 0.12 Ga.

STRUCTURE

The highly irregular shape and outline of the Greenlands greenstone remnant is a function both of the irregular shape of the window formed in the surrounding Karoo strata, as well as of the major structural features within the remnant and its environs. The most important structural elements within the greenstone remnant are a number of ductile and brittle shear zones, which are more or less orthogonally arranged along north-northeast and east-southeast orientations, as shown in Figure 2.

Mylonite Zones

The most prominent regional structural feature is the steeply northwest dipping mylonite fabric of the northeast-southwest-trending Broodkop Shear Zone, which affects the migmatitic granite gneiss basement on the farm Broodkop 304 (Fig. 2). Detailed investigation of the Broodkop Shear Zone by Colliston and Reimold (1990) has shown that it is the locus of a steeply dipping, northwest-over-southeast reverse fault.

In the northeasterly extension of the Broodkop Shear Zone (about 4.5 km to the northeast), metavolcanics of the greenstone remnant on farms Avondale A112 and Benshoop 74 are cut by a 500 m wide shear with a protomylonitic fabric. This shear zone could well be the northeasterly extension of the Broodkop Shear Zone and may therefore be responsible for controlling the more or less linear northwestern boundary of the Greenlands Greenstone Complex (Fig. 2). On the northern portion of Avondale A112, the mylonite is, in places, highly ferruginous and crosscuts several local units of banded iron formation. The spatial orientations of the mylonitic fabric and of rodding (pencil) structures are shown in Figure 21.

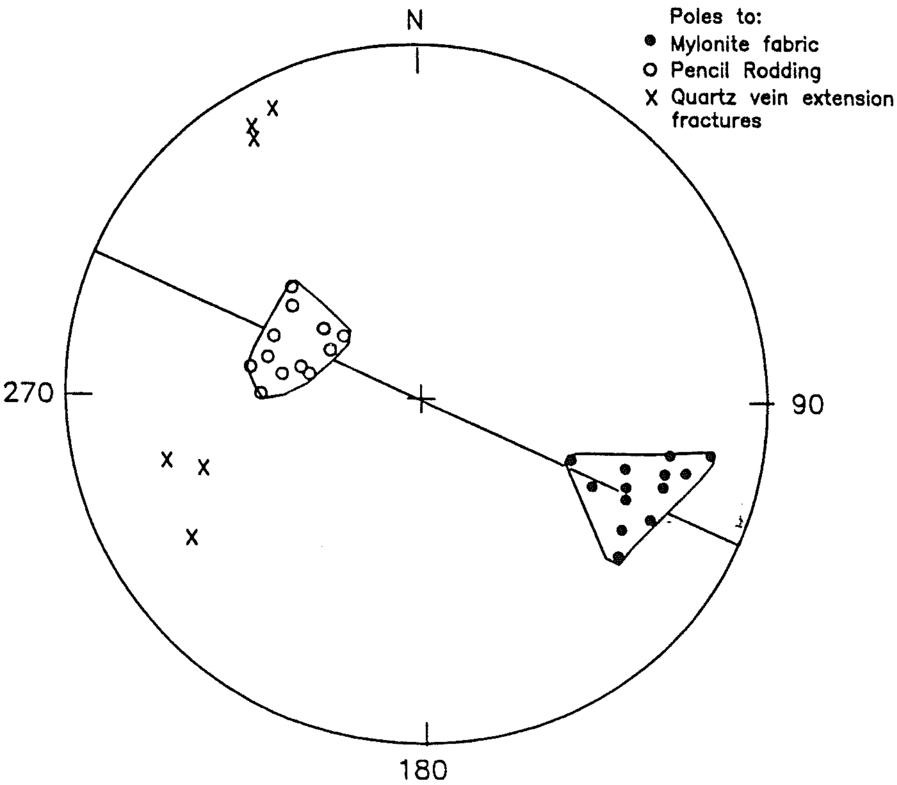


Figure 21: Equal area plot of poles to orientations of mylonite fabrics, pencil rodding, and quartz vein extension fractures in metavolcanics on farms Avondale A112 and Benshoop 74.

Two northwest-southeasterly trending mylonite zones are developed on farm Avondale A112, near the T-junction in the main road between Greenlands and Vredefort (Fig. 2), which crosses the farm in suboutcrop of komatiitic lavas. The fabric in these mylonitized zones strikes east-southeast and dips steeply (75°) to the south. It was not possible to determine the shear sense of these zones.

Shear Zones

In the eastern and southeastern extremities of the Greenlands greenstone remnant several narrow (2 - 10 m wide), northwest-southeast orientated, ductile shear zones are developed (Fig. 2). The shear zone in the southeastern corner of the farm Blaauwboschpoort 13 is cut by a quartz-filled extension fracture. The sigmoidally deformed quartz vein indicates a sinistral sense of shear. The shear zone on the farm Enkelbosch 98 exhibits well-preserved S-C fabrics which also indicate a sinistral sense of displacement along this shear zone.

In addition, a number of shear zones in the Greenstone Complex have northeast-southwesterly orientations.

The three small outcrops of Orange Grove orthoquartzite on farm Prospect A59 are cut by an array of vein-quartz-filled extension fractures (Fig. 2). These fractures are thought to be related to a northwest-southeast orientated fault that forms part of the shear zone developed in the metavolcanics on farm Blaauwboschpoort 13. These data are illustrated in Figure 22.

Kink Bands and Crenulation Folds

In the northeast-southwest trending portion of the Greenlands Greenstone Complex, on farm Blaauwboschpoort 13, structures formed during a later deformation phase of the strongly cleaved and sheared, mafic to intermediate, tuffaceous rocks have been preserved. These structures consist of kink bands, reverse kink bands, and crenulation folds that occur individually or, rarely, in the form of conjugate pairs and indicate overall regional shortening of the planar fabric (cf. Figs. 12 and 13). The very pronounced cleavage in the fine-grained tuffaceous rocks is subparallel to the regional foliation fabric (trending northwesterly and dipping steeply towards the south) in the southeastern limb of the complex (Fig. 2). A feature of the kink band development in this area is that the kinks are not evenly distributed across the complex, even though there is a strongly developed homogeneous schistosity across the whole area. Instead, the kink bands are confined to lensoid zones, 2 to 4 m wide and up to 10 m long.

The finely cleaved metavolcanic rocks contain only one prominent set of upright kink bands with axial planes having a strike of 015°, dipping 68° west-northwest, and an internal kink cleavage striking at 322° and dipping at 78° to the southwest. The external (regional) cleavage strikes at 100° and dips at 59° to the north (Figure 23). The general tendency for one set of kink bands to be more prominently developed than any other was noted by Anderson (1968). Ramsay and Huber (1989, p.428) suggested that this effect is a result of heterogeneous strain distribution during deformation. In cases where only one set of kinks

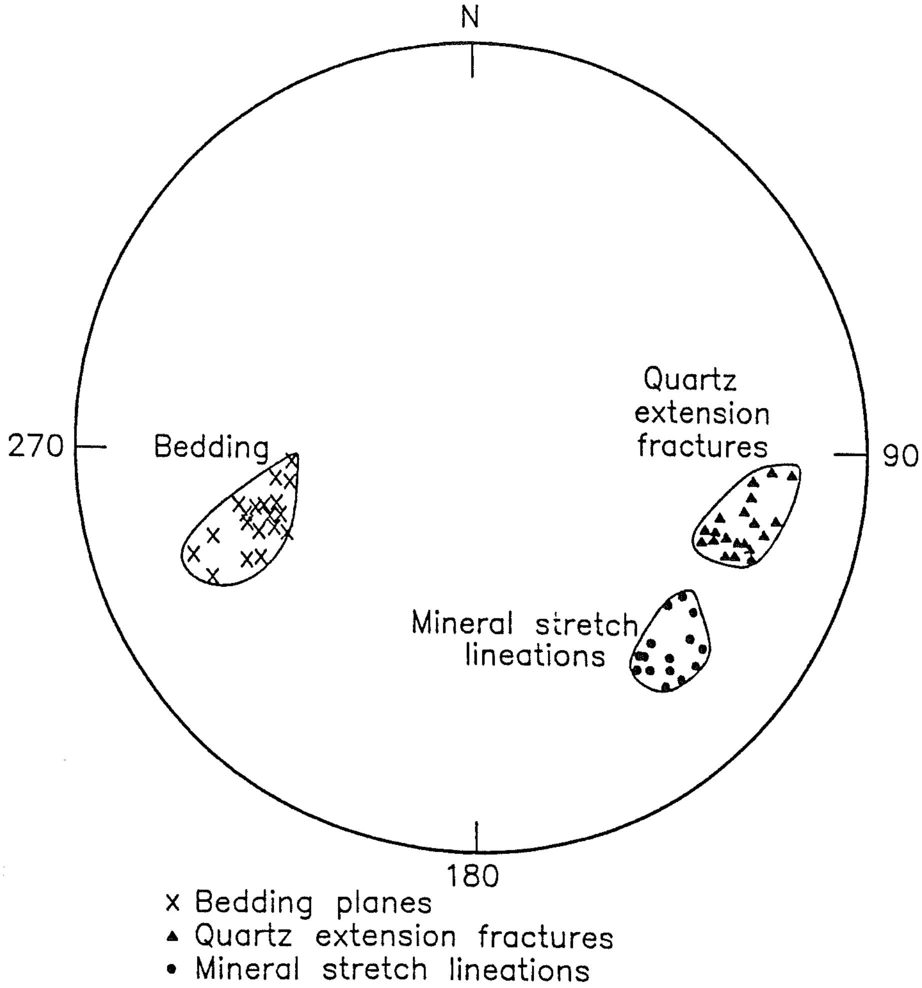


Figure 22: Equal area plot of poles to bedding planes, quartz-filled extension fractures, and mineral stretching lineations in Orange Grove Quartzite exposures on farm Prospect A59.

is developed, such as in this section of the Greenlands Greenstone Complex, the principal directions of the overall bulk strain are markedly oblique to the unkinked sectors of the foliation surfaces. In this case the principal stress σ_1 lies in the acute angle between the unkinked surfaces and the axial planes of the kink bands. If conjugate kink bands are developed, the principal strain directions are parallel and perpendicular to the regional foliation (Ramsay and Huber, 1989, p.428).

From kink band symmetry it can be inferred that kink band structures (Figure 23) developed in a northwesterly directed shear system. Vergence in the reverse kink bands is towards the northwest.

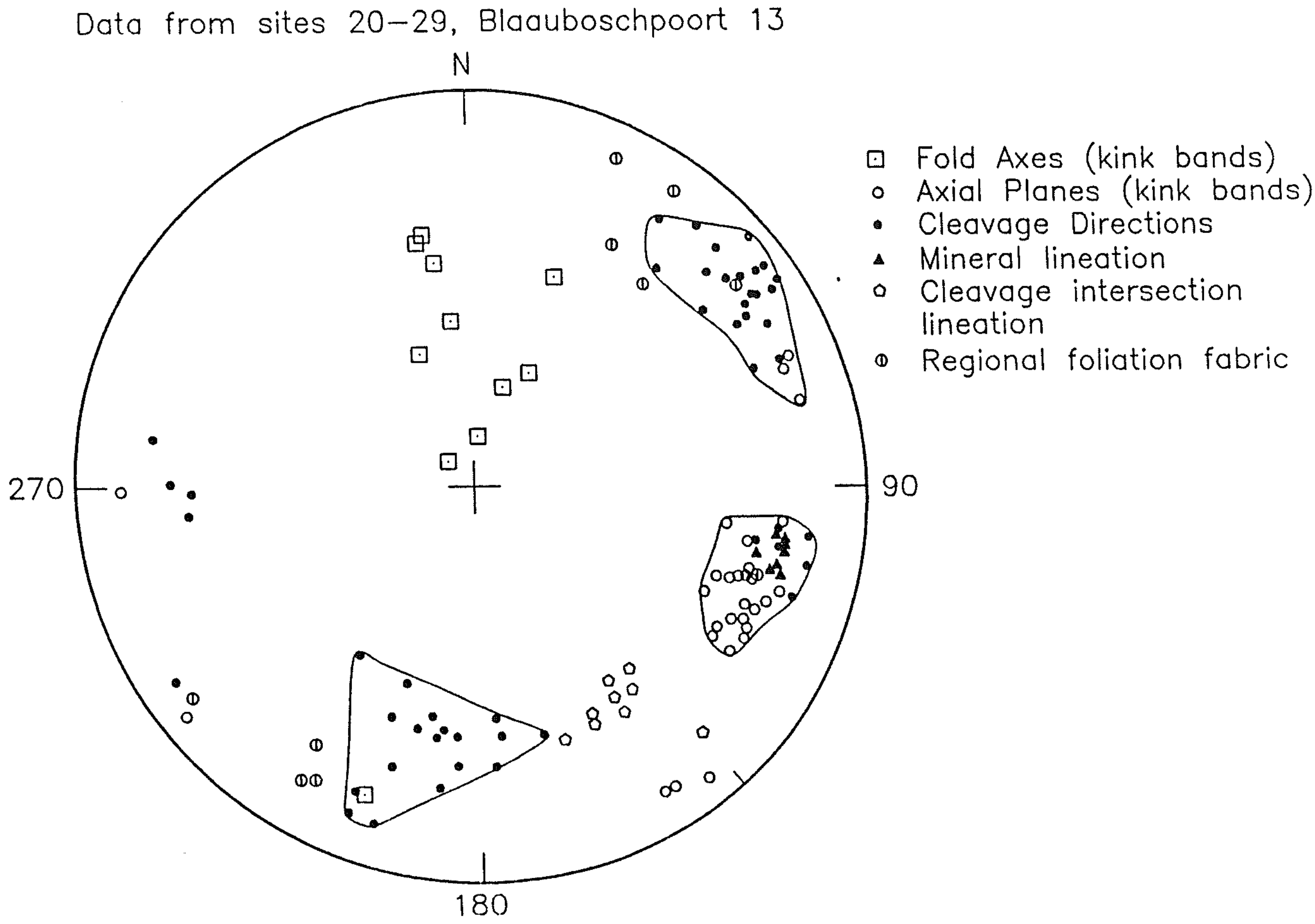


Figure 23: Equal area plot of poles to fold axes and axial planes to kink bands, cleavage, mineral stretching lineations, cleavage intersection lineations, and regional foliation in mafic to intermediate tuffaceous metavolcanics on Blaauwboschpoort 13.

Near the western end of this belt, close to the boundary between Blaauwboschpoort 13 and Van der Merwes Dam 37, is an exposure of finely cleaved mafic metavolcanics with asymmetric, upright kink bands. It is possible that these structures are parasitic folds on the limbs of a larger fold structure. It was noted by Ramsay and Huber (1989, p.429) that, if a parallel array of wide first kink bands undergoes reactivation resulting in a conjugate array of kinks, the chevron folds so formed have limb lengths proportional to the spacing of the first formed kinks. The long limb sectors of the chevron folds are caused by the early formed, widely spaced kinks, whereas the closely spaced second kinks appear as parasitic folds.

Brittle Fracturing

A phase of brittle fracturing can be identified in the mafic metavolcanics on the farms Blaauwboschpoort 13 and Avondale 112. The deformation is manifest as conjugate sets of brittle shear fractures that cut the lavas with no apparent displacement along the fracture planes. Four fracture sets were identified from the data plotted in Figure 24. The data in the northwest and southeast fracture sets are more tightly constrained than the others.

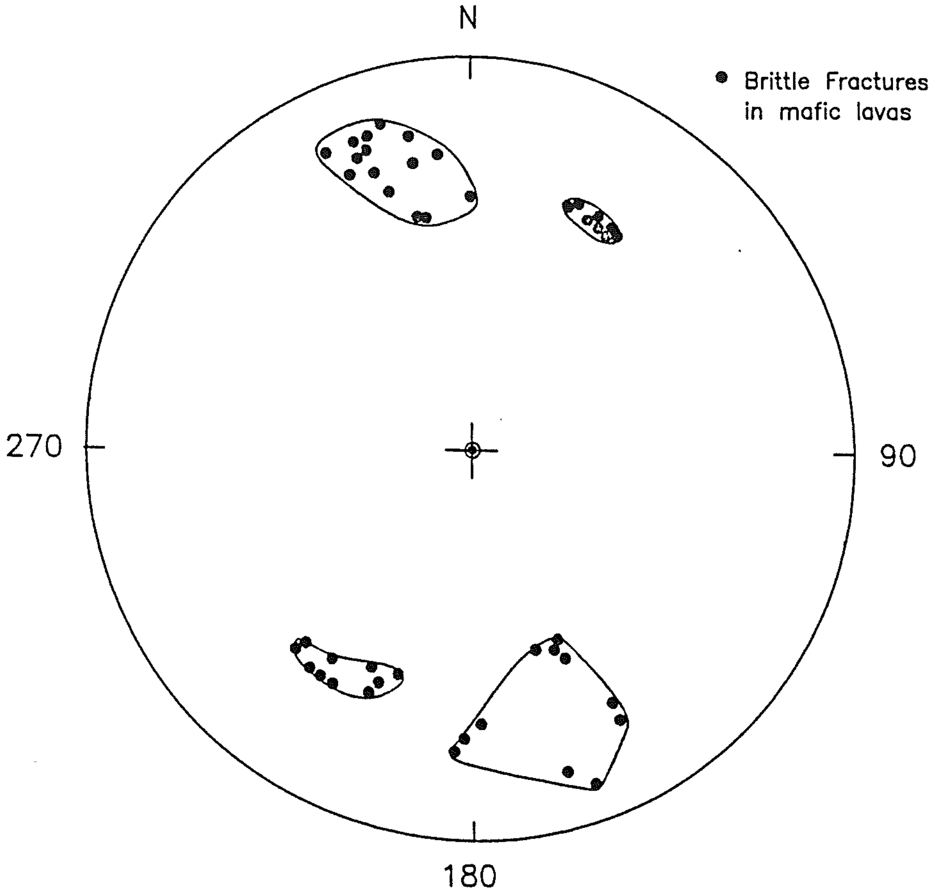


Figure 24: Equal area plot of poles to orientations of brittle fractures in mafic lavas on Blaauwboschpoort 13 and Avondale A112.

Pseudotachylite

A single veinlet of pseudotachylite, about 0.5 cm wide and 20 cm long, was observed in komatiitic lava on the farm Hattingsrust 68. Small amounts of pseudotachylite (Fig. 15) also occur in the diabase sill on farm Blaauwboschpoort 13 (sample UP-85) where the breccia occurs as anastamozing veinlets, only a few millimetres wide, with total lengths rarely exceeding 30 cm. These highly irregular veinlets also have very variable dips that can range, within one vein, from near-vertical to subhorizontal attitudes. Similar irregularity of pseudotachylite orientations has been observed in tectonically produced occurrences, such as the Sand River Gneiss of the Northern Transvaal (Brandl and Reimold, 1990) or along the Letaba Shear Zone at the northern margin of the Murchison Range (G. Brandl and W.U. Reimold, unpubl. observations).

The Li-bearing pegmatites on farms Avondale 600 and 12 also contain pseudotachylite in up to 2 cm wide veinlets of generally irregular orientation and highly variable attitude.

Exposures rarely permit these occurrences to be traced for more than 15 cm. Should it be shown in future that these alkaline rocks are coeval with the 2.1 - 2.2 Ga alkali granitic intrusives in the northwestern collar of the Vredefort Dome (Walraven and Elsenbroek, 1992), then this would provide an upper age limit for pseudotachylite formation in the southeastern sector of the dome.

Shatter Cone Orientation

Structural measurements on the shatter coned pavement in Orange Grove Quartzite on farm Prospect A59 indicate a bedding orientation of about north-south, dipping at 50°E. Orientations of major joint sets are 70-265, 64-244, 77-293, 82-345, 75-148, and 67-149. The authors consider that these major joint sets (cf. Fig. 16) all represent multi-striated joint surfaces (MSJS), some of which were exploited by weathering agents.

Contrary to Albat and Mayer (1989) who only recognized one, or at most two conjugate sets of, what they term, "megascopic planar shock fractures" in the collar rocks of the Vredefort Dome, the authors have identified more than 2 sets of MSJS (on the basis of Albat and Mayer's description of their "shock fractures" it must be concluded that they represent individual sets of MSJS, as defined by Nicolaysen and Reimold, 1987; however, MSJS are generally non-planar and instead distinctly curviplanar - Fig. 16). For the study area in the southeastern quadrant of the Vredefort Dome, Albat and Meyer reported "shock fracture" orientations for their study locations 40 and 41 in NE and SW orientations, respectively.

Manton (1962) determined the orientation of a (so-called master) shatter cone axis at a locality on farm Prospect A59 and reported a strike direction of 152° and a plunge of 70°N. His bedding orientation is: strike 80°, dip 50°N.

Discussion

The main structures, namely mylonite zones and shear zones, are probably the oldest deformation structures in the study area. Tectonic readjustments in the later stages of the regional deformation history led to the development of kink banding and crenulation folding in the finely cleaved schistose units.

Pseudotachylite veins are sparsely developed in the Greenlands Greenstone Complex, but crosscut the oldest extrusive volcanic rocks as well as the younger intrusive sills. There is no indication as to whether these veins originated during a single deformation event or not. However, recent laser Ar dating (Spray et al., 1995) of Broodkop pseudotachylite, in conjunction with the findings of multiple generations of pseudotachylite mentioned by Colliston and Reimold (1990) and the chronological results by Reimold et al. (1988), strongly suggest formation of at least two generations of pseudotachylite in the southeastern sector of the Vredefort Dome, namely at about 2 Ga ago and at post-1.6 Ga times. Contrary to other parts of the Vredefort Dome, where various crosscutting relationships between pseudotachylite and shatter cones have been observed, it was not possible in this study to find constraints on the relative age relationships between such features in the Greenlands

Greenstone complex.

Finally, the last deformation event resulted in the development of fractures in an extensional tectonic phase.

GRANITE GNEISSES OF THE ARCHAEAN BASEMENT

The granitic gneisses of the Archaean basement in the southern portion of the Vredefort Dome are to a large extent covered by Lower Karoo strata, the latter mainly consisting of shales. The problem of poor exposure is most acute in the southeastern quadrant of the dome, where the veneer of sedimentary cover is particularly thick. Basement gneisses only crop out on the farms Mara 1084, Klipplaat 53, and Samaria 484 to the south and southwest of the Inlandsee pan (Fig. 1). These exposures occur as flat pavement outcrops of migmatized quartz-feldspar-biotite gneiss. Together these outcrops constitute a mappable surface area of only 0.4 km^2, but provide important insights into the stratigraphic and structural attributes of the basement rocks in this area.

Lithologies

The gneisses exposed on the farm Mara 1084 occur as isolated outcrops and pavements which are exposed in an area surrounded by agricultural development terrane, as shown in Figure 25. The gneisses are cut by a north-south trending mylonite zone which has affected both granitic rocks and a minor outcrop of metavolcanic rock (Figure 25). Pseudotachylite occurs as short and highly irregular, less than 1 cm wide, veinlets in both rock types in some of the larger outcrops in the northeastern portion of the farm. Some large boulders of pseudotachylite float are also found, together with blocks of mylonitized quartzo-feldspathic and garnet-bearing gneisses, along the northern extensions of the mylonite zone. A dyke, probably of Karoo age and orientated subparallel to the regional foliation, was also mapped in this area.

The detailed geology of two large granite gneiss pavements on the farm Mara 1084 is shown in Figures 26 and 27. The pavement shown in Figure 26 (Site No. 44) lies within the area affected by the mylonite zone. The gneisses within a 20 m wide envelope are classified as protomylonites, as reworking has not obliterated the primary character of the parent gneiss. The protomylonite consists of foliated, fine-grained bands of even-textured gneiss, in which all mineral grains have been flattened. Protomylonite comprises less than 25 per cent matrix, which surrounds unaltered protoliths (Coward and White, 1989). Veins of pseudotachylite, which cut the protomylonite fabric, are unaffected by this deformation and, hence, are younger than the shear deformation.

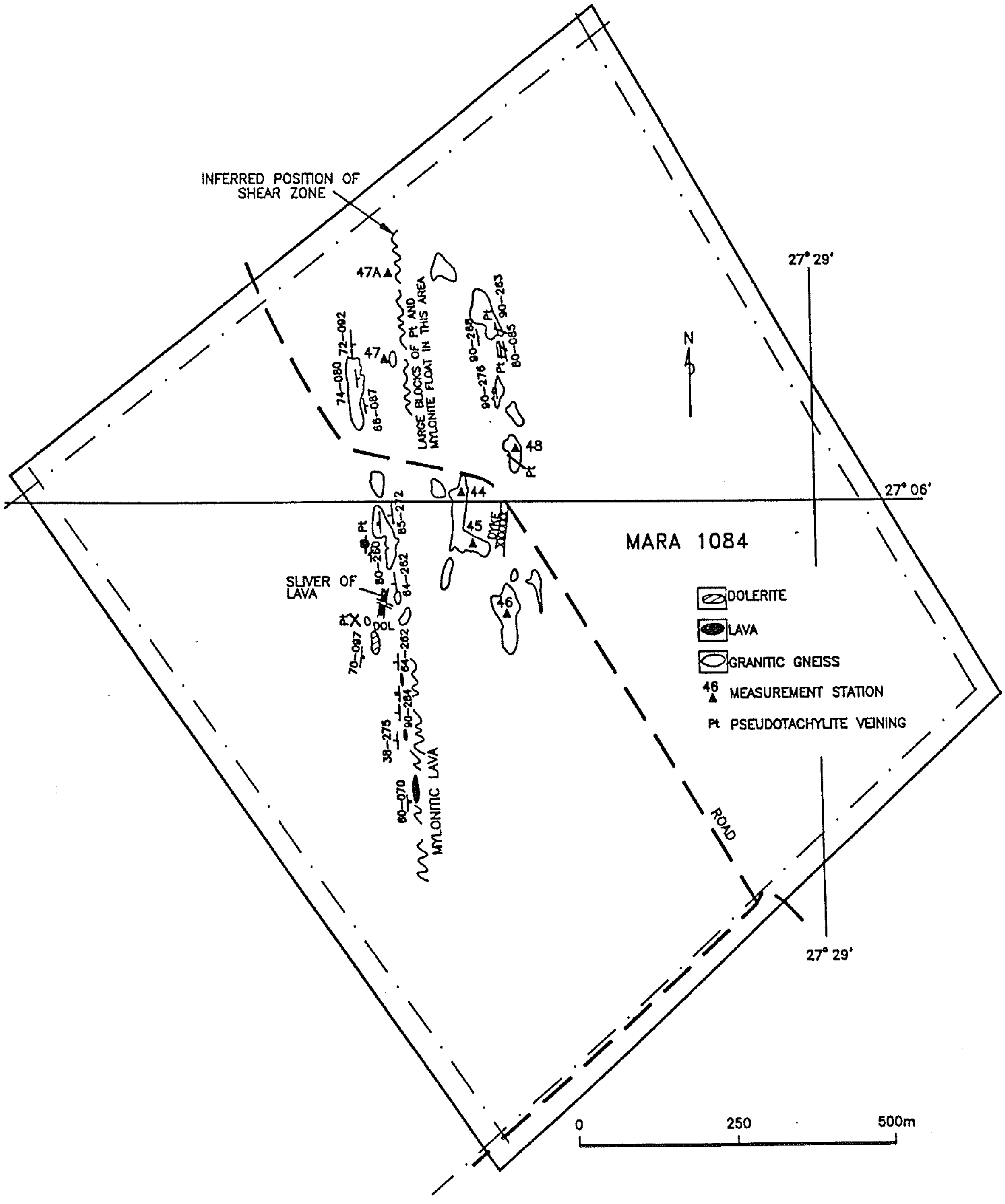


Figure 25: Geological map of farm Mara 1084 showing the distribution of major migmatized granite-gneiss pavements (compare sites 44 and 46 on Figures 26 and 27 , respectively) and the ca 1000m long, north-south trending shear zone.

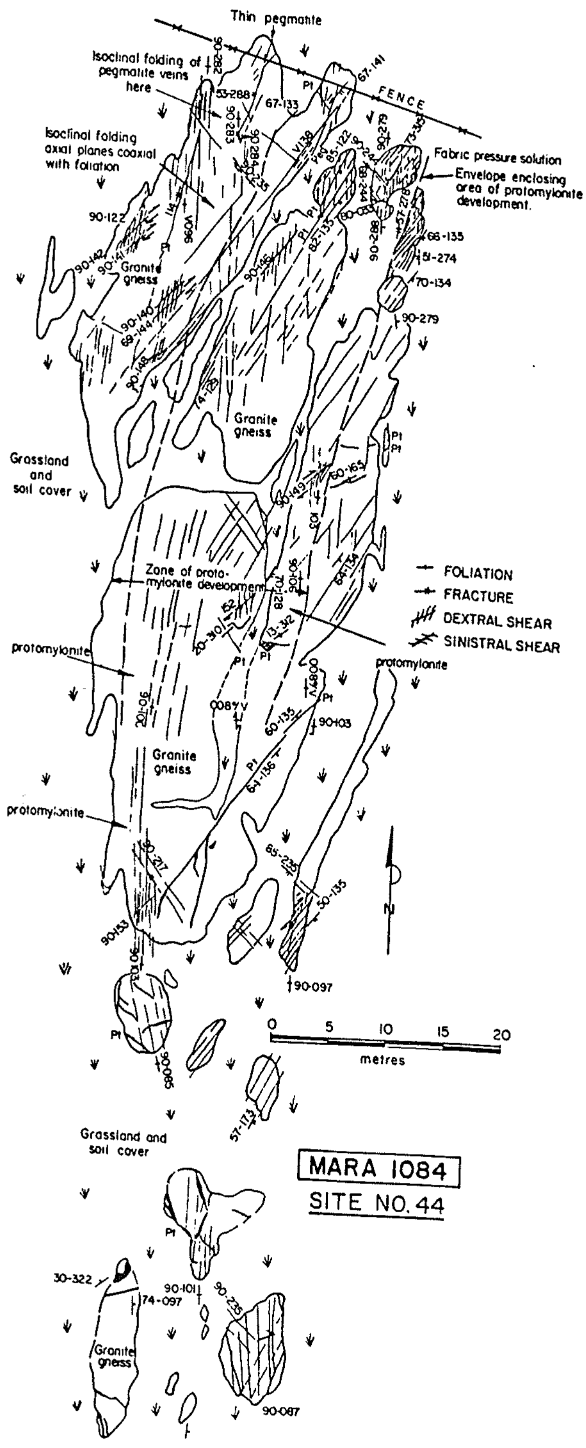


Figure 26:
Detailed outcrop map of migmatized granite gneiss and protomylonites on farm Mara 1084 (site 44).

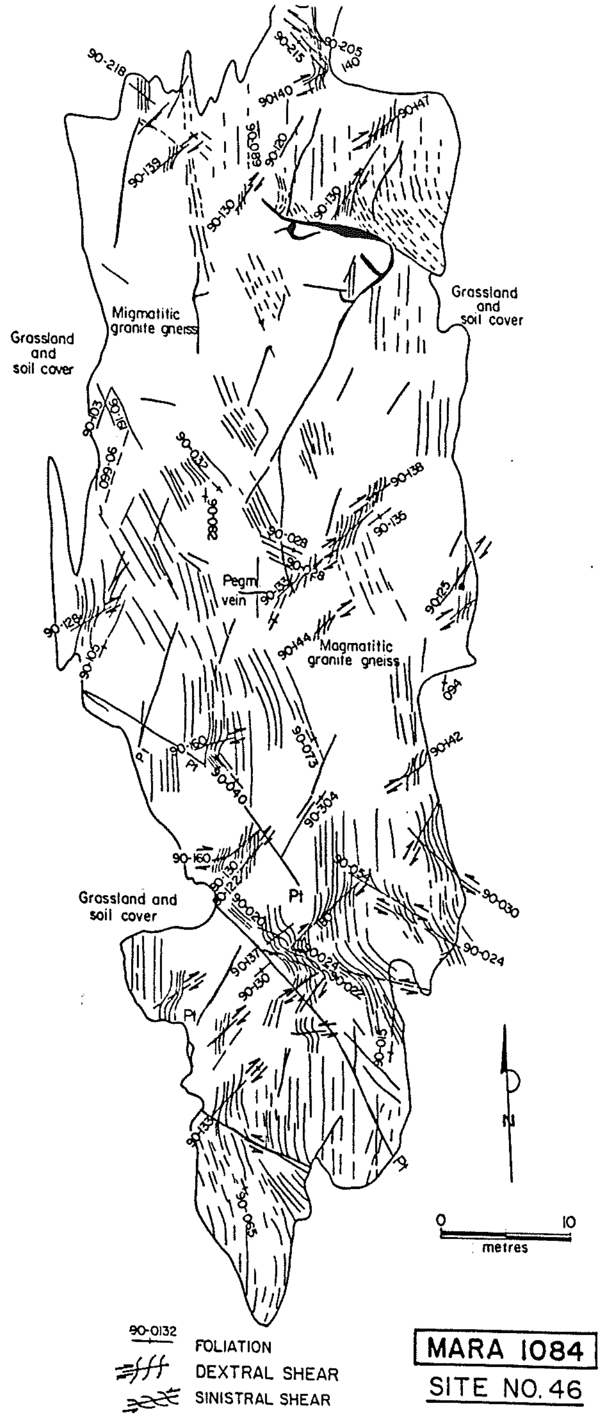


Figure 27:
Outcrop map of migmatized granite-gneisses containing single and conjugate sets of upright ductile shear zones at site 46 on farm Mara 1084.

The pavement on Mara 1084, shown in Figure 27 (Site No. 46), consists of strongly foliated quartz-feldspar-biotite gneiss. The fabric is locally deformed by ductile shear zones that generally subscribe to a pattern of conjugate shear zones (see also Colliston and Reimold, 1990). Both dextral and sinistral shear senses were accommodated in these shear zones (Figures 28 and 29).

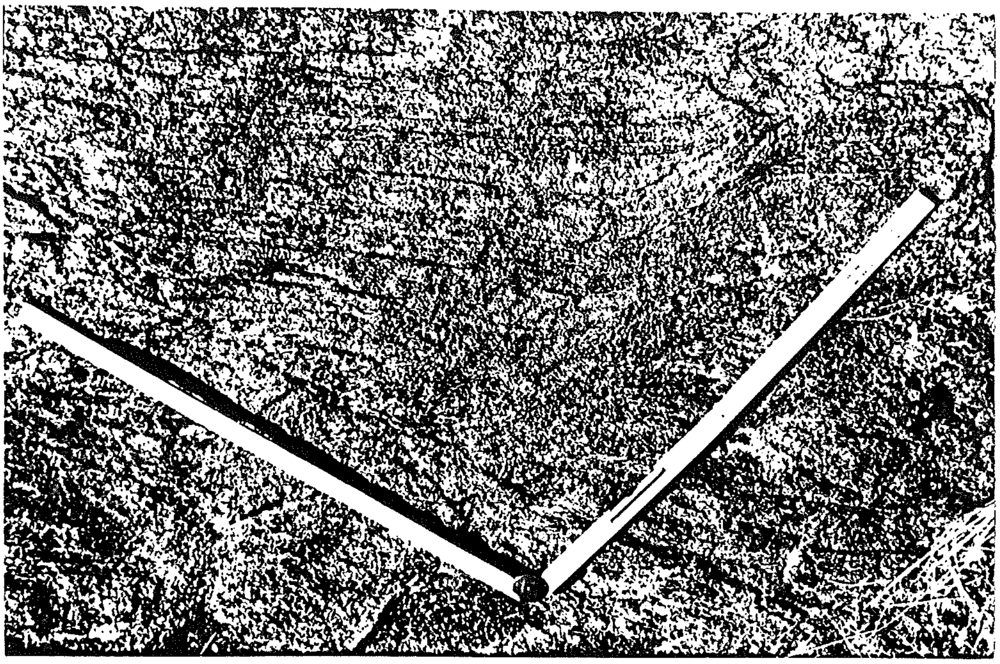


Figure 28: Single irregular (non-linear), right-lateral ductile shear in strongly foliated migmatized granite-gneiss. Length of ruler arm = 30 cm.

Figure 29: Conjugate set of ductile shears in granite-gneiss on farm Mara 1084 (Site 46). Movement along shears is left-lateral. Length of pen = 14 cm.

A number of outcrops of migmatitic granite gneiss are found on farms Klipplaat 53 and Samaria 484 (Fig. 30). The pavement-type exposures of migmatite on Samaria 484 also include a minor amount of strongly foliated quartz-feldspar-amphibole-magnetite gneiss (apparently a large xenolith in the migmatitic granite gneiss), and some wide (up to 10m) irregular veins of pseudotachylite - as shown on the detailed map of this area (Figure 25).

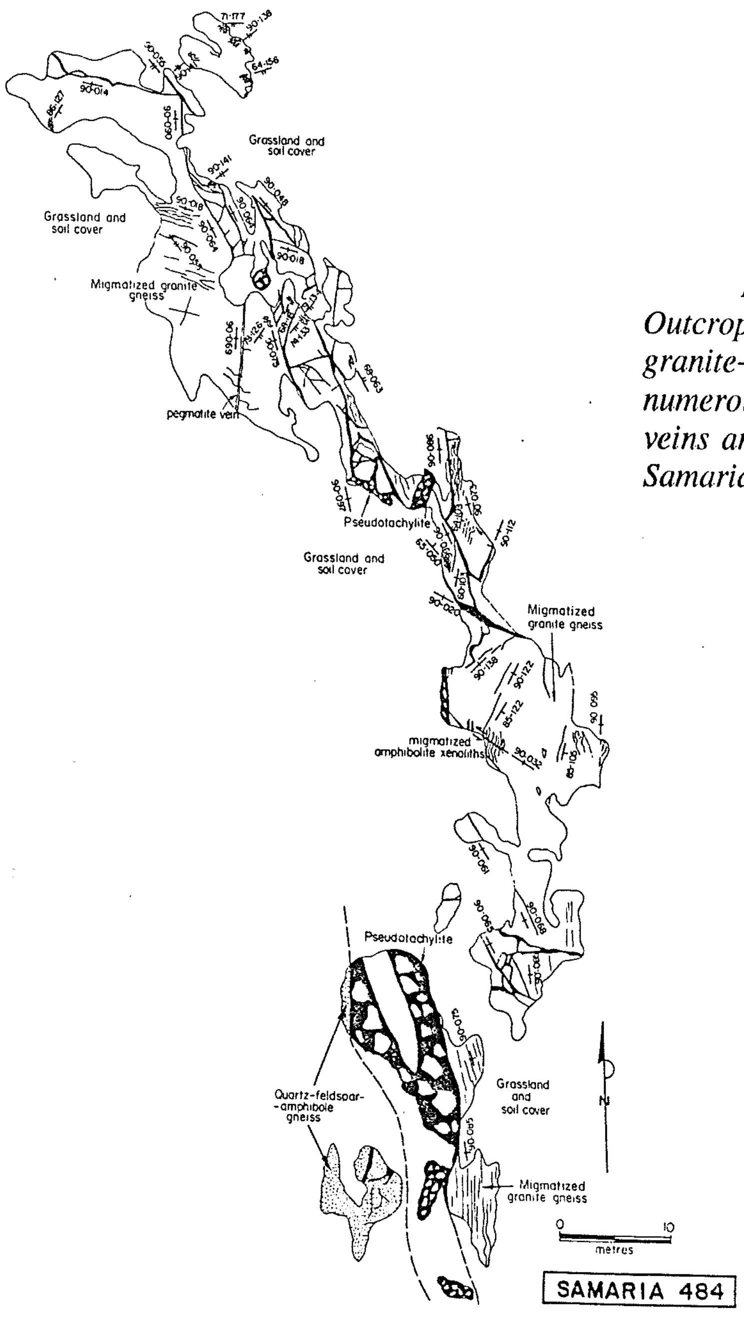


Figure 30:
Outcrop map of migmatized granite-gneiss cut by numerous pseudotachylite veins and 'pods' on farm Samaria 484.

A number of generally narrow (< 2 m wide) dykes of altered mafic intrusives were identified on Samaria 484 and, further to the southwest, on the neighbouring farm Pretoriuskraal 987. Some of these intrusives appear similar to Karoo dykes, others are cut by pseudotachylite (< 1 cm wide veinlets) and obviously are older. These exposures are rarely wider than a few metres.

Foliation

Foliation in the granitic gneisses from the southern portion of the Vredefort Dome has been described in detail by Colliston and Reimold (1990). These authors defined foliation as "...the planar reorientation of biotite and/or subparallel, elongated augen of feldspar and stretched quartz grains". They found that the strike and dip of the foliation fabric varied considerably from place to place and determined three main foliation strike directions, namely northeast-southwest, northwest-southeast, and east-west.

In the migmatitic gneiss pavements mapped on the farms Mara 1084, Klipplaat 53, and Samaria 484, however, only one, namely the north-northwest/south-southeast direction is dominant, as shown in the equal area plot for the structural data from these three farms in Figure 31.

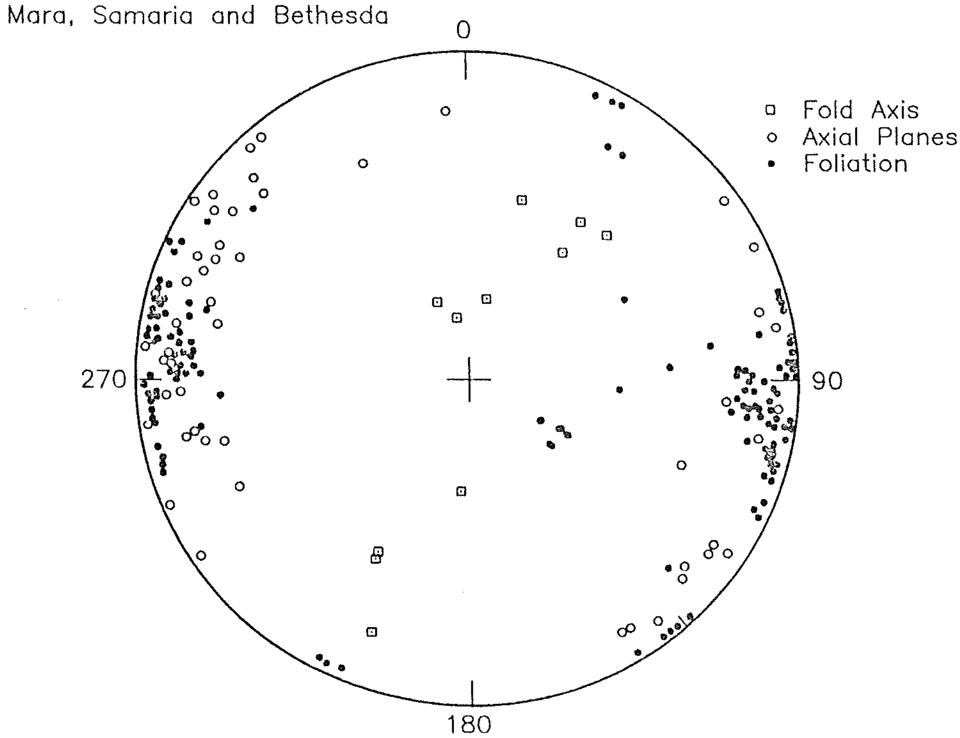


Figure 31: Equal area plot of poles to axial planes and fold axes to upright isoclinal folds and of the regional foliation fabric on farms Mara 1084, Samaria 484 and Klipplaat 53.

Folds

Upright isoclinal folds are predominantly developed in the migmatitic gneisses on Klipplaat 53 and Samaria 484. The distribution of poles to subvertical axial planes (Fig. 31 indicates that foliation and axial planes of folds define similar, roughly north-south, trends. The fold axes of these isoclinal folds dip from shallow to steep angles, both to the south-

southwest and to the north-northeast (with the latter orientation appearing as the dominant one - Figure 31). This situation is interpreted as the result of deformation and rotation of these folds by the later, northwest-directed, shearing. The subhorizontal foliation and early recumbent isoclinal folds referred to by Colliston and Reimold (1990) elsewhere in the southern portion of the Vredefort Dome were not identified in the portions of Archaean basement examined during this study.

Ductile Shear Zones

The regional gneissic fabric in the migmatite outcrops has been deformed by subvertical ductile shear zones, which range in length from less than one metre to nearly 10m. The shear zones post-date the event of subvertical foliation formation and the accompanying isoclinal folding. They may occur singly, with either sinistral or dextral shear sense, or as conjugate pairs (Colliston and Reimold, 1990). Poles to the shear planes are plotted in Figure 32. They indicate that the ductile shears form a conjugate pair with planes orientated northwest-southeast and northeast-southwest.

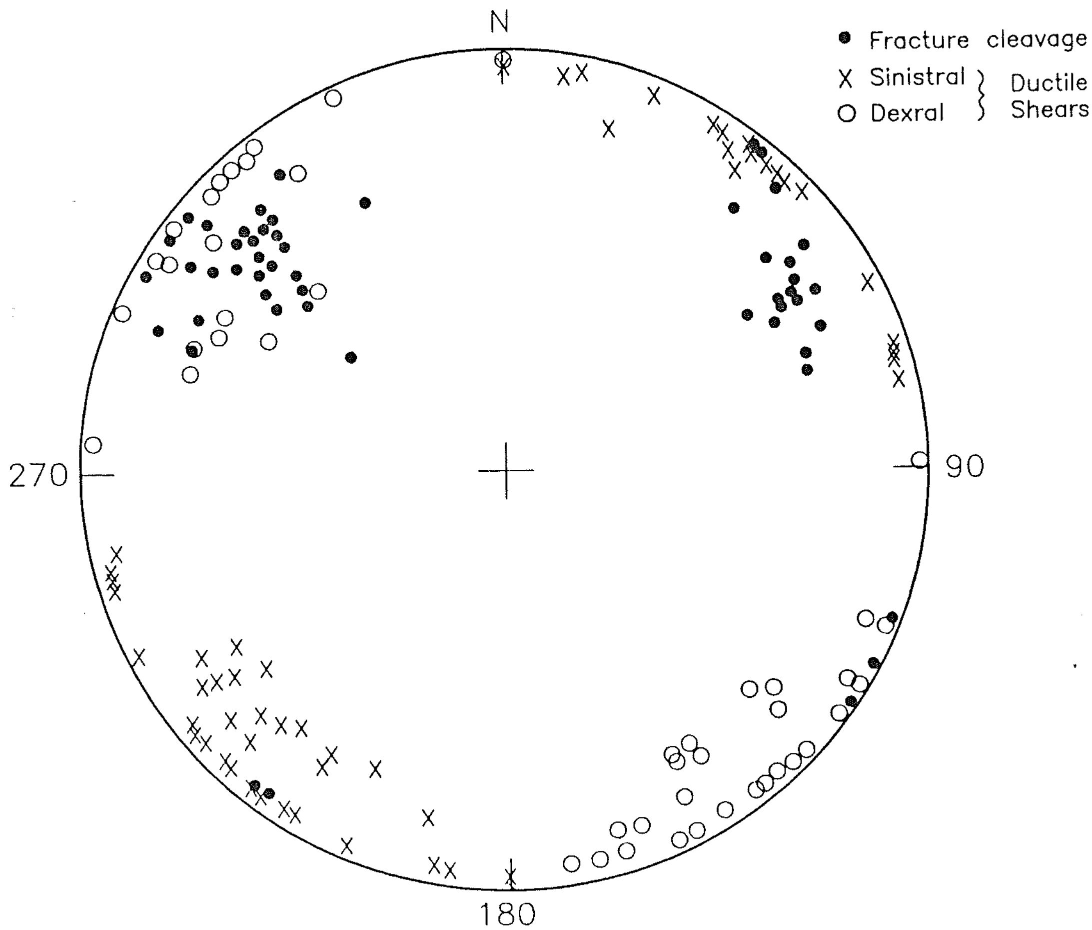


Figure 32: Equal area plot of poles to sinistral and dextral ductile shears, as well as fracture cleavage, in migmatized granite gneisses from various localities.

Colliston and Reimold (1990) have inferred a minimum age of 3.07 Ga for this shearing event, because they could show that Dominion Group and Witwatersrand Supergroup strata (for a review of chronological data, cf. Walraven et al., 1990) are not affected by this deformation.

Fracture Cleavage

Brittle deformation in the form of closely spaced fractures (which here are termed fracture cleavage rather than joints) occur in all the migmatite exposures studied. The fracture cleavage planes are predominantly subvertical in orientation, as can be seen from the plot of their poles in Figure 32. Two major fracture cleavage directions exist and are vertically coincident with the joint sets recorded by Colliston and Reimold (1990, page 8). These authors also identified an additional three sets of joints in the gneisses from Broodkop Hill, but these do not appear in the other exposures of the southern portion of the dome.

Pseudotachylite Occurrences

Pseudotachylite occurs as veins or dykes, varying in thickness from one millimetre to several metres (for example, near the farm-house on Samaria 484), which occupy fractures parallel to the foliation direction, the cleavage direction, and/or ductile shear directions. In addition, some occurrences are randomly orientated. The distribution of the poles to the veins around the perimeter of the net (Fig. 33) indicates that they are predominantly vertically orientated, but veins dipping anywhere from 10° to 90° are also present. The fact that apparently vertical pseudotachylite veins may change their orientation drastically on a centimetre to decimetre scale may be easily overlooked in terrane of mainly two-dimensional exposure. The measurements taken in the southern part of the Vredefort Dome indicate a predominant orientation of pseudotachylite veins in a roughly north-south direction with a notable paucity of veins with an east-northeast orientation (Fig. 33).

Microdeformation

The typical microdeformation features of the migmatites from the Broodkop Shear Zone, as described by Colliston et al. (1987), are also observed in the gneisses from the study area. All samples studied petrographically display a variable, but always high, degree of annealing. The recrystallization degree of a given sample is related to its structural setting: specimens from mylonite or ductile shear zones are more strongly recrystallized than others from brittle deformation regimes. Typical mylonite fabrics consist of quartz ribbon structures and phenocrysts of (mainly) feldspar (K-feldspar > plagioclase) minerals. These are usually set in a fine-grained, often mosaic-textured matrix, in which 120° triple junctions can be observed between quartz or feldspar crystals.

Planar microdeformations (apparently relics of Planar Deformation Features [PDFs] - Leroux et al., 1994) in quartz are very rare (as noted for all gneiss samples from the southern part of the dome). Where present, they can be identified as either planar fluid inclusion trails or as open planar fractures. More than one set of "features" per host crystal has never been observed in this sample suite. Biotite and muscovite may occasionally be

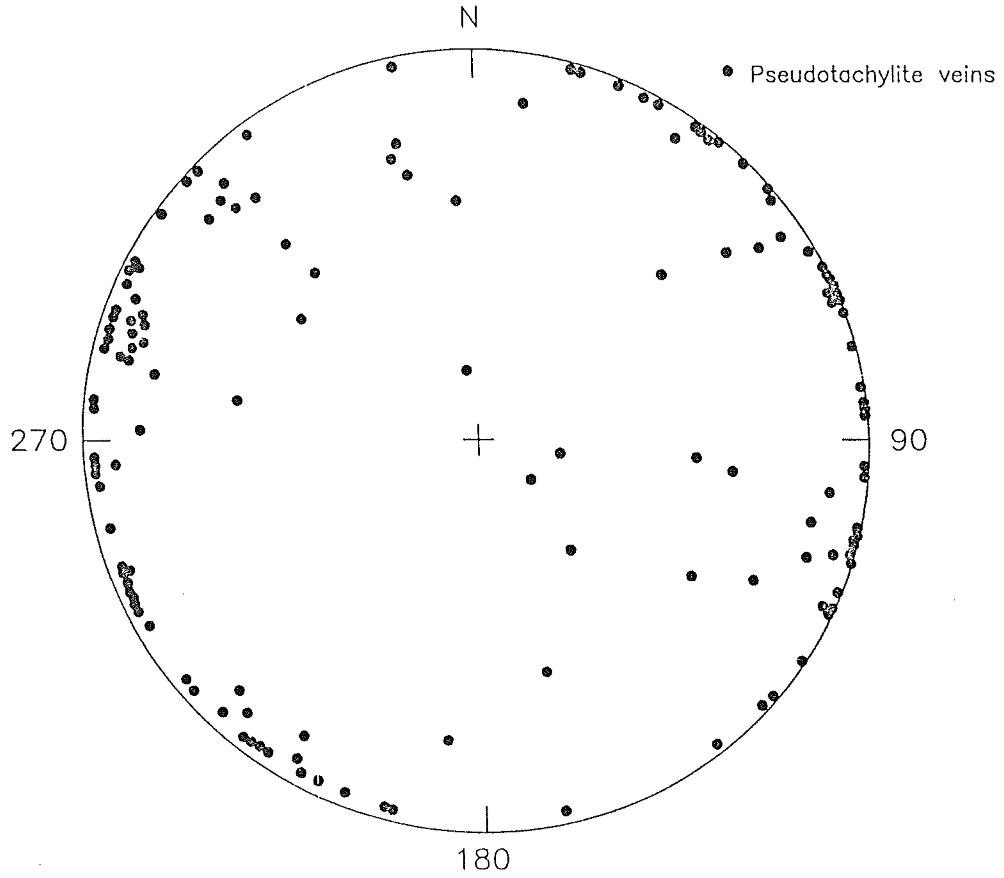


Figure 33: Equal area plot of poles to pseudotachylite vein orientations (n = 123) from various granitoid localities in the study region.

kinkbanded. In places, planar microdeformations are the loci for annealing in the typical (for Vredefort microdeformation) form of microscopic stringers of elongated quartz subcrystals.

Summary of Structural Data

According to the investigations of Colliston and Reimold (1990), the earliest structural event recorded in the granitic gneisses in the southern portion of the Vredefort Dome is a subhorizontal foliation-forming tectonism. This resulted in the formation of early recumbent isoclinal folds which contain a coplanar foliation. During this study upright isoclinal folds, which plunge at varying angles to the northeast and southwest, were documented. These fold axes lie along a vertical great circle which is approximately coplanar with the axial planes of the folds. The axial planes are spread out around the perimeter of the net (Fig. 31) indicating that the orientation of folds varies from north-northwest to northeast. The dispersion of the poles to foliation is more restricted and indicates that the predominant orientation of this structural element is north-northeast and is roughly coplanar with the axial planes of the folds, as mentioned by Colliston and Reimold (1990, page 5).

Later readjustments of the stress fields led to deformation of the earlier foliation along conjugate sets of ductile shear zones. The final event that affected these rocks was a brittle deformation event that produced conjugate sets of fracture cleavage.

SYNTHESIS

The Greenlands Greenstone Complex probably represents a small remnant of a larger and lithologically more complex, pre-existing greenstone belt assemblage. It has none of the sedimentary components usually associated with the more extensive greenstone belts in South Africa, such as the Barberton, Murchison, or Pietersburg greenstone belts. The volcanic, tuffaceous and intrusive, rock types comprising the Greenlands Greenstone Complex appear similar, in terms of mineralogy and chemical composition, to the volcanic sequences in the lowermost stratigraphic positions of the major greenstone belts in South Africa. These usually comprise a dominantly komatiitic basalt assemblage with a minor komatiitic ultramafic component and a variable proportion of tholeiitic volcanic rocks. The cherty component of the stratigraphically lowermost volcanic assemblages, which is common in other greenstone belts, is absent in the Greenlands remnant, but feldspar porphyry units are present.

The relative ages of the various structural elements in the Greenlands Greenstone Complex are not obvious. However, the impression was obtained that the most intense deformation styles are the oldest. Accordingly, the mylonite zones were probably the first to have formed, followed by the pervasive cleavage-forming event and, then, by the formation of ductile shear zones.

Tectonomagmatic Evolution

Table 2 summarizes events in the basement rocks as established from field relations and preliminary radiometric dating (cf. Colliston and Reimold, 1990).

TABLE 2

TECTONOMAGMATIC EVOLUTION OF THE GREENLANDS GREENSTONE COMPLEX

1. Sequence of events established from studies of the granitoid basement

A. Early Archaean, pre-Dominion Group structural events in the Granitoid Basement rocks (pre-3.07 Ga): (arranged from oldest to youngest)

(i) Intrusion of granitoids/development of a sialic crust;

(ii) Early migmatization and ductile deformation with production of a subhorizontal shear fabric and associated folds (granulite metamorphism, e.g., Steynskraal Metamorphic Zone?);

TABLE 2 (continued)

(iii) Development of NE- and NW-trending conjugate ductile shear zones with predominantly horizontal displacement and associated with retrograde amphibolite metamorphism (e.g., Broodkop Shear Zone);

B. Archaean to Proterozoic Deformation Events in the Granitoid Basement:

(iv) Emplacement of pegmatites (ca. 2.8-2.9 Ga);

(v) Intrusion of "epidiorites" (thought to be Ventersdorp-related - e.g., Pybus, 1994) at ca. 2.7 Ga ago, associated with extensional faulting, which also affects the supracrustal rocks;

(vi) Broodkop brittle shear event (re-activation of earlier ductile shear) at about 2.2 - 2.3 Ga ago.

(vii-1) Quartz vein development.

(vii-2) Pseudotachylite generation at a) 2 Ga ago
b) post-2 Ga times (e.g., at about 1.6 Ga ago near Broodkop.

2. Sequence of Events recorded in the Greenstone Complex:

A. Pre-Dominion Group Events

(i) Formation of komatiitic-tholeiitic sequence (around 3.3-3.4 Ga ago (?));

(ii) Regional ductile shearing event (only observed in the Steynskraal Metamorphic Zone);

B. Pre- or Post-Dominion Group Events

(i) Emplacement of pegmatites and quartz porphyries;

C. Post-Dominion Group Events

(iv) Brittle shear event giving rise to shear zones, mylonite zones, kink bands, and crenulation zones;

(v) Intrusion of tholeiitic sills and dykes;

(vi) Pseudotachylite/shatter cone formation;

South East Boundary Fault

The so-called South East Boundary Fault was introduced by Hart et al. (1990) and was said to juxtapose deeper-level greenstone terrane with higher-level granitoid basement. The position of this fault was given as trending across the Broodkop Shear Zone towards the northeast.

Hart et al. (1990) failed to supply supportive field evidence to justify their section and interpretation. According to field mapping undertaken during this study, the stratigraphy continues either side of the Broodkop Shear Zone. This contradicts the interpretation of Hart et al. (1990) that movement along this shear gave rise to the juxtaposition of higher and lower level strata. Instead of producing evidence for the existence of a laterally extensive fault, mapping along the suggested trace of the South East Boundary Fault (e.g., on farms Kronenbloem 51 and Goedgunst 315) provided evidence for the existence of conjugate northeasterly and northwesterly trending shear zones. The authors therefore favour the interpretation that the Greenlands Greenstone Complex represents a large xenolith in enveloping gneisses, and the Hart et al. (1990) suggestion that different terranes were tectonically juxtaposed along a South East Boundary Fault cannot be supported.

Structure

Comparison of the structural data obtained in the greenstone remnant (Figs.23 and 24) and in gneissic terrane (Figs, 31 and 32) reveals similar deformation styles (mylonite zones, shear zones), but different styles are favoured in the respective terranes (i.e. shear zones in gneiss, mylonite zones in greenstones). Competency contrasts between the greenstones and the enveloping gneisses could provide an explanation for the differences recorded. If the greenstone remnant is regarded as a competent body within the gneisses, it is possible that the strain was deflected at the edges of this body. Deflection and concentration of strain may have been concentrated in the shear zones in the gneisses exposed along the northwestern/northern margin of the greenstone complex (Fig. 2).

Chronology

The chronological control on the various magmatotectonic phases in the evolution of the Greenlands Greenstone Complex is just as limited as that reflecting the evolution of the basement to the Vredefort structure. Dating of zircon populations from the various felsic lithologies, as well as further Rb-Sr and Sm-Nd dating of mafic intrusives, may resolve the stages in the evolutionary history of the region.

Metamorphism

Understanding of the metamorphic overprint on the general basement to the Vredefort Dome, including the southeastern and southern sectors, still requires considerable detailed analysis. Questions that need to be resolved include:

1. are the Greenlands Greenstones related to the Steynskraal mafic and felsic granulites and if so, why did they experience independent metamorphic histories?

2. the main fabric-forming, subhorizontal event is associated with anatexis and granulite metamorphism - (Steynskraal Metamorphic Zone); this fabric is not obvious in the greenstones. What then is the relationship between these two geological units? and

3. what could be expected from metamorphic, microstructural and thermochronological studies of drillcores through the basement to the Vredefort structure?

CONCLUSIONS

In the absence of a three-dimensional, seismic-based, understanding of the structure within the basement of the Vredefort Dome it is mandatory to obtain detailed structural data for a major part of the Dome. This study contributes only some of the data needed to determine a comprehensive understanding of the multi-phase evolution of this unique complex. The uniqueness of the Vredefort structure, and its central disposition to the economic province of the Witwatersrand Basin makes resolution of its evolution an important objective.

ACKNOWLEDGEMENTS

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