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A GEOLOGICAL MODEL OF SHEAR ZONE GOLD DEPOSITS IN THE PIETERSBURG GREENSTONE BELT, SOUTH AFRICA

by

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ABSTRACT

The Pietersburg greenstone belt is located in South Africa, about 300 km northeast of Johannesburg. It hosts a significant amount of gold mineralization and just over 1000 kg of gold have been produced from its various reefs and secondary deposits.

The greenstone belt is interpreted as an Archean ophiolite complex. It comprises a volcano-sedimentary succession (the Pietersburg Group) which is subdivided into a basal greenstone sequence, interpreted as oceanic crust, and an upper sedimentary cover sequence. A number of major shear zones, which are thought to represent thrusts that developed during the subduction of the greenstone sequence, form an integral part of the stratigraphy. Four stages of deformation (D_1-D_4) and four phases of metamorphism (M_1-M_4) (three of which are correlatable with the peak stages of deformation) are recognized.

The primary gold deposits are all shear zones related, but they are subdivided into greenstone, sedimentarion and granite-hosted types. Geographically, they occur in three distinct goldfields : Eersteling, Roodepoort and Marabastad. The greenstone-hosted Pienaar-Doreen shear complex is in the Eersteling goldfield and hosts eight gold occurrences. Within the complex, Girlie North Reef is the 640m-long "pay" section of the Girlie North shear zone. This reef is characterized, macroscopically, by a quartz-carbonate-chlorite-sulphide assemblage and, microscopically, by the presence of tourmaline, arsenopyrite and Au. Geochemical evidence indicates that mineralizing fluids were H_2O- and CO_2-bearing and rich in S, K and Al. The wall rock alteration was isochemical but is manifest as a change in mineralogy from a hornblende + plagioclase assemblage to an actinolite/tremolite + quartz + clay assemblage. This is best developed in the hanging wall of the reef and is thought to have been caused by hydrogen ion metasomatism.

The Arsenopyrite Reef was one of the main sediment-hosted shear zone gold producers in the Marabastad goldfield. This reef is interpreted as the basal margin of a shear zone whose top contact is probably represented by the Quartz Vein Reef. The shear zone consists predominantly of quartz and carbonate, and the two "pay" reefs are characterized by tourmaline, arsenopyrite and Au. No wall rock alteration was identified in this study. Based on the mineralogy and geochemical signature of the Girlie North Reef and the Arsenopyrite Reef, it is proposed that both were formed at the same time.

Textural evidence indicates that tourmaline, arsenopyrite and Au were all very late in the paragenesis of mineralization. The presence of tourmaline also indicates a probable granite association. It is proposed that the main gold mineralizing event was synchronous with the intrusiuon of granitoids (and therefore also with D_3-D_4 and M_3-M_4) and that most of the Au was derived from felsic magma. Gold was partitioned into a magmatic hydrothermal fluid and then transported into the greenstone belt as a chloride complex. These magmatic fluids were channelled up shear zones which had already been mineralized with a quartz-carbonate-chlorite - sulphide assemblage by previous metamorphic fluids, generated during the dynamic (D_2-related) M_2-phase of metamorphism. The Au was then deposited as the result of a change in a fluid variable, such as temperature, pH, fO_2, or the activity of Cl (some Au may have been transported in a sulphur complex and so the activity of reduced S could also have been important).

CONTENTS

APPENDIX

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

1. INTRODUCTION

The Pietersburg greenstone belt is one of the major belts preserved within the Kaapvaal craton of South Africa. It is located in the Northern Transvaal, about 300 km northeast of Johannesburg (Fig. 1.1).

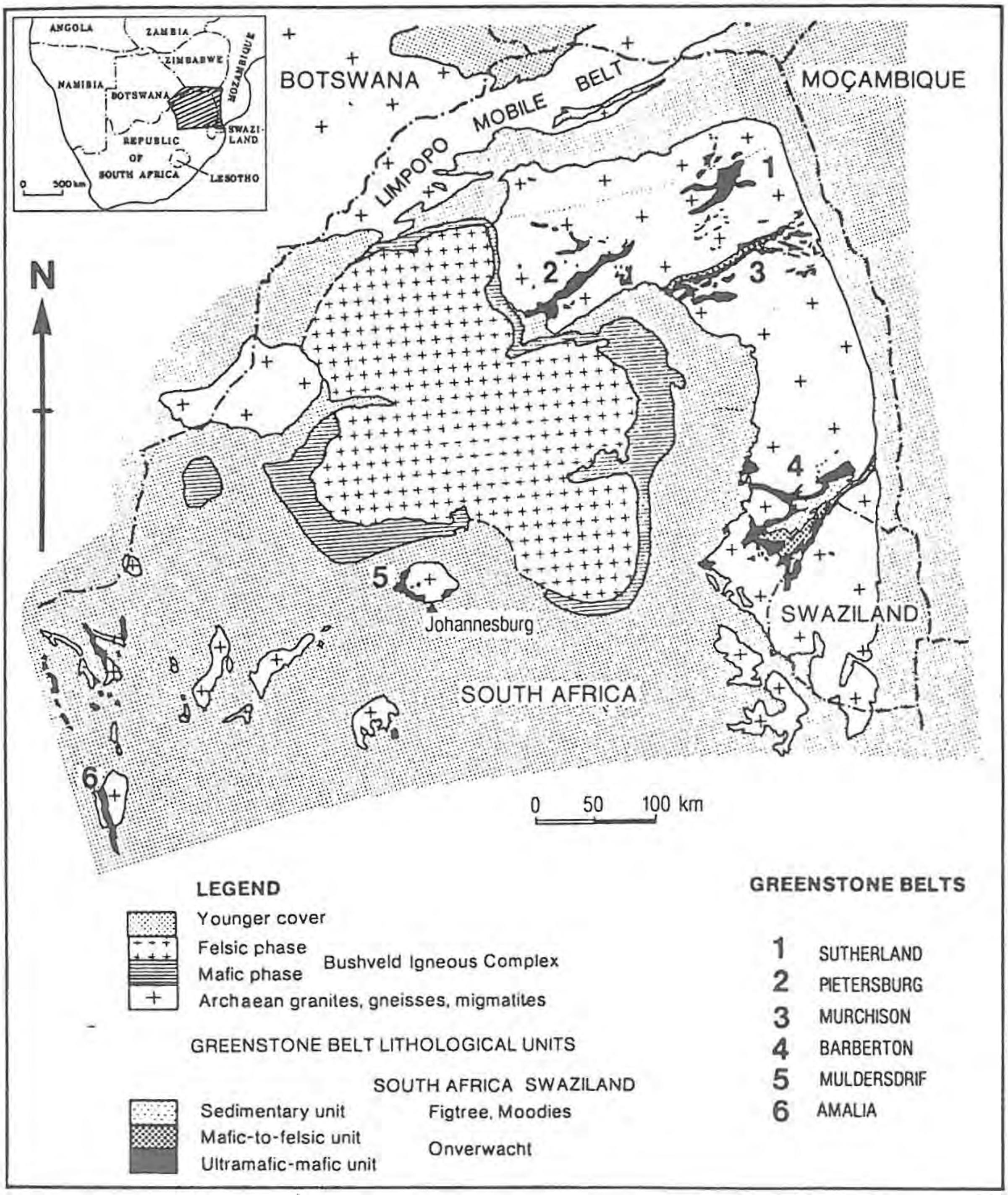


Figure 1.1. The greenstone belts of South Africa. (Modified from Anhaeusser, 1986.)

In common with other major greenstone terranes of the world, the Pietersburg belt has produced a significant amount of gold. In fact, the first gold reef to be discovered in South Africa was in the Pietersburg belt, on the farm Eersteling 17KS in 1871 (Willemse, 1938). From that date, until the last mines closed in 1935, just over 1000 kg of gold were produced from various reefs and alluvial workings (Table 1.1).

During the recent boom in gold exploration, two major companies (Anglo American Prospecting Services and Southern Sphere Mining and Development) have been actively involved in exploration for new gold deposits in the Pietersburg belt. Their main strategy has been to re-evaluate old mines and prospects in the area, although a certain amount of grass-roots exploration has also been carried out by Anglo American. Results to date suggest that there is significant potential for new mining ventures, but that these are likely to be small-scale operations. For a large company like Anglo American several such operations would be required to make a feasible mining venture, in which each small working would provide the feed to a centrally located plant (this is referred to as the "cluster concept").

Table 1.1. Approximate production figures of gold from the Pietersburg greenstone belt

Goldfield	Farm	Period	Crushed ore (tonnes)	Recovered Au (kg)	Alluvial Au (kg)	Total production of goldfield (kg Au)
	EERSTELING 17KS	1906-1937	49 010	320.43 (1)		
Eersteling	WATERVAL 18KS	1913-1935	1 712	4.36	97.14	438.94
	VRISCHGEWAAGD 33KS	1906-1937	4 275	17.01 (2)		
	ROODEPOORT 744LS	1905-1937	25 778	159.86 (3)		245.08
Roodepoort	PALMIETFONTEIN 24KS	1907-1936	10 067	72.44 (4)	0.42	
	WILDEBEESTFONTEIN	1907-1937	2 021	12.36 (5)		
Marabastad	SNYMANSDRIFT 738LS	1907-1910	21 837			334.55
	ZANDRIVIER 742LS	1907-1937	5	56.25 (6)	-	
Mount Robert Occurrence	Potberg Mine	?				Undisclosed

GRAND TOTAL RECORDED = 1018.57 kg

(1) Includes some from Vrischgewaagd 33KS.
(2) Includes 0.09 kg from an unknown source.
(3) Includes 6.36 kg from an unknown quantity of ore.
(4) Includes 1.13 kg from by-products.
(5) Includes 0.04 kg from an unknown source.
(6) Includes some from Snymansdrift 738LS.

Source : Willemse (1938).

In addition to its economic potential, the Pietersburg greenstone belt provides some classic geological exposures which illustrate a number of new concepts in greenstone belt geology. The recognition of major thrust zones has been particularly important in this respect.

The aim of this work is to formulate geological guidelines for gold exploration in the Pietersburg greenstone belt. More specifically, the objectives are :

1. To provide a geological overview of the entire greenstone belt in light of the most recent research.
2. To describe, in detail, the greenstone-hosted shear zone gold deposits of the Eersteling goldfield.
3. To compare the greenstone-hosted deposits of (2), with the sediment-hosted shear zone gold deposits of the Marabastad goldfield.
4. To define a genetic model for all shear zone gold deposits, utilizing the findings of (2) and (3).

In addition, an appendix is attatched to the report in which the exploration techniques and procedures used in the search for this type of deposit are discussed.

Except for the geological overview, the thesis is a little biased towards the greenstone-hosted deposits because of the author's personal experience in this environment. Also, Mike Jones of Imperial College, London, is completing a Ph.d. study in November 1987, which has been primarily directed at the sedimentary sequence of the Pietersburg succession (and its associated gold deposits). It is hoped, therefore, that this thesis and that of Mike Jones will complement each other to provide a unified picture of the shear zone-hosted gold mineralization in the Pietersburg belt.

The data presented in this thesis are derived from a comprehensive literature survey, and from the results of an exploration programme carried out by Anglo American over the last five years. The author was a participant in this programme for two and a half years from June 1983 to January 1986, and the work included geological mapping, geochemical soil sampling, lithogeochemical sampling (mostly in trenches), geophysics (including magnetic, S.P., I.P. and E.M. surveys), and drilling. A substantial part of the thesis research, however, in addition to the field work, comprised a petrological examination of drillcore from two Anglo American prospects (Girlie and MMV), and an analysis of geochemical data from the same.

2. GEOLOGY OF THE PIETERSBURG GREENSTONE BELT

The geological literature on the Pietersburg greenstone belt (Table 2.1) all refers to the region southwest of Pietersburg town. The focus of attention on this particular region has been due to the presence of gold mineralization (see Chapter 3). The most recent work was that of de Wit (1985) who re-interpreted the geology of the Mount Mare range on the basis of regional geological mapping. His work is currently being followed up by Mike Jones (in prep.). Because it is necessary to infer much of the geolocial history of the belt from the well exposed Mount Mare range, the overview presented here is drawn extensively from de Wit's work. In order to avoid repetitous reference that work is not specifically quoted within the text.

A regional geological map, compiled from all of the listed works in Table 2.1, is presented as Figure 2.1. In addition, Figure 2.2 is a reproduction of de Wit's original map of the Mount Mare range and Figure 2.3 is a geological interpretation of the Eersteling goldfield. The latter is based mainly on Willemse's map (1938) and recent prospect mapping by Charles Byron (Barton et al., 1986) and the author. This map represents the first re-interpretation of this poorly exposed area carried out in the light of structural information gained from the recent mapping of Mount Mare. (These three figures are filed in the pocket at the back of this thesis.)

The **Pietersburg Group**, which constitutes the greenstone belt, comprises a volcano-sedimentary succession that Gunter Brandl (in SACS, 1980) subdivided into six lithological formations (Table 2.2). The distribution of these is shown on the simplified map of Figure 2.4. Based on his own mapping, de Wit proposed a less complicated subdivision into a simatic "basement" or **greenstone sequence** and a sedimenatry **cover sequence** (it is preferential to call the former the greenstone sequence rather than basement so as not to cause confusion with the Archean "granite-gneiss basement). The simplest of these two schemes is favoured because many of the formational contacts of the first are difficult to identify in the field, and in some cases appear to have been arbitrarily defined (pers. obs.).

Table 2.1. Geological literature on the Pietersburg greenstone belt.

Author	Date	Area of Interest	Map
F.H. Hatch	1904	Mount Mare range	No
A.L. Hall	1908	East of Potgietersrus	Yes
A.L. Hall	1909	Mount Mare range	No
J. Willemse	1938	Southwest of Pietersburg	Yes
D.P. Van Rooyen	1947	Northeast of Potgietersrus	Yes
N. Grobler	1972	Southwest of Pietersburg	Yes
G. Brandl	1974	Southwest of Pietersburg	Yes
M.J. de Wit	1984	Mount Mare range	Yes
M. Jones	(in prep.)	Mount Mare range	Yes

Table 2.2. Lithostratigraphic subdivision of the Pietersburg greenstone belt.

Formation (SACS, 1980)	Lithology	Maximum thickness	Correlation (de Wit, 1984)
Uitkyk	Quartzites, conglomerates, shale, quartz-mica schists, B.I.F.s.	1 500	Cover Sequence
Vrischgewaagd	Chlorite and quartz schists	500-1 000	
Zandriviersspoort } (coeval)	Mafic meta-lavas with inter layered magnetite quartzite	500	
Eersteling } (coeval)	Mafic meta-lavas with subordinate ultramafics, quartz-feldspar porphyry and felsic lavas	10 000	Greenstone Sequence
Ysterberg	Felsic lavas and tuffs, shales, inter bedded quartz schist, banded chert, B.I.F., quartzite	1 400	
Mothiba	Ultramafics with minor amphibolite, quartz schist, quartz-feldspar porphyry, B.I.F.	7 500	
	Various types of granite and gneiss intrusive into all formations		

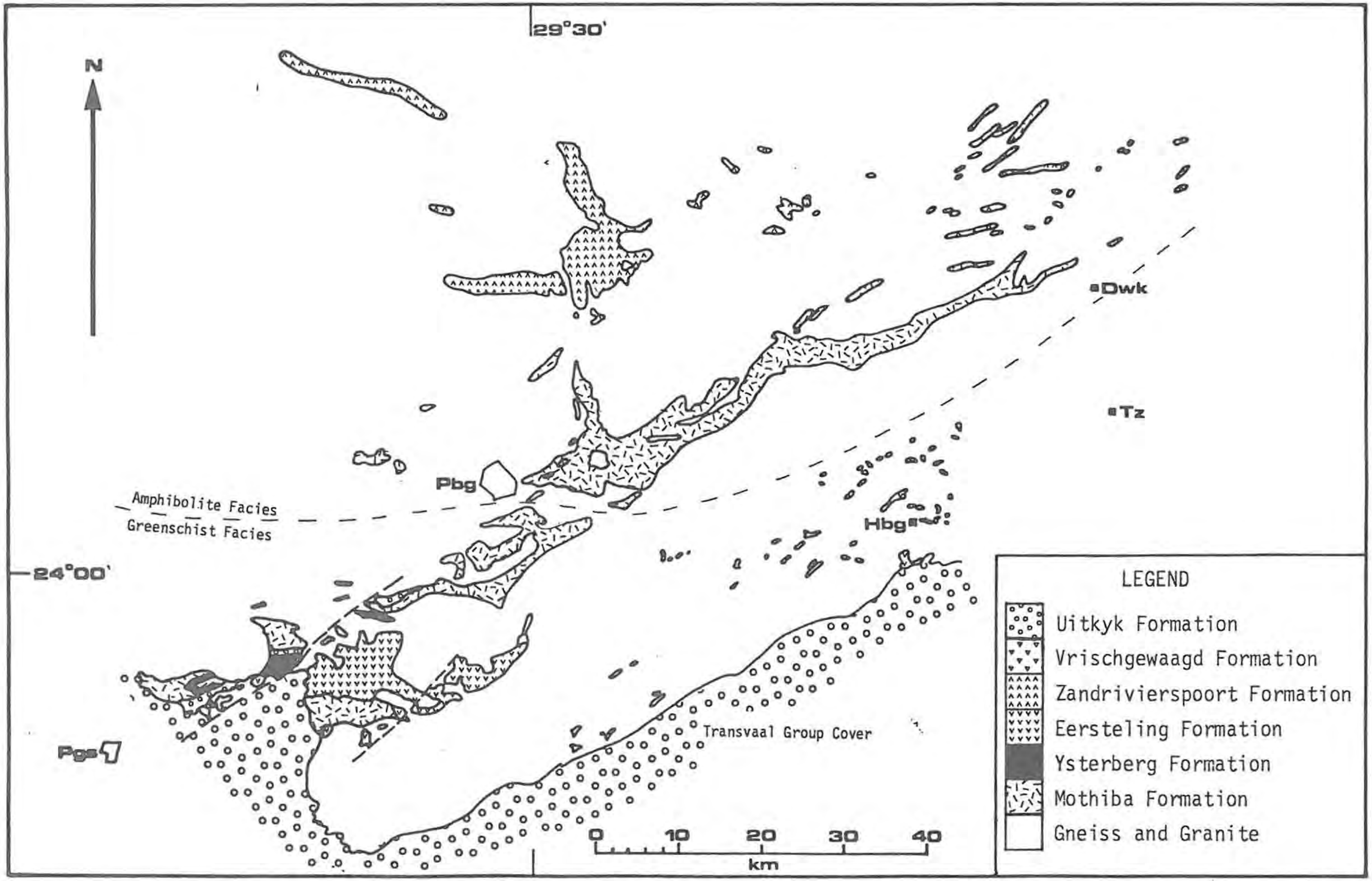


Figure 2.4. The distribution of lithological formations of the Pietersburg Group, as defined by SACS (1980). The metamorphic isograd is from van Reenen et al. (1986). Pbg-Pietersburg, Pgs-Potgietersrus, DWK-Duiwelskloof, Tz-Tzaneen, Hbg-Haenertsburg.

2.1. Stratigraphy

2.1.1. The Greenstone Sequence

The greenstone sequence is exposed over about 95% of the Pietersburg greenstone belt and it hosts the gold deposits of the Eersteling goldfield. It comprises mafic and ultramafic igneous rocks (thought to be predominantly intrusive and extrusive, respectively) and interlayered B.I.F.s.

Mafic igneous rocks underlie most of the Eersteling goldfield and various other areas in the region southwest of Pietersburg. They also constitute most of the Zandrivierspoort Formation (considered to be coeval with the Eersteling Formation - Table 2.1), which forms the northern inliers of the whole belt (Fig. 2.4). On surface these rocks are usually weathered to a light brown chlorite schist, but when fresh (as in stream sections) they occur as green or grey, fine- to medium-grained outcrops of metabasalt (amphibolite) in which pillow structures are occasionally preserved (Plate 2.1). Good examples occur in a road cutting on the farm Waterval 18KS, and

Plate 2.1. Fresh outcrop of metabasalt in stream section on the Girlie prospect, Eersteling 17KS (see Fig. 2.3 for location). Pillow structures are just discernable; the arrow points to the margin of one.

also just to the north of the western end of the Kuschke shear zone in the Mount Mare range. Minor tuffaceous horizons, volcanic breccias, and coarser-grained gabbroic layers have also been recognized in drillcore from various prospects in the Eersteling-Waterval area. Because the rocks are now composed of a metamorphic assemblage, an immobile trace element plot (the Nb-Zr-Y diagram : Meschede, 1986) was used to try and identify the original type of basalt (Fig. 2.5). However, the plot does not discriminate between MORB, volcanic arc basalts and within plate tholeiites, and it is concluded that this kind of diagram (derived from modern basaltic rocks) cannot be used to distinguish between the various types of Archean basalts.

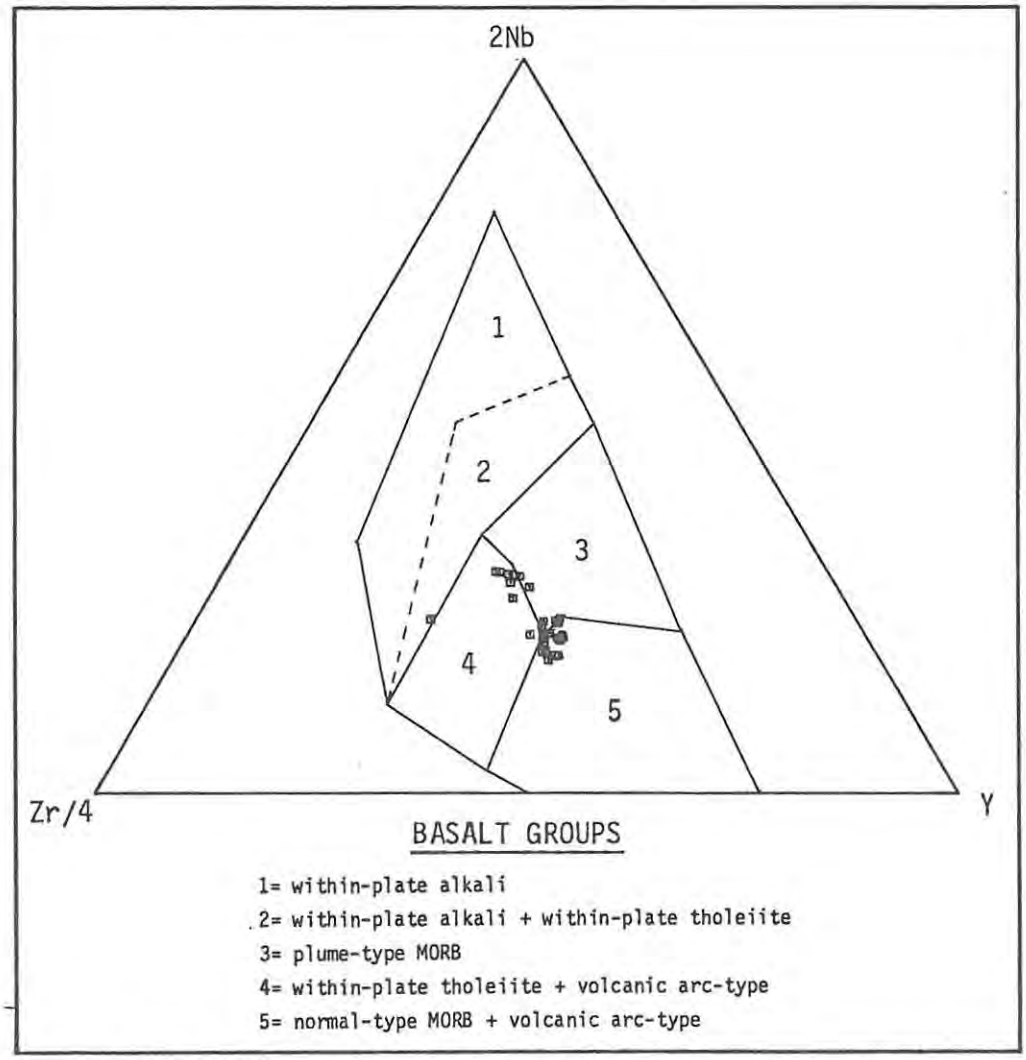


Figure 2.5. Nb-Zr-Y plot of 28 metabasalt samples from Eersteling 17KS. The plot illustrates that this kind of discrimination diagram, derived from modern rocks, cannot be used to distinguish between various types of Archean basalts.

According to the distribution of Brandl's six lithological formations (Fig. 2.4), ultramafic rocks of the Mothiba Formation underlie the main outcrop of the greenstone belt northeast of Pietersburg. They also form significant areas of exposure in the southwestern region where the most common rock-type is a coarse-grained serpentinite which weathers to produce a characteristic dark-brown pitted surface on outcrops (Brandl, 1974)(Plate 2.2). The igneous mineralogy of the rocks has rarely been preserved but thin-section evidence suggests that they were once meta-dunites to meta-pyroxenites (eg. original olivine grains are often outlined by magnetite dust). On the northern ridge of the Mount Mare range (Fig. 2.2), serpentinites (meta-peridotites) are intruded into the ± 50 m-thick Kuschke B.I.F. which, as a

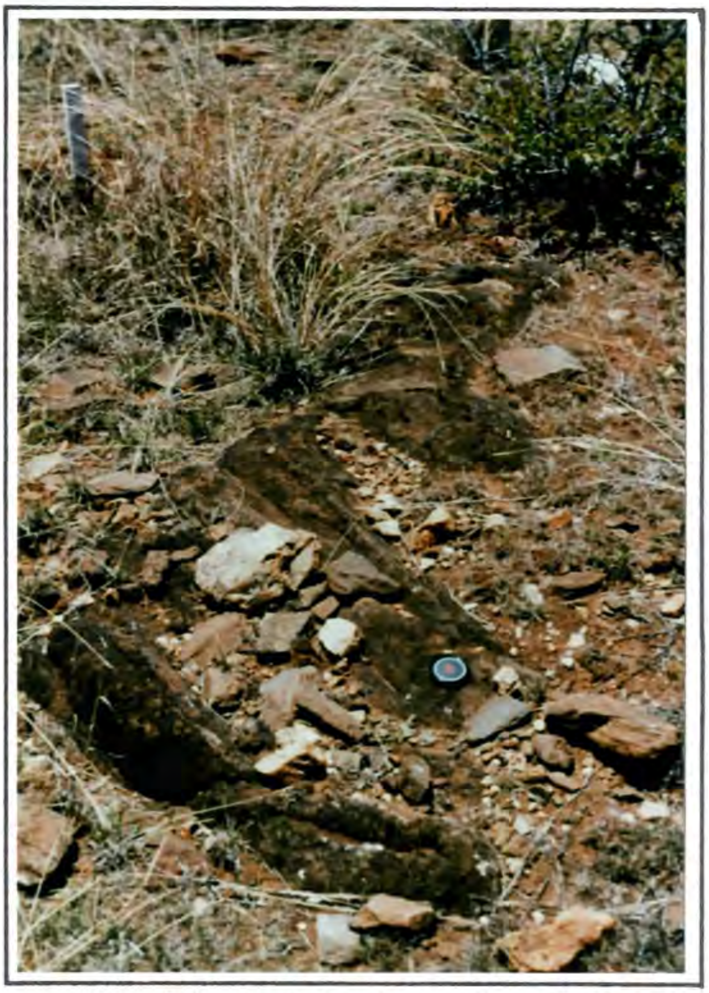


Plate 2.2. Typical outcrop of weathered ultramafic rock; the dark-brown pitted surface is characteristic. Clarke's Working, Vrischgewaagd 33KS.

result, has been disrupted into a train of mega-xenoliths. The intrusive relationship is unequivocally confirmed by cross-cutting contacts, chill zones in the serpentinites, and the occasional hornfelsed margin of a B.I.F. xenolith. The Kuschke B.I.F. itself is composed of magnetite, microcrystalline quartz and goethite (after Fe-rich carbonate) (Jones, 1986).

Various types of ultramafic-derived schists are also common in the southwest region of the belt. These are made up of various proportions of talc, chlorite and carbonate, and are thought to be the product of CO_2-rich metasomatism which may have been related to the gold mineralizing event.

Based on mineralogical evidence only, Grobler (1972) was the first to suggest that the Pietersburg ultramafic rocks could be komatiitic in nature. This was later confirmed geochemically by Viljoen et al. (1982) (Fig. 2.6).

As well as the major B.I.F. units (including Kuschke, Snymansdrift, Hollandsdrift and Ysterberg), numerous smaller beds have been mapped throughout the greenstone sequence in the Eersteling goldfield (Fig. 2.3). Thin-section examinations of the Girlie B.I.F. (pers. obs. and Jones, 1986) have revealed that individual laminations are composed of the following assemblages :

1. Microcrystalline quartz only.
2. Fe-rich amphibole (grunerite and ferro-actinolite) + sericite + opaques (magnetite and sulphides).
3. Magnetite $\pm$ minor amphibole $\pm$ sericite.
4. Garnet + amphibole + chlorite.
5. Fe-rich carbonate only.
6. Sulphides only (mostly pyrrhotite).

And in addition, quartz, chlorite, carbonate and sulphides occur in cross-cutting veins.

de Wit proposed that most, if not all, of the B.I.F.s. were originally shale or some other fine-grained argillaceous sediment, and that they formed by Fe- and Si- metasomatic replacement. In this scheme both Fe and Si are thought to have been derived from the surrounding greenstone rocks. However, it is considered more likely that at least some of the B.I.F.s represent original chemical precipitates, especially since this is in line with the

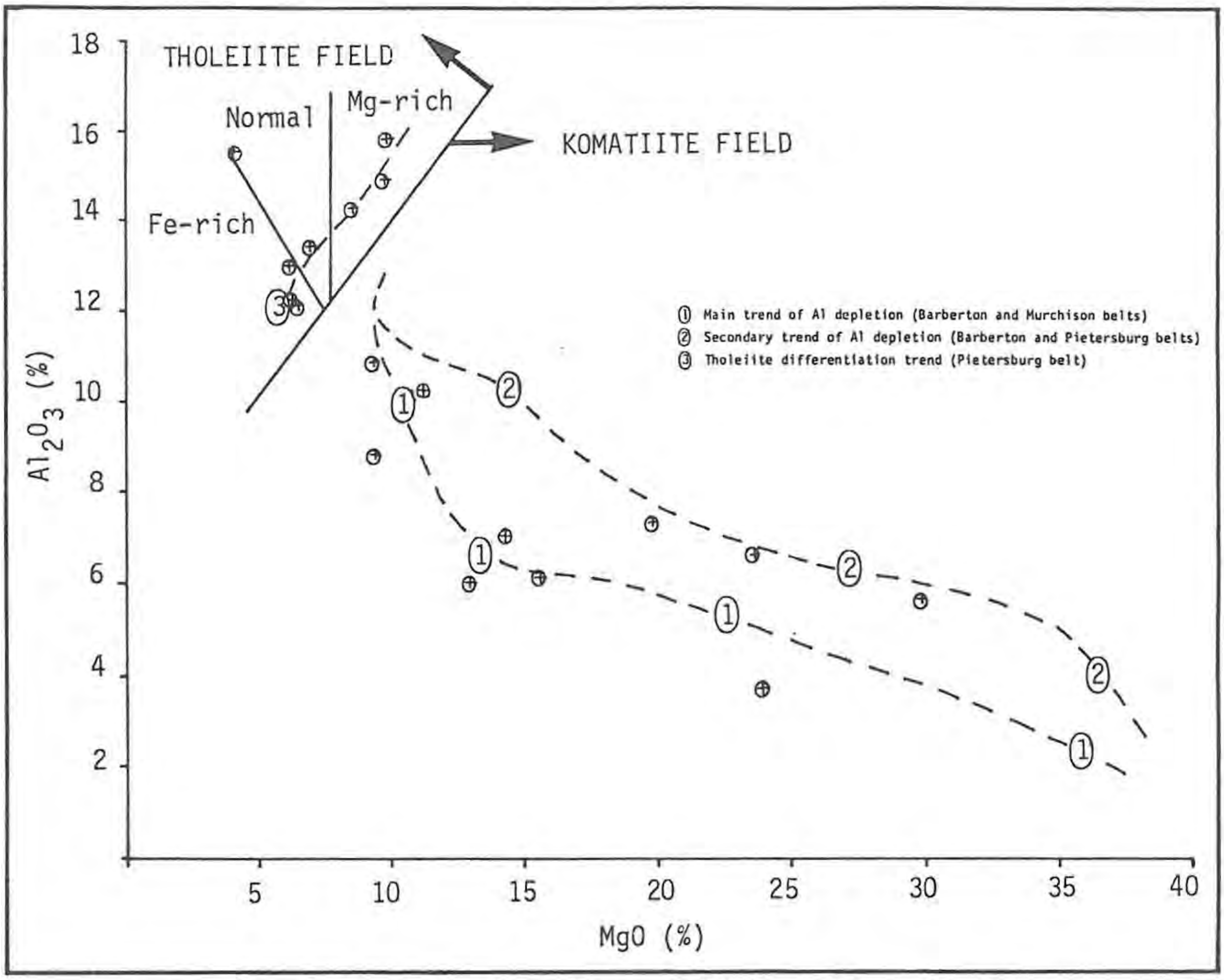


Figure 2.6. Al_2O_3-MgO plot of komatiites and allied rocks from the Pietersburg greenstone belt. Note (1) the trend of moderate Al_2O_3 depletion which is much less pronounced than for the Barberton belt data, so it does not give the high Ca:Al ratios which are a characteristic of that belt, and (2) the well-defined linear trend of tholeiites, from Mg-rich through normal to Fe-rich varieties. (Modified from Viljoen et al., 1982.)

current ideas on oceanic spreading ridge environments (see Section 2.5 for a discussion of the tectonic belt's setting).

2.1.2. The Cover Sequence

The cover sequence is only exposed over about 5% of the Pietersburg greenstone belt, but is important because it hosts the gold deposits of the Marabastad goldfield and the Mount Robert gold occurence. The resistance of the cover sequence lithologies to weathering also means that they form the major topographic features of the belt - the Mount Mare and Mount Robert ranges of hills. The lithologies are mainly coarse-to fine-grained clastic

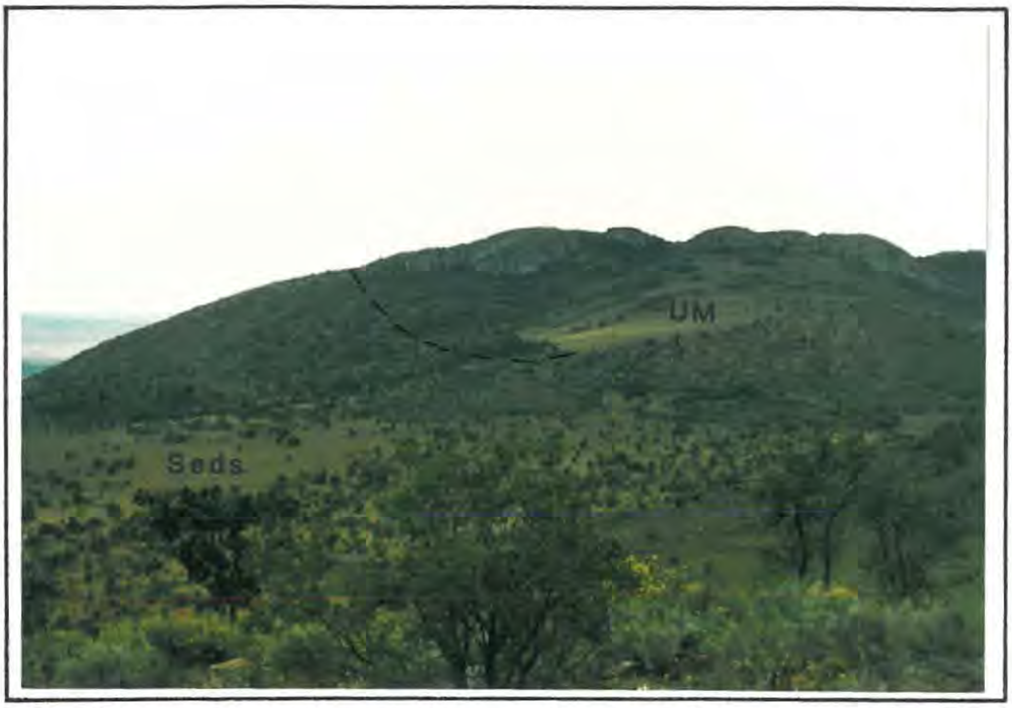


Plate 2.3. View, looking northeast, towards the basal unconformity of the cover sequence (see Fig. 2.2 for location). The main ridge is the Kuschke B.I.F. and the bare ground to the immediate south is underlain by ultramafic rocks of the greenstone sequence; the foreground and the tree-covered area to the west of the B.I.F. is underlain by sediments of the cover sequence. The approximate trace of the unconformity is dotted (Photograph courtesy of Maarten de Wit.)

sediments, and the entire cover sequence unconformably overlies the greenstone sequence (Plate 2.3). Though it is interesting to note de Wit's interpretation in which the Mount Robert range is considered a part of the overlying Transvaal Supergroup (Fig. 2.7), the more orthodox view that it constitutes a part of the greenstone belt's cover sequence is adopted here, mainly because of the lack of evidence to the contrary.

In the Mount Mare range, the greenstone sequence forms an ellipsoidal dome, bordered on its northern margin by the Kuschke shear zone. The cover sequence is draped off this dome and youngs and dips away from it to the east, west and south. The most complete stratigraphic section occurs in the west where the sediments have an average 55°W dip and the sequence is upward-coarsening.

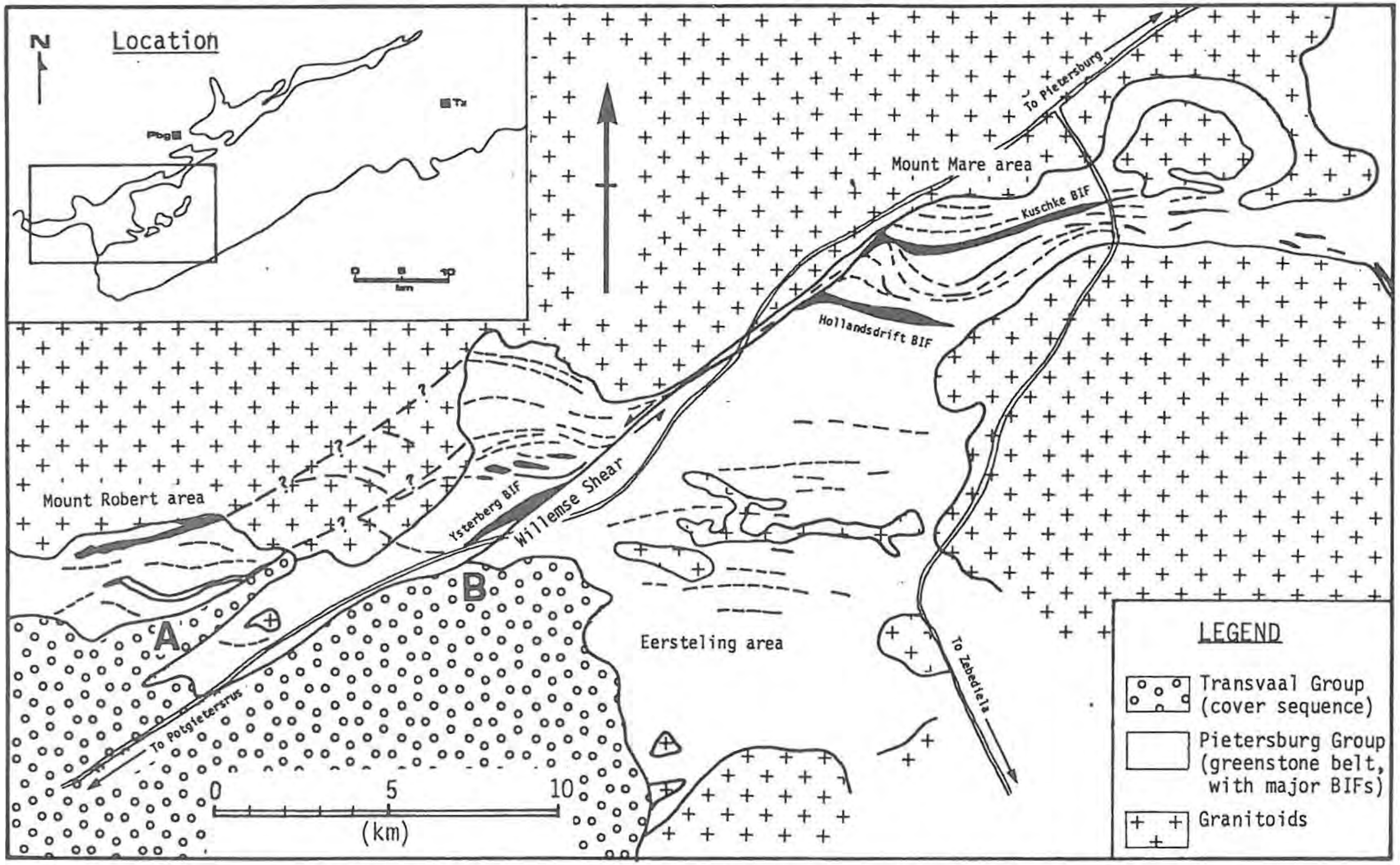


Figure 2.7. Simplified geological map of the Pietersburg greenstone belt to illustrate the regional interpretations of de Wit (1985). Note that the Mount Robert range is a part of the Transvaal Supergroup which overlies the greenstone belt (A), and that the Willemse shear zone disappears beneath this Transvaal cover (B). (From de Wit, 1985.)

Green chlorite-rich shales and mudstones, which are presumably derived from the underlying greenstone sequence, are interbedded with sandstones, grits and occasional conglomerate lenses at the base of this type section, close to the unconformity. Planar and trough cross-beds are common in the sandstones, and fuchsite, which is probably diagenetically altered chromite detritus, is often concentrated along the foresets. In drillcore from the Snymansdrift No. 3 Hill prospect, about 1 km to the southeast of this type section (see Fig. 2.1 for location), detrital pyrite layers have also been recognized, and these are thought to have given rise to gossanous beds of goethite and hematite at surface. The coarser sediments are generally mature with well-rounded clasts, but they are often ill-sorted (Plate 2.4). The most common clast types are weathered meta-basalt, various types of chert, intra-formational sediments (sandstones predominate), and vein quartz. The largest of these are up to 20 or 30 cm in diameter. In addition, silicic porphyry clasts become increasingly abundant towards the top of the section and the occasional granitoid cobble has been identified. B.I.F. clasts, however, are rare.

Plate 2.4. Outcrop of ill-sorted conglomerate, Snymansdrift 738LS. The most common clast types are weathered meta-basalt, various types of chert, intra-formational sediments, and vein quartz. Fuchsite (bright green), which is probably diagenetically altered chromite detritus, stains both clasts and matrix. (Photograph courtesy of Maarten de Wit.)

Plate 2.5. Well-sorted and graded conglomerate, Snymansdrift 738LS. Individual beds in this area are between 0.5 and 5m thick. They are thought to have been deposited by turbidity currents. (Photograph courtesy of Maarten de Wit.)

About halfway up the section, conglomerates become the dominant rock-type. These are clast-supported, with clasts being well-sorted and graded (Plate 2.5), and individual beds are thicker (0.5-5m) than further down in the section. de Wit suggests that they may have been coarse turbidites. Finally, at the top of the section, the conglomerates become ill-sorted once again and clasts up to 50 cm in diameter are common. The entire section is cut off abruptly at the Hollandsdrift shear zone by a gneissose fuchsite-rich quartzite.

Detailed mapping, by Jones (in prep.), covers the cover sequence exposed from the Snymansdrift No. 3 Hill prospect northeastwards to the Marabastad-Zebediela road. Similar litholgies to those found in de Wit's type-section occur in this area, but a much greater proportion are fine-grained and conglomerates are restricted to lensoid units only (Plate 2.6). Their dip is also much steeper (average 74^{o}S). 5 to 8 m-thick sedimentary units are recognized, and bedding-cleavage relationships and primary sedimentary structures, such as small-scale channels (up to 50 cm deep and 5 to 10 m wide), cross-bedding and grading (which fines upwards in contrast to de

Plate 2.6. A thin conglomerate/breccia unit, interpreted as a gravel wash. Zandrivier 742LS.

Wit's section), all indicate that the sequence youngs to the south away from its basal tectonic contact with the greenstone sequence (see Section 2.3). The finer-grained sediments include ferruginous shales and siltstones which interfinger with quartz-sericite and chlorite schists. It is not yet clear whether these latter rock-types represent volcanic material (possibly tuffs ?) or whether they are simply the metamorphosed equivalents of sediments (Mike Jones, pers. comm., 1986).

The reports of Saager and Muff (1978; 1986) and Muff and Saager (1979) indicate that the cover sequence rocks around the old Potberg gold mine at Mount Robert are similar to those in the Mount Mare range. These authors interpret the sediments as braided river deposits. This is not completely at variance with a turbidite origin, suggested by de Wit for some of the conglomerates in his type-section, because mass-flow deposits are a common phenomena in the proximal reaches of a braided river environment.

2.1.3. Tectonic Units (Major Shear Zones)

The structure and deformation of the Pietersburg belt will be dealt with in Section 2.5, but it is appropriate to describe some of the major shear zones here because they form a significant, albeit minor, part of the total stratigraphy. (For this reason, the latter should strictly be referred to as a tectono-stratigraphy). The discussion in this section will be entirely descriptive.

de Wit was the first to recognize the three major shear zones in the Mount Mare range, and Mike Jones (pers. comm., 1986) has subsequently identified two others on the northern slopes of the same range. The latter two have not yet been described but they probably have the same general characteristics that are typical of the others. These are summarized below.

At the base of the cover sequence, between the Snymansdrift No. 4 Hill prospect and the MMV prospect, a chaotic breccia, known as the **Snymandsdrift Tectono-Sedimentary Melange Zone**, is variably developed (Fig. 2.2). This zone, which varies in thickness up to 100m, is composed of B.I.F. clasts set in a brown to red shaley matrix. The clast size ranges from cm- or mm-scale fragments which grade into the shaley matrix, up to large slabs measuring 20m in length and 1 to 2m across (Plate 2.7). In most cases the larger slabs show no signs of internal deformation, but along their edges there is evidence of the spalling process that produced the smaller fragments. In a few places, where the margins of slabs are folded, the folds are axial planar to the fabric developed in the matrix and their axes are parallel to the stretching lineation (see Section 2.3). In this situation, however, the fold hinge is often sheared out, leaving breccia clasts (the ex-fold limbs) orientated at high angles to the tectonic fabric. This is an unusual feature because generally the clasts are alligned subparallel to the fabric.

The lower contact of the breccia zone cuts across the general strike of the underlying greenstone sequence, and the actual contact between the two is marked by an intensely cleaved schist zone. The upper contact on the other hand is very poorly defined and there is a transition zone in which the breccia grades, over 10s of metres, into the conformably overlying sediments. The interpretation of this contact as sedimentary was the reason for calling the entire zone a tectono-sedimentary melange. The melange defines the **Snymansdrift Shear Zone** (Plate 2.8).

In the latest re-interpretation, Jones (1986) has extended the width of the

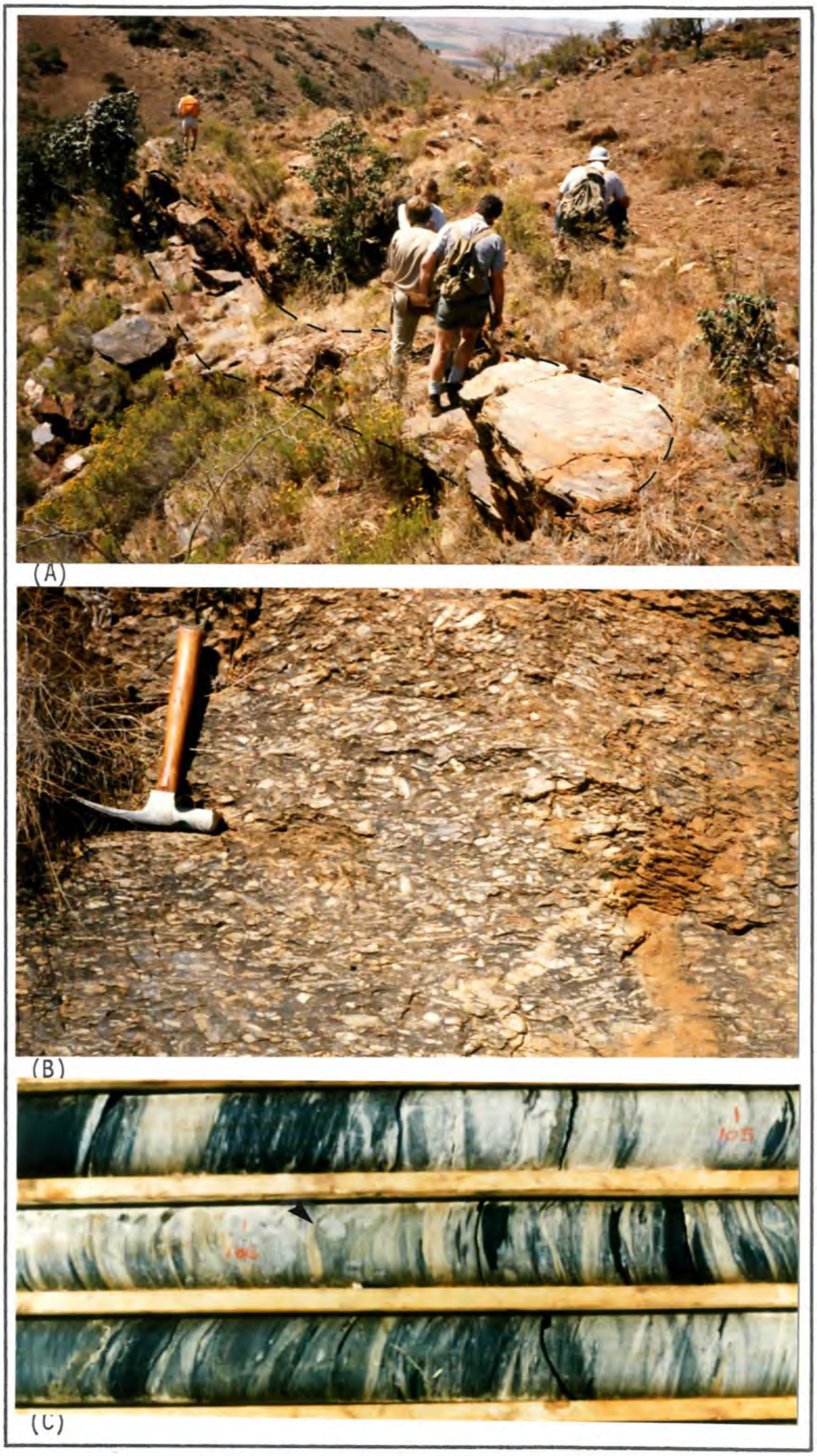


Plate 2.7. The Snymansdrift tectono-sedimentary melange zone. **(A)** This large slab of B.I.F. (which measures about 20m x 2m in size) is a mega-clast within the melange zone. **(B)** Outcrop of finely ground breccia. This material is more typical of the melange zone, but note the oblong section of most clasts which is similar to that of the megaclast in A. See Figure 2.2 for location of A and B. **(C)** The melange zone as exposed in drillcore from ZR1. Note the extreme flattening of clasts and the tapered terminations of some (arrowed). This latter feature is due to pressure solution and is characteristic of ductile deformation.

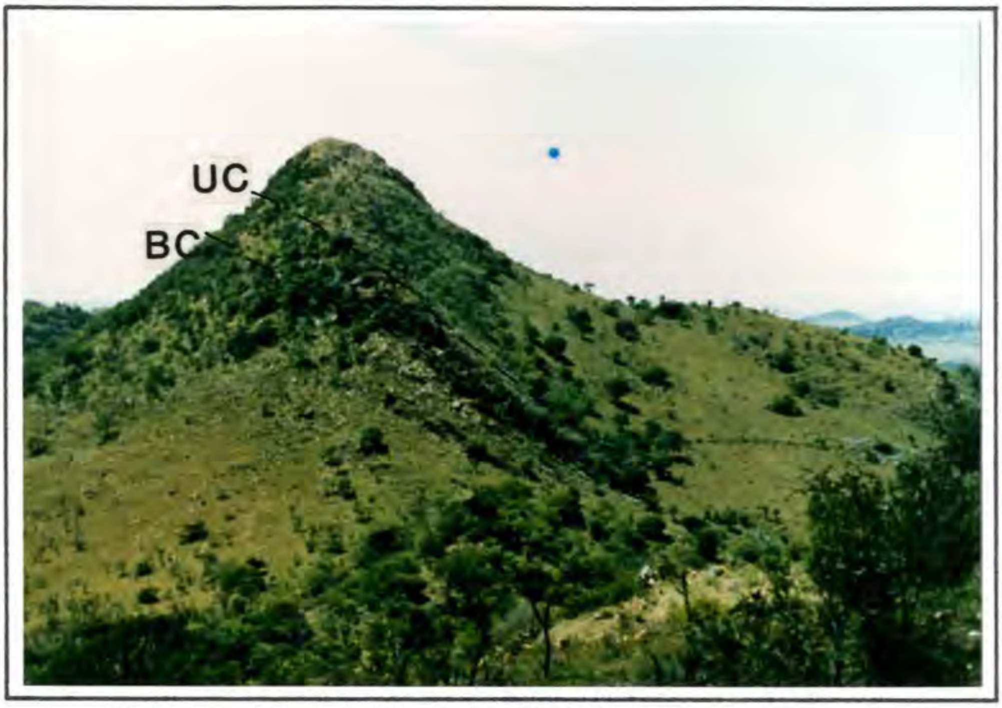


Plate 2.8. View, looking east, of the Snymansdrift shear zone. The basal contact (BC) is represented by a schist zone and cross-cuts the underlying greenstone sequence (left of plate); the upper contact (UC) is gradational and conformable. See Figure 2.2 for location. (Photograph courtesy of Maarten de Wit.)

Snymansdrift Shear Zone to include almost the whole cover sequence package between the Snymandsdrift No. 4 Hill prospect and the Greenwalds prospect. This is considered to be a somewhat over-zealous interpretation, even though there is evidence throughout the package for at least some degree of shearing. It is therefore noted here, that various shearing effects are seen in the hanging-wall zone of the Snymansdrift shear zone, but the zone itself is only recognized as originally defined (ie. equivalent to the tectono-sedimentary melange zone).

The tectonic transition zone between the cover sequence rocks that host the Snymansdrift No.3 Hill prospect, and the greenstone rocks to the south, is called the **Hollandsdrift Shear Zone.** This shear zone is up to 500 m wide. It contains lenses of relatively undeformed sediment and greenstone material (sedimentary strucutres such as cross-bedding and pillow structures are well preserved in each, respectively) bound by high strain schistose zones. In some places isoclinal folds are developed within the greenstone lenses (observed as talc + carbonate + chlorite $\pm$ fuchsite layers) and these are axial planar to the shear zone fabric. Remnant bedding within the schist zones is also subparallel to this fabric.

Bedding, in sediments immediately north of the Hollandsdrift shear zone, is systematically rotated into the high-strain, schist-gneiss zone which represents the latter's northern margin. The sense of rotation is sinistral (anti-clockwise).

The **Kuschke Shear Zone** is located in the greenstone sequence just north of the Kuschke B.I.F., and it runs adjacent to the latter along its entire exposed strike length (Fig. 2.2). The dominant rock types within the shear are fuchsitic quartz gneiss and brown meta-carbonate, but, as in the Hollandsdrift shear zone, greenstone material is included as lenses and these are isoclinally folded. Obviously, because of its position within the greenstone sequence, no lenses of sediments occur within the Kuschke shear zone.

The shear zones described above, and the two found by Mike Jones, are the only major shear zones that have been recognized to date. However, it seems more than likely that others will soon be recognized elsewhere.

2.2. Intrusive Rocks

Virtually no study has been made of the granitoid rocks that surround the Pietersburg greenstone belt (Fig. 2.1), but in this geological overview they are all deemed to be intrusive. This is probably a fair assumption. Barton et al. (1986) interpreted the Geyser granite (dated at $\pm$ 2800 Ma) and the Uitloop and Turfloop plutons (late-stage emplacements) to be intrusive bodies, and evidence to support this conclusion includes cross-cutting relationships, stoped marginal greenstone rocks, and the effects of contact metamorphism. The same authors, however, point out that the relationship between the greenstones and the Baviaanskloof gneiss (date at $\pm$ 2800 Ma) is as yet uncertain.

The Uitloop pluton (called the Potgietersrus granite by Brandl, 1974) is exposed to the north of Mount Robert (Fig. 2.1). It consists mostly of a light pink, coarse, even-grained granite made up of orthoclase, quartz, microcline and albite, with clusters of hornblende and biotite. A second phase of this pluton is recognized as a red, fine- to coarse-grained rock, which is porphyritic in places, and the contact between the two phases is transitional. Both are characterized by a complete lack of pegmatites and the presence of blue opaline quartz.

The Turfloop pluton (called the AG2 granite by Brandl, 1974) is exposed to the south of the greenstone belt. It is a white- to grey-coloured, fine- to medium-grained rock made up of plagioclase, quartz, biotite and muscovite. This less siliceous (tonalitic) composition, compared to the other granites, explains why it weathers so easily to form the flat terrain surrounding the greenstone belt (Brandl, 1974). It is possible that the Roodepoort pluton, which is an intensely altered body of albitite (Barton et al., 1986), could be a highly evolved differentiation product of the main Turfloop intrusion.

An important observation was made by Hall (1908). He noted the presence of abundant tourmaline in granite veins at the eastern end of the Mount Mare range. The note probably refers to the Geyser granite (?), and it is considered to be important for the development of a model of shear zone-hosted gold deposits (Chapter 3, Section 3.4).

Other felsic rocks include aplitic veins, too numerous to mark even on a large-scale map. They intrude into the interior of the presently exposed greenstone belt. In the field these veins weather to a friable quartz + sericite rock and they are almost certainly genetically related to the surrounding plutons. A similar genetic origin is proposed for the syenite on Eersteling 17KS, and the 50m-thick quartz porphyry which intrudes the Turfloop granite on Rietfontein 34KS (Willemse, 1938; Brandl, 1974). It is possible that the syenitic composition of the Eersteling intrusion may, in part, have been due to post-intrusive hydrothermal alteration, possibly caused by the mineralizing fluids that deposited gold in this area. This suggestion is based on Brandl's assumption that the syenite occupies a shear zone, and Grobler's report (1972) that a zone of epidotization can be traced farther southwestwards beyond the outcrop of syenite.

Finally, a note should be made of the pyroxenites, on Turfontein 14KS (Fig. 2.1), which were interpreted by Willemse (1938) as separate "dyke-like" bodies that had been uralitized (amphibolitized) when the surrounding granite plutons were intruded. The current interpretation is that they are indeed intrusive, but that they formed during the evolution of the greenstone sequence and not after its development (as inferred by Willemse), and that they were altered by seafloor metasomatism-as will be discussed in Section 2.5.

2.3. Structure and Deformation

The first structural analysis of the Pietersburg belt was undertaken by Grobler (1972) who proposed that the stratigraphy in the southwest region had been repeated by isoclinal folding. He cited the three parallel B.I.F.s (Hollandsdrift, Snymansdrif and Kuschke on Fig. 2.2), which he suggested were one and the same, as evidence for this. However, that interpretation seems to have been largely influenced by the "geosynclinal downwarp" models of greensotne belt evolution, which were prevalent in the early 1970s, and it does not take account of the major shear zones in the area because these were not recognized.

While re-mapping the Mount Mare range, de Wit identified four stages of deformation which he designated D_1 through to D_4. The first stage, D_1, occurred prior to deposition of the cover sequence but the only direct evidence of it is preserved in a small outcrop of serpentinite at the western end of the Kuschke shear zone. This is a flat-lying carbonate-fuchsite gneiss foliation. However, an indirect effect of D_1 is manifest as the steeply plunging axes of D_2 folds, which necessarly infers that there was a pre-D_2 period of deformation.

The main stage of deformation, D_2 caused the development of a prominent and pervasive upright cleavage (S_2) which is orientated in a more-or-less constant northeast-southwest direction. This is parallel, or at least sub-parallel, to the major shear zones and faults in the area and these, together with the major folds that have S_2 as an axial planar cleavage, are also attributed to the D_2 event.

The movement direction along the major shear zones has been established as northwest-southeast from the orientation of quartz-fibres which grow by

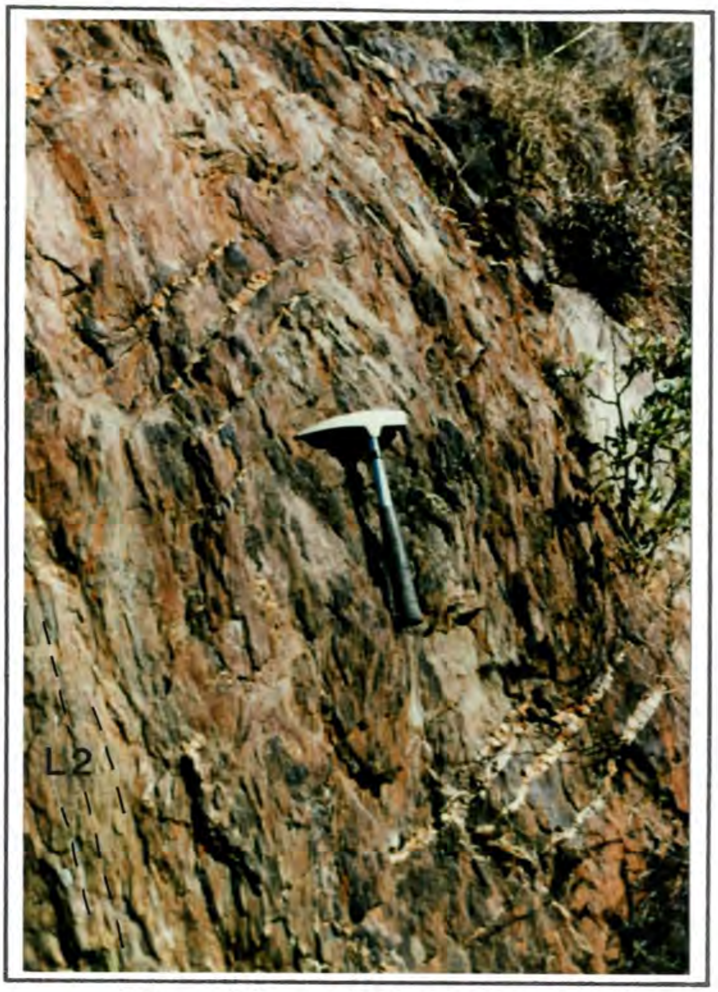


Plate 2.9. Dilation veins in argillaceous sediments on the MMV prospect, Zandrivier 742LS. Quartz fibres, which grow at right angles to the vein walls, indicate the movement direction along the shear zones in the cover sequence. Note that the L_2 mineral elongation lineation is orientated at right angles to the vein walls (ie. parallel to the quartz vein fibres). Thus, L_2 also indicates the movement direction along the shear zones.

incremental extension during the opening of dilation veins (Plate 2.9) (Ramsay and Huber, 1983). The shear zones were interpreted as thrusts, by de Wit, on the basis of their syn-D_2 age of formation (ie. they formed during the compression event across the belt), but he pointed out that this was not consistent with the sinistral sense of horizontal motion, as deduced from the rotation of bedding just north of the Hollandsdrift shear zone (Section 2.1.3). Jones (1986) supports the thrust interpretation

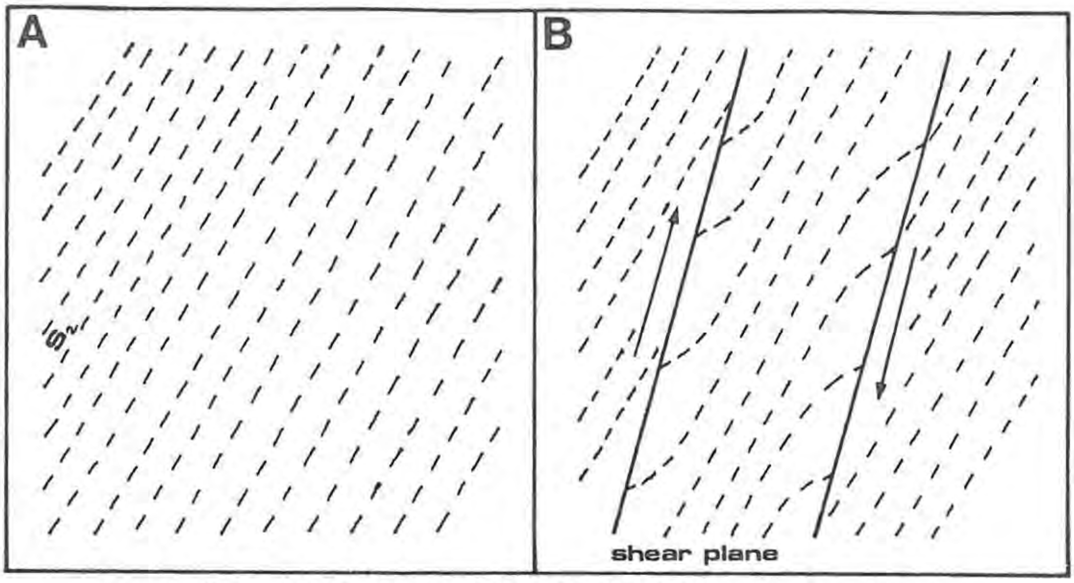


Figure 2.8. Sketch to illustrate the deformation of S_2 cleavage within shear planes in the Mount Mare range. This feature is used as corroborative evidence for the interpretation of major shear zones as thrusts rather than reverse faults. (A) Undeformed S_2 cleavage produced as a result of the flattening of the greenstone belt. (B) Subsequent deformation of S_2 cleavage by thrusting during the late stages of D_2.

because of the corroborative evidence of deformed (sigmoidal) cleavage within discrete shear planes (Fig. 2.8). A schematic model of thrust development is depicted in Figure 2.9.

The Hollandsdrift B.I.F. contains the most prominent F_2 folds in the area but the Kuschke B.I.F. is not folded at all (rather, it appears to be boudinaged). These two styles of deformation were probably caused by a difference in the pre-D_2 strike directions of the B.I.F.s (possibly up to 90^o) as illustrated in Figure 2.10. Moreover, since this difference could have been the result of the D_1- stage of deformation, it is possible that the two B.I.F.s were once part of the same unit.

The axes of F_2 folds in the cover sequences, at both ends of the Mount Mare range, plunge at a much shallower angle than those in the greenstone sequence. This is because the cover sediments were not affected by D_1. Also, it is probable that fold plunges in the cover rocks at least partially reflect the paleoslope down which the sediments were deposited, so, in effect, the amount of plunge imparted to these folds by the D_2 deformation would have been less than that now measured in the field.

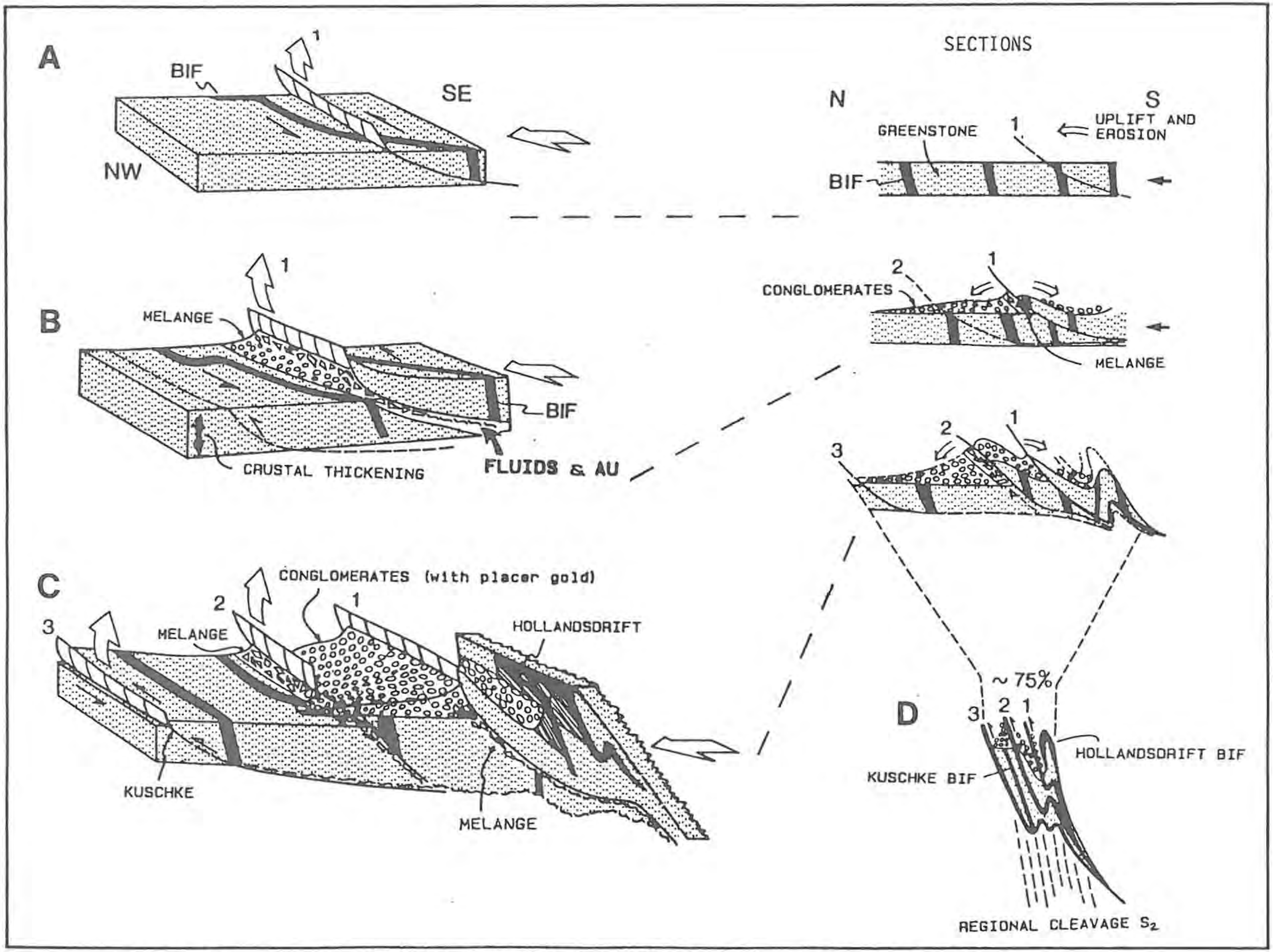


Figure 2.9. Schematic model of the structural evolution of the Mount Mare range during the D_2-stage of deformation. The major shear zones (thrusts) are numbered : 1 - Hollandsdrift S.Z., 2-Snymansdrift S.Z. (incorporating the tectono-sedimentary melange) and 3-Kuschke S.Z. (Modified from de Wit, 1985.)

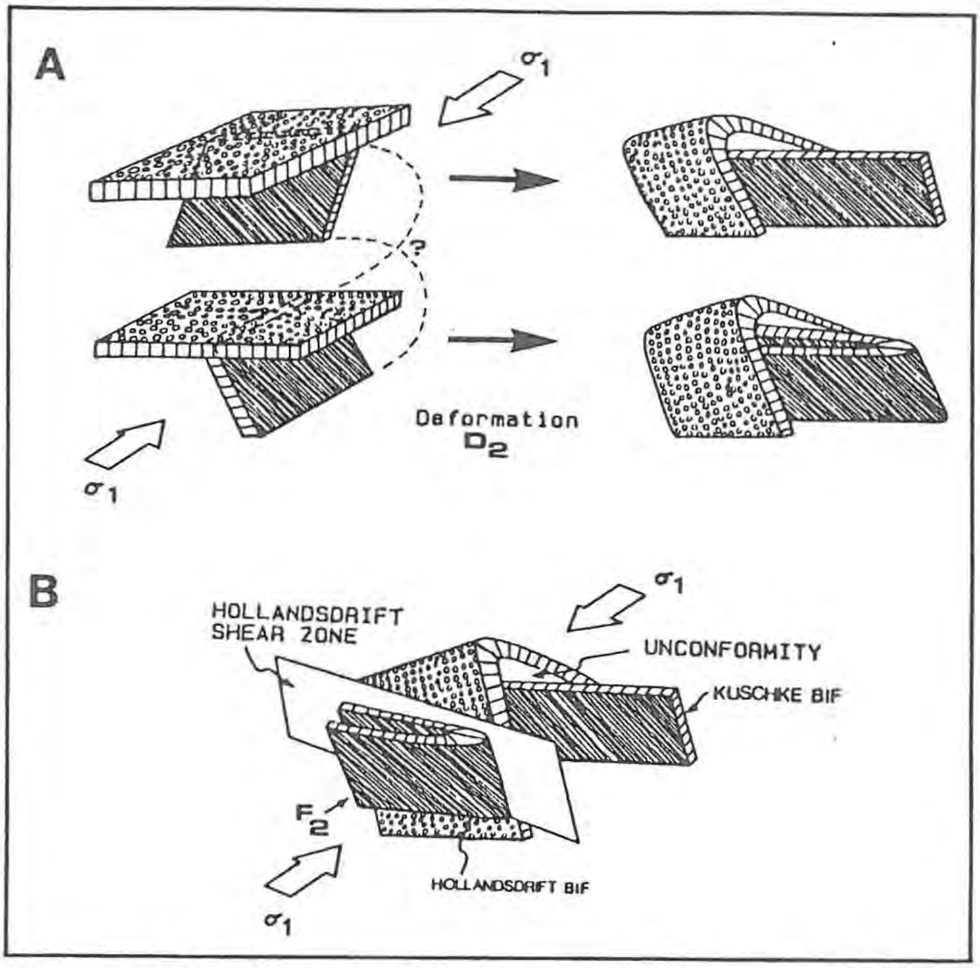


Figure 2.10. (A) Schematic interpretion of the pre- and post- D_2 outcrop patterns of the Kuschke and Hollandsdrift B.I.F.s. (top and bottom respectively). Note that these two units could have been a part of the same unit prior to D_2. (B) Present disposition of B.I.F.s. (Modified from de Wit, 1985.)

A further manifestation of D_2 is a pronounced mineral-elongation lineation (L_2) which is best developed in the high strain zones close to, or within, the major shear zones. In these zones, the axes of minor folds and the quartz fibres within extension veins (Plate 2.9) plunge parallel to L_2. Hence, L_2 also indicates the tectonic transport direction of the thrust sheets.

In general, the strain across the Mount Mare range, and by inference across the entire greenstone belt, is extremely variable. Low strain zones are evident, particularly at the western end of the range, by the perfect preservation of sedimentary structures (such as cross-bedding) and high-strain zones are represented by the major shear zones (described in Section

Plate 2.10. Sample of pillow basalt to show the ocelli used as markers in the strain analysis of the Mount Mare range. (Photograph courtesy of Maarten de Wit.)

2.1.3). de Wit carried out a strain analysis of the area using ocelli in pillow basalts as markers (Plate 2.10), samples of which were collected from three localities (Fig. 2.2). Table 2.3 is a summary of the measurements which indicate that, in places, the flattening across the cleavage was greater than 70% and the stretching along the lineation was greater than 180%. (These are strictly minimum values because in the highest-strain zones the ocelli are deformed beyond recognition and are therefore unsuitable for reliable strain analysis).

Table 2.3. Strain analysis on deformed ocelli of pillow basalts, Mount Mare range.

	Snymansdrift Shear Zone	Hollandsdrift Shear Zone	Kuschke Shear Zone
Strain ellipse (X:Y:Z)	5.8:3.6:1	3.7:2.2:1	10.1:4.6:1
Number of measurements	36	36	76
Radius of undeformed ocelli	1.30	1.01	1.8
Deformation:			
X	3.05	1.72	6.52
% stretching along lineation	111%	85%	181%
Y	0.85	0.18	1.00
% extension	31%	9%	27%
Z	-1.75	-1.02	-2.60
% shortening across cleavage	63%	50%	72%

From : de Wit (1985).

Like for the D_1-stage, there is very little direct evidence of the D_3- and D_4- stages of deformation. What little there is, is best seen at the eastern end of the Hollandsdrift B.I.F. At this locality, tight to isoclinal F_3 folds have refolded F_2 structures into a complex interference pattern (Plate 2.11). The F_3 and F_2 folds are coaxial but the F_3 axial planes are orientated at a slight angle (10-20^o) to those of F_2. When viewed down-plunge the F_3 folds have a predominantly 'S'-type vergence and they could, therefore, be parasitic folds on the southern limb of a regional F_3 fold- now manifest as the large-scale bend in strike of the Mount Mare range (Fig. 2.2). It follows from this argument that a crenulation cleavage developed within the Kuschke shear zone in the hinge of the bend may also be a D_3 feature (and can be referred to as S_3).

The D_4- stage of deformation formed open folds (F_4) with a large wavelength to amplitude ratio (10:1). In outcrop these may appear kink-like and they may form easily-recognized conjugate sets.

Plate 2.11. Complex interference pattern of F_2 and F_3 folds. This type of interference structure is best seen at the far eastern end of the Hollandsdrift B.I.F. outcrop which is where this outcrop occurs (see Fig. 2.2 for location). (Photograph courtesy of Maarten de Wit.)

On the regional geological map presented as Figure 2.7 de Wit has shown the Willemse shear zone disappearing beneath the younger Transvaal Supergroup. This interpretation contrasts with those of Willemse (1938) and Grobler (1972) who both show this shear zone affecting the Transvaal cover. The relationship is an important one because it constrains the timing of movement along the shear zone. If it can be proven that the shear zone developed prior to the deposition of Transvaal sediments, then it might be possible to relate movement along it to one or other of the later stages of deformation which affected the greenstone belt only (ie. D_3 or D_4). Furthermore, if the Ysterberg and Hollandsdrift B.I.F. units prove to be one and the same (as assumed by Willemse, 1938) a minimum order of displacement of 10 km will be established for this age of shearing.

So far this section has only considered the structure and deformation of the Mount Mare range because this is where the most recent and detailed analyses have been carried out. It will certainly be possible to carry out similar studies in areas of comparable outcrop (eg. the Mount Robert range), but this will not be the case for the majority of areas underlain by greenstone rocks because these are usually poorly exposed (eg. the Eersteling goldfield). It is necessary, therefore, to interpret the strucutre of the poorly exposed areas (underlain by greenstones) in the light of information gained from the better exposed areas (underlain by sediments). Figure 2.3 is the first attempt at such an interpretation for the Eersteling goldfield, based mainly on regional mapping by Willemse (1938), Grobler (1972) and Brandl (1974), and prospect mapping by the author and Charles Byron (refer to Barton et al., 1986).

It is appropriate at this point to note that the deep structure of the Pietersburg belt is to be discussed by Stettler et al. (in prep. - quoted by de Beer and Stettler, 1986), based on the results of a geophysical study using the Schlumberger sounding technique. Figure 2.11 is a gravity profile - with interpretation - across the belt just to the northeast of Pietersburg. The implications of this profile are discussed in Section 2.5 at the end of this chapter.

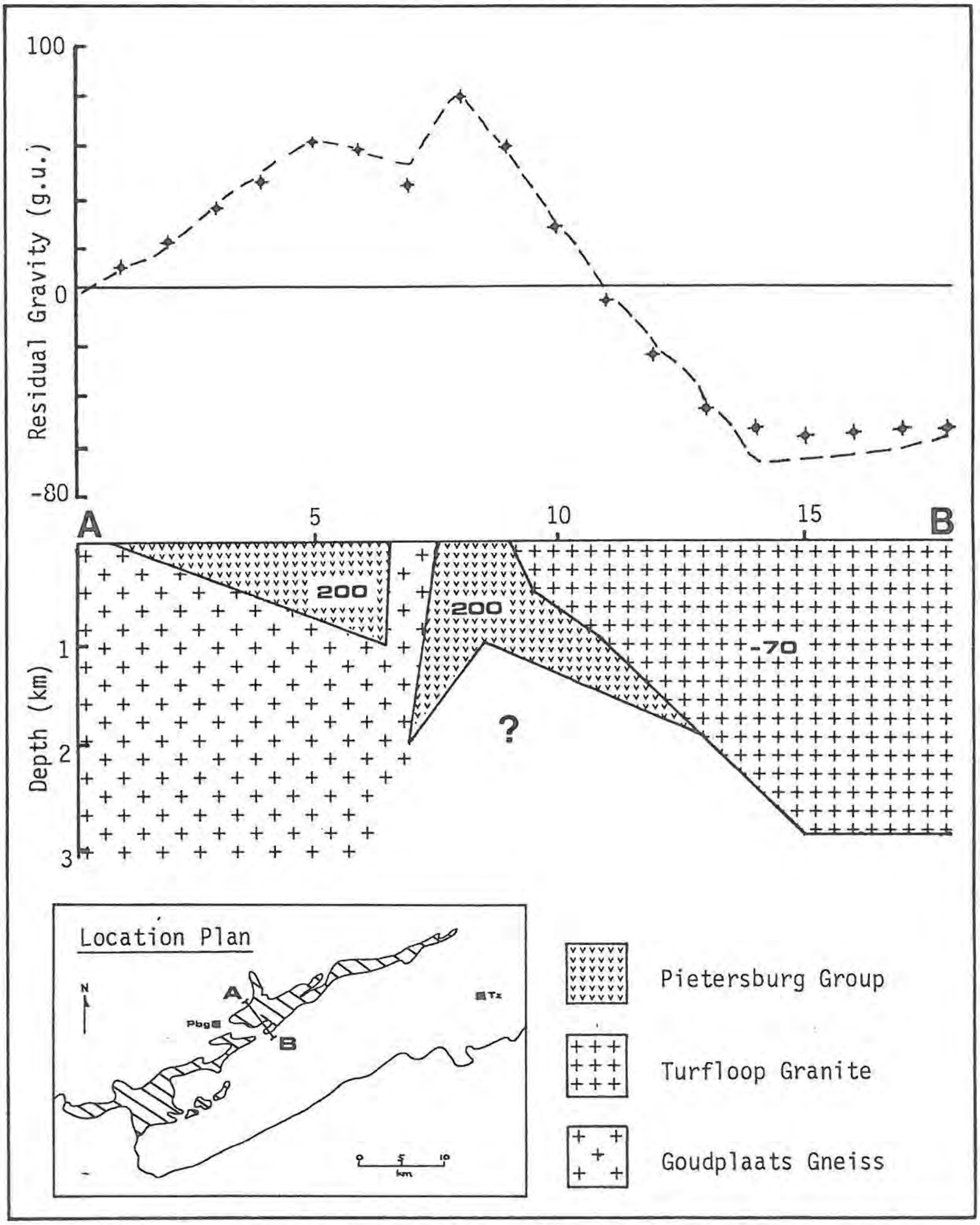


Figure 2.11. Residual Bouguer gravity profile and model of deep structure across the Pietersburg greenstone belt. The figures indicate the density differences with respect to granitic country rock (the Goudplaats Gneiss = the Geyser Granite ?) which is 2670kg m^{-3}. (From de Beer and Stettler, 1986.)

2.4. Metamorphism

The physical conditions of metamorphism in the Pietersburg greenstone belt (eg. temperature, pressure, fluid composition, etc.) have not yet been quantified but a number of qualatative observations have been made. In his regional study of the Mount Mare range de Wit recognized metamorphic textures in thin-section which he attributed to four periods of metamorphism, or at least four metamorphic peaks, designated M_1 through to M_4. The texture attributed to M_2 forms a distinctive alligned fabric and must, therefore, have developed under conditions of directed stress (ie. during the main stage of deformation, D_2). This was a period of "dynamic" metamorphism while the others (M_1, M_3 and M_4) are considered to have been "state" in nature.

M_1 was a regional hydration process which occurred under greenschist to lower amphibolite facies conditions. It affected the greenstone sequence only. The fact that it did not affect the cover sequence is proven by the presence of metamorphosed greenstone clasts in conglomerates with virtually no other signs of metamorphic change. M_1 is represented by mineral assemblages made up of talc, serpentine, chlorite, actinolite/tremolite, biotite, quartz, epidote, calcite $\pm$ hornblende and garnet.

Hornblende, and andradite (Ca+Fe) and almandine (Fe+Al) garnets, are interpreted as contact metamorphic minerals (Plate 2.12). Keith Kenyon (pers. comm., 1983) suggested that these minerals may have formed during the intrusion of granite plutons (in which case they are due to M_3 or M_4 - see below), but de Wit attributed them to the emplacement of ultramafic (to mafic) intrusions, similar to the pyroxenites identified on Turfontein 14KS (and emplaced during the evolution of the greenstone sequence). The former idea is favoured because, as Franco Pirajno pointed out (pers. comm., 1986), contact metamorphism in or close to an oceanic spreading ridge environment would only be very slight (and perhaps only a few centimetres wide) because of the high regional thermal gradient in this type of tectonic setting (See Section 2.5 for discussion of tectonic setting). Also, these environments are characteristically "wet" and anhydrous minerals such as garnet would not be expected to form. However, it is difficult to explain the restricted development of the higher-grade minerals by granite-induced formation.

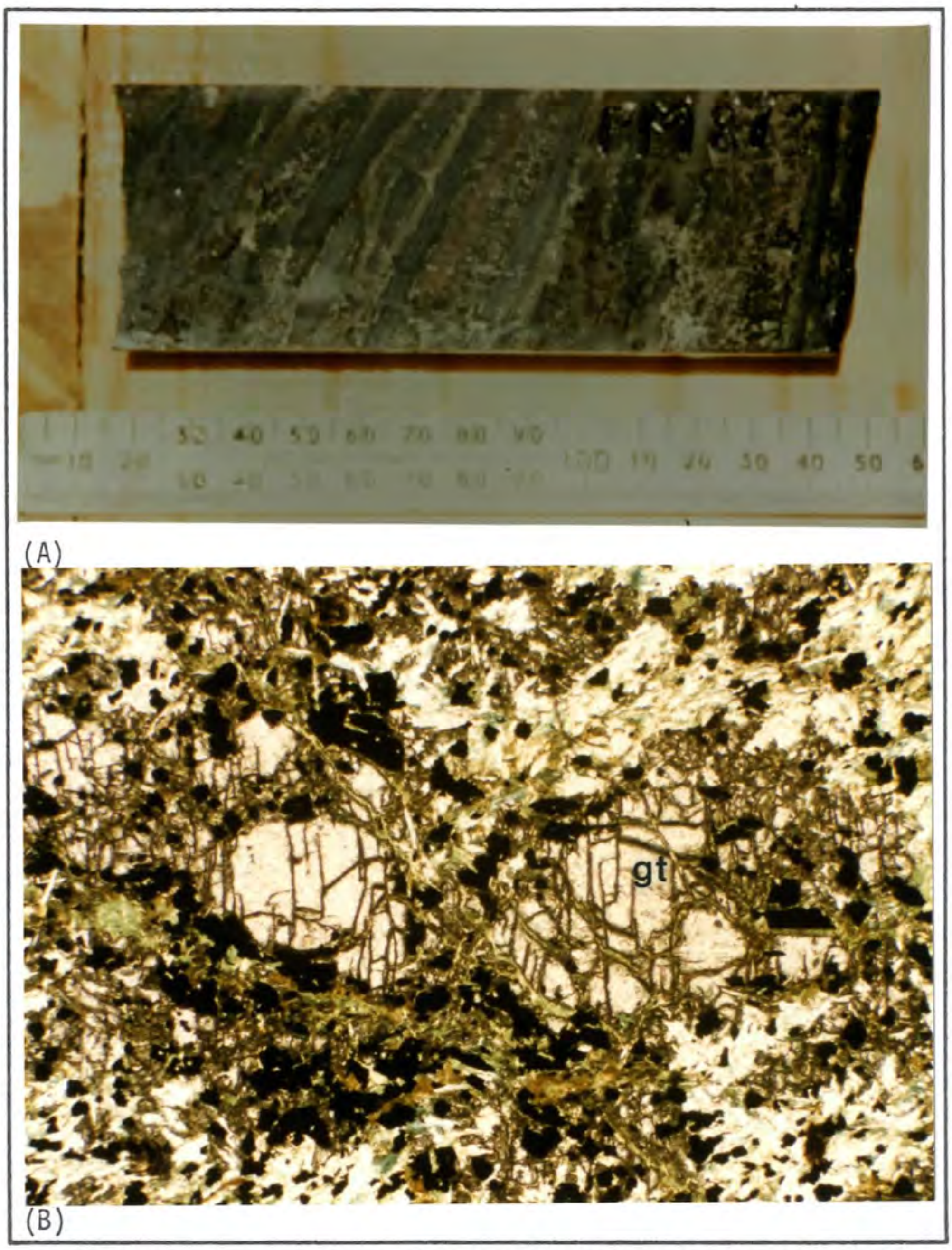


Plate 2.12. The development of andradite garnet in the Eersteling area. **(A)** Drillcore sample from GR2; garnet is pink mineral. **(B)** Photomicrograph of garnet in actinolite/tremolite-sericite-chlorite groundmass. Sample comes from drillcore of GR2 (92m). Plane polarized light, mag.x2.5.

In view of the geological and metamorphic relationships observed (and inferred) the rest of the M_1 metamorphic assemblage is interpreted as a product of seafloor metamsomatic alteration, similar to that which is taking place in modern oceanic ridges today.

It is only possible to detect M_2 metamorphic assemblages of chlorite + biotite + muscovite (in sediments), and chlorite + actinolite/tremolite to hornblende (in greenstones), close to the major shear zones. This demonstrates that it is related to D_2 and the above minerals clearly define the S_2 cleavage. Obviously, these minerals overprint and in many cases actually obliterate, the M_1 texture.

The M_3 metamorphism is represented by porphyroblasts of a brittle-mica (Plate 2.13). These occur in a green-brown schist at the Zandriver prospect in the Mount Mare range. There appears to be some confusion as to the exact type of brittle mica present because Hall (1908; 1909) and Willemse (1938) called it ottrelite, which is a variety of chloritoid, de Wit (1985) called it margarite, and Keith Kenyon (pers. comm., 1983), after an X.R.D. analysis, called it ephesite*. Never-the-less, according to de Wit, these brittle-mica porphyroblasts are predominantly post-D_2, even though a minor boundinaging of S_2 around some is probably due to late-D_2 flattening. This suggests that M_3 could be correlated with middle- to late-D_2, whereas M_2 should be strictly attributed to early-D_2 (when S_2 developed). Since there is a genetic relationship inferred between M_3 and M_4, and the emplacement of granite plutons around the greenstone belt, this interpretation would concur with the observation that a part of the Geyser granite to the north of the Willemse shear zone exhibits a foliation (Brandl, 1974). This is presumed to have formed during the later stages of D_2.

Finally, M_4 is represented by idiomorphic crystals of the same brittle mica as above, that overgrow the M_3 porphyroblasts. In addition, Hall (1908; 1909) reported the presence of andalusite laths which are thought to be of the same age.

de Wit has hinted at a relationship between M_3 and M_4 and D_3 and D_4 (though this need not necessarily be respective). It follows that if this can be proven there might exist a genetic relationship between D_3 and D_4 and the emplacement of granitoid plutons. It is possible, therefore, that these two stages of deformation were the result of structural manoeuvres to accomodate the intruding granitoid plutons.

***Footnote** : 1. Chloritoid (or ottrelite) is an (Fe,Mg,Mn) Al silicate hydroxide.
2. Margarite is a (Ca,Al) silicate hydroxide.
3. Ephesite is a (Na,Al) silicate hydroxide.

Plate 2.13. Porphyroblasts of brittle mica (of M_3 age) overgrowing the S_2 cleavage in the quartz-sericite groundmass. Note the brittle mica's hourglass structure defined by dark inclusions; this is characteristic of chloritoid (Kerr, 1959). Sample comes from drillcore of MMV1 (92m). Plane polarized light, mag.x 10.

2.5. Summary - A Geological History with Special Reference to Tectonics.

2.5.1. Stage I : Central Rift or Mid-Ocean Ridge Environment?

In a discussion of greenstone belt tectonic settings Franey (1986) emphasized the importance of including an evolutionary element into models proposed, which could account for the vast heterogeneity in the greenstone belts of the world. For example, some workers suggest that greenstone belts are the preserved remnants of an ancient rift environment, while others suggest that they represent Archean ophiolites (ie. slabs of oceanic crust originally produced at a spreading ridge). Based on the fact that the geochemistry of greenstone rocks resembles that of modern oceanic crust (Beaty and Taylor, 1982; Hoffman, 1984; Hoffman et al., 1986), an oceanic origin of greenstone belts is generally favoured by most workers. However, to account for those that do not conform to this model, it is suggested that a narrow rift and a wide ocean could represent the end-members of a continuous spectrum of environments, in which the greenstone sequence of any belt could have formed. It is true that most appear to have originated in an oceanic environment, though not necessarily in a wide ocean. For example, a narrow back-arc marginal sea could generate a typical greenstone belt, as proposed by Burke et al. (1976) and Tarney et al. (1976). It must have been in this kind of environment (ocean or rift ?) therefore, that the greenstone sequence of the Pietersburg belt formed.

The extrusion of mafic lavas, the deposition of interflow sediments (B.I.F.s), and the emplacement of ultramafic intrusions are all thought to have been more or less concurrent, and the entire pile (greenstone sequence) is therefore considered as one unit. During the build-up of this pile, seafloor metasomatism effected an alteration of the rocks, designated M_1.

2.5.2. Stage II. Closure of the Basin and Obduction.

The compressional structures that are characteristic of greenstone belts everywhere were probably formed during the closure of the basin in which the greenstone sequence was originally formed. In the case of an ocean (wide or narrow), subduction would have consumed most of this sequence and the only remnants (greenstone belts) would be those slabs that were obducted onto continental crust (the Archean granite-gneiss terrain). For a narrow rift-related greenstone belt, on the other hand, the entire greenstone sequence would be preserved. The depth of a greenstone belt might then be a clue to its mode of formation. The shallow depth of the Pietersburg belt, as determined by regional geophysics (See Section 2.3), suggests that it most probably represents an ophiolite. The deformational history of the belt is therefore interpreted along these lines. (It is pertinent to note at this point, that the geologists who are drawing the greenstone belt-ophiolite analogy are those that have mapped in both greenstone belts and modern ophiolite complexes. This is considered to be a significant fact and one that lends great weight to the whole hypothesis).

The initial D_1-stage of deformation is thought to have been the first effect of the obduction process, which probably occurred during the detatchment of the obducted slice from the subducting oceanic plate.

The main D_2-stage was then due to the actual obduction process of thrusting the slab of oceanic crust (greenstone sequence) onto the continental crust. It was during this process that the major shear zones (thrusts) developed and the entire belt was flattened. As an individual thrust block propogated

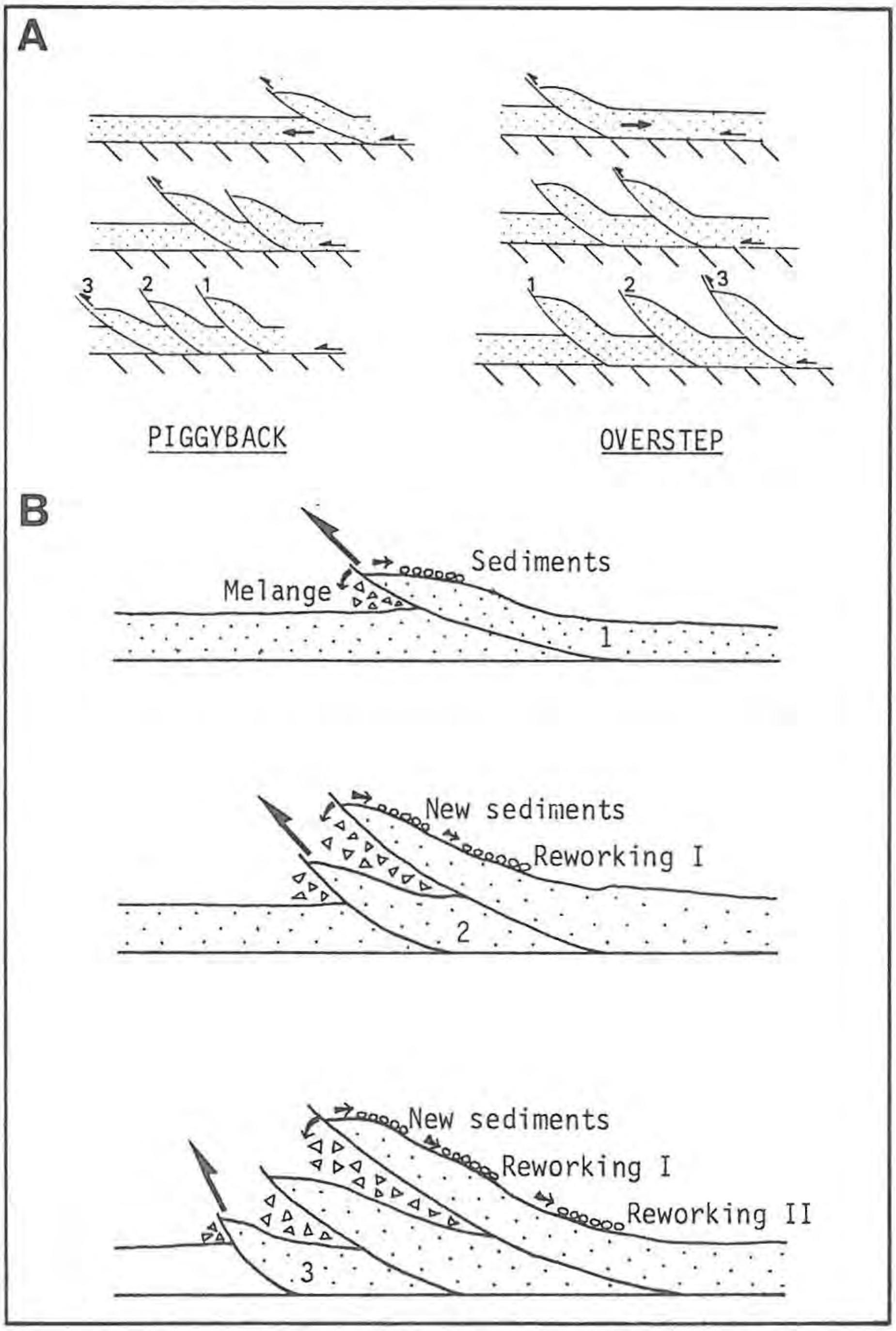


Figure 2.12. Model of successive thrust development to show how the cover sequence sediments were reworked. **(A)** The **Piggyback** and **Overstep** sequences (From Park, 1983.) **(B)** Postulated piggyback sequence for Pietersburg greenstone belt.

forward (and upward), its leading edge began to shed clastic detritus, both into the path of advancement and backwards onto the thrust block itself. In the former case the detritus was caught up in the plane of the thrust and a melange zone was formed, while in the latter case the detritus was deposited in a network of braided streams. The evidence for this scenario is preserved in the Snymandsdrift tectono-sedimentary melange zone and its hanging-wall. Successive thrusts may have developed in a **piggyback** or **overstep** sequence (Fig. 2.12), and if the former was the case, there might have been an opportunity for the reworking of braided stream sediments - and the concentration of placer-type gold deposits (eg. the Mount Robert occurrence ? - see Chapter 3, Section 3.1). During this stage of the belt's evolution, metamorphism was restricted to the immediate vicinity of the thrust planes.

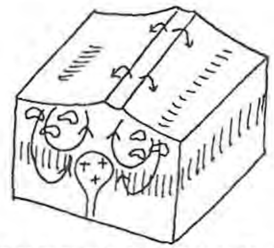
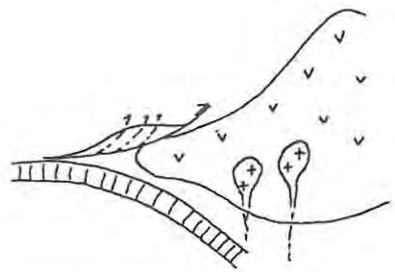
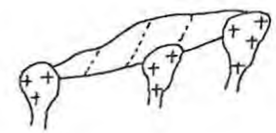
2.5.3. Stage III. Granitoid Intrusion

The granitoids that intrude most greenstone belts of the world are of tonalitic or trondhjemitic composition. These are typical granitoids derived by the transformation of basalt and/ or gabbro during subduction along an ocean-continent convergent plate boundary.

The first granitoid intrusions into the Pietersburg belt probably actually occurred during the later period of Stage II. This is suggested by the presence of a gneissose fabric in a few granitoid outcrops. The main period of intrusion, however, post-dated the D_2-stage of deformation (ie. it occurred after the final emplacement of the obducted greenstone slab). At least two ages of granitoid emplacement are inferred from the deformation and metamorphic effects that are thought to have been related to each.

A schematic summary of the geological history of the Pietersburg greenstone belt is presented in Table 2.4.

Table 2.4. Geological history of the Pietersburg greenstone belt.

STAGE	LITHOLOGIES	DEFORMATION	METAMORPHISM	SCHEMATIC ILLUSTRATION
I Production of oceanic crust (greenstone sequence)	Pillow lavas Interflow sediments (B.I.F.s) Ultramafic intrusions		M_1 seafloor metasomatism	
(unconformity)				
II Basin closure and obduction (and development of cover Sequence)	Shales, sandstones and conglomerates Tectono-sedimentary melanges and shear zones	D_1 (due to detatchment of oceanic slab D_2 thrusting, isoclinal folding and bulk horizental shortening (due to obduction)	M_2 (restricted to the vicinity of shear zones-thrusts)	
(overlap)				
III Granitoid intrusion	G_1 granitoids G_2 granitoids	D_3 structural adjustment ? D_4 strucutral adjustment ?	M_3 contact metamorphism M_4 contact metamorphism	

3. GOLD DEPOSITS

As indicated in Table 1.1, the gold production from the Pietersburg greenstone belt has been from both primary and secondary deposits. The primary deposits are, without exception, shear zone-related and they are interpreted as epigenetic hydrothermal deposits. The secondary deposits have been described as eluvial and alluvial but, on the basis of distribution, the latter appears to be predominant - though the former undoubtedly also exists/existed. These deposits were first described in detail by Willemse (1938), who visited some of the mines before they closed down. For those that were inaccessible, Willemse acquired information from both private individuals and old plans which were borrowed from the Government Mining Engineer. Because many more of the old workings have collapsed since Willemse's work, his report is the only geological record of most of the gold deposits in the area.

However, as mentioned in the introduction, recent exploration activity has largely concentrated on old workings, with the aim to re-evaluate these in terms of modern mining and extraction methods and a higher gold price. This work has involved at least two detailed drilling programmes (plus subsidiary programmes) and one project of underground development. The aim of this chapter is to review and expand upon the accounts of Willemse in the light of present-day knowledge, and to propose a genetic model for the most important, shear zone-hosted type of gold deposit. (Willemse's 1938 report is not specifically referenced in the text).

3.1. General

Three goldfields and one isolated gold occurrence have been discovered in the Pietersburg greenstone belt.

These are :

1. The **Eersteling Goldfield** : situated on the farm Eersteling 17KS and extending onto the adjacent farm Waterval 18KS, Vrishgewaagd 33KS and Rietfontein 34KS.
2. The **Roodepoort Goldfield** : situated on the farm Roodepoort 744LS and extending onto Weltevreden, Palmietfontein 24KS, and the southeastern portion of Zandrivier 742LS.

3. The **Marabastad Goldfield** : which covers the Mount Mare range on the farms Hollandsdrift, Snymansdrift 738LS and Zandrivier 742LS.
4. The **Mount Robert Gold Occurrence** : situated on the farm Amatava, and briefly worked as the Potberg gold mine.

After subdivision into primary and secondary deposits, the individual workings within each goldfield (including the Mount Robert occurrence) can be classified into one of the following types.

Primary deposits :
1. **Greenstone-hosted shear zones**
2. **Sediment-hosted shear zones**
3. **Granite-hosted shear zones**

Secondary deposits :
1. **Ancient placer accumulations**
2. **Recent placer accumulations**

The Eersteling and Roodepoort goldfields comprise mainly greenstone-hosted shear zone deposits, whereas the Marabastad goldfield comprises mainly sediment-hosted shear zone deposits. These two types are by far the most important in the entire region and they are described in detail in the following sections of this chapter. However, in order to provide a complete review of gold mineralization in the Pietersburg belt, the other types of deposit are briefly described below.

Four shear zone deposits are hosted by granite. These are the Palmietfontein, Hope, and Knight's Pietersburg deposits in the Roodepoort goldfield, and the Waterval deposit in the Eersteling goldfield. A number of quartz veins in granite on the farm Langgenoeg are also rich in gold but they are too small and too erratic to have warrented exploitation. The Palmietfontein deposit was described by Hall (1908) as a white quartz vein of variable width (average 0.5 m) in a fresh coarse-grained, grey granite. The vein evidently stopped abruptly at the contact with the greenstones. Its average grade was 7g/t.

The Hope, Knight's Pietersburg, and Waterval mines worked various mineralized zones at the granite - greenstone contact. This contact is usually gradational and characterized by greenstone xenoliths which were

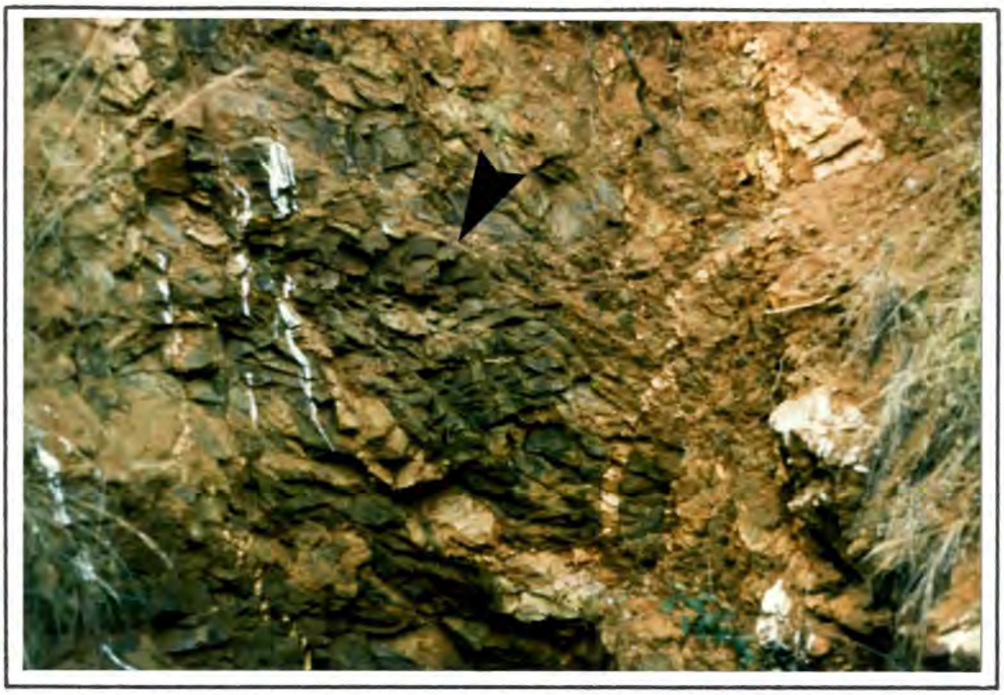


Plate 3.1. Large greenstone xenolith within granite country rock in the sheared contact zone of the greenstone belt. Note the granitic veins which cross-cut the xenolith. The xenolith occurs just above the portal to the No. 6 Incline, Waterval Mine, Waterval 18KS.

stoped off from the country rock by the intruding granite (Plate 3.1). Gold mineralization is usually confined to shears within the contact zone. For the Knight's Pietersburg mine, Barton et al. (1986) report that free gold and gold associated with pyrite occur in three settings : (1) As small rich pockets in ultramafic talc schist close to the Roodepoort pluton, (2) in quartz-sericite schist, which may represent a shear zone along the talc schist-Roodepoort pluton contact, and (3) disseminated along shears within the Roodepoort pluton itself.

For the Waterval mine, the calculated average grade is 2.5 g/t (from production records : Willemse, 1938). This overall low grade suggests that the gold distribution was very erratic because the old miners would only have begun mining with the promise of a much better grade. In other words, the occasional sample must have had a much higher grade (this has been confirmed during recent exploration).

These granite-hosted gold deposits are important not so much for their economic worth, but because they demonstrate that gold mineralizing fluids were active after, or at least during the late stages of granite intrusion and consolidation (see Section 3.4).

The Mount Robert gold occurrence is the only ancient placer to have received any prospecting attention in the Pietersburg greenstone belt. Although there are signs of other heavy mineral accumulations in the coarse-grained sediments of the cover sequence, they appear to have been mostly of chromite (now fuchsite) and pyrite. Several companies have evaluated the Mount Robert deposit but surface sampling has always yielded subeconomic grades. The deposit has also been the focus of academic interest because of its similarities with the Witwatersrand conglomerate gold deposits. Saager and Muff (1978; 1986) and Muff and Saager (1979) provide a detailed picture of the deposit with particular emphasis on the petrographic and mineragraphic aspects of the ore. Very briefly, the placer deposits are hosted by matrix supported, poorly-sorted, polymictic conglomerate lenses within a thick pile of coarse clastic sediments. Combined with the presence of scour channels and well developed sandbars, these features indicate a proximal source for the sediments and deposition in a braided river system. Pyrite is the most abundant ore mineral but leucoxene-rutile, chromite, molybdenite, zircon, carbonaceous matter (fly-speck carbon), and brannerite, in addition to gold, also occur. The poor grades of gold are attributed to the fact that the sediments did not undergo the repeated cycles of reworking that concentrated the Witwatersrand ores.

In terms of a regional model of gold mineralization, the Mount Robert occurrence is significant because it suggests that there were at least moderate concentrations of gold within the greenstone sequence (from which the cover sequence was derived) prior to the deposition of the host sediments themselves.

Almost all the alluvial and eluvial workings are confined to the Eersteling goldfield, and most diggings occur on the farms Eersteling 17KS, Waterval 18KS and Vrischgewaagd 33KS. Three reasons are suggested for this restricted distribution : (1) The greenstone host rock is more amenable to erosion than the cover sequence sediments, (2) the proximity of the escarpment causes a higher rainfall in this area compared to the rest of the region southwest of Pietersburg and the greater relief causes the streams on

Plate 3.2. Alluvial gold, panned from the Girlie Creek on Eersteling 17KS.

Eersteling, especially, to run more swiftly and therefore erode more rapidly, and (3) the gold content of this goldfield was inherently greater than elsewhere. The only other goldfield from which alluvial gold has been produced is Roodepoort (Table 1.1) which, like Eersteling, is underlain by greenstones.

Hall (1908) described the secondary deposits as... "small earthy "paddocks", containing quartz float and about three feet thick, resting on greenish schists" (the greenstone bedrock).

According to the old diggers (quoted by Willemse), the gold was always associated with fine quartz leaders. Willemse pointed out that these need not have been the primary vein source of gold because they could equally well have acted as barriers, against which transported gold accumulated. Supporting evidence for this suggestion is the fact that the leaders thinned out and disappeared at shallow depths, and never led to a definite "reef".

The effects of chemical transport of gold in this area are not known but recent research in Western Australia (Mann, 1984; Wilson, 1984) suggests that it may be an important mechanism for the redistribution of gold in the supergene environment. Occasionally, fairly large nuggets have been found in the goldfield and Willemse's report includes a photograph of one that contained 2.37 kg of gold and 0.19 kg of silver. Large nuggets such as this are thought to be indicative of a chemical accumulation of gold in the supergene environment, especially since the angular nature of many nuggset shows that they have not been transported far, and could not, therefore, have formed by the mechanical coalescence of many smaller grains. Plate 3.2 illustrates some alluvial gold which was panned from one of the main drainages on Eersteling 17KS.

3.2. Greenstone-Hosted Shear Zone Deposits

The majority of old workings in the Eersteling and Roodepoort goldfields are located along east-west trends which have been recognized as steeply dipping ($\pm$ 60^{o}) shear zones. The Pienaar-Doreen shear zone complex on Eersteling is the largest of these and has produced the most gold. Others that have also been exploited include the Malan and Clarke shear zones on Eersteling 17KS, and the Old Freda and Southern Line shear zones on Roodepoort 744LS.

Most currently available information relates to the Eersteling deposits. However, Barton et al. (1986) report that the Roodepoort shear zones are represented by a carbonate-quartz-chlorite-talc "augen schist" which is intensely carbonatized and silicified. Gold is evidently free or associated with pyrrhotite and arsenopyrite. Willemse reported that the Lone Tree mine on the farm Wildebeestfontein is located on the westerly continuation of one of these shear zones. Quartz veins of variable thickness and grade were worked at this locality.

3.2.1. The Eersteling Goldfield

The greenstone sequence, which underlies the majority of the Eersteling goldfield, is represented by fresh outcrops of amphibolite (in stream sections :Plate 2.1) and a variety of mafic schists. The schistose assemblages include quartz, chlorite, carbonate, and chlorotoid as major consitutents, in various proportions, and they typically weather very easily (the whole of the southern half of Eersteling 17KS is unexposed). Minor lenses of ultramafic material occur as serpentinites and talc-carbonate

Plate 3.3. View, looking northwest from Clarke's workings (see Fig. 2.3 for location), across the Eersteling goldfield. The underlying greenstone sequence weathers easily to give rise to the low topography. This is broken by two prominent mountains : the Ysterberg (Y) composed of B.I.F., and Button Kop (BK) which is a part of the Transvaal escarpment. Black Reef crops out on the latter.

schists. Stocks of granitic material are intruded into the greenstone sequence and are elongate parallel to the regional east-west trending foliation (S_2). Plate 3.3 is a view, looking northwest, across the Eersteling goldfield.

The main Pienaar-Doreen shear complex is traceable over 7km of strike and is, on average, between 700 and 800m wide. Charles Byron (pers. comm., 1985) interpreted it as an overturned isoclinal syncline, based on repeated stratigraphy and younging directions, but the field evidence for this is tenuous (pers. obs.) and is not considered convincing. The northern and southern limits of the complex are represented by the Pienaar and Doreen shears, respectively, and in between these there are a number of cross-cutting shears which dip to the northwest and define a vague ladder vein-type arrangement. The Pienaar shear splits into two at its western end and the two branches, which extend for about 1500m of strike, are known as the Girlie North shear and Girlie South shear.

Mining (and/or underground prospecting) was carried out at eight localities within the shear complex, and Willemse noted that most of these occur at, or close to, a bend in the strike of an individual shear, or at the intersection between two seperate shears. The old workings were the Girlie Mine, Pienaar's Mine, Jeweller Shop and Fair Maid of Perth on the Pienaar shear, de Villiers Mine on the Doreen shear, and Maltz's Mine, Dog Shaft and Good Hope Mine on various cross-cutting shears. A geological summary of each deposit is presented in Table 3.1 (above the dotted line). They are all extremely variable along strike, and presumably, therefore, down dip as well - but most are characterized by the presence of quartz. As a general rule, the darker the quartz the better it is mineralized. The pure white variety (referred to as "buck quartz") is typically barren of sulphides and gold.

Though Saager and Muff (1986) recently described the Girlie (North) Reef as a sulphidic B.I.F., this has been unequivocally disproven by means of an extensive drilling programme. This has shown that the gold - bearing zone is a quartz-filled shear which cross-cuts an otherwise barren B.I.F. horizon. This particular reef is described in detail in the following section (3.2.2).

Both the Malan and Clarke shear zones are poorly exposed, except where they have been opened up by old-time miners and prospectors. For this reason their extension between the various correlated workings (Fig. 2.3) is strictly speculative, although their overall parallel allignment with the Pienaar-Doreen complex strongly suggests that it is correct. The extension of the Malan shear across the southern portion of Eersteling 17KS is indicated on an older plan obtained from the Government Mining Engineer. Geological summaries of deposits hosted by the Malan and Clark shears are included in Table 3.1 (below the dotted line). Close to the eastern border of Vrischgewaagd 33KS, Willemse (on his original map) indicated a quartz vein which probably intersected the main Malan shear at Malan's Workings. And close to the western boundary of the same farm, the distribution of prospecting pits and winzes which constitute Clarke's Workings indicates that the Clarke shear splits into two at this locality. These structural features are thought to have influenced the old time diggers because, despite detailed lithogeochemical sampling at each of these workings (and

Table 3.1. Gold deposits of the Eersteling goldfield

Working	Host shear	Structural control	Nature of reef	Sulphides	Grade (g/t)	Thickness (cm)	Strike (m)
GIRLIE MINE	Girlie North	?	Quartz-filled shear cross-cutting B.I.F. Carbonate alteration	po py cp apy with gold	7*	63	670
PIENAAR'S MINE	Pienaar	Intersection with Girlie North shear	Quartz-carbonate-chlorite assemblage	py po cp No apy	18*	80	150
JEWELLER SHOP	Pienaar	Intersection with cross-cutting shear	Quartz-rich ferruginous zone	?	Good?	50-100	±100?
FAIR MAID OF PERTH	Pienaar	?	Ferruginous shear with associated B.I.F.	py+ ?	Good?	50	±500?
DE VILLIERS' MINE	Doreen	?	Quartz-rich ferruginous zone	?	+5	50	±100?
MALTZ'S MINE	Maltz	Bend in shear-faulting	Siliceous shear with dolomite and calcite alteration	po+py+apy (+cubanite)	+5	200	±150
DOG SHAFT	Cross-cutting shears/fractures	Intersections and bends in shears/fractures	?	?	Rich(?) in places	±100	±300?
GOOD HOPE MINE	Good Hope	Intersection with Girlie North shear and bend in Good Hope shear	Quartz vein with very thin alteration halo (interpreted as tension gash)	apy po+py cp	6*	20	±100
MALAN'S WORKINGS	Malan	Intersection with cross-cutting shear	Quartz veins	None ?	Poor*	50	±500
REDELINGHUYS' WORKINGS	Malan	?	Quartz-rich ferruginous zone	?	Poor*	±20	±100
CLARKE'S WORKINGS	Clarke	Intersection with sub-parallel shear	Quartz-carbonate-chlorite assemblage	Minor	Poor*	±100	±200
RIETFONTEIN MINE	Clarke?	?	Quartz veins	?	Poor	?	?
LE ROUX'S WORKING	Clarke?	Intersection with cross-cutting shear	Quartz veins	None ?	Poor	Irregular	?

* Calculated from Anglo American drilling results.

Redelinghuys' Workings), only minor indications of gold have been found.

In the Eersteling goldfield, apart from Girlie North Reef, the only shear to have shown any promise of potential during the last few years has been the Maltz Reef at Maltz's Mine. Southern Sphere developed a drive along this reef for approximately 600m as part of a feasibility study to assess the viability of mining, but the project was shelved in 1986 for political reasons. The only shear to have actually produced gold recently is the Doreen Reef at de Villiers' Mine. However, it is worked on a very small scale only and production is rather erratic.

3.2.2. Girlie North Reef

The Girlie North shear zone represents the northern branch of the main Pienaar shear zone which splits into two at the site of the Pienaar Mine (Fig. 2.2). The "reef" or "pay"* section of this shear zone is known to exist about 600m from the split and it extends westward, for 640m, to a point just beyond the Good Hope Reef intersection.

Mining and exploration:

Historically, only a small part of the reef was mined. An old plan, obtained from the Government Mining Engineer, shows that the Girlie Mine comprised two levels serviced by a shaft and an adit. The latter was driven along the upper level from the valley of Girlie Creek (Fig. 3.1). Most of the mine's stopes occur between the surface and upper level (in the oxidized ore zone) and it would appear that the lower level was an exploration drive only (probably in sulphide ore ?). It is estimated that about 1000 tonnes of ore were mined overall. Sample values marked on the old plan (from an unknown source) indicate the following : 13.2 g/t Au X 69 cm X 129m. Based on this information, an exploration programme was launched to investigate the strike and depth extent of the reef.

Those old workings that were accessible (only the main shaft down to the upper level, and a few subsidiary shafts and prospects) were sampled to confirm the values indicated on the old mine plan. At the same time, the reef was traced along strike at surface by following lines of old diggings and collapsed stopes. It was trenched at regular 50m intervals. The

***Footnote** : The term "pay" generally means economically viable. This is obviously dependant on a large number of variables and so in this report "pay" is strictly defined as "... of economic potential".

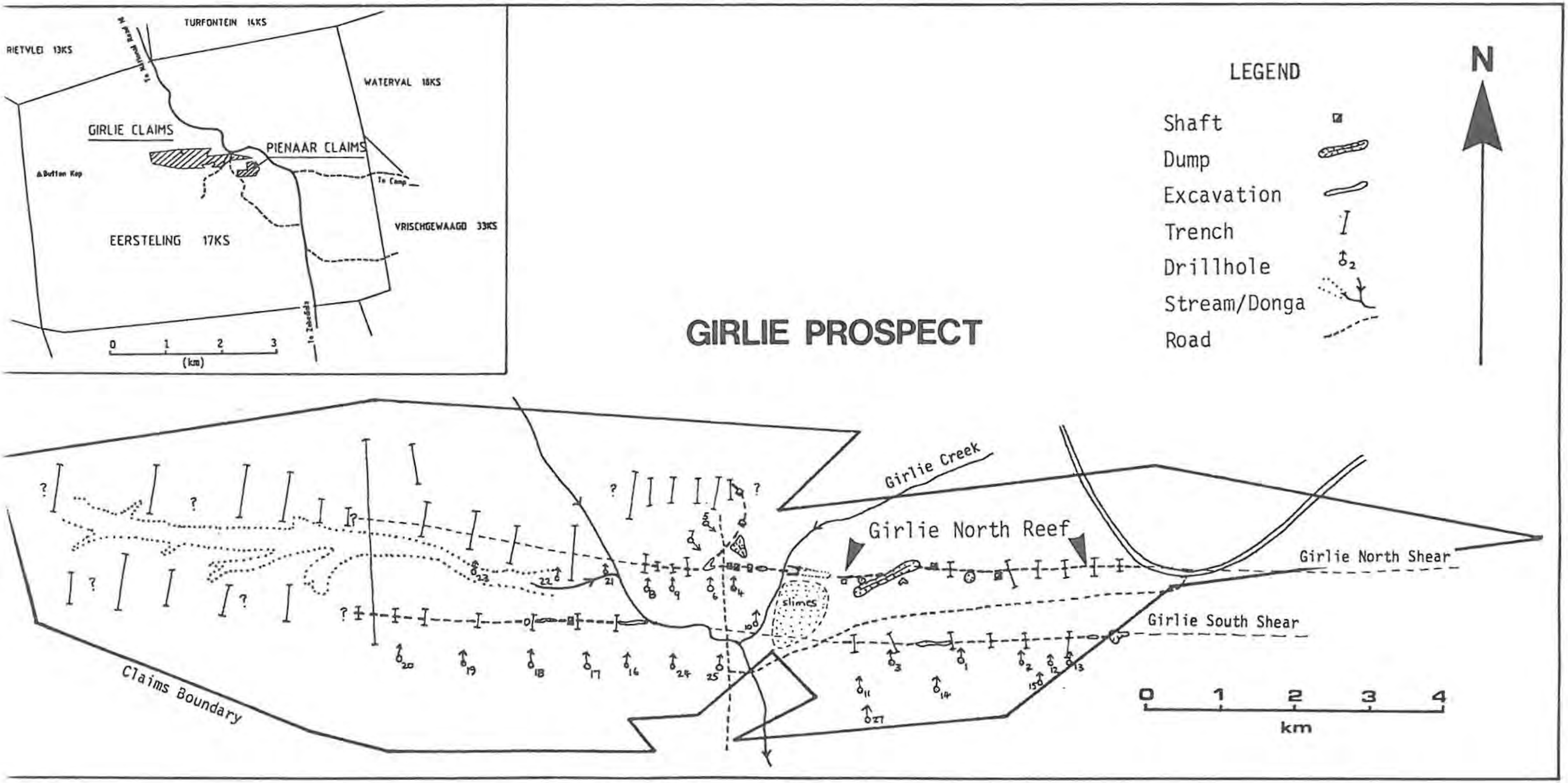


Figure 3.1. Sketch plan of the Girlie prospect.

Plate 3.4. View, looking east, along the Girlie North (N) and South (S) shear zones to illustrate the detailed trenching programme used to delineate the strike extent of each.

results of underground sampling and trench sampling, combined, give the following : 3.9 g/t Au X 88cm X 180m, and farther west 5.0 g/t Au X 82cm X 30m. These values were considered good enough to warrant drilling and consequently, five holes were drilled into North Reef (and two into Good Hope Reef). This first-stage drilling programme proved that significant gold values persisted to depth.

The strike extent of the North and South shear zones (the latter is the southern, sub-parallel branch of the main Pienaar shear zone, west of Pienaar Mine) were traced at surface as far as possible, using soil geochemistry, lithogeochemistry (trench sampling), and geophysics (magnetics and I.P.). Plate 3.4 is a view looking east along the two shear zones to illustrate the extensive trenching programme. A second-stage drilling programme was proposed to define the strike extent of North Reef and to investigate the South shear zone. In the end, seventeen holes intersected the North shear zone (twelve of these defined the known reef) and twelve holes intersected the South shear zone (two defined a short reef zone, 120m long).

Geology:

North Reef does not generally crop out at surface but it is exposed at the top of old workings and in trenches. In the best exposures it occurs as a sheared, highly ferruginous quartz-rich zone. More often than not however, the shear zone itself is not obvious and can only be found by first identifying an associated B.I.F. unit. This may also be poorly preserved but it can usually be recognized by the presence of small fragments of cherty material in weathered bedrock (Plate 3.5).

Based on routine core logging and a detailed macroscopic examination of all the reef intersections, Franey (1985) summarized the geology of North Reef and, also, the drilled out "non-pay" section of the North shear zone (refer to Fig. 3.1).

"From drillhole GR13 in the east to GR9 in the west North Reef consists of one, or more (eg. GR10), quartz-filled fracturs. These are surrounded by a quartz-carbonate-chlorite unit ..... in which pyrrhotite and chalcopyrite always occur. Pyrite may or may not be present. Only in GR13, GR11, GR10, and GR9 is there a well developed planar fabric indicative of ductile shearing. Gold is always associated with arsenopyrite, and both are associated with the main quartz vein, usually occuring along its margins (Plate 3.6 C).

Beyond GR9 (ie. GR8, GR21, GR22, GR23, and GR20) no arsenopyrite occurs and the gold values are very low. There is also no major quartz vein, which is a characteristic of the "pay reef", developed. Chalcopyrite appears to be more abundant (although it is still a minor constituent of the whole zone) and epidote becomes quite prominent (especially in GR21, where it is logged as the second most important mineral). The best gold value from these holes was 10.9 g/t Au X 18.1cm from GR8DEF, but this is thought to be remobilized gold from the true "pay reef" to the east.

The main quartz vein in the east (the reef zone) cross-cuts stratigraphy - it occurs at the top B.I.F. contact in GR2, towards the base of the B.I.F. in GR3, and 4m above the B.I.F. in GR11."

Plate 3.5. Surface exposure of shear zones in the Eersteling golfield. **(A)** Trench exposure of the main Pienaar shear zone at Fair Maid of Perth to illustrate the ferruginous, quartz-rich shear zone (SZ) and an adjacent B.I.F. unit (the laminated ferruginous zone against which the hammer in leaning). **(B)** The Girlie North Reef in a trench close to the Main Shaft. The shear zone (between the sample tickets) is poorly preserved but the associated B.I.F. is represented by banded chert fragments; the shear zone sample assayed 17.8 g/t 40cm.

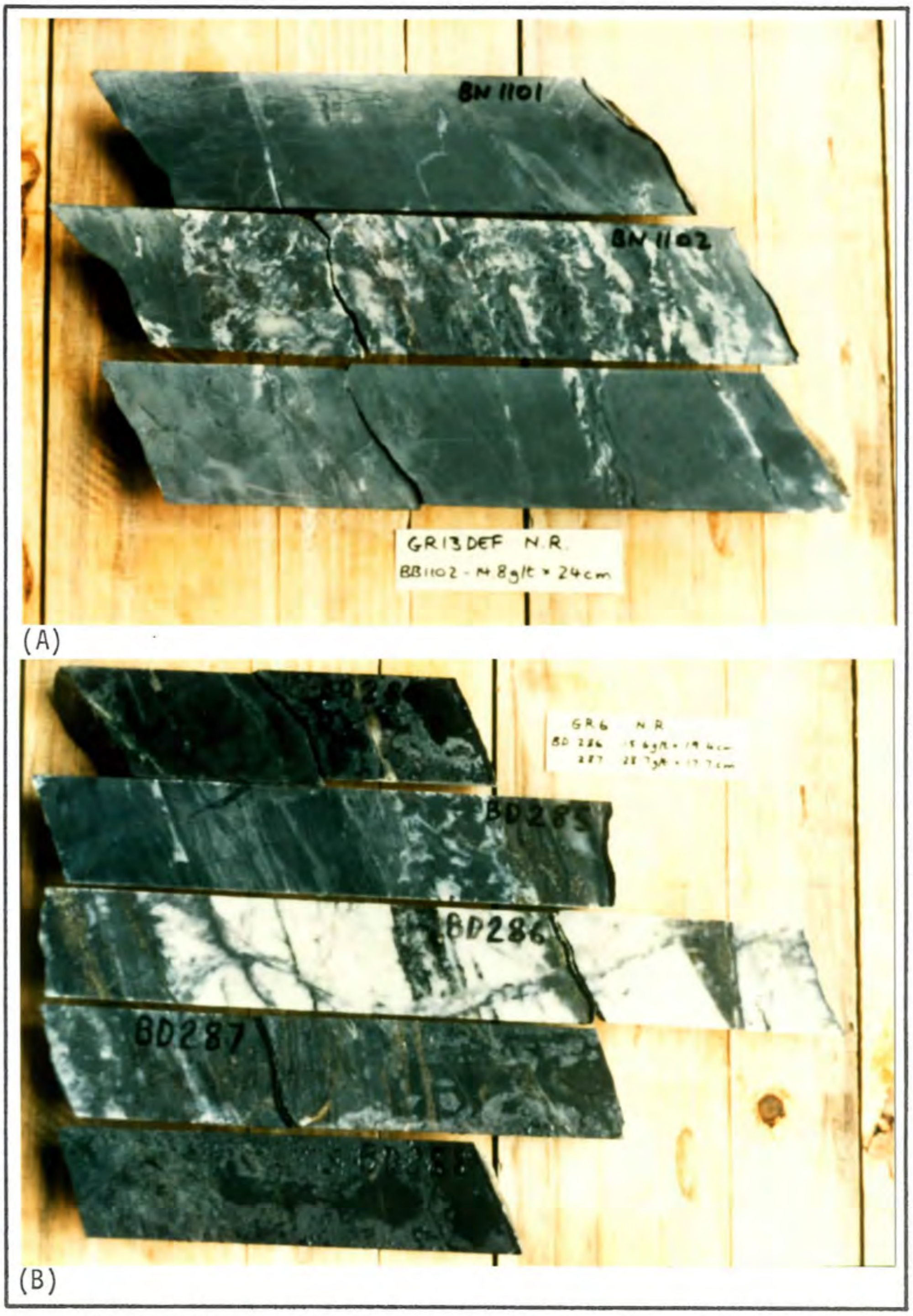


Plate 3.6. Drillcore profiles of Girlie North Reef. (A) GRI3 DEF. Note that no white quartz vein is developed in this profile. (B) GR6. Note the fractured nature of the main white quartz vein and the high gold values associated with it. **(contd.)**

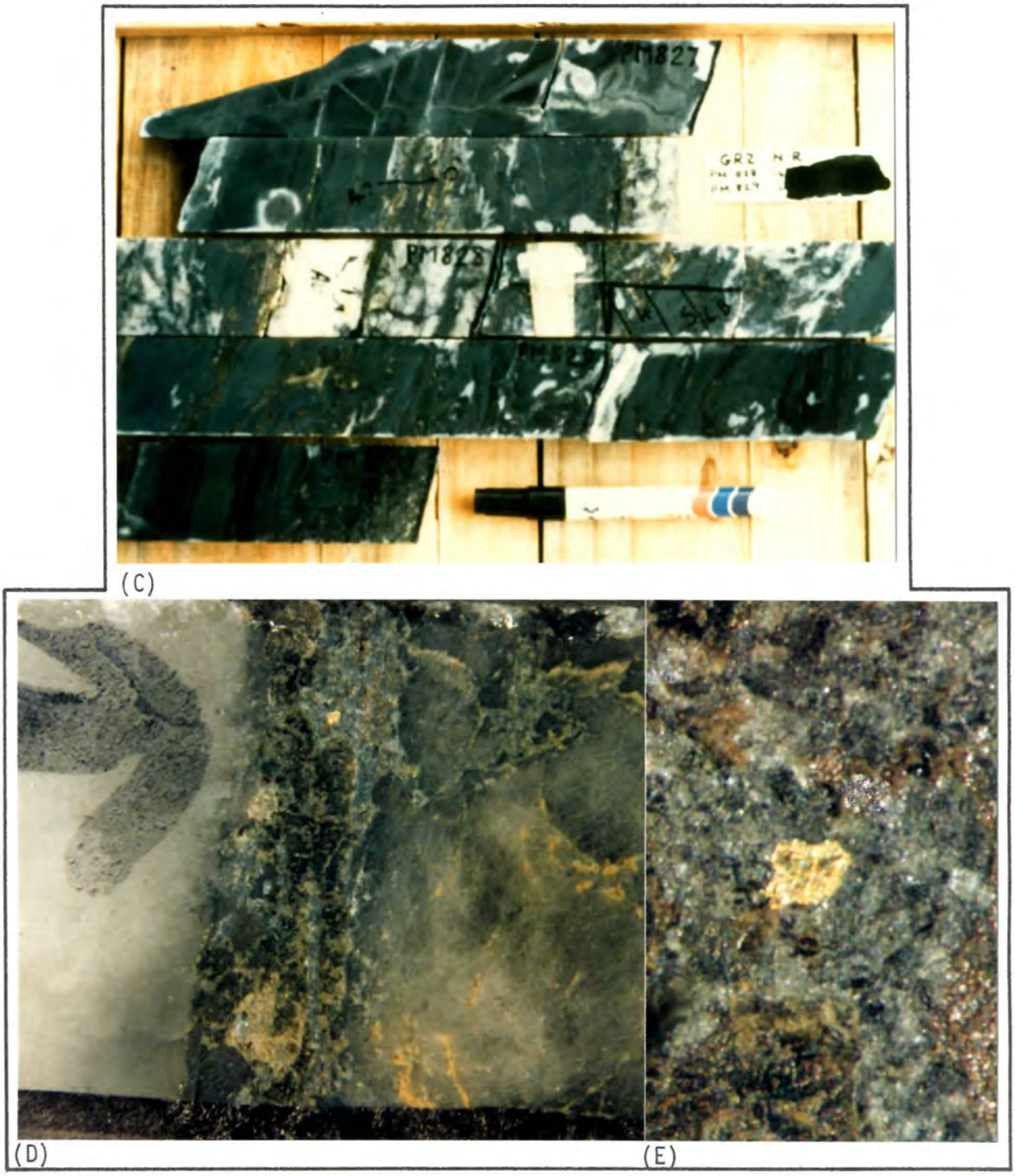


Plate 3.6. (contd.). (C) GR2. Note visible gold on contact of main white quartz vein. Sample results : PM 828 = 16.7 g/t x 39cm, PM 829 = 6.45 g/t x 42cm. **(D)** Thin section GR2-2 (see Fig. 3.2 A for location). Close-up of quartz vein contact; mag.x 0.8. Note the difference between white quartz (left) and smokey grey quartz (right). **(E)** Close-up of gold grain in D; mag. x 5.

Mineralogy:

To determine the nature of the reef more accurately, two profiles of reef were examined. These were from GR2 at the eastern end of the reef zone, and from GR6 at the western end. Thin-sections were cut from samples of drillcore and studied by transmitted and reflected light microscopy. The main aims of the study were to characterize the mineralogy of wall rock alteration and to establish a paragenetic sequence of mineralization. Samples were taken at regular intervals away from the visible reef (½ , 1m, 1½ m, 2m, 2½ m, 3m, 4m, 5m, 10m, 15m, 20m, 25m) and of selected samples in the reef. The location of the latter are shown on the detailed logs of each reef profile presented in Figure 3.2 (A and B).

Figure 3.3 gives a mineralogical summary of this wall rock alteration study. A number of features are immediately apparent from these plots (Plate 3.7):

1. Actinolite/tremolite is the predominant amphibole in the hanging-wall of the reef, whereas hornblende is predominant in the footwall.
2. Plagioclase is only preserved in the footwall of the reef.
3. Quartz appears to take the place of plagioclase in the hanging-wall of the reef, and also in the footwall in GR6.
4. When the volume of quartz exceeds about 35% a clay-type mineral becomes a significant constituent of the rock.

Numerous cross-cutting veinlets, comprising assemblages of quartz, carbonate, chlorite, epidote, and sulphide, in various proportions, were also observed in thin-section. Routine core logging however, showed that the density of veinlets did not increase towards the reef, and it is concluded, therefore, that they consist of material exsolved from the rock groundmass during regional metamorphism.

Macroscopically, the reef itself is defined by an abrupt increase in quartz,carbonate, chlorite and sulphide (Fig. 3.2, A and B). In thin-section various fields comprise the following assemblages : (1) q only (vein), (2) q-ser-CO_3-sulph, (3) q-ser-chl$\pm$ sulph, (4) q-CO_3-chl, (5) q-chl, (6) q-CO_3-tourm (Plate 3.8), and (7) chl-ser-epid. At least two phases of quartz were recognized from the grain size distribution. The coarser-grained variety was logged as "white" quartz during macroscopic examination, while the finer-grained variety was logged as "smokey grey" quartz (Plate

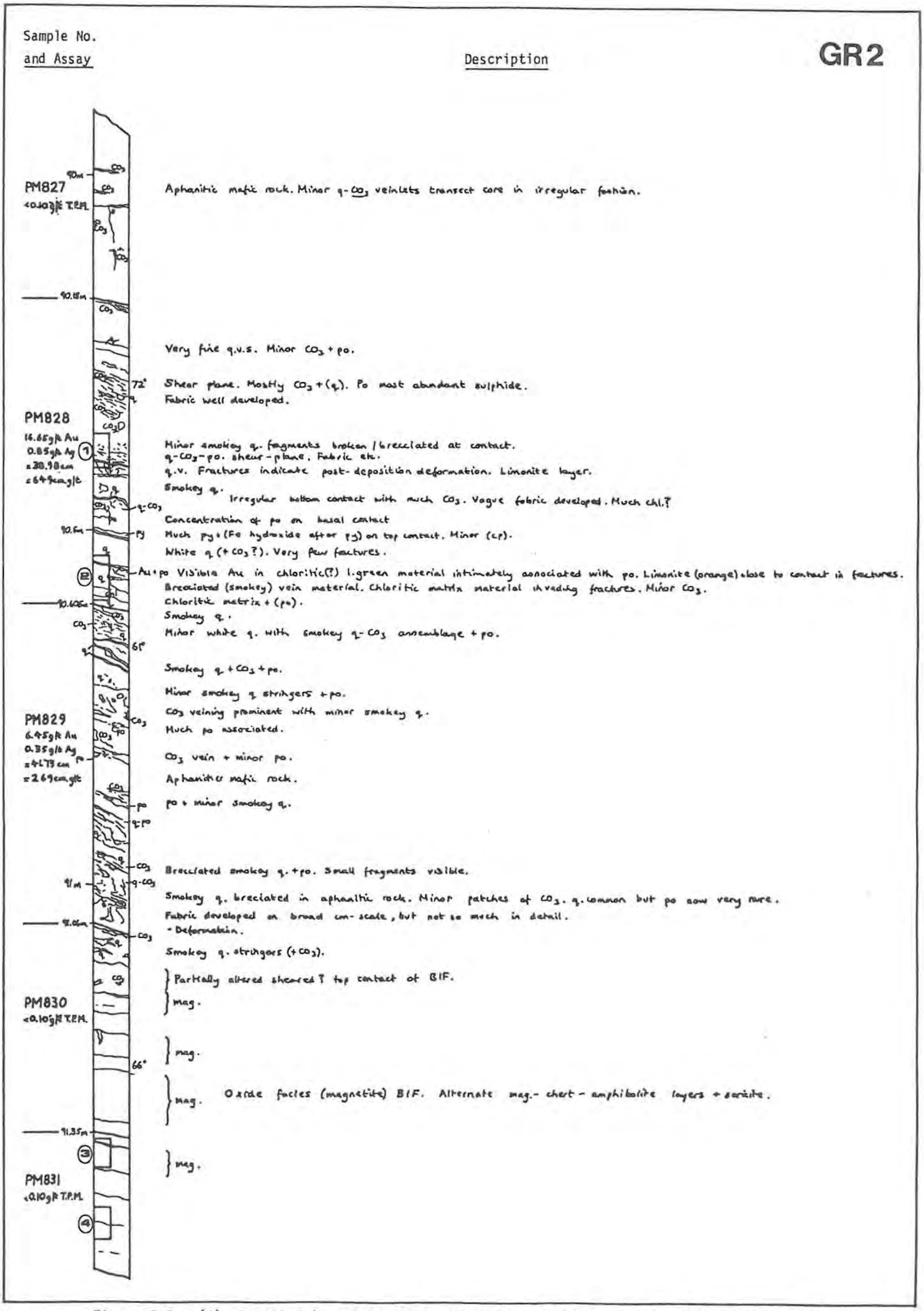


Figure 3.2. (A) Detailed log of Girlie North Reef profile in DDH GR2. Thin-sections are numbered.

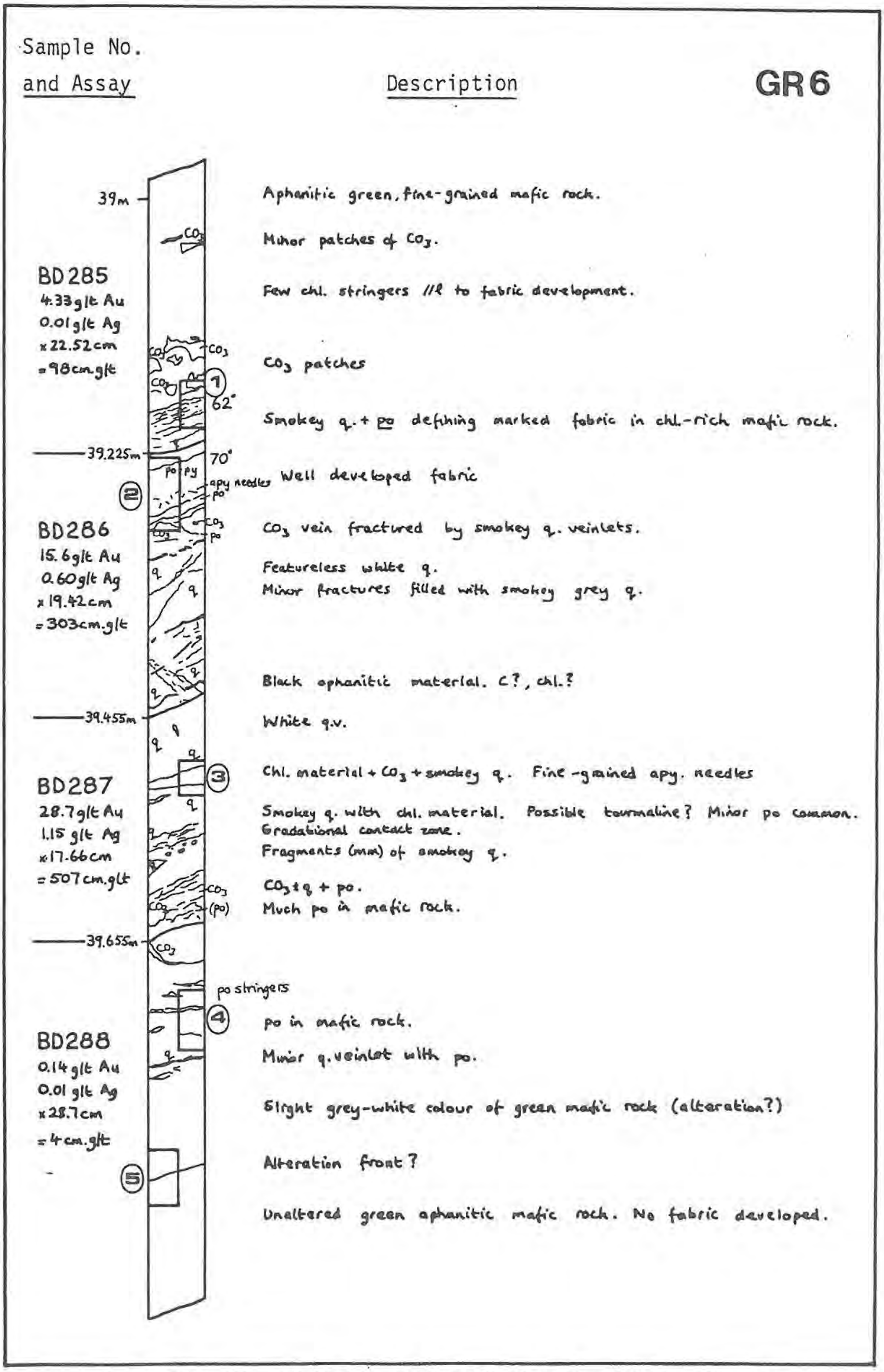


Figure 3.2. (B) Detailed log of Girlie North Reef profile in DDH GR6. Thin-section samples are numbered.

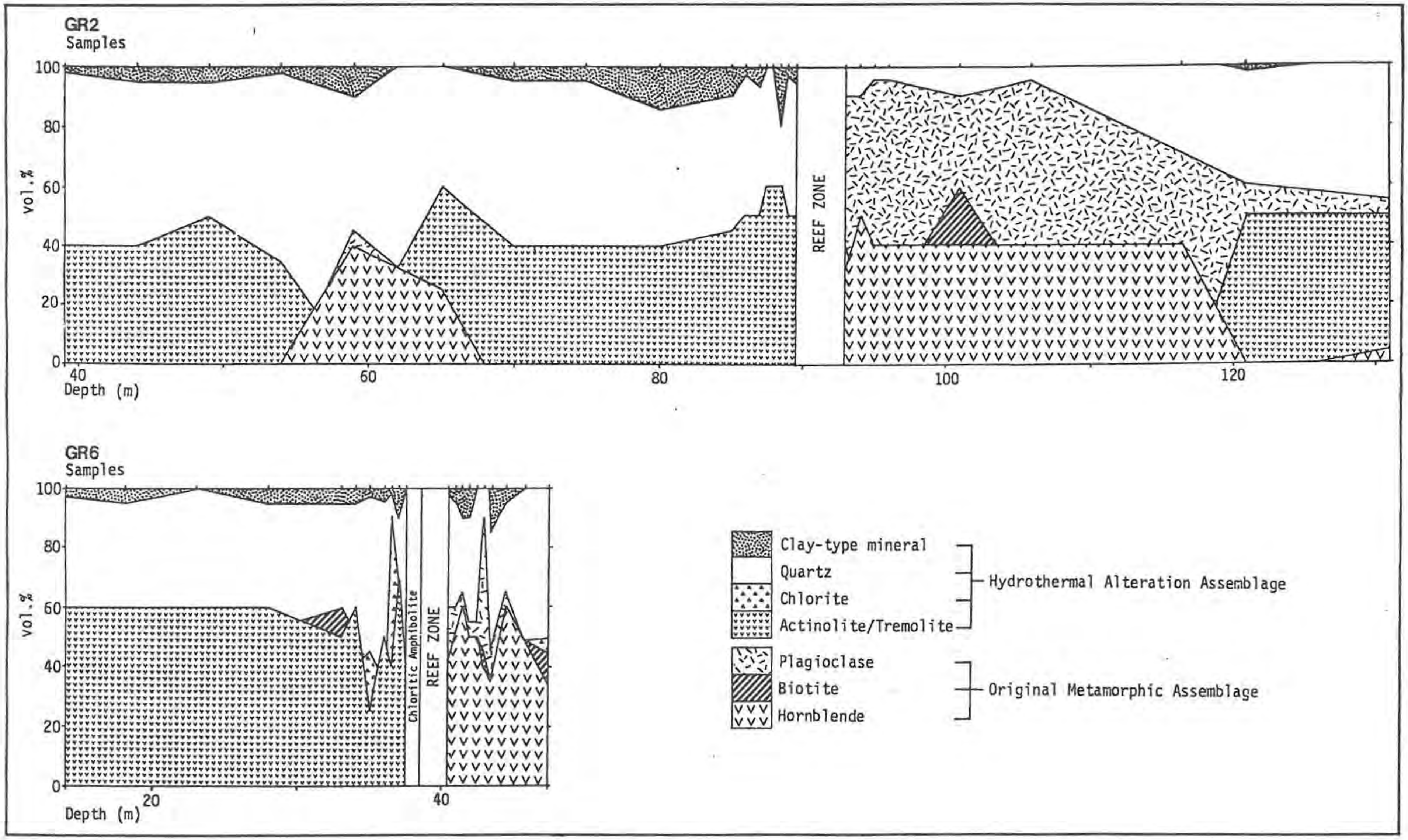


Figure 3.3. Approximate modal mineralogy of Girlie North Reef wall rock in DDH GR2 and GR6, as estimated from thin-section examination. See text for discussion.

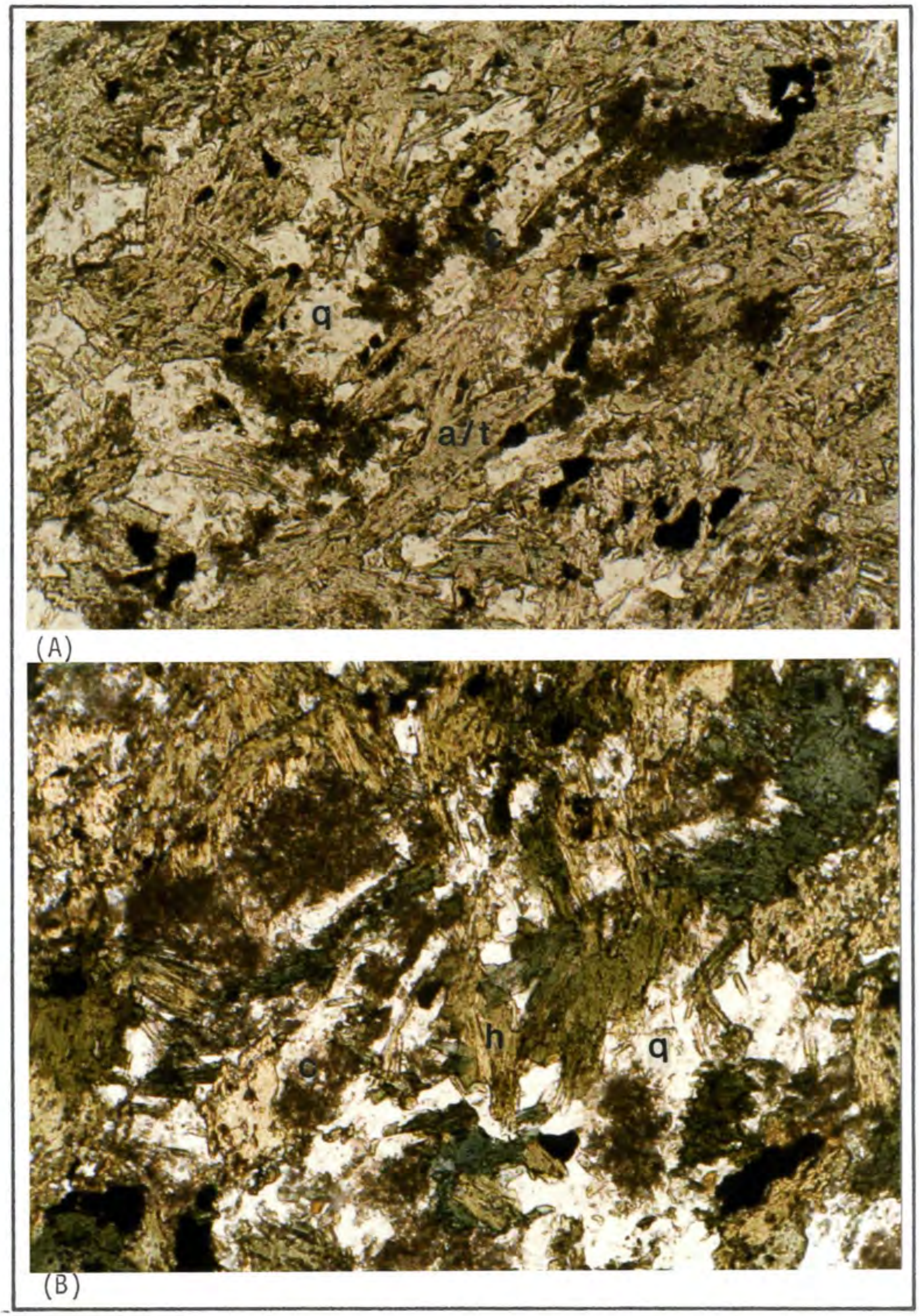


Plate 3.7. Photomicrographs of the hanging wall (A) and footwall (B) assemblages of Girlie North Reef. **(A)** Actinolite/tremolite-quartz-clay. Sample of drillcore from GR2 (85m). **(B)** Hornblend-quartz-clay. Sample of drillcore from GR6 (41.5m). (Plane polarized light, mag.x2.5).

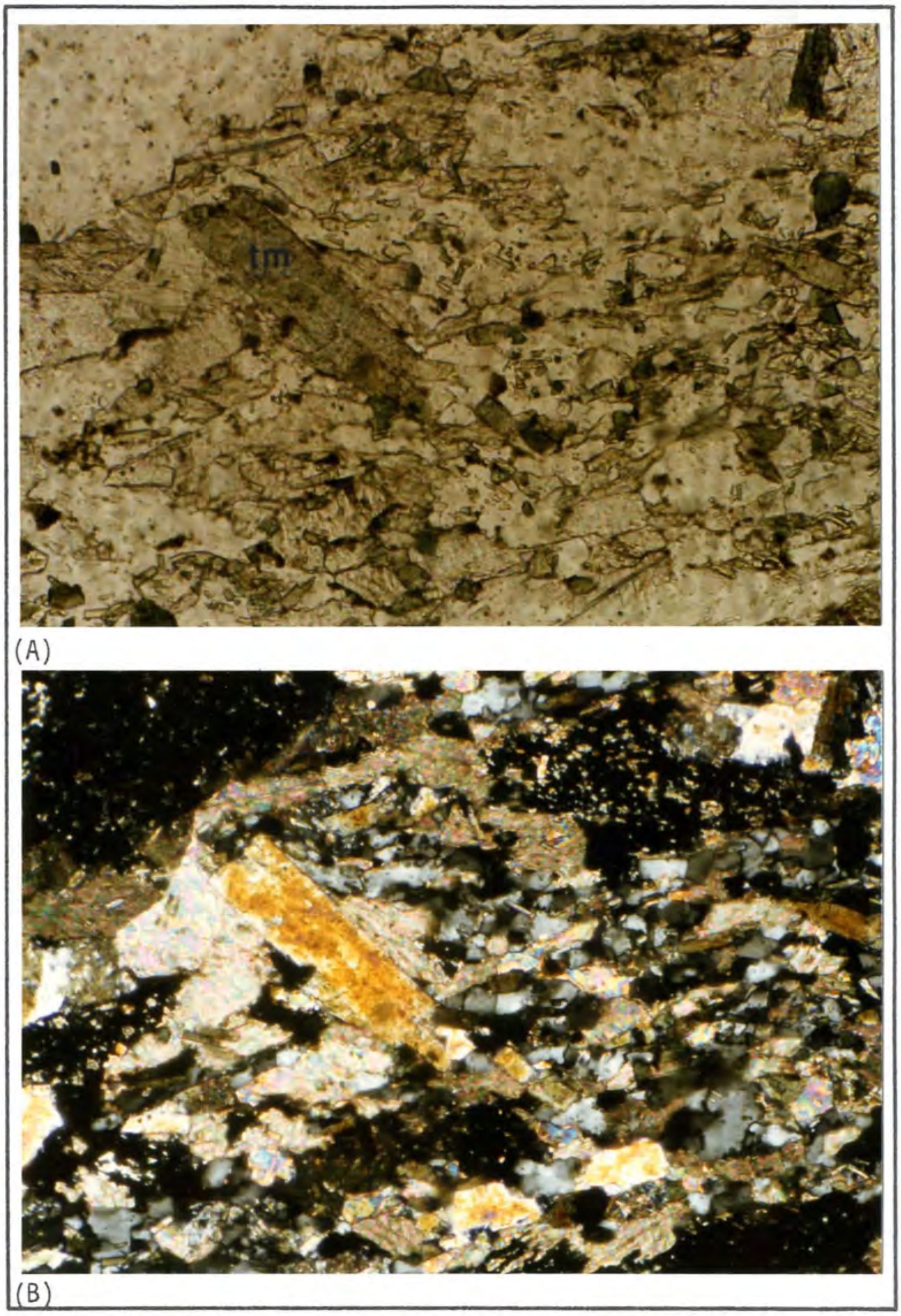


Plate 3.8. Photomicrograph of quartz-carbonate-tourmaline assemblage in thin-section GR2-1 (see Fig. 3.2 A for location). The presence of tourmaline in the Girlie North Reef zone is important because it suggests that the late-stage mineralizing fluids, which deposited Au, arsenopyrite and tourmaline (all cross-cut the general shear zone assemblage), were the same as the late-stage fluids that mineralized the shear zones in the cover sequence. **(A)** Plane polarized light, and **(B)** cross-polarized light, mag.x 10.

3.6 D). The sulphides, which occur as stringers and disseminations throughout the reef zone, were identified as pyrrhotite (predominant) with minor chalcopyrite and pyrite. Arsenopyrite only occurs locally, in close proximity to the white quartz veins, but there appears to be a correlation between the presence of this mineral and high gold values. Based on textural evidence, the following paragenetic sequence is proposed:

1. Quartz I ("smokey grey" variety) ± sericite.
2. Carbonate
3. Chlorite
4. Pyrrhotite ± chalcopyrite ± minor pyrite
5. Quartz II ("white" variety)
6. Tourmaline ± (arsenopyrite + gold)

The last stage of this sequence is inferred because tourmaline was not observed in the same section as arsenopyrite. However, the two minerals overgrew all the others and both occur in the same setting, close to the white quartz veins. It is possible, never-the-less, that both were introduced seperately.

Geochemistry:

Chemical analyses from three drillcore profiles of North Reef are listed in Table 3.2. Unfortunately a complete set of analyses from DDH GR2 is not available and a direct correlation with mineralogy is only possible for GR6.

All of the data, including ratios of K/Na and Rb/Sr were plotted as histograms (eg.Fig. 3.4). It was then possible to detect overall enrichments and depletions in the reef and wall rock by visual inspection. Sulphur, Rb, Au, As, K/Na, and Rb/Sr are enriched in the reef, and Al, Ti, Mg, Na, P, Sr, Zr, and Y are depleted. In two of the profiles (GR3 and GR4) there is also an enrichment in volatiles (which are assumed to be the components registered as "lost on ignition" in the analyses). These are probably H_2O and CO_2, both of which are required to account for the reef and wallrock mineralogy (the presence of clay and carbonate, respectively). The data therefore indicate that the mineralizing fluids were H_2O- and CO_2-bearing and rich in S, K, Rb and Au. This interpretation is in agreement with the work of Phillips (1986) - on the major Kalgoorlie deposit in

Table 3.2 A. Chemical analysis of GR3 drillcore profile.

SAMPLE NO	DEPTH From	DEPTH To	SiO2 (%)	TiO2 (%)	Al2O3 (%)	Fe (%)	Mn (%)	Mg (%)	Ca (%)	Na (%)	K (%)	P2O5 (%)	S (%)	TOTAL (%)	L.O.I. (%)	Ba (ppm)	Rb (ppm)	Sr (ppm)	Zr (ppm)	Y (ppm)	Cu (ppm)	Zn (ppm)	Pb (ppm)	As (ppm)	Au (ppb)	K/Rb	Rb/Sr
AQ 964	77.00	78.00	54.70	1.2	9.80	9.90	.3	8.00	4.00	2.10	.4	.8	0	91.20	8.80	140	4	184	125	35		114	4	16	3	.19	.02
AQ 965	78.00	79.00	52.60	1.1	9.30	10.50	.3	7.10	4.80	2.00	.5	1.1	0	89.30	10.70	152	9	219	118	35	182	118	11	22	3	.25	.04
AQ 966	79.00	80.00	53.40	1.2	9.00	10.00	.3	6.70	5.30	2.10	.5	.8	0	89.30	10.70	152	9	216	122	37	119	109	13	23	3	.24	.04
AQ 967	80.00	81.00	50.30	1.3	10.40	10.80	.3	6.80	4.40	1.80	.5	.8	0	87.40	12.60	153	9	197	137	41	111	129	8	21	3	.28	.05
AQ 968	81.00	82.00	53.60	1.3	9.20	10.40	.3	5.70	4.30	1.70	.6	.6	0	87.70	12.30	238	19	203	128	36	91	120	5	20	5	.35	.09
AQ 969	82.00	83.00	55.80	1.2	9.30	9.80	.3	5.40	5.80	1.70	.5	.9	0	90.70	9.30	139	17	284	126	37	136	103	13	24	5	.29	.06
AQ 970	83.00	84.00	53.90	1.3	10.40	10.30	.3	6.40	4.30	2.20	.5	1	0	90.60	9.40	137	8	105	132	37	99	112	10	23	5	.23	.08
AQ 971	84.00	85.00	51.50	1.3	10.30	10.50	.3	6.30	4.80	2.00	.5	1	0	88.50	11.50	134	8	176	122	38	81	113	-1	22	5	.25	.05
AQ 972	85.00	86.00	54.80	1.2	11.50	9.90	.3	6.10	3.80	2.20	.4	.7	0	90.90	9.10	154	6	90	120	35	79	104	1	20	3	.18	.07
AQ 973	86.00	87.00	58.50	1.3	9.70	10.00	.3	6.00	3.90	2.30	.4	.6	0	93.00	7.00	158	7	100	126	36	76	104	8	14	3	.17	.07
AQ 974	87.00	88.00	64.60	1.1	8.40	9.10	.3	5.60	3.60	2.40	.5	.7	0	96.30	3.70	183	11	59	113	32	81	92	1	27	10	.21	.19
AQ 975	88.00	89.00	53.10	1.3	9.90	9.20	.3	4.80	6.50	2.10	.6	.7	0	88.50	11.50	87	12	99	114	32	79	91	8	49	20	.29	.12
AQ 976	89.00	90.00	55.00	1.3	11.90	10.20	.3	6.10	4.70	2.70	.5	.9	0	93.60	6.40	147	14	63	124	35	97	101	8	29	5	.19	.22
AQ 977	90.00	91.00	59.80	1.2	8.90	9.10	.3	5.20	4.50	2.00	.6	.6	.1	92.30	7.70	157	23	47	115	32	107	102	6	34	5	.30	.49
AQ 978	91.00	92.00	55.30	1.2	8.50	8.50	.2	3.30	5.40	1.20	.8	.9	.1	85.70	14.30	231	21	73	110	33	138	98	11	48	5	.67	.29
AQ 979	92.00	93.00	53.70	1.4	11.60	8.30	.3	4.20	5.90	1.70	.8	.8	.1	89.30	10.70	141	31	80	115	32	82	109	8	40	3	.47	.39
AQ 980	93.00	94.00	52.70	1.3	10.10	9.50	.3	4.90	5.90	1.60	.7	.7	0	87.70	12.30	105	21	157	116	36	170	116	17	42	10	.44	.13
AQ 981	94.00	95.00	56.90	1.2	10.30	10.00	.3	5.40	4.30	2.20	.9	1	0	92.50	7.50	269	31	123	126	36	99	110	12	24	5	.41	.25
AQ 982	95.00	96.00	55.30	1.3	9.60	10.20	.3	5.90	4.70	2.20	.6	1	0	91.40	8.60	197	22	136	123	36	110	171	29	17	3	.27	.16
AQ 983	96.00	97.00	55.30	1.3	8.90	9.20	.3	5.30	5.50	1.90	.7	.3	0	90.60	9.40	139	21	241	118	33	107	135	21	19	10	.37	.09
AQ 984	97.00	98.00	54.10	1.2	11.00	10.20	.3	6.00	5.00	2.10	.6	1	.1	91.60	8.40	167	22	147	125	36	80	157	13	19	3	.29	.15
AQ 985	98.00	99.00	53.70	1.3	9.00	9.70	.3	5.70	4.80	2.20	.6	1.2	0	88.50	11.50	142	14	109	123	37	46	199	6	25	3	.27	.13
BD 251	99.00	99.27	45.10	.9	4.90	15.09	.4	2.10	7.20	.20	.9	.7	.7	78.10	21.90	113	45	35	72	30	195	1209	-23	118	3	4.50	1.29
BD 252	99.27	99.77	54.20	.7	3.50	14.10	.4	2.10	6.60	.10	.5	.6	.6	83.40	16.60	78	20	26	43	20	168	470	-17	149	3	5.00	.77
BD 253	99.77	100.09	57.00	1.3	5.30	8.10	.4	3.20	5.70	.60	1.1	.6	0	86.30	13.70	164	35	95	101	34	16	326	-4	23	3	1.83	.37
BD 254	100.09	100.63	53.80	1.3	8.20	9.70	.4	3.60	4.90	.50	1.1	.5	0	84.10	15.90	200	45	153	111	40	17	279	-1	22	3	1.83	.29
BD 255	100.63	101.00	47.60	1.3	5.90	11.60	.4	3.20	6.90	.20	.8	.7	.1	78.70	21.30	105	37	96	102	37	46	395	-10	17	3	4.00	.39
BD 256	101.00	101.43	51.40	.3	4.50	15.10	.4	2.10	3.40	.10	.9	.7	1.1	80.50	19.50	197	56	27	66	33	262	825	-20	21	3	9.00	2.07
BD 257	101.43	101.68	54.30	.7	2.50	17.50	.4	1.80	2.20	.10	.9	.2	2	82.60	17.40	236	61	9	44	25	428	765	-34	49	250	9.00	6.78
BD 258	101.68	101.97	49.20	.7	2.60	17.30	.4	2.00	2.70	.10	.5	.9	2.7	79.80	20.20	179	31	10	45	21	352	781	-20	27	3	5.00	3.10
BD 259	101.97	102.49	51.10	.7	3.50	18.20	.6	2.00	3.60	.10	.7	.7	.8	82.00	18.00	216	49	20	45	24	159	527	-29	19	3	7.00	2.45
BD 260	102.49	102.77	43.40	.6	1.70	25.10	.7	2.40	3.70	.10	.3	.7	.4	79.10	20.90	174	0	26	28	19	64	578	-41	17	3	3.00	.00
BD 261	102.77	103.10	49.00	.7	1.60	22.60	.6	2.30	3.10	.10	.4	.6	.3	81.30	18.70	223	23	33	33	17	39	427	-38	49	3	4.00	.70
BD 262	103.10	103.36	53.30	.6	-.40	20.80	.6	1.90	4.20	.20	.5	.4	.6	82.70	17.30	192	47	57	14	23	63	314	-36	24	3	2.50	.82
BD 263	103.36	103.33	48.20	.7	1.00	19.90	.6	2.20	4.00	.20	.6	.5	.9	78.80	21.20	226	64	81	31	22	114	274	-34	163	250	3.00	.79
BD 264	103.83	104.29	72.80	.6	.60	10.50	.4	1.30	3.40	.01	.5	.2	1.1	91.41	8.59	110	17	105	21	11	125	141	-8	2668	1570	50.00	.16
BD 265	104.29	104.49	44.50	1	4.60	17.00	.4	2.30	5.40	.20	.7	.9	.9	77.90	22.10	147	38	103	71	25	207	277	-21	169	3	3.50	.37
BD 266	104.49	104.76	49.00	1.5	8.10	13.40	.3	2.30	4.00	1.40	1.1	.5	.1	81.70	18.30	341	74	130	146	43	47	304	-15	31	3	.79	.57
AQ 986	104.76	106.00	46.80	1.4	9.30	12.20	.4	3.00	5.00	1.50	1.2	1.1	.1	81.90	18.10	247	67	222	149	40	123	255	9	34	3	.80	.30
AQ 987	106.00	107.00	51.30	1.4	10.40	11.20	.4	3.50	5.70	2.60	.7	1	.3	88.50	11.50	167	31	286	149	35	145	151	18	23	10	.27	.11
AQ 988	107.00	108.00	55.00	1.4	11.80	12.29	.4	3.90	4.60	3.10	.6	1.1	.2	94.30	5.70	195	15	301	165	37	137	168	10	26	3	.19	.05
AQ 989	108.00	109.00	52.40	1.3	12.50	12.20	.3	4.30	4.00	2.60	.7	.7	.1	91.10	8.90	204	14	321	167	42	114	218	8	31	3	.27	.04
AQ 990	109.00	110.00	55.80	1.3	9.50	12.40	.4	3.80	5.00	2.60	.7	.9	0	92.40	7.60	186	16	321	157	35	109	180	16	26	3	.27	.05
AQ 991	119.00	111.00	43.70	1.4	9.30	9.00	.3	2.30	11.90	1.70	.9	.9	.7	82.10	17.90	24	30	230	109	30	309	122	34	25	3	.53	.13
AQ 992	111.00	112.00	51.40	1.4	11.30	10.60	.3	3.30	5.90	2.50	.8	1.1	.1	88.80	11.20	240	28	299	153	37	105	148	1	16	3	.32	.09
AQ 993	112.00	113.00	51.00	1.3	8.90	12.40	.3	3.50	5.60	2.50	.6	.9	0	87.00	13.00	236	15	356	161	38	124	182	17	27	5	.24	.04
AQ 994	113.00	114.00	51.00	1.4	9.00	12.00	.4	3.30	7.10	2.30	.7	.7	0	87.90	12.10	160	15	433	146	37	156	168	19	28	5	.30	.03
AQ 995	114.00	115.00	54.10	1.3	9.10	12.00	.4	3.60	5.10	2.60	.6	.8	0	89.60	10.40	243	17	306	146	34	154	161	17	19	3	.23	.06
AQ 996	115.00	116.00	54.70	1.4	9.60	12.70	.3	3.80	4.90	2.80	.7	1	0	91.90	8.10	230	11	308	157	36	142	182	17	15	3	.25	.04
AQ 997	116.00	117.00	55.00	1.4	9.40	12.30	.3	3.70	5.10	2.50	.6	.9	0	91.20	8.80	286	15	267	157	35	142	176	11	38	3	.24	.06
AQ 998	117.00	118.00	50.60	1.3	9.70	12.10	.4	3.40	5.00	2.00	.6	1.1	0	86.20	13.80	227	14	290	162	36	171	182	1	43	3	.30	.05
AQ 999	118.00	119.00	53.30	1.4	9.50	11.60	.3	3.30	5.90	1.80	.6	.9	.1	88.70	11.30	184	10	341	156	38	145	166	-2	45	10	.33	.03
AQ 1000	119.00	120.00	51.00	1.4	9.00	12.30	.4	3.50	6.00	2.60	.6	.7	0	87.50	12.50	190	14	252	150	35	158	176	10	43	10	.23	.06
AQ 1001	120.00	121.00	52.20	1.3	11.30	12.40	.3	3.60	5.40	2.80	.7	.9	.1	91.00	9.00	218	20	226	154	34	171	155	16	42	3	.25	.09
AQ 1002	121.00	122.00	55.00	1.5	10.50	13.00	.3	3.70	4.50	3.20	.6	.9	0	93.20	6.80	180	10	197	177	40	106	166	15	26	5	.19	.05
AQ 1003	122.00	123.00	56.40	1.1	9.30	12.60	.3	3.40	4.50	2.90	.6	1.1	.1	92.30	7.70	191	17	264	203	43	176	149	11	36	5	.21	.06
AQ 1004	123.00	124.00	54.80	1.5	8.90	12.40	.3	3.50	5.20	2.80	.6	1	.1	91.10	8.90	201	13	280	169	37	161	159	8	50	5	.21	.05
	E.O.H.																										

Method of Analysis : By X-ray fluorescence of standard 36 element batch (Anglo American Research Laboratories, Crown Mines, Johannesburg).

Note : Because the samples were analyzed in pressed powder briquettes, and in part by using an energy dispersive spectrometer, the results for the major elements (marked %) are relatively less accurate and less precise than the values given for the trace elements.

Table 3.2 B. Chemical analysis of GR4 drillcore profile.

SAMPLE NO	DEPTH From	DEPTH To	SiO2 (%)	TiO2 (%)	Al2O3 (%)	Fe (%)	Mn (%)	Mg (%)	Ca (%)	Na (%)	K (%)	P2O5 (%)	S (%)	TOTAL (%)	L.O.I. (%)	Ba (ppm)	Rb (ppm)	Sr (ppm)	Zr (ppm)	Y (ppm)	Cu (ppm)	Zn (ppm)	Pb (ppm)	As (ppm)	Au (ppb)	K/Na	Rb/Sr
AQ 763	16.00	17.00	55.80	1.3	10.30	10.10	.4	5.50	5.90	2.20	.5	.70	.00	92.70	7.30	172	16	202	121	35	99	112	5	20	3	.23	.08
AQ 764	17.00	18.00	55.80	1.4	10.20	10.10	.3	5.30	6.30	2.70	.6	.70	.00	93.40	6.60	169	21	139	118	35	137	109	2	14	3	.22	.15
AQ 765	18.00	19.00	54.50	1.3	13.20	10.50	.3	5.80	5.70	3.00	.5	1.00	.00	95.80	4.20	143	15	142	130	36	127	127	9	15	5	.17	.11
AQ 766	19.00	20.00	56.70	1.4	12.60	10.80	.4	5.60	5.30	3.30	.5	.90	.00	97.50	2.50	137	14	100	141	38	85	111	9	9	3	.15	.14
AQ 767	20.00	21.00	55.70	1.3	11.40	11.10	.4	5.40	5.60	3.10	.6	1.20	.00	95.80	4.20	166	20	112	132	36	84	116	4	13	3	.19	.18
AQ 768	21.00	22.00	53.30	1.4	9.50	10.00	.3	4.80	8.00	2.10	.5	1.00	.10	91.00	9.00	30	14	165	121	39	158	106	9	15	5	.24	.08
AQ 769	22.00	23.00	52.90	1.3	9.90	10.10	.3	5.10	5.80	2.10	.6	.60	.00	88.70	11.30	153	19	185	125	34	67	128	12	14	3	.29	.10
AQ 770	23.00	24.00	58.30	1.3	10.60	9.80	.3	5.00	5.90	2.00	.5	.90	.10	94.70	5.30	142	13	152	127	35	107	127	7	14	3	.25	.09
AQ 771	24.00	25.00	56.50	1.2	1.80	1.00	.3	5.40	5.40	2.30	.5	.70	.00	75.10	24.90	158	12	212	129	36	125	130	6	15	3	.22	.06
AQ 772	25.00	26.00	55.90	1.3	11.40	9.70	.3	4.90	6.00	1.90	.6	.80	.00	93.00	7.00	166	18	248	123	34	92	119	7	15	3	.32	.07
AQ 773	26.00	27.00	55.70	1.3	10.70	9.50	.3	5.50	5.40	1.90	.7	.60	.00	91.60	8.40	197	21	217	132	35	124	121	8	17	3	.37	.10
AQ 774	27.00	28.00	56.00	1.4	9.60	9.80	.3	5.30	5.80	1.80	.6	.70	.00	91.30	8.70	176	20	228	140	40	159	119	4	21	3	.33	.09
AQ 775	28.00	29.00	54.50	1.4	11.40	.80	.3	5.00	7.10	1.80	.5	.80	.10	83.70	16.30	13	11	279	116	39	136	109	15	18	5	.28	.04
AQ 776	29.00	30.00	55.30	1.2	10.80	9.00	.3	5.90	6.80	2.40	.4	.90	.10	92.80	7.20	77	8	179	122	34	113	115	9	15	3	.17	.04
AQ 777	30.00	31.00	55.50	1.2	9.70	9.70	.3	5.50	6.30	2.40	.5	1.10	.00	92.20	7.80	89	11	213	124	35	110	113	9	18	3	.21	.05
AQ 778	31.00	32.00	58.00	1.3	9.80	9.30	.3	5.90	5.40	2.50	.5	.80	.00	93.80	6.20	184	17	261	127	36	101	122	9	13	3	.20	.06
AQ 779	32.00	33.00	57.50	1.2	10.90	9.30	.3	5.70	5.60	2.60	.6	.80	.10	94.60	5.40	154	12	261	127	36	116	125	10	17	3	.23	.05
AQ 780	33.00	34.00	56.20	1.3	10.80	9.00	.3	5.60	5.90	2.40	.6	1.10	.00	93.20	6.80	149	13	244	129	35	110	115	4	15	3	.25	.05
AQ 781	34.00	35.00	54.70	1.3	13.10	8.90	.3	5.80	5.60	2.50	.6	.90	.00	93.70	6.30	148	14	261	126	39	79	118	13	22	3	.24	.05
AQ 782	35.00	36.00	54.30	1.1	9.80	11.10	.3	7.50	4.40	3.30	.4	.90	.00	93.60	6.40	151	7	118	126	35	76	135	5	19	3	.12	.06
AQ 783	36.00	37.00	54.70	1.2	10.30	10.10	.3	6.30	5.10	2.60	.4	.80	.40	92.20	7.80	100	10	124	113	33	319	141	5	27	3	.15	.08
AQ 784	37.00	37.88	54.20	1.3	10.20	10.10	.3	5.80	5.60	2.80	.5	1.00	.10	91.90	8.10	141	11	166	122	34	103	148	9	24	3	.18	.07
PM 839	37.88	38.30	22.60	.9	4.90	10.70	.3	3.10	7.20	1.10	.6	.40	.20	52.00	48.00	41	12	132	125	39	76	16	8	35	3	.55	.09
PM 840	38.30	38.68	35.60	.5	2.40	5.70	.2	.70	5.10	.20	1.5	.20	.90	53.00	47.00	404	48	45	38	15	126	60	15	2562	6150	7.50	1.07
PM 841	38.68	39.03	25.00	.5	1.60	11.70	.3	.90	7.90	.20	.8	.20	3.90	53.00	47.00	36	27	71	52	25	420	64	1	2681	9600	4.00	.38
PM 842	39.03	39.32	25.00	.6	3.30	12.40	.3	2.10	5.20	.80	.6	.30	2.00	52.60	47.40	126	31	134	91	27	423	149	7	29	100	.75	.23
PM 844	39.32	39.75	23.70	.9	6.00	11.10	.3	3.10	5.10	2.30	.9	.40	.20	54.00	46.00	145	64	9	157	47	106	171	3	37	3	.39	7.11
AQ 785	40.22	41.00	54.80	1.4	12.30	12.60	.4	3.60	5.10	3.50	.5	1.00	.10	95.30	4.70	152	12	125	161	38	169	155	7	27	3	.14	.10
AQ 786	41.00	42.00	57.00	1.4	10.60	12.60	.4	3.60	5.30	3.40	.6	1.00	.10	96.00	4.00	162	17	118	166	39	192	150	10	35	3	.18	.14
AQ 787	42.00	43.00	55.50	1.4	9.00	11.00	.3	2.90	7.20	2.30	.5	.80	.00	90.90	9.10	91	13	170	148	34	117	135	4	25	5	.22	.08
AQ 788	43.00	44.00	5.10	1.4	10.70	12.40	.4	3.40	5.20	3.40	.5	1.00	.10	43.60	56.40	153	8	165	160	38	200	145	9	29	3	.15	.05
AQ 789	44.00	45.00	59.70	1.3	9.60	10.20	.4	3.20	5.90	2.40	.5	.70	.10	94.00	6.00	102	8	154	140	33	131	117	10	18	3	.21	.05
AQ 790	45.00	46.00	56.10	1.4	10.80	11.80	.4	3.40	4.60	2.40	.6	.80	.10	92.40	7.60	182	12	88	149	33	95	131	9	18	5	.25	.14
AQ 791	46.00	47.00	53.30	1.4	9.20	10.50	.3	3.10	6.00	2.40	.5	.90	.00	87.60	12.40	154	12	89	146	35	160	120	8	19	5	.21	.13
AQ 792	47.00	48.00	53.50	1.4	8.90	11.90	.3	4.00	5.70	2.00	.5	.60	.00	88.80	11.20	137	15	185	147	38	172	149	14	23	3	.25	.08
AQ 793	48.00	47.00	54.00	1.3	10.60	10.90	.3	5.00	7.00	2.50	.5	.90	.10	93.10	6.90	192	16	296	112	31	157	112	6	17	3	.20	.05
AQ 794	49.00	50.00	50.60	1.4	10.70	10.30	.3	4.30	7.60	1.80	.7	.90	.00	88.60	11.40	128	25	165	108	30	148	114	8	21	3	.39	.15
AQ 795	50.00	51.00	53.40	1.3	11.20	10.00	.4	4.90	6.70	2.10	.6	.80	.00	91.40	8.60	112	19	172	108	32	135	110	7	24	3	.29	.11
AQ 796	51.00	52.00	53.30	1.5	9.30	11.10	.3	5.30	6.40	2.20	.6	.60	.00	90.60	9.40	142	16	219	110	32	158	111	7	20	3	.27	.07
AQ 797	52.00	53.00	49.40	1.4	10.10	10.90	.3	4.90	6.60	1.60	.7	.70	.00	86.60	13.40	144	22	194	108	30	123	114	9	33	3	.44	.11
AQ 798	53.00	54.00	54.20	1.3	10.40	11.10	.3	5.70	6.10	2.90	.6	.80	.00	93.40	6.60	170	16	192	108	35	113	111	-1	16	3	.21	.08
AQ 799	54.00	54.28	55.50	1.2	11.60	10.80	.3	5.80	6.20	3.10	.5	1.00	.00	96.00	4.00	100	14	195	112	32	219	107	-4	19	3	.16	.07
		E.O.H.																									

Method of Analysis : By X-ray fluorescence of standard 36 element batch (Anglo American Research Laboratories, Crown Mines, Johannesburg).

Note : Because the samples were analyzed in pressed powder briquettes, and in part by using an energy dispersive spectrometer, the results for the major elements (marked %) are relatively less accurate and less precise than the values given for the trace elements.

Table 3.2 C. Chemical analysis of GR6 drillcore profile.

SAMPLE NO	DEPTH From	DEPTH To	SiO2 (%)	TiO2 (%)	Al2O3 (%)	Fe (%)	Mn (%)	Mg (%)	Ca (%)	Na (%)	K (%)	P2O5 (%)	S (%)	TOTAL (%)	L.O.I. (%)	Ba (ppm)	Rb (ppm)	Sr (ppm)	Zr (ppm)	Y (ppm)	Cu (ppm)	Zn (ppm)	Pb (ppm)	As (ppm)	Au (ppb)	K/Na	Rb/Sr
AQ 1043	17.00	18.00	51.70	1.30	11.10	8.30	.30	2.70	6.60	1.00	1.30	.80	0	85.10	14.90	171	58	103	116	32	119	105	5	49	3	1.30	.56
AQ 1044	18.00	19.00	50.90	1.40	10.10	9.40	.30	4.40	7.00	1.50	.50	.60	.1	86.20	13.80	51	8	199	117	35	79	108	5	39	5	.33	.04
AQ 1045	19.00	20.00	53.90	1.20	10.20	9.90	.30	5.20	6.00	2.00	.50	.60	0	89.80	10.20	118	9	207	122	37	103	116	5	25	3	.25	.04
AQ 1046	20.00	21.00	50.90	1.40	9.30	10.00	.30	5.40	6.20	1.70	.40	.70	0	86.30	13.70	62	5	241	128	38	114	117	6	25	3	.24	.02
AQ 1047	21.00	22.00	54.40	1.40	11.40	10.30	.30	5.60	5.50	2.40	.40	.90	.1	92.70	7.30	146	11	182	125	37	101	125	.01	19	3	.17	.06
AQ 1048	22.00	23.00	54.60	1.30	11.60	10.10	.30	5.40	6.10	2.60	.60	1.20	0	93.30	6.20	87	11	172	125	36	99	121	7	17	5	.23	.06
AQ 1049	23.00	24.00	54.50	1.30	9.60	10.40	.30	5.50	7.00	2.80	.40	.90	0	92.70	7.30	48	6	164	127	38	94	116	-7	17	3	.14	.04
AQ 1050	24.00	25.00	59.60	1.40	11.00	9.50	3.00	4.60	7.00	2.80	.40	.50	.1	100.20	-.20	41	8	250	119	34	115	103	6	17	5	.14	.03
AQ 1051	25.00	26.00	56.70	1.30	10.10	9.20	.30	4.80	6.30	2.10	.50	.70	0	92.20	7.80	152	8	216	134	38	111	120	12	15	3	.24	.04
AQ 1052	26.00	27.00	55.30	1.50	8.50	9.50	.30	3.90	8.30	1.60	.50	.80	.2	88.40	11.50	22	12	161	142	39	142	94	1	15	3	.31	.07
AQ 1053	27.00	28.00	54.80	1.40	11.70	9.40	.30	4.90	6.30	1.90	.60	1.00	.1	92.40	7.60	137	12	251	132	37	146	112	5	19	5	.32	.05
AQ 1054	28.00	29.00	50.60	1.20	11.00	9.50	.30	5.60	5.90	1.70	.50	.90	0	85.70	13.30	126	9	199	126	36	124	118	8	11	3	.29	.05
AQ 1055	29.00	30.00	52.40	1.30	10.80	9.40	.30	5.80	6.20	1.90	.50	.50	0	89.40	10.60	131	11	203	121	35	74	107	8	13	3	.26	.05
AQ 1056	30.00	31.00	52.50	1.30	11.10	9.40	.30	6.00	5.20	1.30	.50	.60	.1	88.20	11.80	113	10	177	127	34	135	115	4	14	3	.28	.06
AQ 1057	31.00	32.00	55.30	1.30	10.50	9.30	.30	5.80	5.70	1.90	.50	.20	0	91.40	8.60	100	11	218	127	36	71	109	9	13	3	.26	.05
AQ 1058	32.00	33.00	53.40	1.30	10.00	9.80	.30	6.20	4.80	1.80	.50	.90	0	89.00	11.00	120	11	185	131	36	73	119	5	12	10	.28	.06
AQ 1059	33.00	34.00	50.90	1.30	8.10	9.70	.30	4.90	7.20	1.50	.40	.60	0	84.90	15.10	51	16	267	132	38	92	119	11	26	3	.27	.06
AQ 1060	34.00	35.00	54.80	1.40	11.60	9.60	.30	5.80	5.70	2.10	.60	.90	0	92.80	7.20	112	19	234	128	38	106	120	12	17	3	.29	.08
AQ 1061	35.00	36.00	53.70	1.30	13.30	9.40	.30	6.20	5.00	2.30	.50	.80	0	92.30	7.20	123	4	217	123	36	104	130	4	25	3	.22	.02
AQ 1062	36.00	37.00	56.30	1.20	10.90	9.40	.30	6.30	4.60	2.80	.60	1.20	0	93.60	6.40	144	14	165	125	36	97	142	10	16	3	.21	.05
AQ 1063	37.00	38.00	50.10	1.40	10.10	10.30	.40	5.10	7.00	1.90	.50	.80	.1	87.70	12.30	35	10	161	114	40	111	148	7	31	3	.26	.06
AQ 1064	38.00	38.51	51.70	1.10	10.20	10.50	.30	4.70	3.40	2.10	1.30	.80	0	86.10	13.90	229	130	58	124	32	51	180	5	34	3	.62	2.24
BD 284	38.51	38.98	57.20	1.30	9.70	10.30	.30	4.30	4.60	2.20	.70	.50	0	91.10	8.90	123	44	74	116	37	50	158	-5	105	3	.32	.59
BD 285	38.98	39.24	56.00	1.20	8.80	8.90	.30	1.60	7.10	.40	1.30	.50	.7	86.80	13.20	243	46	65	93	44	85	113	-1	62	4330	3.25	.71
BD 286	39.24	39.46	97.10	.40	-1.00	5.40	.20	.60	2.60	.10	.50	.01	1.5	109.41	-9.41	74	9	18	15	6	110	33	30	5792	15600	5.00	.50
BD 287	39.46	39.66	84.40	.60	.50	5.00	.30	.40	6.10	.10	1.00	.20	1.1	99.70	.30	156	24	53	37	18	95	43	6	13123	28700	10.00	.45
BD 288	39.66	39.98	55.10	1.50	10.90	9.00	.30	1.20	3.70	.60	1.90	.50	.5	85.20	14.80	756	61	67	169	54	128	147	1	237	140	3.17	.91
AQ 1065	39.98	41.00	49.70	1.60	12.60	10.80	.40	3.20	7.10	2.60	.50	.80	.2	89.50	10.50	63	13	154	170	44	262	143	11	33	20	.19	.08
AQ 1066	41.00	42.00	54.00	1.40	11.10	12.10	.40	3.50	5.50	2.60	.70	.90	0	92.20	7.80	170	16	160	160	36	161	158	12	33	3	.27	.10
AQ 1067	42.00	43.00	53.70	1.30	10.30	12.10	.30	3.30	5.70	2.50	.60	.80	0	90.60	9.40	162	11	193	161	37	114	164	13	24	3	.24	.06
AQ 1068	43.00	44.00	54.90	1.40	7.80	11.50	.30	2.90	6.20	2.30	.50	.60	0	88.40	11.60	126	11	214	152	35	129	141	10	20	3	.22	.05
AQ 1069	44.00	45.00	54.40	1.40	11.10	12.50	.30	3.60	5.20	2.80	.70	1.20	0	93.20	6.80	197	12	154	165	39	151	151	12	19	3	.25	.08
AQ 1070	45.00	46.00	52.70	1.50	12.20	13.00	.40	3.70	4.70	3.00	.60	.90	0	92.70	7.30	222	12	115	173	38	138	156	8	24	25	.20	.10
AQ 1071	46.00	46.50	57.70	1.30	9.20	10.70	.40	3.00	5.90	2.20	.60	1.00	.4	92.40	7.60	177	19	113	131	36	257	119	-4	20	3	.27	.17
		E.O.H.																									

Method of Analysis : By X-ray fluorescence of standard 36 element batch (Anglo American Research Laboratories, Crown Mines, Johannesburg).

Note : Because the samples were analyzed in pressed powder briquettes, and in part by using an energy dispersive spectrometer, the results for the major elements (marked %) are relatively less accurate and less precise than the values given for the trace elements.

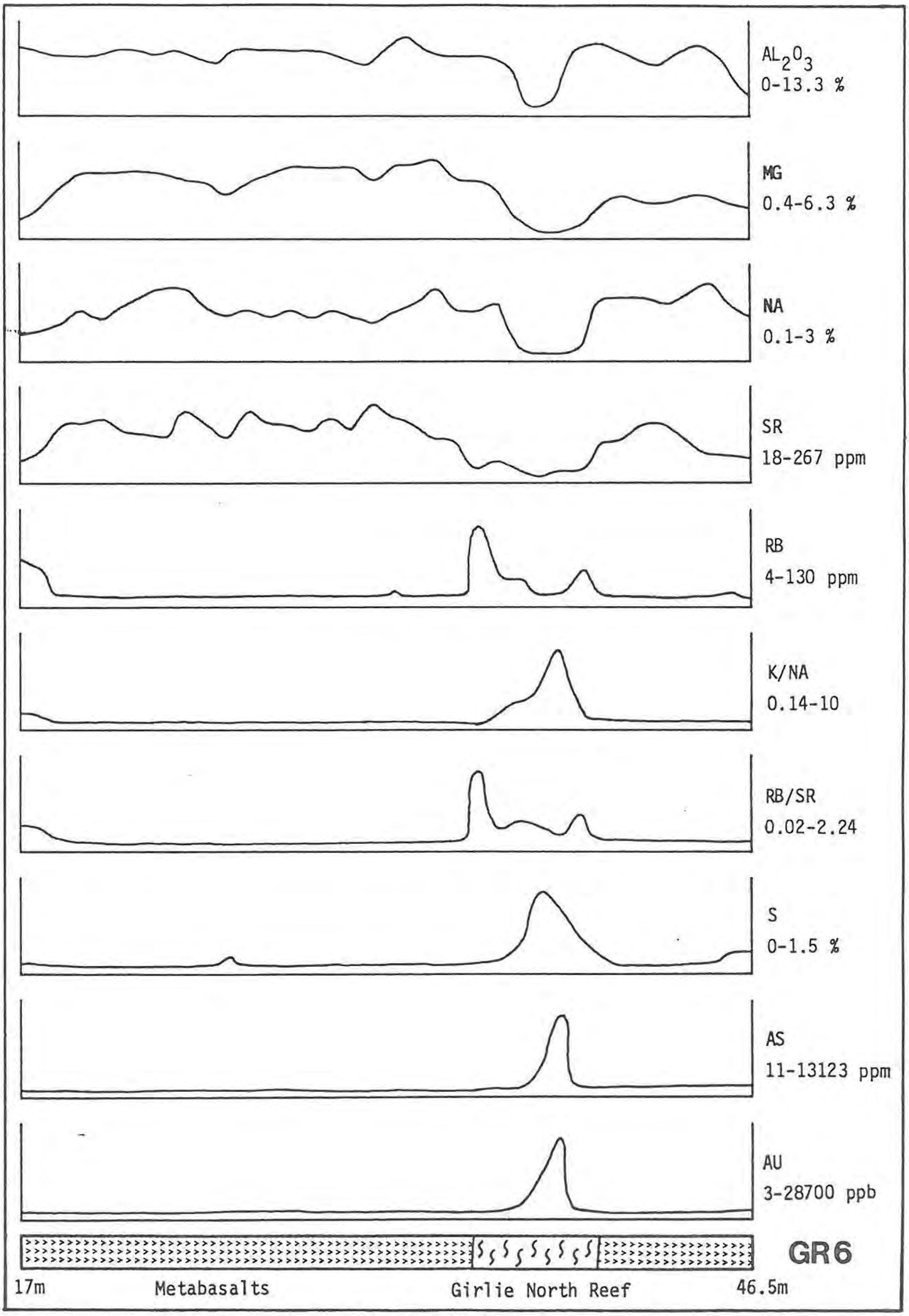


Figure 3.4. Geochemical profile of Girlie North Reef and wall rock in DDH GR6. (Selected elements.)(Not to scale)

Western Australia, and the work of Robert and Brown (1986)-on the Sigma deposit in the Abitibi greenstone belt. The elements depleted in the reef zone are thought to reflect the breakdown of albite (Al, Na and Sr), amphibole (Mg), rutile (Ti), apatite (P and Sr), and zircon (Zr and Y) - even though the latter three minerals were not actually identified in the thin-sections examined (a more thorough examination and more samples would probably reveal their presence).

For the wall rocks there is a definite enrichment of Fe and depletion of Mg in the footwall of the reef (measured relative to the hanging wall), but all the other elements show no variation in concentration throughout the sampled profiles. From these data, it is concluded that there were no gains or losses of any elements with respect to the original component system (the variations in Fe and Mg are interpreted as due to differences in the original rock composition) and, therefore, that the mineralogical changes in wall rock composition were accomplished by isochemical reactions. This conclusion differs markedly from the results of Phillips (1986) and Robert and Brown (1986), who determined, respectively, that there was addition of S, K, Rb, and CO_2 to the wall rocks at Kalgoorlie, and addition of Ca, Na, S, P, B, Au, and CO_2 to, and losses of Mg, Fe, Al, and H_2O from, the wall rocks at Sigma.

The chemical differences between reef and wall rock were also assessed using the scheme of Robert and Brown (1986). In this scheme, the components of the Ca- K- Na- Fe+Mg system are considered as representing calcite, muscovite/sericite, albite, and chlorite, respectively, and they are plotted on the apices of an unfolded tetrahedron. In this particular study the Fe+Mg component must also represent amphibole, and at least some of the Ca component Ca-bearing plagioclase and epidote. The chemical data were assigned to one of three groups. The "reef" group comprises samples from the shear zone with anomalous gold concentrations, the "reef margin" group comprises samples from the shear zone with background gold concentrations, and the wall rock group comprises samples from outside the shear zone altogether. A plot of the GR6 data is presented in Figure 3.5, together with a schematic diagram illustrating the general trends obtained from all three data sets (GR3, GR4 and GR6). The trends are interpreted as follows:

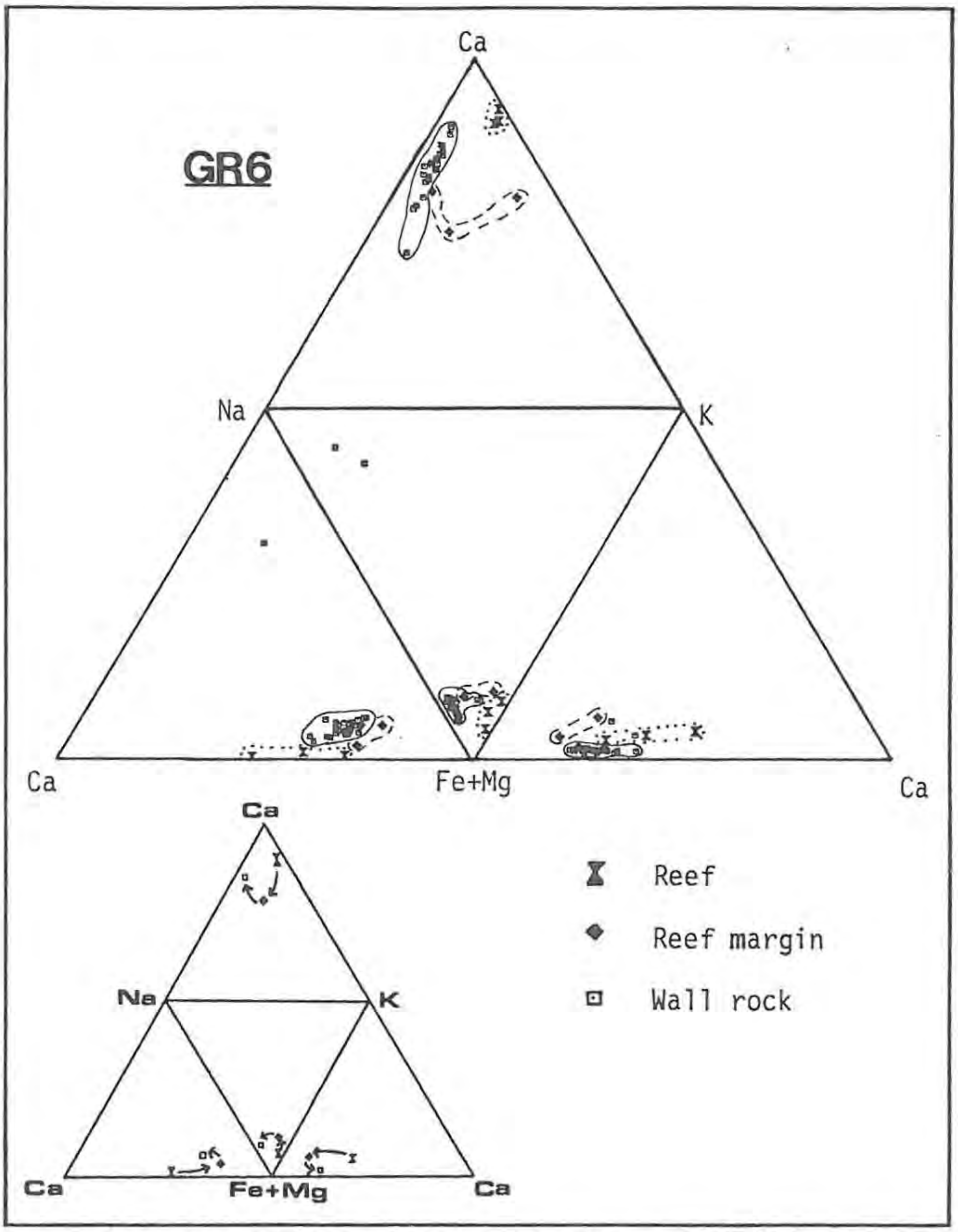


Figure 3.5. Relative chemical variation between reef and wall rock in the Ca-K-Na-(Fe+Mg) system. For clarity, the data are presented from GR6 and the general trends, as defined in GR3, GR4 and GR6, are shown on a seperate plot. The arrows indicate the approximate path from reef to chemically unaltered wall rock.

1. Potassium and Ca are both relatively enriched in the "reef" samples, which reflects the introduction of K in the mineralizing fluid and the development of calcite from Ca liberated during the breakdown of plagioclase.
2. The transition to "reef margin" shows a decrease in the concentration

of Ca, with a consequent increase in the relative concentrations of Na and Fe+Mg. This is thought to reflect the removal of some Ca liberated from plagioclase within the shear zone (the GR3 reef profile shows a mild depletion in C) even though most appears to have been redeposited as calcite.

3. The transition to wall rock shows a decrease in the concentration of K, with a consequent increase in the relative concentrations of Ca, Na and Fe+Mg. This is indicated as an abrupt change by the tight grouping of wall rock samples on the plot (if it had been gradual the wall rock samples would have plotted as a dispersed group trending towards the "reef margin" sample). The drop in concentration indicates that K did not penetrate into the wall rock. Ca in this sample population is thought to represent plagioclase (with Na), calcite and epidote, and Fe+Mg represents amphibole.

Wall rock alteration:

Having recognized the mineralogical effects of wall rock alteration (Fig. 3.3) and having established its isochemical nature, the following questions still have to be answered : What caused the alteration and what process was involved?

From Figure 3.3 the finite wall rock alteration reaction can be written qualatatively as :

Hornblende + plagioclase $\rightarrow$ Actinolite/tremolite + quartz + clay.

The process which converts plagioclase to quartz + clay is hydrogen ion metasomatism. The following reactions can be written (Pirajno, 1985) :

$$\underset{\text{Albite}}{1.5\ NaAlSi_3O_8} + H^+ \rightarrow \underset{\text{Paragonite}}{0.5\ NaAl_3Si_3O_{10}(OH)_2} + 3\ SiO_2 + Na^+$$

$$\underset{\text{Paragonite}}{NaAl_3Si_3O_{10}(OH)_2} + H^+ + 1.5\ H_2O \rightarrow \underset{\text{Kaolinite}}{1.5\ Al_2Si_2O_6(OH)_4} + Na^+$$

or

$$1.17\ NaAlSi_3O_8 + H^+ \longrightarrow 0.5\ Na_{0.33}Si_{3.67}O_{10}(OH)_2 + 1.67\ SiO_2 + Na^+$$

Albite Na-montmorillonite

$$3\ Na_{0.33}Si_{3.67}O_{10}(OH)_2 + H^+ + 3.5\ H_2O \longrightarrow 3.5\ Al_2Si_2O_5(OH)_4 + 4\ SiO_2 + Na^+$$

Na-montmorrilonite Kaolinite

The simultaneous conversion of hornblende to actinolite/tremolite involes the ejection of Al from the amphibole lattice:

$$Ca_2(Mg,Fe,Al)_5(OH)_2 \cdot n(Si,Al)_4O_{11}{}^{\circ}2 \longrightarrow Ca_2(Mg,Fe)_5(OH)_2(Si_4O_{11})_2 + 13\ Al$$

Hornblende Actinolite/tremolite

The liberated Al presumable combined with H_2O and quartz to form more clay-minerals.

Hydrogen ion metasomatism can therefore account for all of the mineralogical changes observed in the wall rocks. Moreover, it explains why no chemical variations occur, because a gain in H^+ ions would not be detected by the rapid X.R.F. technique of whole rock analysis. In addition, out of all the elements, H^+ ions are the easiest to diffuse through any rock mass because of their low ionic mass. This explains why they were able to penetrate into the wall rock when all the other fluid components (such as S and K) were confined to the shear zone channelway.

Summary:

Girlie North Reef is the 640m-long "pay" section (ie. mineralized with gold) of the Girlie North shear zone. It is defined, macroscopically, by an abrupt increase in quartz, carbonate, chlorite and sulphide, but a microscopic examination is required to determine a paragenesis (which is as listed). Tourmaline, arsenopyrite and gold are restricted to the immediate vicinity of a late-stage quartz phase, which is white in colour and readily distinguishable from the early smokey grey-coloured quartz.

Geochemical evidence indicates that the mineralizing fluids were H_2O- and CO_2-bearing and rich in S,K,and Al, and also that wall rock alteration was isochemical. The latter is manifest as a change in mineralogy from a hornblende + plagioclase assemblage to an actinolite/tremolite + quartz +

clay assemblage. This is best developed in the hanging wall of the reef and is thought to have been caused by hydrogen ion metasomatism.

3.3. Sediment-Hosted Shear Zone Deposits

All sediment-hosted shear zone deposits occur in the Marabastad goldfield.

3.3.1. The Marabstad Goldfield

The geology of the Marabastad goldfield (the Mount Mare range) is described by de Wit (1985) (see chapter 2) and illustrated in Figure 2.2.

The major old workings of this goldfield all occur in the sedimentary cover sequence which forms the southern line of hills in the Mount Mare range. From west to east these are the Snymansdrift No. 3 Hill Mine, Snymansdrift No.4 Hill Workings, Porcupine Workings, Zandrivier Mine, MMV Workings and Greenwalds Workings (Fig. 2.2). A geological summary of the deposits is given in Table 3.3. (above the dotted line), and although each appears to be in its own unique setting they are all related to structural traps of D_2 age.

The mine at Snymansdrift No. 3 Hill was the largest in the whole greenstone belt (Plate 3.9). In just four years, between 1907 and 1910, it produced nearly all of the 278 kg of gold recovered from Snymansdrift 738LS (Table 1.1). Extensive stoping on the Red, Green, and Blue Reefs (Anglo American names) was carried out down to No.2 Level but a third level, approximately 120m below surface, was also developed - partly on reef. As yet, no depth extensions to this mine have been discovered.

Underground sampling and closely spaced drilling, which have both proven ore-grade mineralization, indicate that the Zandrivier Mine has the best exploration potential. Of major significance at this mine is the fact that the old-time miners exclusively worked the Quartz (Vein) Reef (Plate 3.10), whereas the best grades in drillcore have been in the Arsenopyrite Reef (this was probably because of the refractory nature of the Arsenopyrite Reef). The latter has been traced, by drilling to the MMV Workings, about 1km along strike to the east, where it is still carrying gold. Although not

Table 3.3. Gold deposits of the Marabastad goldfield

Working	Reef	Host rock	Nature of reef (relative to bedding)	Sulphides	Grade (g/t)	Thickness (cm)	Strike (m)
SNYMANSDRIFT	Blue R.	Sheared shale	Q.V. (conformable)	?	3	60	35
NO.3 HILL MINE	Red R.	Contact shale-sandstone	Q.V. (conformable)	py+cp+apy	24	58	80
	Green R.	Sandstone	Q.V. (slightly X-cutting)	py+cp+apy	22	39	27
	Yellow R.	Sandstone	Q.V. (conformable)	?	Poor	±50	15
SNYMANSDRIFT NO.4 HILL WORKINGS	Various	Shale and sandstone	Q.V.s (conformable and X-cutting)	py+cp	32 (1 reef)	52	70
	Arsenopyrite R.	Contact shale-sandstone	Shear zone	apy	?	?	?
PORCUPINE	Quartz R.	Sandstone	Q.V. (conformable)	py+cp	?	-50	±200
WORKINGS	Arsenopyrite R.	Contact shale-sandstone	Shear zone	apy	?	?	±200
ZANDRIVIER	Quartz R.	Sandstone	Q.V. (conformable)	py+cp+po	±8	±50	1100
MINE	Arsenopyrite R.	Contact shale-sandstone	Shear zone	apy	±4	20-300	1100
	Intrusion R.	Contact sandstone-mafic intrusion	Shear zone?	apy	±10	50-150	?
M.M.V.	Quartz R.	Eliminated by mafic intrusion					
WORKINGS	Arsenopyrite R.	Contact shale-sandstone	Shear zone	apy+py+cp+po	43	312	±500
GREENWALDS	Quartz R.	Sandstone	Q.V. (conformable)	py+cp	±2	20-50	±200
WORKINGS	Arsenopyrite R.	Contact shale (B.I.F.-sandstone	Shear zone	apy	±1	±100	±200?
- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -
	(4)	Mafic greenstones	Q.V.s. (?)	py	?	±50	±200
EVELYN	Quartz R.?	Sandstones/greenstones?	Q.V. (X-cutting)	?			
WORKING	Arsenopyrite R.?	Sheared sandstones/greenstones?	Shear zone	apy+?	?	-50	±300
CATHEDRAL ADIT	-	Snymansdrift melange zone	Q.V. (X-cutting?)	?	?	-50	±50?
HOLLANDSDRIFT PROSPECT	-	Hollandsdrift B.I.F.	Q.V. (X-cutting)	py+ ?	?	±50	±50?

Sources : Willemse (1938); Personal observations.

Plate 3.9. View, looking east, of the Snymansdrift No. 3 Hill Mine (see Fig. 2.2 for location). The dumps indicate the position of the adits. Between 1907 and 1910 this mine produced nearly 278kg of gold.

proven yet, it is possible that the main Quartz Reef and Arsenopyrite Reef are correlatable between Snymansdrift No. 4 Hill Workings and Greenwalds Working (Fig. 2.2). This would give a total strike length of nearly 4km. A more detailed discussion of the Arsenopyrite Reef (at MMV) is presented in the following section of this chapter (3.3.2).

The Ph.d. study of Mike Jones (in prep.) has been primarily concerned with the mineralized cover sequence of the Marabastad goldfield, and particular emphasis has been directed towards the Zandrivier Mine. Field work has involved the detailed mapping of most of the goldfield at a scale of 1:5000 (1:500 over the Zandrivier Mine) and the collection of a representative suite of rock samples for geochemical analysis. The aim of the final year of study is to intergrate geochemical data with field observations, and to formulate a model for the geological evolution of the area with special reference to gold mineralization.

In addition to the major sediment-hosted deposits, a few much smaller workings were developed along shears in the greenstone sequence of the

Plate 3.10. The Quartz Vein Reef exposed in old workings of the Zandrivier Mine. The reef is about 30cm thick. Note the brecciated chert which occurs just below the reef.

Marabastad goldfield. The most extensive of these was the Kuschke mine, situated just to the north of the major Kuschke shear zone (and Kuschke B.I.F.) at the western end of the Mount Mare range. According to Hall (1908), this deposit consisted of at least three or four quartz veins which displayed both conformable and cross-cutting relationships with the host schists. The other workings, such as Evelyn Mine, Cathedral Adit, and the prospect on Hollandsdrift are associated with the major B.I.F. units, though each one is also related to a structural trap of D_2 age. Brief descriptions of each are included in Table 3.3 (below the dotted line).

3.3.2. Arsenopyrite Reef

The Arsenopyrite Reef is a prime exploration target in the cover sequence of the Pietersburg greenstone belt. This is because, despite containing significant gold, it has never been mined in the past -presumably because of the expected extraction difficulties. It is ironical that recent metallurgical testwork on drillcore has shown that much of the gold is actually free (Pete Mann, pers. comm., 1987).

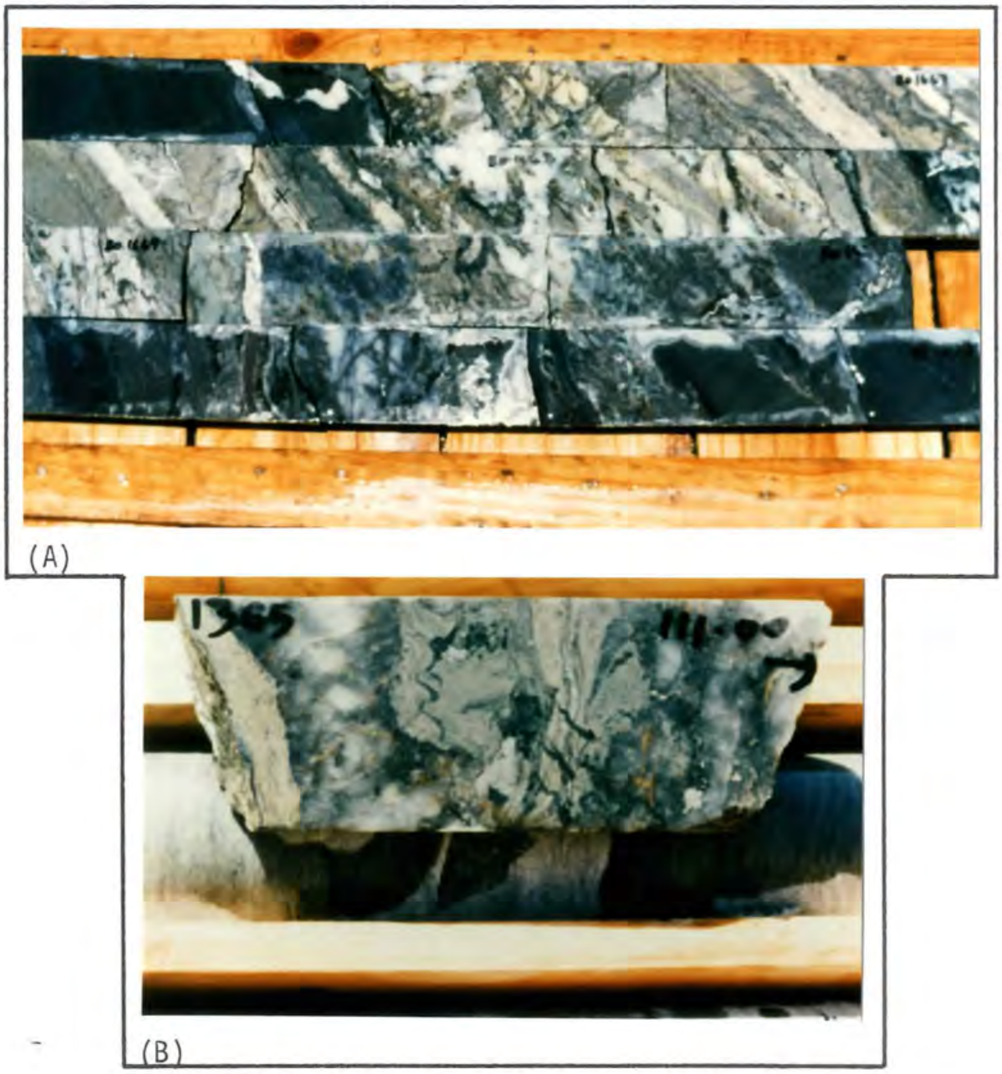


Plate 3.11. The Arsenopyrite Reef. **(A)** The MMV1 profile; the reef mostly comprises alternating bands of quartz (white) and dolomite (light brown). **(B)** Section of ZR3 DEF2-profile. Close-up of arsenopyrite-rich zone.

Exploration:

The Arsenopyrite Reef was first recognized in drillcore (Plate 3.11). An underground sampling programme of the Zandriver Mine workings has shown that a "pay shoot" existed in the Quartz Vein Reef. This plunged parallel to the mineral-elongation lineation in the area, and a drilling programme was proposed to investigate the shoot at depth. As a routine exploration procedure, the first drillhole on a prospect is always drilled well past the target reef intersection. In the case of DDH ZR1 (see Figure 3.6 for location), it was decided to drill right through the entire cover sequence package to obtain a complete profile of fresh rock. The Arsenopyrite Reef was intersected about 3m below the main Quartz Vein Reef in ZR1, and it was only then subsequently recognized in the underground workings and at surface.

After encouraging gold values were obtained from the first three drillholes (in both the Quartz Vein Reef and Arsenopyrite Ree) the programme was extended, both in the vicinity of the Zandrivier Mine workings and farther along strike in the area known as the MMV prospect. A total of 11 holes have been drilled to date. Plate 3.12 is a general view of the MMV prospect and the adjacent Zandrivier Mine workings.

Geology;

The geology of the Zandrivier and MMV prospects has been mapped in detail (1:500 scale) by Pete Mann and Mike Jones, and the author, respectively. A simplified map is presented as Figure 3.6. The detailed stratigraphy on the Zandrivier prospect was established, by Mike Jones, from fieldwork and detailed petrographic work (utilizing transmitted light microscopy and X.R.D. analyses), while that on the MMV prospect is based on fieldwork alone. The following geological description is taken mostly from Jones (1986), and for completeness a short description of the Quartz Vein Reef is included.

The Snymansdrift tectono-sedimentary melange zone (see Section 2.1.3) represents the northern boundary of the cover sequence package in the Zandriver Mine area. The upper (southern) contact of this zone is gradational into a unit of red ferruginous shales/schists. The exact nature of these schists is not known because of the effects of deformation and

Plate 3.12. View, looking northwest, of the MMV prospect (MMV) and the adjacent Zandrivier Mine workings (ZR). The Kuschke B.I.F. is the high ridge on the skyline in the middle of the plate and the flat foreground is underlain by the Turfloop pluton; the tonalitic composition of this rock makes it weather easily. See Fig. 2.2 for location.

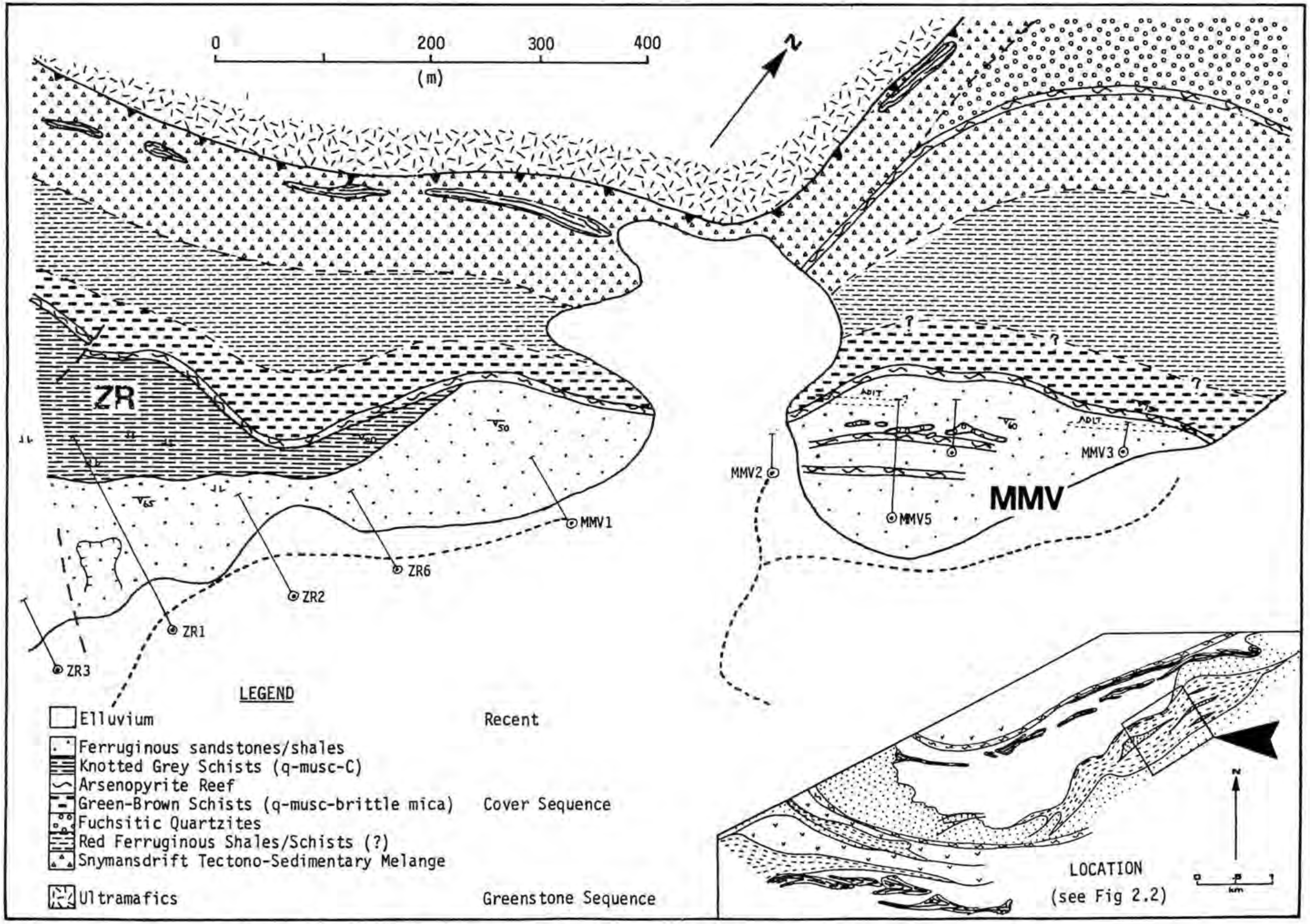


Figure 3.6 Sketch plan of the MMV and adjacent Zandrivier (ZR) prospects.

weathering. It is possible that they might represent mafic schists - in which case the Snymansdrift melange zone would be located within the greenstone sequence, and the northern boundary of the cover sequence would be moved to the south.

Just north of the MMV prospect, however, the red shales/schists pass upwards, very quickly, into cross-bedded fuchsitic quartzites. At least in this area the melange zone is truly tectono-sedimentary. The Snymansdrift shear zone (represented by the melange) is an extremely important regional structure, as far as exploration is concerned, because all the shears and fractures that host gold mineralization are thought to be directly related to it.

The red shales/schists grade southward into pale green-brown schists. These comprise an assemblage of quartz, muscovite, and possibly paragonite (the Na-bearing equivalent of muscovite), in which dark green porphyroblasts of a brittle mica are developed. The green-brown schists are intermittantly gossanous over about 500m of strike and the gossan zones are enriched in Au, As, Ni, Co, Cu, and Zn. They correlate with the Arsenopyrite Reef in the old workings and in drillcore, and are therefore interpreted as the surface expression of that reef (Plate 3.13).

Plate 3.13. Outcrop of the Arsenopyrite Reef on the MMV prospect. The strike extension of this outcrop, on Zandrivier, is enriched in Au, As, Ni, Co, Cu, and Zn.

The Quartz Vein Reef is developed above the Arsenopyrite Reef at the contact between the green-brown schists and the overlying "knotted" grey schists (the "knots" in the latter are strained, angular quartz clasts which lie in a matrix of muscovite, paragonite and free carbon). Shear movement along this contact resulted in the brecciation of a grey and white banded chert bar (Plate 3.10) which occurs close to it. The ±50 cm-wide reef zone comprises a set of smokey grey to black quartz veins with only minor amounts of sulphide included (pyrite and chalcopyrite).

Another feature of interest in the Zandriver Mine area is the presence of a thick mafic igneous body. This was intersected over 72m in DDH ZR4 just below the Arsenopyrite Reef. It is considered most likely that this body was tectonically emplaced into position because there are no visible (or chemical) signs of contact metamorphism in the sediments. The margins of the body are mineralized with significant gold which is probably related to shearing along its contact.

Mineralogy:
Thin-section samples of drillcore from MMV1 were studied by transmitted and reflected light microscopy. As for the Girlie North Reef, these were taken at regular intervals away from the visible reef and from the reef zone itself. The location of the latter are shown on a detailed log of the reef profile presented in Figure 3.7. The following description is supplemented with information from Pete Mann (pers. comms., 1986) and a petrographic report on six samples from DDH ZR1 (Kenyon, 1986).

Samples from the footwall of the visible Arsenopyrite Reef zone are composed mostly of the following mineral assemblage (average vol. % in brackets) : quartz (50)- sericite (40) - chlorite (5) - chloritoid (5). This is a normal assemblage for the green-brown schists (as described above) which suggests that there is no petrographic wall rock alteration beneath the reef.

The hanging-wall assemblage is composed mostly of quartz (50), dolomite (35), chlorite (10), sulphide (5), which is the same as the assemblage comprising the reef itself. It is concluded from this observation that the hanging-wall of the Arsenopyrite Reef is a part of the host shear zone, and

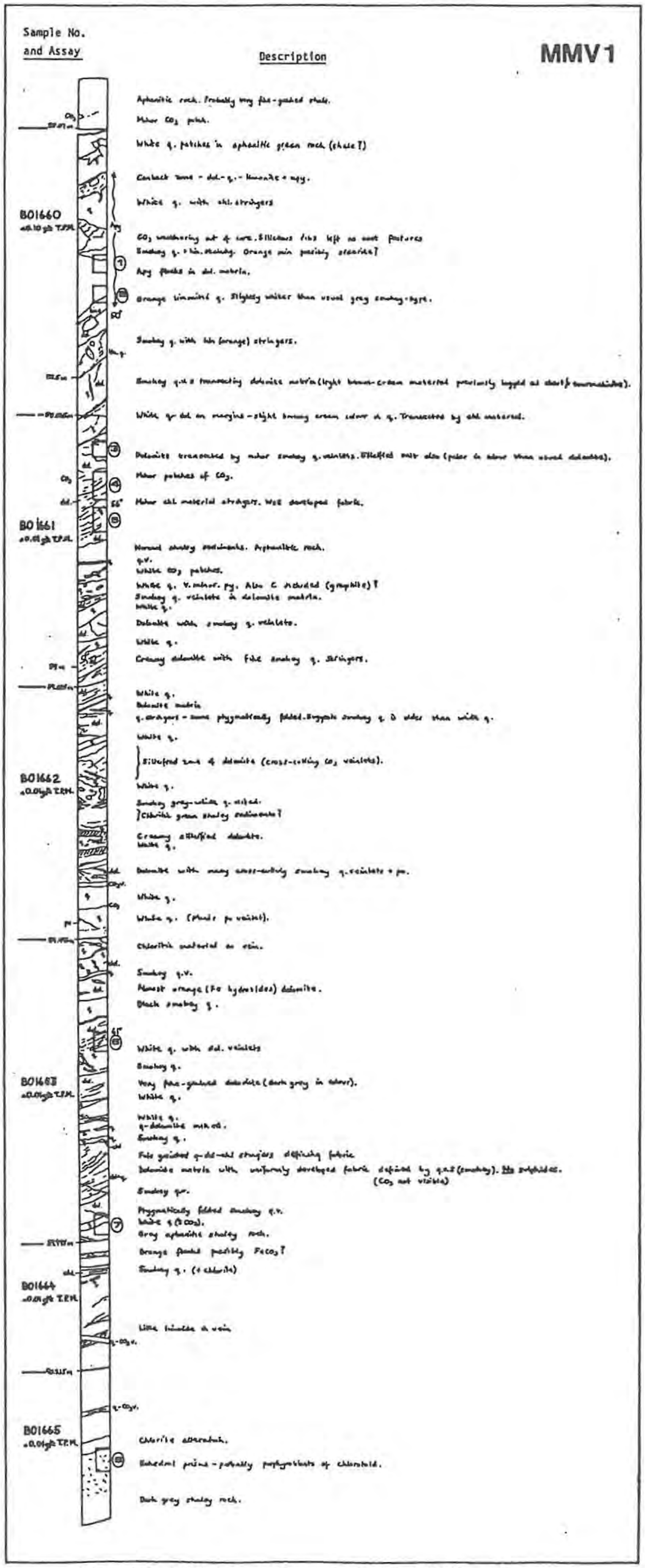


Figure 3.7. Detailed log of Arsenopyrite Reef in DDH MMV1. Thin-section

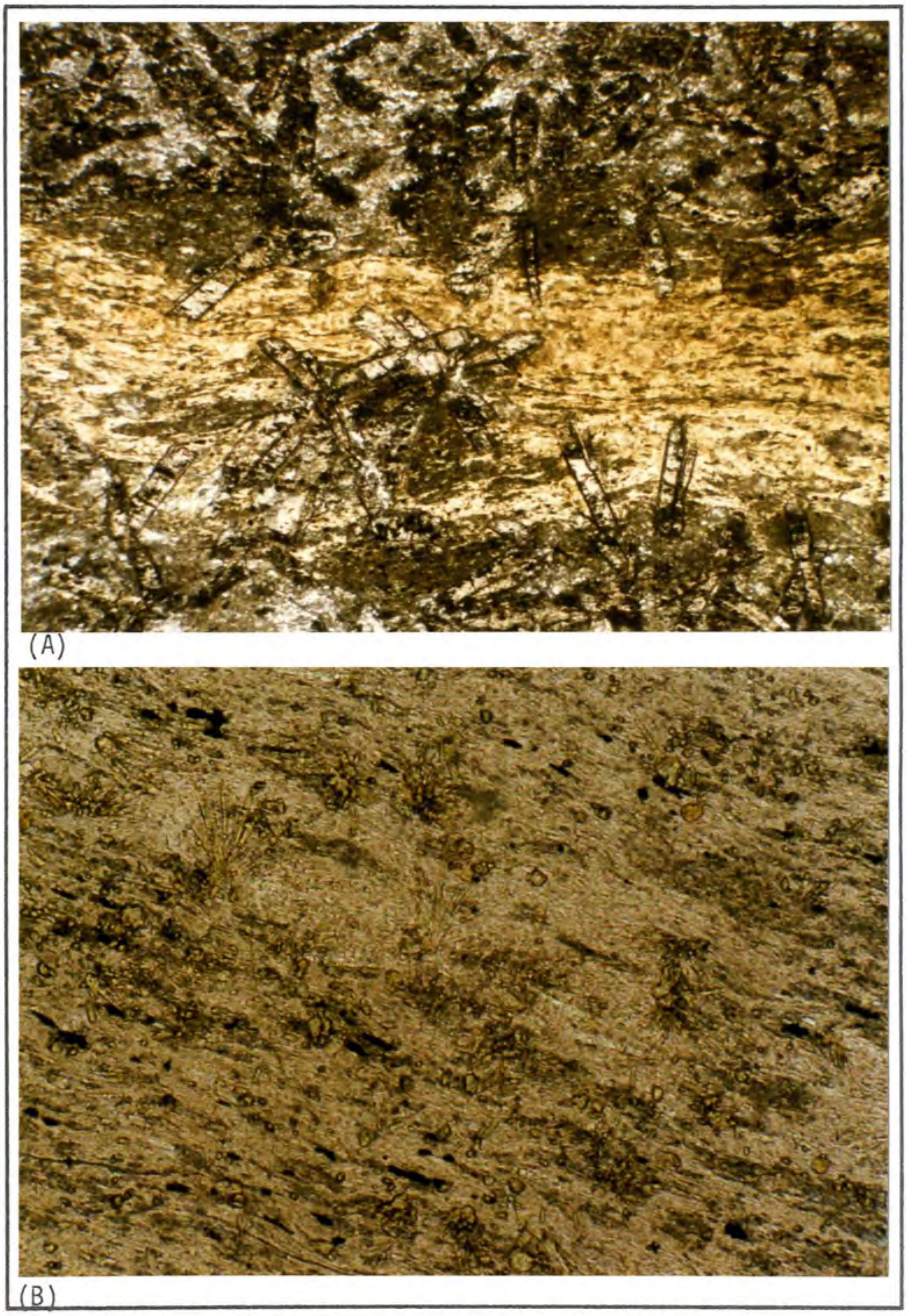


Plate 3.14. Prismatic tourmaline crystals, occuring individually and as aggregates, in a quartz-sericite groundmass. **(A)** Sample from drillcore of MMV1 (95m); **(B)** (93m). Both plane polarized light; mags.x2.5 and x 10 respectively.

it follows that the "pay" reef is located on the bottom contact of this zone. A complete profile from the Arsenopyrite Reef to the Quartz Vein Reef was not examined during this study (the Quartz Vein Reef is not developed on the MMV prospect) but it is suggested that the latter could be located on the top contact of the host shear zone in the Zandrivier Mine area.

In addition to the minerals mentioned above, the reef and wall rock are characterised by the presence of tourmaline. This is usually present as prismatic crystals which occur individually or in aggregates (Plate 3.14), although it occurs as aggregates of xenomorphic grains as well. An X-ray powder diffraction analysis of one reef sample from ZR1 revealed that tourmaline and arsenopyrite are the principal constituents. The latter is the most abundant sulphide mineral in the reef zone, although minor pyrite and chalcopyrite are also present. The arsenopyrite is generally idiomorphic when in contact with gangue minerals, and isolated grains of gold (with an average diameter of 8.0 microns : Kenyon, 1986), pyrrhotite and iron-rich sphalerite occur within it. Kenyon also reports that substantial amounts of rutile are present in the vicinity of arsenopyrite.

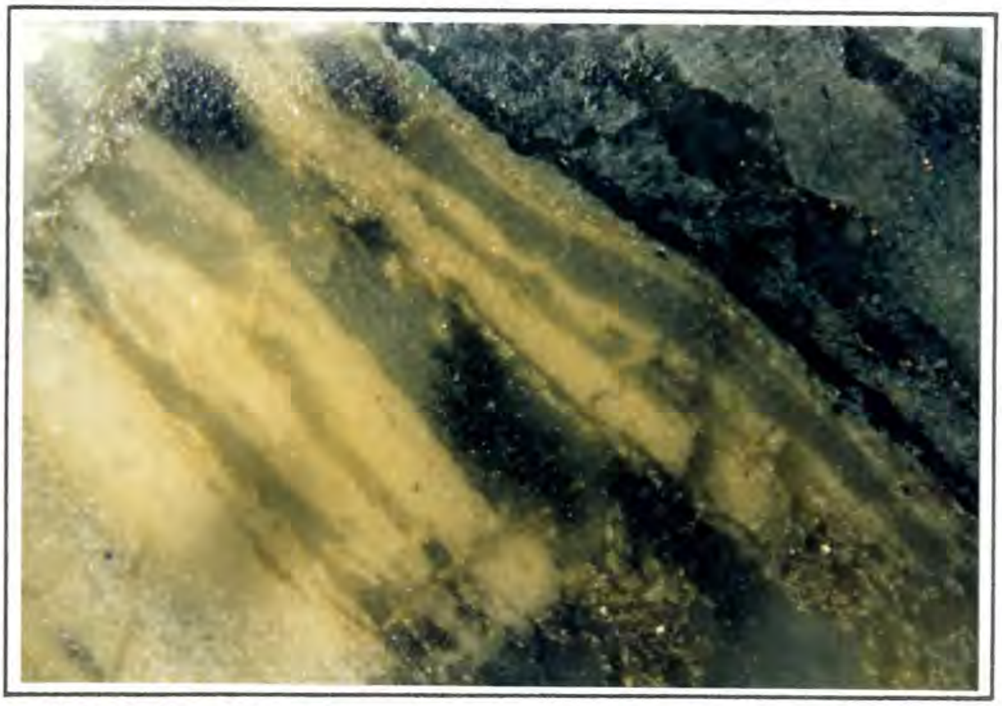


Plate 3.15. Alternating layers of quartz and dolomite make up the Arsenopyrite Reef. Note the fabric development. Sample comes from drillcore of MMV1 (same location as thin-section MMV1-4 : see Fig. 3.7). Mag.x0.8.

Fine-grained quartz and dolomite comprise most of the reef assemblage (Plate 3.15). They occur, either seperately or intergrown, as granoblastic mosaic-textured layers. Chlorite is often developed along the boundaries of these layers which are probably micro-shear planes. The shear planes, and veinlets of quartz and dolomite which cross-cut the matrix, represent the most likely channelways along which tourmaline and arsenopyrite were introduced; these latter two minerals overgrow everything else. This and other textural evidence indicates the following paragenetic sequence :

1. Quartz + carbonate
2. Chlorite
3. Tourmaline
4. Arsenopyrite.

Geochemistry:

The only drillhole on the MMV prospect for which a complete chemical analysis is available is DDH MMV5 (see Fig. 3.5 for location). The chemical analysis of the MMV5 profile is listed in Table 3.4. Unfortunately, this means that it is not possible to correlate the mineralogy and geochemical data of a single drill profile through the Arsenopyrite Reef (on the MMV prospect).

The chemical data of MMV5 were plotted as histograms (Fig. 3.8) and a visual inspection of the graphs revealed three zones of interest. The first, which occurs at the top of the hole (from 0 to 47m), is enriched in Ti, P, Rb, Zr, Y, Cu, and Zn and is correlatable with a mafic igneous body that was identified during routine core logging (by Pete Mann). This body is similar to the one intersected in DDH ZR4.

The second zone of interest is about 15m thick and occurs directly beneath the mafic igneous body. This zone is enriched in K, Ba, K/Na and Rb/Sr, and depleted in Mg, Ca, Na and Sr. The third zone correlates with the Arsenopyrite Reef and is enriched in S, As, Au, K/Na and Rb/Sr, and depleted in Mg, Ca, Na and Sr. The similar geochemical signature of these latter two zones, and that of Girlie North Reef, suggests that all three are shear zones which developed during the same deformation event so that similar fluids were able to pass through each. A shear zone interpretation for the second geochemical zone of interest in MMV5 is compatible with its location

Table 3.4. Chemical analysis of MMV1 drillcore profile.

SAMPLE NO	DEPTH From	DEPTH To	SiO2 (%)	TiO2 (%)	Al2O3 (%)	Fe (%)	Mn (%)	Mg (%)	Ca (%)	Na (%)	K (%)	P2O5 (%)	S (%)	TOTAL (%)	L.O.I. (%)	Ba (ppm)	Rb (ppm)	Sr (ppm)	Zr (ppm)	Y (ppm)	Cu (ppm)	Zn (ppm)	Pb (ppm)	As (ppm)	Au (ppb)	K/Na (%)	Rb/Sr (%)
PLN 1989	0	17.80	52.30	2.10	11.00	12.10	.3	3.00	5.00	1.80	.80	.40	0	88.80	11.20	312	77	215	391	59	336	399	10	11	0	.44	.36
PLN 1990	17.80	20.69	52.90	2.00	11.90	12.00	.3	3.40	5.50	2.00	.80	.30	0	91.10	8.90	333	63	173	332	55	259	321	3	18	8	.40	.36
PLN 1991	20.69	23.86	52.30	2.00	10.90	11.80	.3	3.30	5.60	1.80	.80	.20	0	89.00	11.00	300	62	161	298	56	462	403	9	6	0	.44	.39
PLN 1992	23.86	25.15	51.70	1.90	11.50	12.00	.3	3.50	5.80	1.80	.80	.30	0	89.60	10.40	257	60	151	298	54	431	470	11	8	15	.44	.40
PLN 1993	25.15	27.09	51.60	1.90	11.20	12.00	.3	3.40	5.80	1.80	.80	.10	0	88.90	11.10	261	62	156	288	63	428	476	-9	8	0	.44	.40
PLN 1994	27.09	28.93	52.80	2.00	11.00	11.70	3	3.60	6.00	1.80	.70	.10	0	92.70	7.30	300	53	176	290	54	298	334	7	16	0	.39	.30
PLN 1995	28.93	30.90	51.80	1.80	11.80	11.60	.3	3.50	5.60	1.80	.90	.20	0	89.30	10.70	293	74	161	270	51	357	381	5	7	0	.50	.46
PLN 1996	30.90	32.83	52.00	2.00	10.20	11.70	.3	3.50	5.60	1.80	.90	.10	0	88.10	11.90	297	77	166	283	52	394	417	10	11	7	.50	.46
PLN 1997	32.83	34.86	52.00	1.90	11.70	11.60	.3	3.20	5.40	1.70	1.00	.20	0	89.00	11.00	375	76	165	291	53	213	269	7	25	0	.59	.46
PLN 1998	34.86	36.88	52.90	2.00	11.70	11.70	.3	3.30	5.80	1.80	.90	.30	0	90.70	9.30	290	69	161	296	54	289	325	8	16	0	.50	.43
PLN 1999	36.88	38.88	53.30	2.10	12.70	11.80	.3	3.30	6.00	1.90	.80	.30	0	92.50	7.50	259	66	153	298	53	297	342	11	11	0	.42	.43
PLN 2000	38.88	40.84	52.40	2.00	11.20	12.10	.3	3.60	5.70	2.20	.70	.20	0	90.40	9.60	290	73	172	358	55	284	358	6	14	0	.32	.42
NJF 1001	40.84	42.77	52.60	2.00	11.00	12.00	.3	3.60	5.60	2.20	.80	.20	0	90.30	9.70	300	72	179	371	53	366	439	14	10	7	.36	.40
NJF 1002	42.77	44.80	53.60	2.10	12.50	12.10	.3	3.60	5.80	2.30	.70	.30	.1	93.40	6.60	310	69	212	365	51	272	355	7	16	9	.30	.33
NJF 1003	44.80	46.89	58.90	1.50	15.20	9.10	.3	.60	.30	.60	2.00	-.10	0	88.40	11.60	551	97	48	110	47	282	294	1	80	0	3.33	2.02
NJF 1004	46.89	48.70	92.80	.40	6.80	2.70	.2	.90	.10	.20	1.40	-.80	0	104.70	-4.70	390	66	19	30	11	232	350	11	49	5	7.00	3.47
NJF 1005	48.70	50.70	62.10	.70	12.90	7.60	.3	1.20	.10	.20	2.00	-.40	0	86.70	13.30	497	90	29	40	31	96	179	-9	55	0	10.00	3.10
NJF 1006	50.70	52.70	51.90	.60	11.20	14.20	.5	2.20	.20	.10	.60	-.30	0	81.20	18.80	481	32	14	35	26	374	185	-8	98	5	6.00	2.29
NJF 1007	52.70	54.75	57.70	.70	12.10	10.90	.4	2.00	.20	.10	1.20	-.40	0	84.90	15.10	513	58	24	33	24	105	165	-15	102	10	12.00	2.42
NJF 1008	54.75	56.74	49.70	.70	11.20	14.80	.5	2.90	.20	.10	.40	-.40	0	80.20	19.80	391	24	11	28	24	154	176	-4	148	0	4.00	2.18
NJF 1009	56.74	58.70	54.80	.70	12.40	11.00	.4	2.10	.20	.20	1.20	-.40	0	82.60	17.40	489	59	22	34	24	109	173	-12	104	0	6.00	2.68
NJF 1010	58.70	60.99	51.20	.60	10.10	14.70	.4	2.80	.10	.10	.30	-.40	0	79.90	20.10	424	25	11	27	23	166	180	-5	146	0	3.00	2.27
NJF 1011	60.99	62.99	49.30	.70	12.20	12.80	.4	2.40	.20	.10	1.00	-.20	0	79.00	21.00	467	56	25	38	24	112	173	-7	69	0	10.00	2.24
NJF 1012	62.99	64.93	52.40	.60	11.80	12.70	.4	2.50	.80	.20	.80	-.30	0	81.90	18.10	431	42	38	36	27	91	181	-9	55	14	4.00	1.11
NJF 1013	64.93	66.92	55.20	.60	11.50	10.20	.4	4.80	2.50	.90	.40	-.10	.1	86.50	13.50	257	21	72	29	19	172	128	-11	9	0	.44	.29
NJF 1014	66.92	68.90	50.90	.60	10.90	8.20	.3	4.50	5.30	.70	.90	-.20	0	82.10	17.90	180	40	89	25	21	111	127	-1	4	7	1.29	.45
NJF 1015	68.90	70.95	55.60	.60	10.80	7.70	.3	4.50	4.10	.50	.90	-.20	0	84.50	15.20	279	43	68	25	21	181	186	-1	19	8	1.60	.63
NJF 1016	70.95	72.77	55.50	.60	10.30	8.90	.3	6.00	3.30	.90	.40	-.60	0	85.60	14.40	200	20	71	29	17	65	154	-3	22	0	.44	.28
NJF 1017	72.97	74.93	57.20	.50	9.60	12.70	.5	4.20	1.60	.70	.20	-.30	.1	87.00	13.00	255	9	57	32	18	146	301	-3	44	0	.29	.16
NJF 1018	74.93	76.95	50.30	.60	7.30	17.20	.6	3.30	3.30	.10	.10	-.20	.2	82.80	17.20	238	8	38	40	20	389	342	-11	90	0	1.00	.21
NJF 1019	76.95	78.95	47.30	.70	10.30	12.70	.4	6.00	4.20	.90	.10	-.20	0	82.40	17.60	167	9	109	37	18	130	197	-2	43	0	.11	.08
NJF 1020	78.95	80.70	61.60	.60	6.20	10.40	.4	4.60	4.00	.80	.20	-.60	0	88.40	11.60	121	10	77	24	15	99	143	-3	47	5	.25	.13
NJF 1021	80.70	83.70	57.00	.90	8.60	12.60	.5	4.60	2.00	.30	.20	-.10	.1	86.70	13.30	268	11	48	65	19	270	187	-6	69	9	.67	.23
NJF 1022	83.70	85.72	61.70	.90	12.90	8.60	.3	3.30	2.20	1.30	1.00	-.20	.1	92.10	7.90	332	35	76	88	25	97	113	-9	37	0	.77	.46
NJF 1023	85.72	86.94	54.90	.70	10.40	8.40	.3	6.30	5.80	1.30	.10	.00	0	88.20	11.80	74	8	91	38	18	120	159	0	6	0	.08	.09
NJF 1024	86.94	89.00	51.00	1.40	11.30	11.30	.3	4.50	5.50	2.00	.40	-.10	0	87.60	12.40	141	40	144	207	46	216	262	-5	11	11	.20	.28
NJF 1025	89.00	91.00	52.50	1.90	11.10	12.10	.3	3.90	5.70	1.90	.60	.10	0	90.10	9.90	239	65	193	289	51	206	260	11	15	0	.32	.34
NJF 1026	91.00	92.92	56.80	1.40	9.80	10.70	.3	4.70	4.90	1.70	.30	-.10	0	90.50	9.50	162	28	97	178	40	156	199	-6	92	11	.18	.29
NJF 1027	92.92	94.87	53.00	.90	12.60	8.20	.3	4.80	4.90	1.60	.70	-.10	0	86.90	13.10	148	27	102	71	30	175	205	1	34	0	.44	.26
NJF 1028	94.87	96.88	51.90	.80	11.90	8.40	.2	6.50	6.50	7.30	.20	-.20	0	88.50	11.50	49	9	136	64	26	124	133	-2	19	0	.09	.07
NJF 1029	96.88	98.90	53.40	.90	11.80	9.00	.3	5.70	4.90	1.80	.30	-.30	0	87.80	12.20	103	15	113	69	29	107	143	-7	30	0	.17	.13
NJF 1030	98.90	100.97	55.00	.90	11.40	8.90	.2	5.70	5.10	2.00	.20	-.50	0	88.90	11.10	117	8	109	68	27	189	181	-7	21	13	.10	.07
NJF 1031	100.97	102.93	53.50	.90	12.10	8.70	.3	6.20	5.40	2.50	.10	-.20	0	89.50	10.50	55	6	110	73	27	141	153	-2	22	8	.04	.05
NJF 1032	102.93	104.92	53.70	.90	12.10	9.10	.2	5.70	5.50	2.00	.10	-.10	0	89.20	10.80	42	5	148	72	27	133	137	-1	34	0	.05	.03
NJF 1033	104.92	106.92	52.50	.90	11.80	8.80	.3	4.80	6.00	2.10	.30	-.10	0	87.40	12.60	88	9	103	66	26	50	89	-7	69	5	.14	.09
NJF 1034	106.92	108.91	56.60	.90	9.90	10.30	.4	2.70	3.40	.90	.40	-.30	.3	87.70	12.30	152	16	75	65	28	186	271	-2	497	45	.44	.21
NJF 1035	108.91	110.90	62.10	1.00	13.10	8.20	.3	2.10	1.50	1.00	.80	-.30	.1	89.90	10.10	217	34	82	99	35	82	226	2	170	12	.80	.41
NJF 1036	110.90	112.92	57.20	1.00	12.30	9.60	.3	3.20	2.90	1.00	.50	-.30	.1	87.80	12.20	186	23	84	101	34	118	159	-3	105	16	.50	.27
NJF 1037	112.92	114.88	55.70	1.00	12.50	8.80	.3	3.20	3.90	1.00	.60	-.10	0	86.90	13.10	169	24	107	93	32	95	163	-3	153	0	.60	.22
NJF 1038	114.88	116.88	53.00	1.00	12.40	9.00	.3	3.70	4.50	1.20	.60	-.20	0	85.50	14.50	135	20	118	88	32	89	120	-3	66	13	.50	.17
NJF 1039	116.88	118.81	59.10	1.00	12.80	9.10	.3	3.90	3.40	1.70	.50	-.20	.1	91.70	8.30	180	20	100	85	29	123	106	-5	47	0	.29	.20
NJF 1040	118.81	120.87	56.10	.90	12.90	9.30	.4	4.10	3.90	1.70	.50	-.20	.1	89.70	10.30	192	18	91	82	30	85	130	-6	39	0	.29	.20
NJF 1041	120.87	122.87	57.00	.90	10.50	9.10	.3	5.00	5.00	1.70	.20	-.30	0	89.40	10.60	151	7	87	71	26	101	125	-5	15	0	.12	.08
NJF 1042	122.87	124.91	55.60	.80	11.30	8.80	.3	7.40	4.30	1.90	.10	-.30	0	90.20	9.80	80	4	108	66	23	74	98	-1	8	0	.05	.04
NJF 1043	124.91	126.80	50.00	.60	9.50	7.60	.2	8.60	5.80	.40	.10	-.20	0	82.60	17.40	25	5	97	46	18	72	88	-9	7	19	.25	.05
NJF 1044	126.80	128.81	57.20	.70	9.50	7.90	.3	9.00	4.90	1.10	.10	-.20	0	90.50	9.50	42	2	83	51	18	68	95	-3	3	0	.09	.02
NJF 1045	128.81	130.90	53.80	.60	9.40	8.10	.3	8.40	4.50	.70	.10	-.30	0	85.60	14.40	75	2	69	52	19	55	110	-8	33	7	.14	.03
NJF 1046	130.90	132.88	49.20	.70	10.20	10.00	.3	7.90	3.50	.70	.10	-.50	0	82.10	17.90	135	3	52	51	17	44	167	0	51	0	.14	.06
NJF 1047	132.88	134.87	66.10	1.00	9.30	8.90	.4	2.70	2.00	.10	.40	-.10	.2	91.00	9.00	221	19	25	79	25	186	242	2	7234	677	4.00	.76
NJF 1048	134.87	136.91	57.80	1.80	9.60	14.60	.6	1.40	1.10	.10	.20	.00	.5	87.70	12.30	214	12	8	135	29	379	287	-8	5993	1066	2.00	1.50
NJF 1049	136.91	137.85	52.80	.50	12.50	11.00	.4	4.30	2.40	1.30	.30	-.50	.9	86.10	13.90	66	17	64	36	20	505	276	-1	1133	696	.20	.27
NJF 1050	137.85	139.81	56.20	.60	16.50	7.30	.3	5.50	2.20	2.00	.50	-.20	0	90.90	9.10	116	17	100	44	20	97	148	-5	90	0	.25	.17
NJF 1051	139.81	140.80	58.00	.60	16.10	6.90	.3	5.10	1.50	2.00	.50	-.60	0	90.40	9.60	120	16	81	37	20	102	140	0	76	11	.25	.20
NJF 1052	140.80	142.70	56.80	.50	15.40	7.30	.3	6.10	2.40	1.50	.40	-.20	0	90.50	9.50	108	11	59	27	19	76	100	-2	60	8	.27	.19
NJF 1053	142.70	145.00	70.10	.50	12.10	8.20	.2	.10	.20	.10	2.40	-.30	0	93.60	6.40	251	99	57	120	33	67	359	52	222	26	24.00	1.74
	E.O.H.																										

Method of Analysis : By X-ray fluorescence of standard 36 element batch (Anglo American Research Laboratories, Crown Mines, Johannesburg).

Note : Because the samples were analyzed in pressed powder briquettes, and in part by using an energy dispersive spectrometer, the results for the major elements (marked %) are relatively less accurate and less precise than the values given for the trace elements.

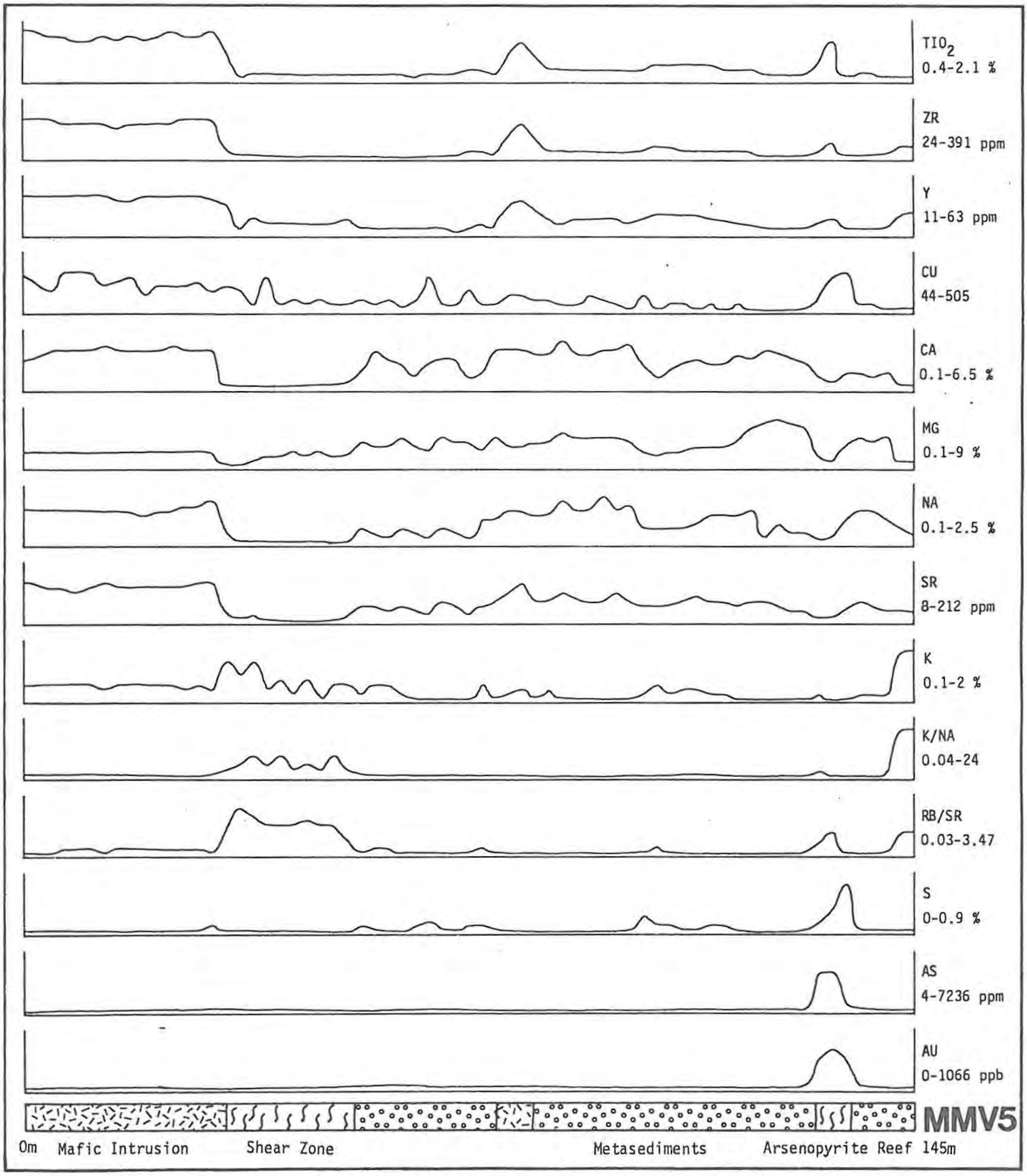


Figure 3.8. Geochemical profile of Arsenopyrite Reef and wall rock in DDH MMV1 (Selected elements.)(Not to scale)

along the basal margin of the mafic igneous body (ie. at a lithological contact). A significant point to be noted here though, is the fact that this shear zone is unmineralized with respect to gold and arsenic (Fig. 3.8).

Summary:

The Arsenopyrite Reef is interpreted as the basal margin of a shear zone, whose top contact may be represented by the Quartz Vein Reef in the Zandrivier Mine area. The mineral assemblage in the shear zone is made up, predominantly, of quartz and carbonate; and the two "pay reef" zones are distinguished by gold associated with arsenopyrite and tourmaline, and gold in prominent quartz veins, respectively. In this study no wall rock alteration (petrographic or chemical) was identified but it is acknowledged that further sampling is required to confirm this - notably in the hanging-wall of the Quartz Vein Reef. Based on the mineralogy and geochemical signature of the reef zone itself, it is proposed that the Arsenopyrite Reef (and another shear zone intersected in DDH MMV5) was formed during the same deformation event as the Girlie North Reef.

4. A GENERAL MODEL FOR THE SHEAR ZONE DEPOSITS

In a recent and comprehensive state-of-the-art review of greenstone belt gold depoists, Hodgson (1985) discusses every aspect of the ore-forming process. An outline of his scheme is given in Table 4.1. A similar approach will be followed here but only the possibilities of each aspect of the ore-forming process that are applicable to the Pietersburg belt will be considered.

Table 4.1. Aspects of gold deposit generation.

Aspect of ore-forming process	Main possibilities
Source of gold :	1. Local host rocks 2. Deep metamorphic zone 3. Deep zone of magma generation
Source of fluid :	1. Magma 2. Deep (granulitic) metamorphic zone 3. Shallow (amphibolitic) metamorphic zone 4. Circulating meteoric
Mechanism of mobilization :	1. Dissolution into fluids (of any origin) during metamorphic recrystallization 2. Leaching by fluids (of any origin) during hydrothermal alteration 3. Partitioning from magma into magmatic hydrothermal fluid
Mechanism of transport :	1. By mass movement of fluid 2. By diffusion through standing fluid
Site of deposition :	1. Submarine hot-spring and associated discharge zone 2. Dilatent zone within or related to a shear zone 3. Chemically favourable "trap"
Cause of deposition :	1. Decrease in fluid temperature 2. Boiling of fluid 3. Fluid mixing 4. Fluid reaction with host rock
Timing :	1. Syn-volcanic 2. Syn- to post-metamorphic 3. Syn-volcanic with metamorphic remobilization

Modified from Hodgson (1985).

4.1. Source of Gold

The primary source of gold in the Pietersburg belt must have been either the greenstone sequence or the late-stage felsic magma (the latter represented by porphyries and granitoid plutons). Any gold derived from the cover sequence must originally have been a part of the greenstone sequence because the former is an erosion product of the latter.

The average concentration of gold in most normal rock-types is very low (it is normally quoted as 3ppb or less), and for this reason many workers have claimed that an enriched source rock is a prerequisite for the formation of gold deposits. It is difficult to determine the original gold content of a potenital source rock because fluid-rock interaction (eg. seawater metasomatism) may have caused a redistribution of gold amongst various lithologies. Keays (1984) tried to overcome this problem by using Pd as an indicator of a rock's original Au content. These two elements are both concentrated in an immiscible sulphide liquid as soon as it separates from a mafic or ultramafic magma (i.e. they behave similarly during magmatic processes), but, whereas Au is easily dissolved during fluid-rock interaction, Pd is insoluble (i.e. they behave differently during alteration processes). Keays found that the most Pd-rich (and where Au was not

Table 4.2. Palladium and gold content of some Archean and Phanerozoic igneous rocks.

Location	Lithology	Pd	Au	Pd/Au
Ocean floor	Low-Mg basalts	1.9	0.6	3.1
Kambalda	Low-Mg basalts	1.6	0.9	1.8
Kambalda	High-Mg basalts	13.8	7.2	1.9
Kambalda	Komatiites	7.3	6.0	1.2
Mt Clifford	Komatiites	7.8	0.5	15.6
Barberton	Komatiites	4.1	0.4	10.2
Belingwe	Komatiites	11.7	1.4	8.4
Munro	Komatiites	8.3	2.9	2.9
King Island	Picrites	19.6	2.8	7.0
Disko	Picrites	11.1	4.2	2.6
Kambalda-	Interflow sediments	9.9	146.0	0.07

Source : Keays (1984).

Low Pd-Au ratios, relative to the mean, may signify Au enrichment and high Pd/Au ratios, Au depletion.

depleted, the most Au-rich) igneous rocks are high-Mg basalts and komatiites with concentrations of 14 ppb Pd and 7 ppb Au, and 8 ppb Pd and 6 ppb Au, respectively (Table 4.2)(the komatiites of Mt. Clifford, Barberton, Belingwe and Munro are all interpeted by Keays to have been depleted in Au by alteration processes).

Keays and Scott (1976) have drawn attention to the accessibility of Au in these types of rocks. They have shown that the crystalline interiors of pillows of modern ocean-floor basalts are depleted in Au relative to their glassy margins. They attribute this depletion to Au that was precipitated on loosely bound sites in the crystalline interiors of pillows (eg. in products of deuteric alteration, mesostasis phases and, in particular, sulphides), which was mobilized into the inter-pillow sites during basalt-sea water interaction; ie. by sea water metasomatism.

Interflow sediments (eg. B.I.F.s) have long been considered favourable source rocks for gold deposits. In the Pietersburg belt, 15 samples of B.I.F. contained an average gold concentration of 191 ppb (range 3.7-667 ppb) while 35 samples of greenstone rocks contained only 2.8 ppb (range 0.3-20.2 ppb) (Saager et al., 1982). Bavinton and Keays (1978) explained a similar enrichment of B.I.F.s from the Kambalda region as due to one of three possible models:

1. A magmatic-exhalative model in which Au (and Pd)- enriched fluids were exhaled during and after each successive extrusive event, thereby enriching contemporaneous interflow sediments.
2. A sea-floor leaching model in which the komatiitic flows (possibly Au-enriched) lost Au to the sea-floor sediments.
3. A metamorphic entrapment model in which Au, released from the enclosing ultramafic rocks during talc-carbonation reactions, was transported over small distances by fluids and deposited as a result of reaction between the fluid and sulphides in the sediments.

Saager and Meyer (1984) have investigated the gold distribution in various Archean granitoids in South Africa. They identified two populations which they termed the background population, with a Au content of about 1ppb, and the "excess value" population, with a higher and variable content (Fig. 4.1 A). Although the "excess value" population's mean concentration is only 4

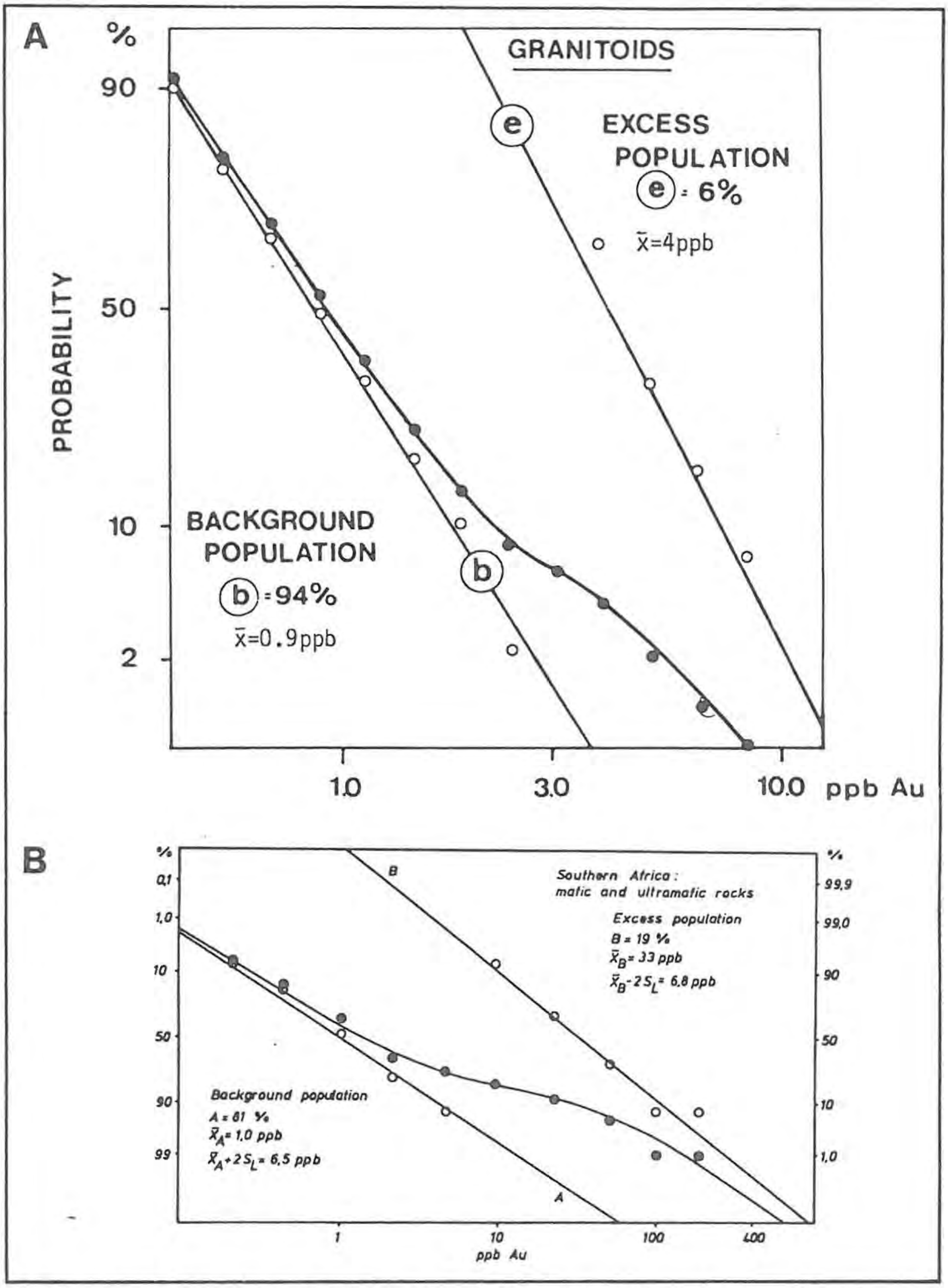


Figure 4.1.(A) Log probability plot of 190 Au values obtained from various Archean granitoids in South Africa. Two populations are identified : background $\bar{x}$ = 0.9 ppb and "excess value" $\bar{x}$ = 4 ppb. (From Saager and Meyer, 1984). (B) A similar plot of 98 Au values obtained from various Archean mafic and ultramafic rocks in South Africa; background $\bar{x}$ = 1ppb and "excess value" $\bar{x}$ =33 ppb. (From Saager et al., 1982.)

ppb, which hardly represents an enriched gold source, it is suggested that the identification of two distinct populations may be significant. As an incompatible element, Au contained within a felsic magma would tend to concentrate into an exsolved magmatic fluid during the magmas consolidation. In a tectonically active environment, such as that surrounding a greenstone

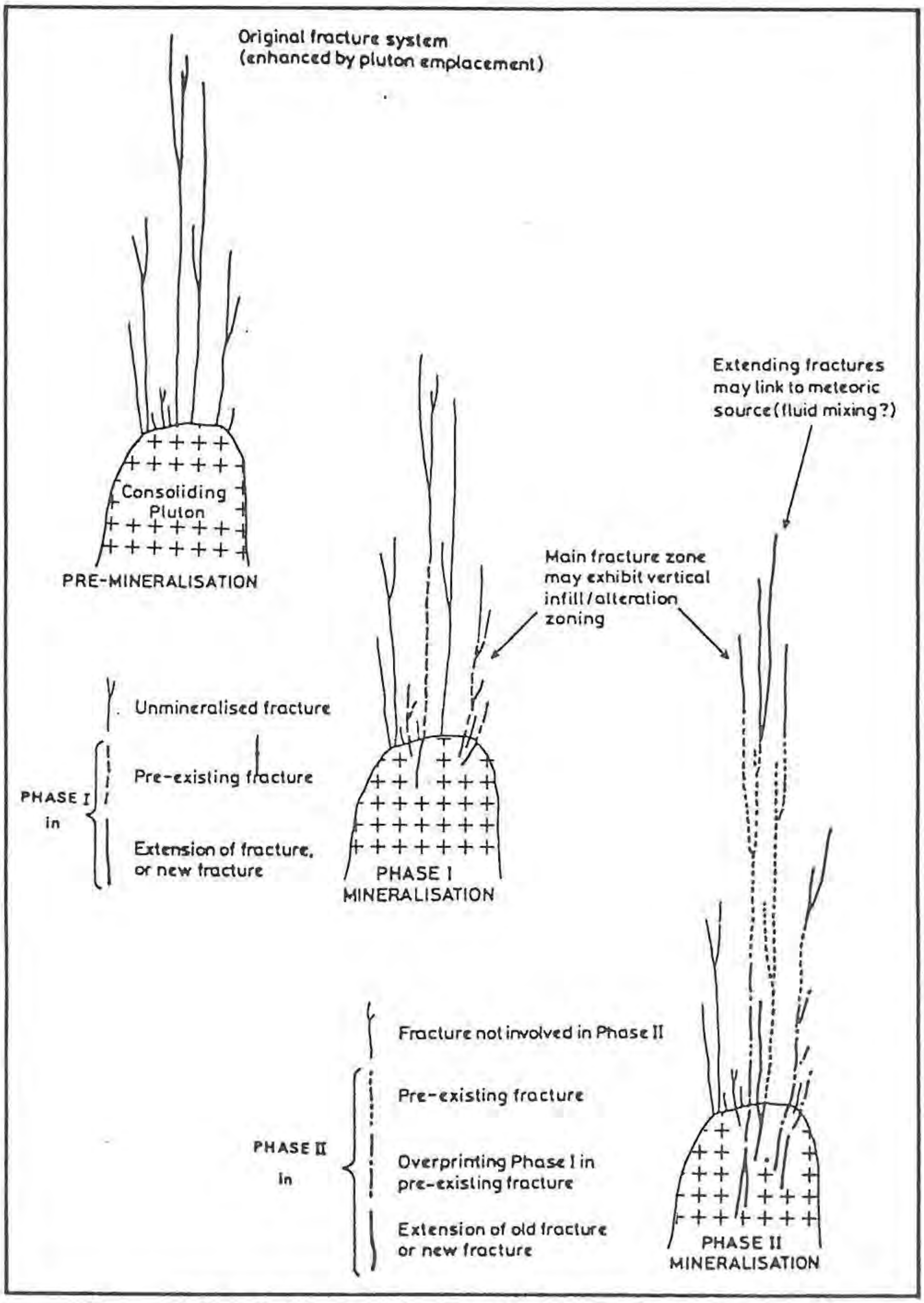


Figure 4.2. Model for development of fracture system and possible mineralization via successive tapping of a magmatic fluid resevoir. (From Taylor and Pollard, 1985.)

belt, most granitoids would have been tapped by fractures at sometime during their evolution (Fig. 4.2) and magmatic fluid (with Au) would therefore have been released into the surrounding rocks. According to this model then, the granitoids of the background population (94% of the total) represent those which released Au into the greenstone belts, whereas the granitoids of the "excess value" population (6% of the total) represent those which remained closed systems during their emplacement - and, therefore, those which retained their original Au content.

If one considers the tectonic setting in which the Pietersburg belt developed (ophiolites occur on the leading edge of subduction-related magmatic arcs), the liklihood that the associated granitoids were gold-bearing is enhanced, as demonstrated in more recent settings by the gold and porphyry copper association.

Despite the large concentration factors involved in the formation of gold deposits, there are some workers who advocate that an enriched source rock is not a prerequisite for their formation. The average grade of a shear

Table 4.3. Concentration factors for some ore constituents in various deposit types.

Metal	Average Concentration (ppm) Crust	Basalt	Granite	Deposit Type	Typical Grade	Concentration Factor
Au	0.003	0.003*	0.002	Lode	6.0 g/t	2000
		0.003*		M.S.D.	0.9 g/t	300
Cu	50	100*	12	M.S.D.	3.0%	300
	50*			Porphyry	0.5%	100
Zn	70	100*	50	M.S.D.	10.0%	1000
Pb	12.5	3.5	20*	M.S.D.	2.0%	1000
Mo	1.5	1.0	1.5*	Porphyry	0.2%	700
W	1.2	0.8	1.5*	Skarn	1.0%	7000

*Value used to calculate concentration factor.

From : Hodgson (1985).

zone-related deposit with marginal economic potential would be about 6 g/t. Assuming a general background gold concentration of 3 ppb, this represents a minimum concentration factor of 2000. Even though this is a very large number, Hodgson (1985) has pointed out that it is within an order of magnitude of concentration factors involved in the formation of many other types of deposit - as shown in Table 4.3. Hodgson concludes from these data that there is no need to invoke an enriched source rock for the formation of gold deposits if this is not a prerequisite for the formation of other ore deposit types.

Also, Phillips and Groves (1983) have pointed out that the concentration of Au in the so-called "enriched soruce rocks" is only 2 to 10 times the general background concentration (up to 50 times for interflow sediments). They suggest that this would probably not affect the potential for ore deposit formation, considering the very large concentration factors involved.

It is clear from the above discussion that, with present knowledge, it is not possible to specify the source rocks from which Au in greenstone belt deposits was derived. The current weight of opinion appears to favour a greenstone source rock but there is no evidence to rule at a contribution from felsic magma. The latter could have been an important source of Au for the Pietersburg gold deposits because at least one granitoid, the Roodepoort pluton, is reported to be anomalously rich in Au (500 to 2000 ppb) (Barton et al., 1986).

4.2. Source of Fluids

Fluid inclusion, isotope, and wall rock alteration mineral assemblage studies have been used to characterize the hydrothermal fluids responsible for gold minerlaization (Phillips and Groves, 1983; Ho et al. 1985; Hodgson, 1985). Currently available data suggest that these were low salinity (less than 2 equiv. wt. % NaCl), H_2O- and CO_2-rich (about 20 to 30 mol % CO_2), alkaline to near-neutral, reduced fluids with densities of 0.7-0.8 g/cm^3. The homogenization temperatures of fluid inclusions indicate that vein quartz was deposited over a temperature range of 250 to 400^oC and at pressures between 1 and 2kb. They typically have low negative values of

$\delta^{13}C$ (0 to -5%), low positive values $\delta^{34}S$ (5 to 8%), and, probably, moderately positive values of $\delta^{18}O$ (5 to 15%).

Because of the low salinities involved there is a general consensus of opinion that the fluids were not circulating seawater. A similar argument has been used to preclude a magmatic origin for the fluid (Phillips and Groves, 1983), although it is now accepted that salinity data alone cannot rule out a possible magma source. For example, the effect of a small amount of CO_2 in an aqueous fluid in equilibrium with a granite is to suppress the concentration of granitic components, particularly the alkalis (Burnham, 1967 : quoted by Ho et al., 1985), thus giving rise to a CO_2-rich and halogen-poor fluid (ie. with the characteristics described above).

Despite this concession to a possible magma source, many workers (and particularly those from Western Australia : Phillips and Groves, 1983; Groves et al., 1984; Ho et al., 1985) advocate a metamorphic devolatilization model to account for the mineralizing fluids (Fig. 4.3). Such fluids, derived from the dehydration and decarbonation of greenstone sequences during metamorphism, are compatible with the characteristics of the hydrothermal fluids as outlined above. An implicit part of this model is that sea water metasomatism led to the partial hydration and early carbonation of the greenstone sequences, and that burial of the sequences resulted in the driving off of any high-salinity pore fluids.

Ho et al. (1985) cite the following major evidence against a magmatic (granitic) source for the fluids in Western Australia :

1. The lack of a spatial relationship between large gold deposits and granitoids.
2. The lack of "mafic" granitoids, which are thought to be good source rocks (for gold-bearing fluids) elsewhere.
3. The low mu values (U/Pb ratios) implied by Pb isotopic studies of most galenas from the gold deposits, which rules out a significantly older "granitic" source.

The first of these points is considered to be applicable to Western Australia only (see below), the second does not preclude the possibility of a felsic magma source, and the third is irrelevant in a discussion concerning the late-stage granitoid plutons as a possible source. It is

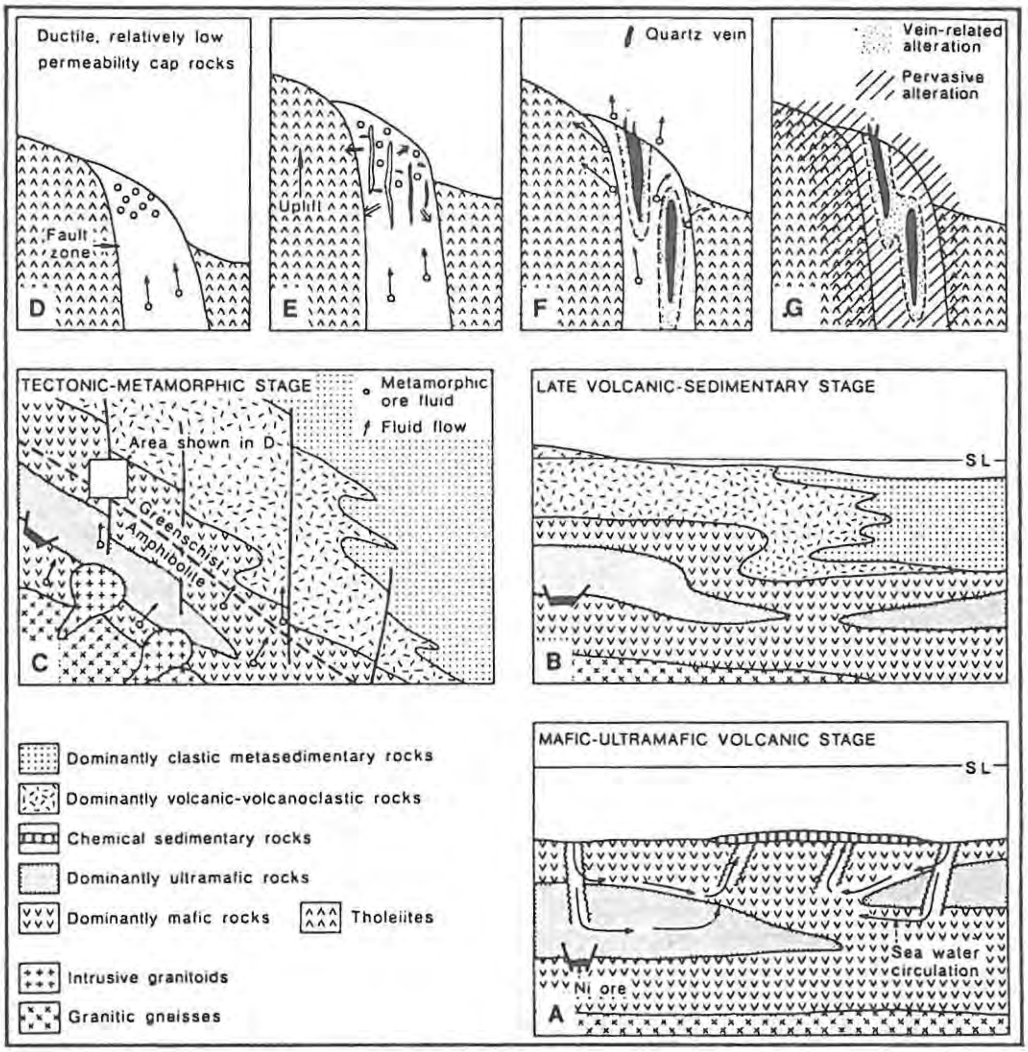


Figure 4.3. Schematic diagram showing the basic elements of the metamorphic model for shear zone gold deposit genesis. (A) Development of dominantly volcanic component of greenstone pile. (B) Further volcanism, major sedimentation, burial, and folding. (C) Rising isotherms, upright folding, regional uplift and faulting, release of auriferous metamorphic fluid following dehydration-decarbonation reactions. (D) Uprise of fluid along fault zone, high fluid pressures below cap rocks. (E) Uplift and hydraulic fracture in or near fault zone. (F) Fluid access to host-rocks, wall rock alteration, Au deposition. Appearance of mineralized zone with vein-related and broader halo of alteration around auriferous quartz veins. (D) to (G) based on Hunt model, Kambalda. (From Groves et al., 1984.)

concluded, therefore, that there is no evidence to emphatically discount the possibility of a felsic magma source for the mineralizing fluids in the Pietersburg belt.

The evidence in favour of a felsic magma source includes (Hodgson, 1985) :

1. The spatial relationship between gold deposits and felsic intrusions (both hypabyssal porphyries and large granitoid plutons) in most greenstone belts of the world.
2. The common association of B, As, W, Mo, and Sb with gold mineralization. These elements are also typical of magmatically-derived ore deposits, such as Sn and W lodes, W Skarns, Mo porphyries, and the tourmaline breccia pipes of porphyry copper environments.
3. The extensive K-metasomatism which is closely associated with gold mineralization.

Hodgson also suggests that the $CO_2:H_2O$ ratio in some fluid inclusions is higher than would be expected from the decarbonation of greenstone sequences. He proposes that this is due to externally dervied CO_2 from a felsic magma.

When contemplating the source of hydrothermal fluids in the Pietersburg greensotne belt, it is pertinent to consider the regional structure and tectonic setting of the belt. It is clearly not possible for any part of a 5km-thick, ophiolitic, greenstone sequence to have reached the amphibolite-facies of metamorphism by burial alone. There are two processes that may have induced the higher grades : deformation and granitoid intrusion. Since there is geological evidence in the Pietersburg belt to suggest that these two processes overlapped in time (eg. a foliation in some granitoid outcrops), it is most likely that the hydrothermal fluids in this belt would have been a mixture of "metamorphic fluids" and "granitic fluids", although the proportions of each could have varied considerably.

4.3. Mechanism of Mobilization

If the mineralizing hydrothermal fluids were metamorphically derived, it is probable that Au was dissolved into them at the time they were generated. One of the arguments advanced in favour of this hypothesis is that, because metamorphic fluids are generated at grain boundaries and in the pore spaces of a rock, they have better access to the total gold content of that rock. However, the question of gold accessibility has already been discussed (Section 3.4.1) and, in light of the findings of Keays and Scott (1976), who showed that Au is enriched in the pillow margins of ocean floor basalts, it is suggested that the argument is invalid. The accessible Au in any rock is mostly tied up in sulphides and is located in sites freely available to most types of hydrothermal fluid (eg. in pillow margins and fractures, etc).

It follows from this discussion that a hydrothermal fluid derived from a felsic magma could have leached Au from a greenstone sequence. However, in this case, there is an alternative possibility. Gold could have been partitioned from the felsic magma itself, into an evolving magmatic hydrothermal fluid.

4.4. Mechanism of Transport

It is more than likely that the physical transport of Au was accomplished by a moving fluid rather than by diffusion through a static fluid. This is because it would take impossibly long periods of time for an ore deposit to form by a diffusive lateral secretion process through a static intergranular fluid (Kerrich and Allison, 1978).

To assess the chemical transport of Au (in solution) it is necessary to detail some of its chemical properties. Phillips and Groves (1983) provide a comprehensive discussion on this topic. The high ionization energy of Au, and the very low stability of Au aquo-ions, mean that complexing ligands are required to transport dissolved Au. Although two ionic forms of Au are common in nature (Au^+ and Au^{3+}), at geological temperatures and oxygen fugacities the solubility of Au^{3+} is negligible (Seward, 1984). It is therefore not discussed further. The Au^+ ion is large and highly polarizable, and as such it has a tendency to form covalent bonds. The most stable Au(I) complexes are those with large polarizable ligands such as CN^- and HS^-. A comparison of Au (I) complex stabilities is given in Table 4.4.

Fluid inclusion and mineral assemblage studies have been used to establish which potential ligands were present in the hydrothermal fluids. Seward (1984) has also examined analyses of high-temperature waters from active geothermal systems (Broadlands and the Salton Sea) to gain the same information. On the basis of these data, Seward claims that the most important Au(I) complexes were those involving Cl^-, HS^-, and S^{2-}. Phillips and Groves (1983) add HCO^{3-} to the list.

Table 4.4. Equilbrium formation constants for Au(I) complexes at 25^{o}C.

	log B_2
$Au(CN)_2^-$	41.8
AuS^-	39.8
$Au(HS)_2^-$	37.2
$Au(SO_3)_2^{3-}$	30.1
$Au(NH_3)_2^+$	26.5
AuI_2^-	22.1
$Au(OH)Cl^-$	19.0
$AuBr_2^-$	15.6
$AuCl_2^-$	12.4
$Au(HCO_3)_2^-$	?

From : Seward (1984).

Phillips and Groves (op.cit.) suggest that a chloride complex can be ruled out because of the selective enrichment of Au, over Ag and the common basemetals, Cu, Pb and Zn. In contrast to Archean gold deposits, Cu, Pb, Zn, Ag and Au are all enriched by similar amounts relative to their crustal abundances (x 1000-10 000) in massive base metal sulphide deposits. This latter type of deposit is generally interpreted in terms of a volcanogenic-exhalative model, in which metals are transported as chloride complexes in circulating sea water. The small non-polar Cl^- ligand does not discriminate between the metal ions to which it becomes bound and so the consequent concentration of metals is in the same proportion as their relative abundance in source rocks. Phillips and Groves further suggest that the sulphur-donor ligands were the most important in Au(I) complexes. This suggestion is based on theoretical considerations (eg. the equilibrium formation -constants in Table 3.8) and the fact that there is a specific association of Au with pyrite in many Western Australian gold deposits.

Seward (1984) reached essentially the same conclusions as the above authors, although he maintains that Au(I) chloride complexes (as $AuCl_2$) would be predominant in a fluid containing high chloride and anomalously low reduced S concentrations or in fluids with an elevated fO_2. This type of fluid could have been derived from the I-type granitoids which intruded the greenstone belts.

At this point it is necessary to digress for a moment. A general survey of the literature reveals that there has been scant attention paid to the mineralogical relationships within shear zone-hosted gold ores. This is considered to be a significant weakness in many of the genetic models proposed for Archean gold deposits. In this study of the Pietersburg shear zone deposits the Au and associated arsenopyrite and tourmaline have been recognized as late-stage components in the overall shear zone assemblage. Cross-cutting relationships and the euhedral shape of arsenopyrite and tourmaline crystals indicate that the gold-bearing fluids overprinted the original minerals. It is possible, therefore, that the gold-mineralizing fluids were quite different in terms of composition and origin to those that

Plate 4.1. Underground exposure of Yellow Reef in the Snymansdrift No. 3 Hill Mine. The reef is stained green by Cu (malachite) which may indicate that at least some of the hydrothermal fluids were Cl-rich. Base-metals (and Au) are readily carried as chlorides in this type of fluid.

produced the major part of the shear zone mineral assemblage. This argument raises the question of whether or not the host shear zone mineralogy (and fluid inclusion and isotopic data obtained from it) really reflects the true nature of the gold-mineralizing fluids.

The Pietersburg belt, in common with most other greenstone belts of the world, contains evidence (albeit minor) of shear zone-hosted base metal mineralization (eg. the base metal prospect in the northwest portion of Eersteling 17KS, and Yellow Reef of the Snymansdrift No. 3 Hill mine : Plate 4.1). It is suggested that this may have been due to chloride-rich hydrothermal fluids, carrying Au and base metals as chlorides in solution, which were channeled along the same shear zones as previous fluids which were low in Cl concentration. In this model, the enrichment of Au over Ag and the base metals could be explained by a low fluid-to-rock ratio (Kerrich and Fryer, 1981), which would be expected if the fluids were mostly derived from an external source, such as a consolidating granitoid. This is the favoured model for gold deposits of the Pietersburg greenstone belt.

4.5. Site of Deposition

By definition, shear zone gold deposits are hosted by shear zones. These may be narrow fractures with sharp contacts, which give rise to vein deposits (brittle shears), or wider zones with a prominent planar fabric and gradational contacts, which give rise to disseminated deposits (ductile shears), or they may have a few mixed characteristics of both types. The Pietersburg deposits are hosted by brittle and relatively narrow, brittle-ductile shear zones.

As exemplified by many of the deposits in the Pietersburg belt, secondary structures are an important control on the siting of mineralization. Many deposits are located where there is a change in the strike or dip of a host shear zone or at the intersection between two seperate shear zones.

Hodgson (1985) cites two points of evidence that indicate relatively deep levels of ore deposition in shear zones : (1) The apparent overlap, in time and space, of ore deposition and structure formed near the brittle-ductile transition in the crust, which the earthquake distribution in fault zones indicates to be at about 15 km; and (2) the relatively high temperatures and pressures of ore deposition indicated by fluid inclusions and the isotope partitioning among coprecipitated minerals. The first point of evidence is rejected because of the effects of pore fluid pressure (a high pore fluid pressure within a shear zone can give rise to ductile deformation at, or at least very close to, surface), and the second is questioned on the grounds of the argument outlined in the previous section (ie. do the fluid inclusion and isotopic data reflect the conditions of deposition of the gold mineralizing fluid - or some other fluid ?).

The evidence cited by Hodgson for shallow levels of ore deposition include (1) open-space filling textures in veins, and (2) the presence of chalcedonic quartz, both of which are typical of Phanerozoic epithermal deposits.

At Pietersburg, the interpreted syn-deformational deposition of the cover sequence indicates that the major shear zones in this belt developed close to surface. Since the structures that host the gold mineralization are all thought to be related to the major shear zones, it is implied that the gold mineralization itself must also have been formed close to surface.

4.6. Cause of Deposition

Figure 4.4 is a compilation of diagrams to illustrate the solubility of Au in S-rich and Cl-rich solutions as a function of temperature, pH and fO_2. The changes in these variables that cause the precipitation of Au are summarized in Table 4.5.

Phillips and Groves (1983) and Ho et al. (1985) discount a decrease in temperature as a cause of gold deposition for most deposits on the basis of fluid inclusion data. These data indicate that there were no significant changes in the depositional temperature of the main phase of quartz veining, over vertical extents of up to about 200m in the mineralized system of Western Australia. (This once again raises the issue of how representative the quartz veining is of conditions prevailing during Au deposition.) These authors also claim that, because of the more complex arrangement of gold solubility contours for $Au(HS)_2$ as compared to $AuCl_2$ (Fig. 3.10 E),

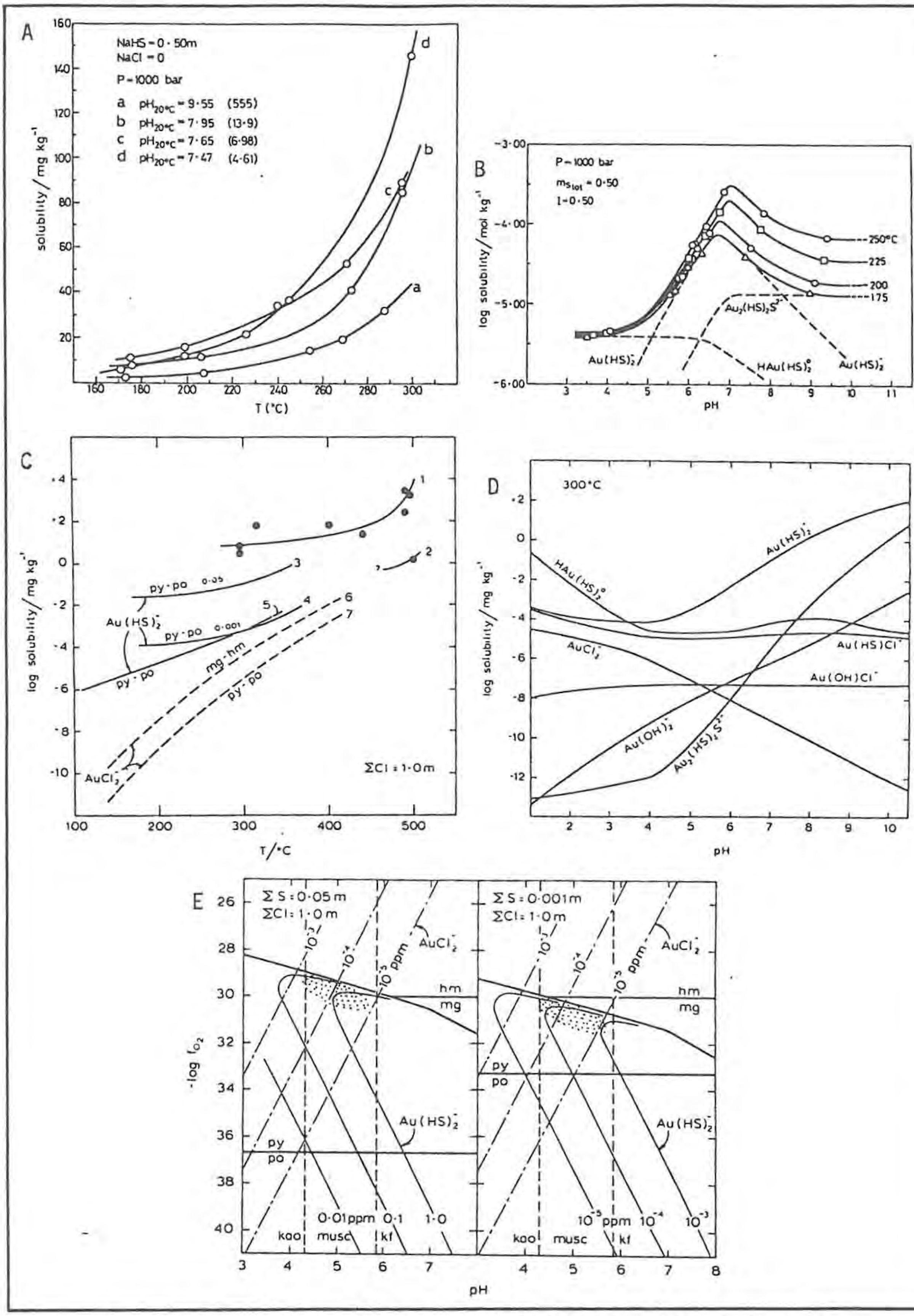


Figure 4.4. Compilation of diagrams to illustrate the solubility of Au in S-rich and Cl-rich solutions as a function of temperature, pH and fO_2. Note for (A) numbers in brackets are the ratio HS/H_2S; for (C) curves 1 and 2 refer to experimental data in 1.0 molar chloride solution, curves 3 and 4 are at pH=5 and total reduced S (H_2S + HS) = 0.05 and 0.001 respectively, curve 5 is same as 3 and 4 but with no excess S, and curves 6 and 7 are at pH=5; and for (E) the stippled area indicates the frequently encountered area of ore deposition. (From Seward, 1984.)

Table 4.5. The causes of Au deposition in S-rich and Cl-rich fluids.

Variable	Change required to cause preciptation of Au S-rich fluid	Cl-rich fluid
Temperature	Decrease	Decrease
pH	Decrease	Increase
fO_2	Decrease/Increase	Decrease
Activity of S/Cl	Decrease	Decrease

Source : Seward (1984).

deposition of Au from $Au(HS)^{-}_{2}$ would be more likely to occur in the wide range of chemical environments in which Archean gold deposits are found. Based on this argument and the observation that pyrite is a characteristic feature of wall rock alteration, they propose that Au was deposited from a thio-complex as the result of a reaction between Au-bearing fluids and Fe-rich wall rocks. Redox reaction can be written as follows :

$$FeO(\text{in silicates}) + HAu(HS)_2 + O_2 = Au + FeS_2 + 1\ H_2O$$

$$Fe_3O_4 + 3\ HAu(HS)_2 + O_2 = 3\ Au + 3\ FeS_2 + 4\ H_2O$$

Notice that in both of these reactions pyrite is a final product together with free Au.

Although the above model neatly explains the apparent Fe-rich host rock control on the location of some deposits (notably those hosted by B.I.F.s), it does not explain the structural control on the location of shear zone-hosted deposits, such as those of the Eersteling goldfield in Pietersburg. The easiest way to explain this control is to invoke a temperature decrease, due to fluid expansion into a permeable zone in the conduit system, as the cause of- deposition (Hodgson, 1985). The change in intensive variables would cause a shift in fluid-wall rock mineral equilibria, which, in turn, would cause wall rock alteration.

Since the gold deposits of the Pietersburg greenstone belt are thought to have formed close to surface, a number of other factors may have caused Au deposition. Seward (1984) claims that the two most effective ways of precipitating Au from a thio-complex are to decrease the activity of reduced S by dilution, or to increase the fO_2 type of fluid, both of which destabilize the complex. These changes would have occurred if hydrothermal fluids had mixed with meteoric waters close to surface. In the case of a chloride complex, Au could have been precipitated as the result of a decrease in the activity of Cl due to dilution with meteoric waters, or as the result of an increase in pH of the fluid due to loss of CO_2 during boiling (carbonation reactions or CO_2 effervescence would raise the pH). Groves et al. (1984) claim that fluid-boiling was not an important process in the generation of most shear zone gold deposits. However, they do state that phase separation (ie. boiling), indicated by the occurrence of two primary fluid inclusion types (one aqueous and the other CO_2-rich), did take place towards the end of ore deposition. But in the Pietersburg greenstone belt deposits, that is precisely when most of the Au was actually precipitated.

4.7. Timing

The occurrence of a few granitoid outcrops with a gneissose foliation suggests that the first granitoids were emplaced prior to the end of the main D_2-stage of deformation in the Pietersburg greenstone belt. It was during this stage that the major shear zones developed and, by inference, the related structures that host gold mineralization. Since textural evidence indicates that Au was introduced into the shear zones as a late-stage component, it is concluded that the main stage of gold mineralization was synchronous with the intrusion of granitoids. Thus, it was also synchronous with the M_3 and M_4 phases of metamorphism.

4.8. Summary

The main gold mineralizing event in the Pietersburg greenstone belt was synchronous with the intrusion of granitoids into and around the margins of the belt, and synchronous with the M_3 and M_4 phases of metamorphism. The Au is thought to have come from two sources. Gold derived from felsic magma was partitioned into a magmatic hydrothermal fluid and transported as a

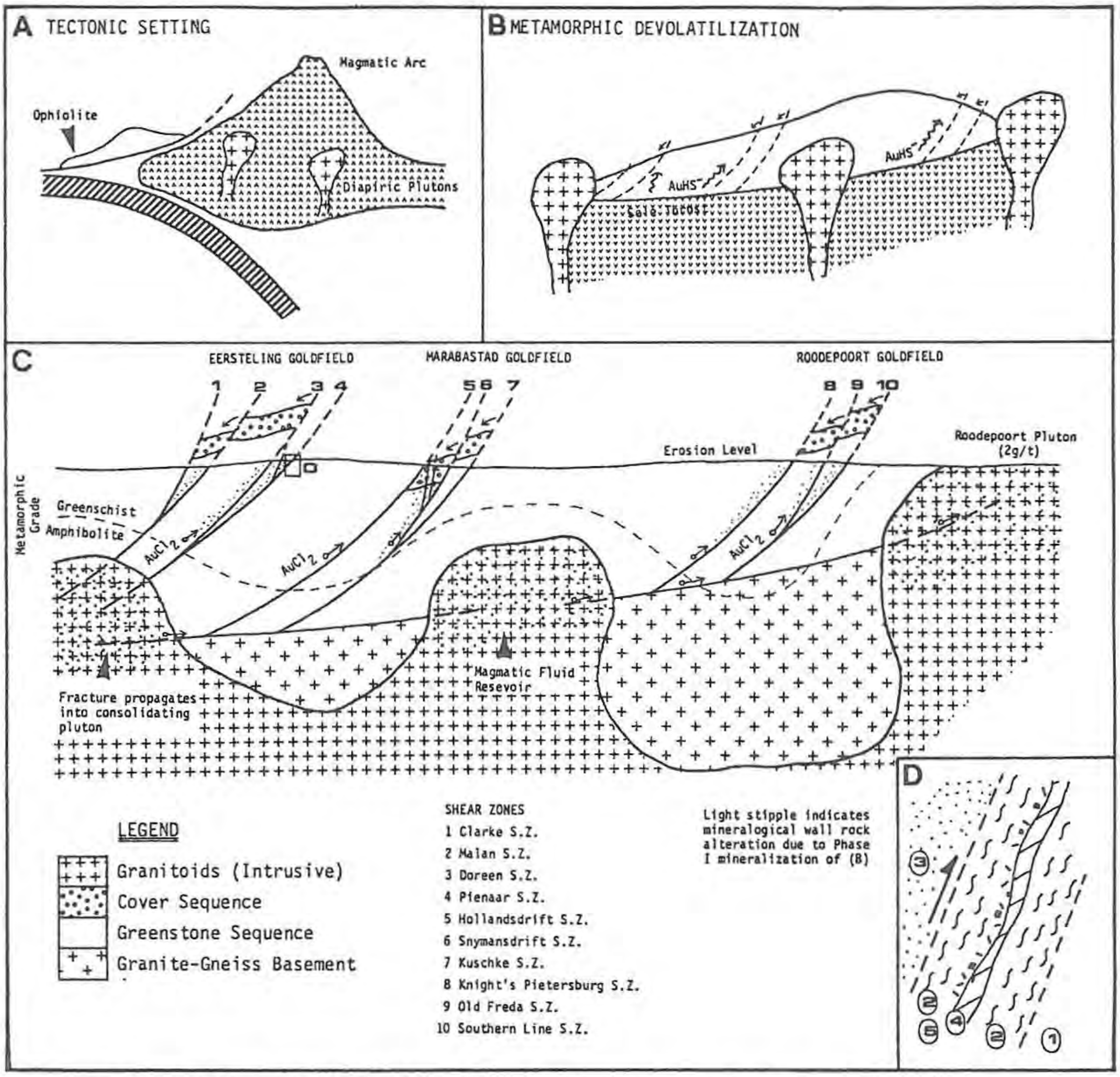


Figure 4.5. Model of shear zone gold deposit genesis in the Pietersburg greenstone belt. **(A)** Obduction of oceanic crust to form ophiolite greenstone belt. **(B)** During obduction process shear zones (thrusts) cross-cut greenstone belt in imbricate fashion and sedimentary cover seqeunce develops at thrust fronts. Tonalitic and trondjhemitic plutons, derived from the subducting oceanic plate intrude the belt and cause devolatilization and decarbonation of the deepest portions. The released fluids ascend into the upper portions of the belt and mineralize the shear zones; some Au may be mobilized during this metamorphism (as $AuHS^-$). This stage of the model is exactly analagous to the metamorphic model of shear zone gold deposit genesis (see Fig. 4.3). **(C)** Shear zones and fractures propagate into granitoid intrusions as they consolidate, according to Taylor's model (1985) (see Fig. 4.2). These tap highly differentiated magmatic fluid resevoirs, containing Au and other incompatible elements, which are liberated into the greenstone belt (as $Au\ Cl_2$) **(D)** Gold and associated mineralization overprints earlier deposited shear zone assemblage : 1- Unaltered footwall; 2- Phase I mineralization deposited during devolatilization and decarbonation metamorphism of B; 3- Mineralogically altered hanging wall; 4- White quartz vein seals shear zone at end of Phase I; 5- Phase II (gold) mineralization is introduced along the margins of the white quartz vein and overprints earlier asasemblage. (Based on Girlie North Reef deposit.)

chloride complex (Au Cl_2) into the greenstone sequence of the belt. In this environment it mixed with a metamorphic fluid which was also charged with Au. This Au, however, was derived from the greenstone sequence and had been dissolved into the metamorphic fluid during metamorphic recrystallization. The resultant hybrid fluid (magmatic + metamorphic) may have leached even more Au from the greenstone sequence as it ascended through the rock pile. At this stage, at least some of the Au was probably transported as a thio-complex.

The fluids were channeled up shear zones, which had already been mineralized with a quartz-carbonate-chlorite-sulphide assemblage by previous metamorphic fluids generated during the dynamic M_2-phase of metamorphism (this was synchronous with the main D_2-stage of deformation). Gold was finally deposited, as the result of a change in a fluid variable (eg. temperature, pH, fO_2) or a change in the activity of reduced S or Cl, in secondary structural traps within the host shear zones. It is possible that some Au was introduced by metamorphic fluids generated during the M_2-phase of metamorphism but, in view of the textural relationships observed, it is thought that this could only have been a minor amount of the total gcld content now in the shear zones.

Figure 4.5 is a schematic diagram that summarises this general model.

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APPENDIX

EXPLORATION - TECHNIQUES AND PROCEDURES

Exploration programmes are often designed to locate one particular type of mineralization (eg. Au, Cu-Pb-Zn, Sn-W, etc.) and sometimes, even, to locate one specific type of ore deposit. Because the primary gold deposits of the Pietersburg greenstone belt are exclusively shear zone deposits, this is considered to be an example of a region in which the latter philosophy should apply. The following discussion refers specifically to the exploration for shear zone gold deposits in the Pietersburg greenstone belt.

The exploration programme is divided into stages, each with a primary objective. These are listed below :

1. **Regional stage** - to locate shear zones.
2. **Local stage** - to determine if the shear zones are gold-bearing and to trace their strike extents.
3. **Detailed stage** - to investigate the shear zones at depth.
4. **Evaluation stage** - to define orebodies and to calculate ore reserves (grade and tonnage).

1. REGIONAL STAGE

Regional geological mapping with the use of **aerial photographs** is the best technique to employ at this initial stage of exploration. However, in areas of poor exposure the geologist has to resort to rapid geophysical techniques, such as **magnetics** and possibly **S.P.**, to locate discontinuities (contacts or shear zones) in buried bedrock. Both of these geophysical techinques are simple methods which require no specialist supervision.

With regard to the S.P. method, an orientation survey over the Girlie North shear zone showed that in the Pietersburg region, because of the very dry climate, it is not as rapid as usual (Franey N.J., 1985: An Orientation Self-Potential Survey over the Girlie Claims. Unpubl. rep., Anglo Amer. Prosp. Serv. Ltd., Ref : NEL 85/338). The dry climate necessitates the watering of stations twice, once 45 minutes prior to and once immediately before taking a reading. This is to establish a reasonable depth penetration of water and to provide a good pot-to-ground contact, respectively. At least 3 minutes is also wasted at each station while waiting for the recorded voltage to stabilize, an effect thought to be due to electro-filtration potentials set up by the watering of the stations immediately prior to taking a reading.

This M.Sc. study has revealed the potential for exploration of **petrographic surveys**, which might be especially applicable to areas with poor exposure. The zones of wall rock alteration surrounding the Girlie North shear zone are at least 20m wide and appear to be best developed in the hanging wall. The alteration is easily recognized by the actinolite/tremolite-quartz-clay assemblage and a single thin-section can be classified as altered or unaltered in a matter of minutes. By identifying outcrops that are altered in any particular area, it might be possible to predict the location of shear zones fairly accurately. At the very least, it would be a means of delineating areas to be followed up by in detail.

2. LOCAL STAGE

Soil geochemistry and **lithogeochemistry** are the best exploration techiques to determine if a shear zone is gold-bearing. An orientation soil survey, using a multi-trace element analysis, should be conducted over a known "reef" (eg. Girlie North Reef) to establish which elements can best be used as pathfinders. Gold and As would probably be the best, and these two have already been used with success.

To cut costs and eliminate the problem of sample turn-around time at the laboratory, larger than normal soil samples (± 1kg) have been taken and their Au contents determined by panning (Charles Byron, pers. comm., 1985). Although the absolute concentration of each sample was only estimated, the trained panners were able to grade the samples relatively on a scale from 1 to 5. This method was used successfully to trace reef zones in the Roodepoort goldfield.

One of the main problems of soil geochemistry, especially in a well established goldfield such as those of the Pietersburg belt, is that of contamination. This can only be overcome by a careful interpretation of results based on a detailed map of the area. Also, because many of the potential discoveries now-a-days are represented by blind orebodies, which would only be expected to give rise to subtle anomalies at surface, it is absolutely essential to utilize every possible means of identifying anomalous data. This means that the use of **probability graphs** (as described by Sinclair A.J., 1978 : Application of Probability Graphs in Mineral Exploration. Assoc. Expl. Geochem., Spec. Vol. 4, pp 95) must be a standard procedure for the interpretation of all geochemical surveys.

A detailed lithogeochemical survey of Girlie North Reef (from trench samples) showed that there is a depletion of Au in the oxidized, near-surface environment. The grade of any surface samples should therefore be interpreted with this fact in mind. It is recommended that, on account of the surface depletion, trench samples should always be analyzed by atomic absorption spectroscopy (A.A.) rather than by fire assay (F.A.) because of the lower detection limits of the former. This would be the only way in which to detect a subtle anomaly in a reef zone strongly depleted at surface. The same pathfinder elements as those used in soil sampling programmes should be used in lithogeochemical surveys.

In places where it is impossible to expose bedrock by trenching it may be necessary to assess the gold-bearing potential of a shear zone by **percussion drilling.** An example of such a situation would be where a shear zone extends along a "donga" valley (eg. at the far western end of the Girlie North shear zone). The drillholes should always be aimed to interseet the target shear zone just beneath the oxidized zone to avoid the effects of near-surface depletion. This became obvious on the Pienaar prospect where seven percussion drillholes intersected the main Pienaar shear zone about 20m below surface (ie. still in the oxidized zone). The grades of the chip samples of "reef" were all negligible. A diamond drillhole (PN1) subsequently intersected the "reef" at about 40m below surface (ie. in fresh rock) and visible gold was identified in the core. The average grade of the reef (from two intersections) was 19 g/t x 62cm.

Even if a shear zone is not gold-bearing, it should always be traced along strike to locate any structural complexities which may have controlled the siting of a blind orebody. Any area with this kind of potential should be followed up in particualr detail (eg. a closer spaced soil sampling grid, closer spaced trenches, etc.). The techniques used to trace a shear zone along strike include all of those mentioned above; i.e., mapping, rapid geophysics, petographic surveys, soil geochemistry, and lithogeochemistry; and, at this stage possibly detailed geophysics (e.g., **I.P.** and **E.M.**). I.P. was used to establish the western continuation of the Girlie North shear zone past its intersection with the Good Hope Reef. The aim at this stage of exploration is to produce a detailed (1:500 or 1:1000 scale) geological map of a prospect which can be used as a baseplan for all subsequent exploration.

Apart from grass-roots exploration, this stage of a project would also include the **appraisal of old mines and prospects.** This involves the detailed mapping and sampling of all accessible workings with the aim of predicting extensions which would then require follow-up. Samples from an old mine would only require a Au analysis, but they should be divided into reef and non-reef batches requiring analysis by fire assay and atomic absorption, respectively.

3. DETAILED STAGE

Having established that a shear zone is Au-bearing, the next step of the exploration programme is to investigate its grade at depth, below the near-surface zone of oxidation. This is always done by **diamond drilling** to provide a continuous and intact sample of reef for detailed analysis. The following analytical procedure is recommended :

1. For the reef zone in every drillhole : fire assay for total precious metals (T.P.M.) of geologically defined split-core samples.
2. For the first drillhole on every prospect : a whole rock analysis (a multi-element X.R.F. scan that includes all the major oxides would be most appropriate) of a continuous sample* taken at 2m intervals along the entire length of recovered core, and of the geologically defined samples of (1) above.
3. For any additional drillholes on a prospect : an atomic absorption analysis for Au only of a continuous sample taken at 2m intervals along the entire length of recovered core, and of the geological defined samples of (1) above.

***Footnote** : The continuous sample may consist of a thin slice cut off the drillcore, or a powder ground off it.

By adhering to a systematic system of drillcore analyses such as this, the treatment of results can be standardized. This treatment should include the calculation of ratios, which may define zones of wall rock alteration more clearly than the elements themselves (eg. K/Na and Rb/Sr), and the plotting of histograms for all the data. It is important to represent the data graphically because subtle anomalies and trends are usually unrecognizable in a list of figures. For the handling of a large amount of data a computer is an essential piece of equipment. Of course, this procedure should be modified to suit situations; for example, if it were possible to identify a geochemical wall rock alteration halo around a particular shear zone, the last few metres of core from nearby drillholes should be submitted for whole rock analyses to ensure that the holes were not stopped just short of a similar shear zone that was previously undiscovered.

This same principle applies to the petrographic wall rock alteration that is recognized around the Girlie North Reef. It would take only one thin-section of core from close to the bottom of a hole to determine whether there was a shear zone just ahead of the drill bit. If a microscope and thin-section-making facilities were available in a field camp this could be a useful method to ensure that a drillhole was not stopped prematurely.

4. EVALUATION STAGE

A shear zone gold deposit can normally be defined by detailed diamond drilling, as was the case for the Girlie North Reef. In certain circumstances, however, **underground development** may be the only reliable means of evaluation. These might arise if a shear zone has a particularly erratic grade or is in a very complex structural situation, for example.

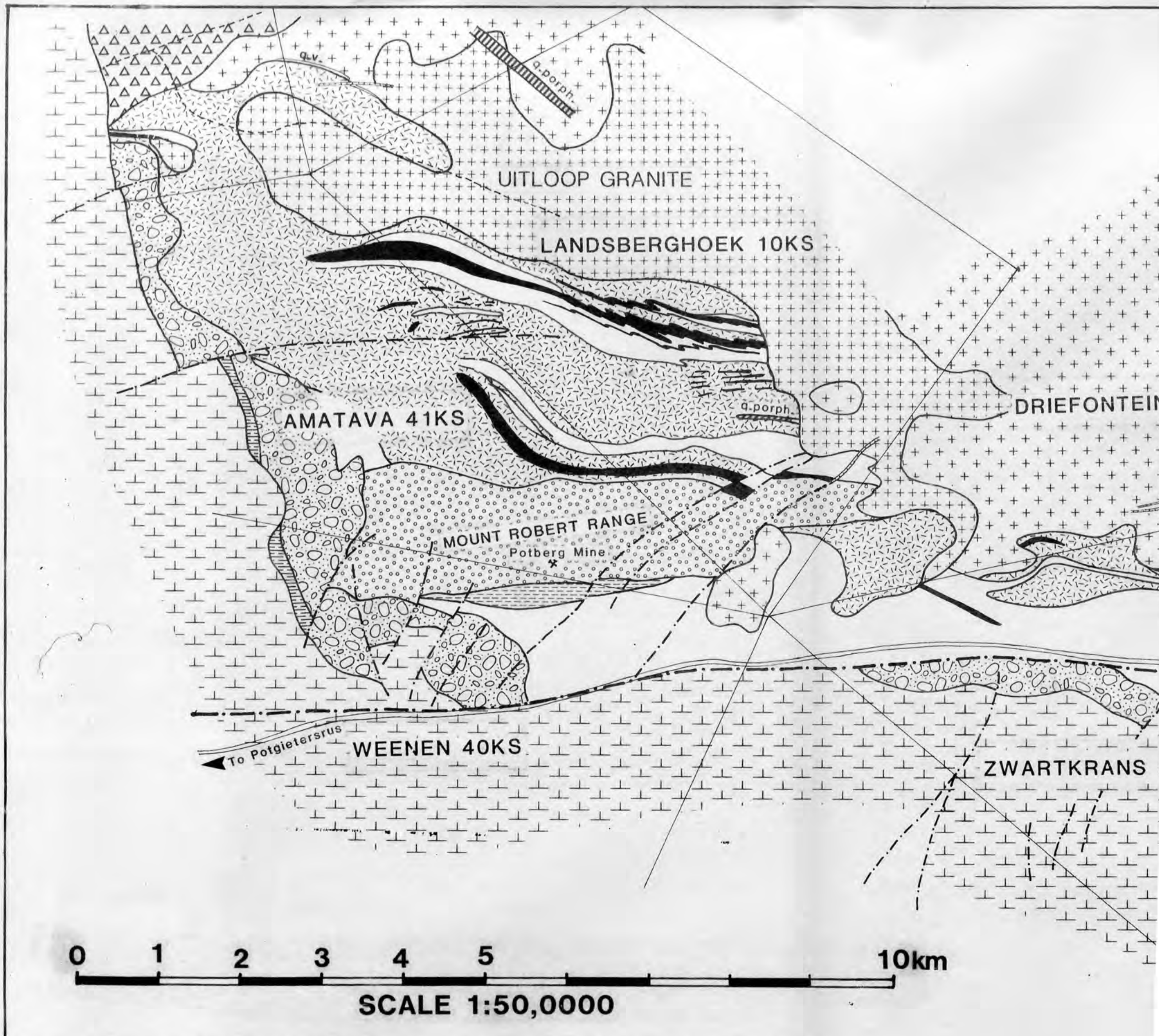
Underground development sampling programmes should be based on the geology, as exposed, and the analytical methods used should be chosen for the information required from each particular sample. It is a good idea to routinely check for anomalous gold, but multi-element scans should not be used indiscriminately along all developments.

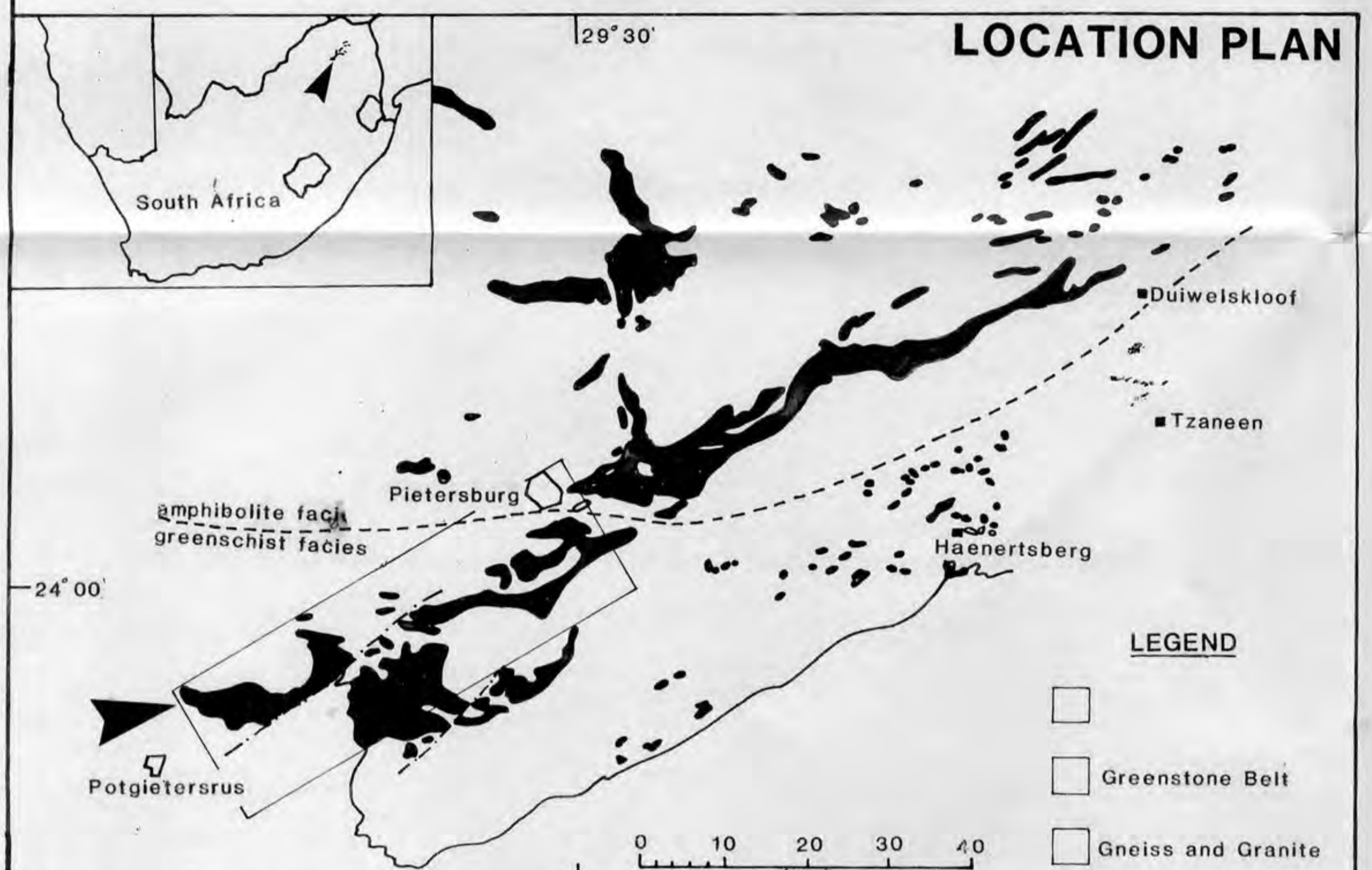
The following table is a summary of the techniques used in the search for shear zone gold deposits.

Summary of exploration techniques used in the search for shear zone gold deposits.

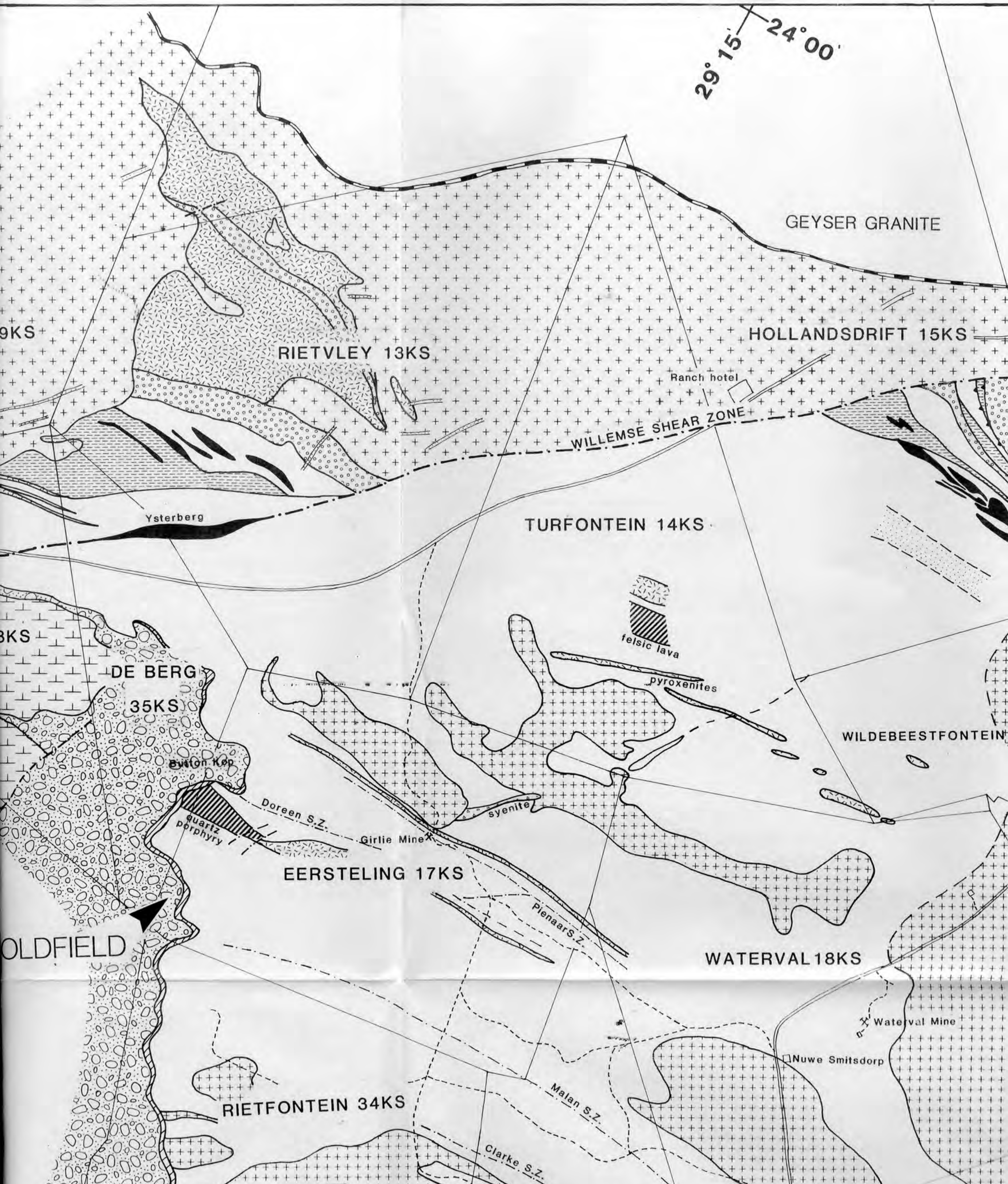
Stage	Technique
Regional	Geological mapping with aerial photographs Magnetic and S.P. surveys Petrographic survey
Local	Soil geochemistry Lithogeochemistry Percussion drilling I.P. and E.M. surveys Appraisal of old mines and prospects
Detailed	Diamond drilling
Evaluation	Underground development

N.B. : Techniques from all early stages may be carried through to subsequent stages.


q.v.
q.porph.
UITLOOP GRANITE
LANDSBERGHOEK 10KS
AMATAVA 41KS
q.porph.
DRIEFONTEIN
MOUNT ROBERT RANGE
Potberg Mine
To Potgietersrus
WEENEN 40KS
ZWARTKRANS
0 1 2 3 4 5 10km
SCALE 1:50,0000


LOCATION PLAN
29° 30'
South Africa
Duiwelskloof
Tzaneen
Pietersburg
amphibolite facies
greenschist facies
Haenertsberg
24° 00'
LEGEND
Greenstone Belt
Gneiss and Granite
Potgietersrus
0 10 20 30 40
(km)

EERSTELING



29°15'
24°00'
GEYSER GRANITE
9KS
RIETVLEY 13KS
HOLLANDSDRIFT 15KS
Ranch hotel
WILLEMSE SHEAR ZONE
Ysterberg
TURFONTEIN 14KS
felsic lava
pyroxenites
3KS
DE BERG
35KS
WILDEBEESTFONTEIN
Button Kop
syenite
Doreen S.Z.
quartz porphyry
Girlie Mine
EERSTELING 17KS
Pienaar S.Z.
OLDFIELD
WATERVAL 18KS
Waterval Mine
Nuwe Smitsdorp
Malan S.Z.
RIETFONTEIN 34KS
Clarke S.Z.
VRISCHGEWAAGD
33KS
To Zebediela
29°15'

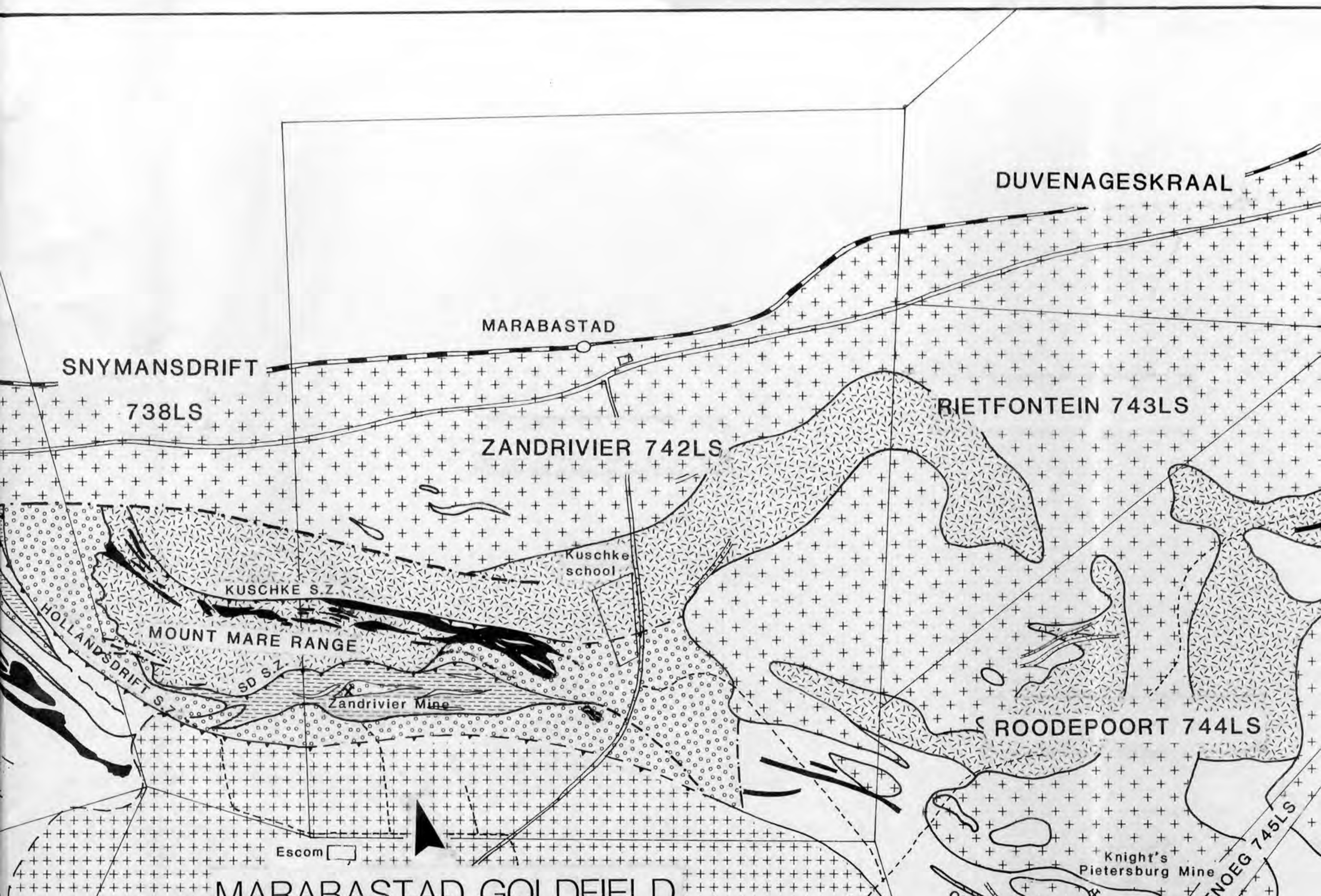
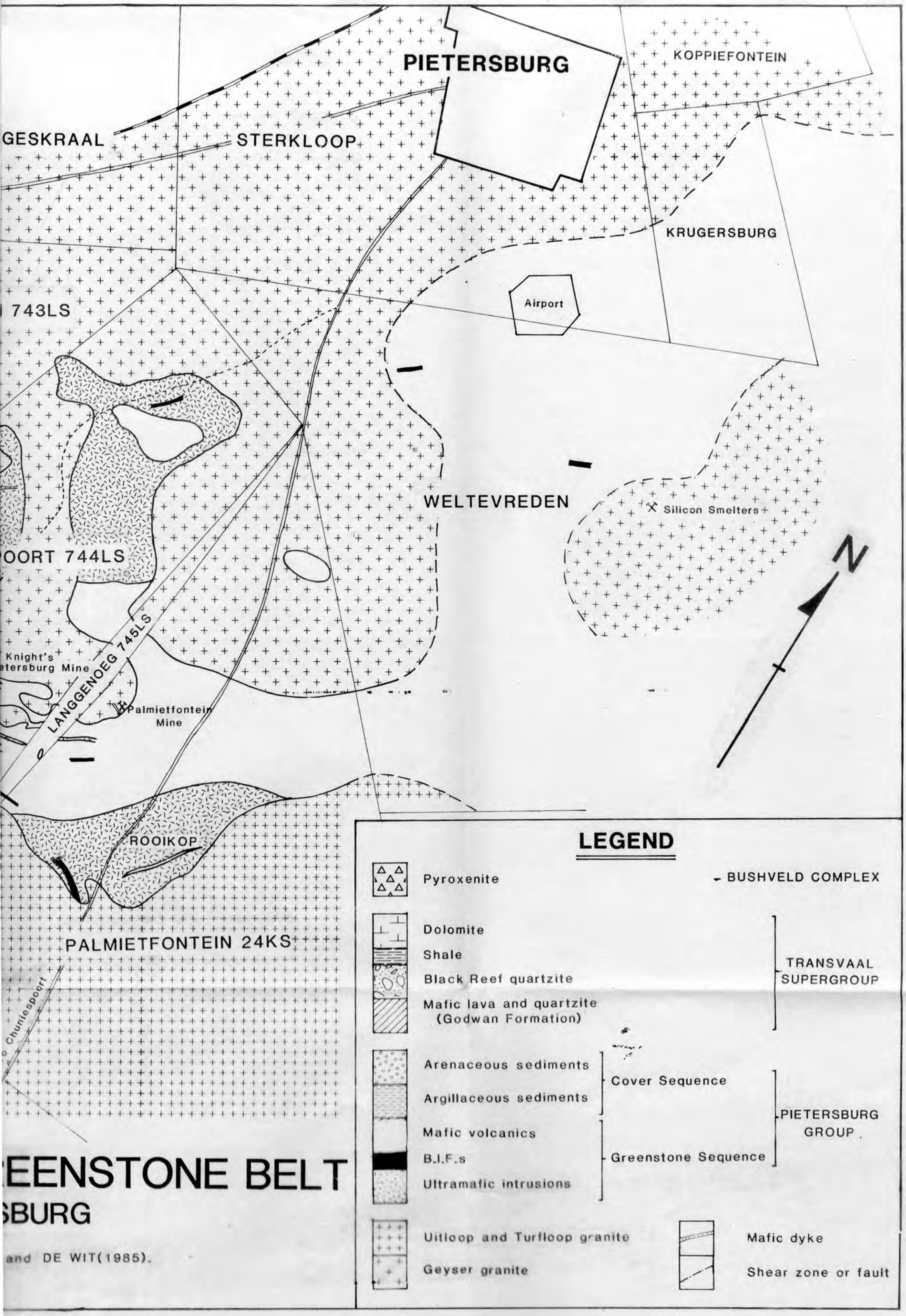


Figure 2.1

GEOLOGY OF THE PIETERSBURG GREENSTO

REGION SOUTHWEST OF PIETERSBURG

Compiled from maps by WILLEMSE(1938), GROBLER(1972), BRANDL(1974), and DE WIT(1985).



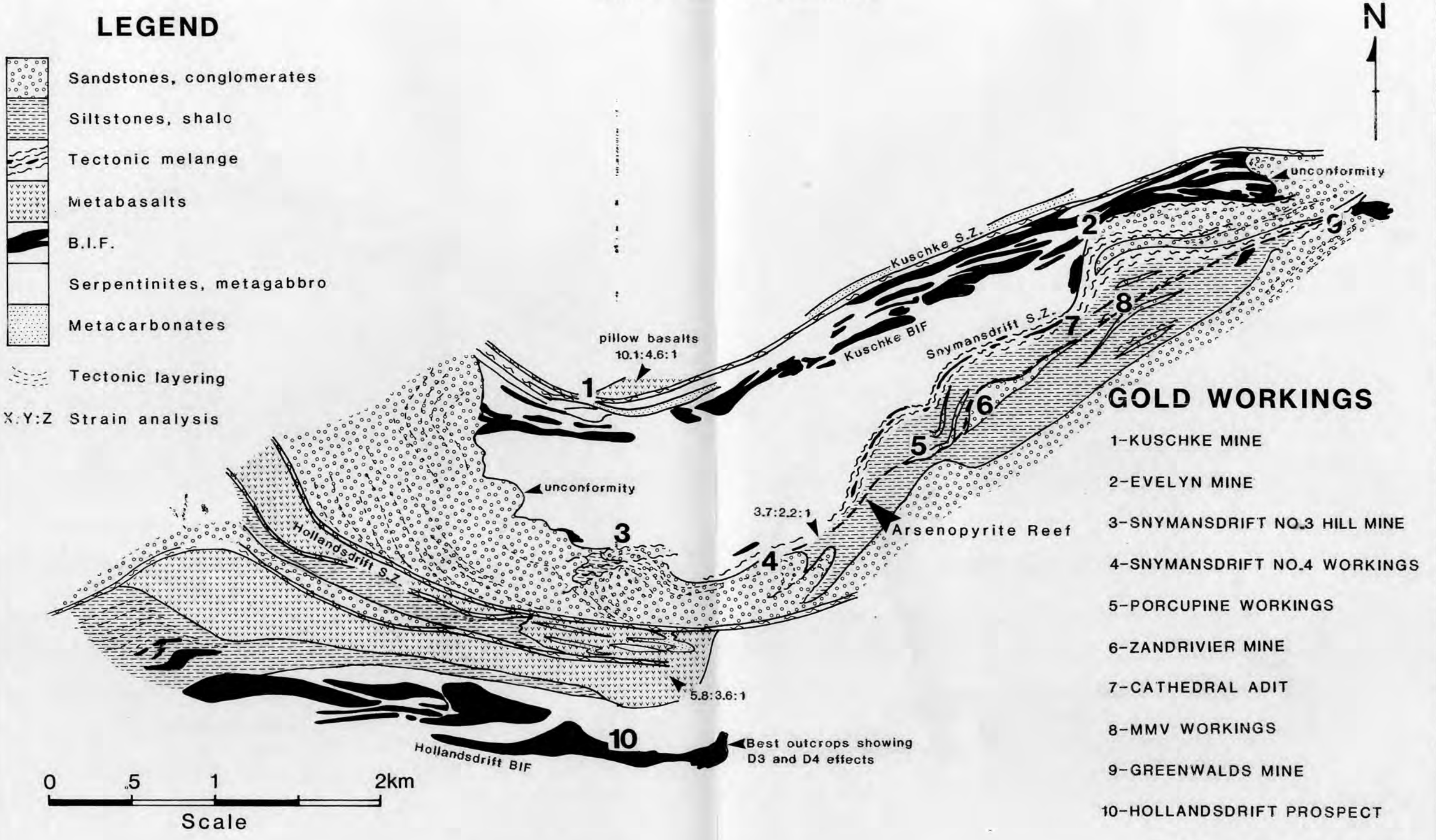
EENSTONE BELT
SBURG

and DE WIT(1985).

Figure 2.2

GEOLOGY OF THE MOUNT MARE RANGE (THE MARABASTAD GOLDFIELD)

Modified from DE WIT(1985)



See Figure 2.1 for location

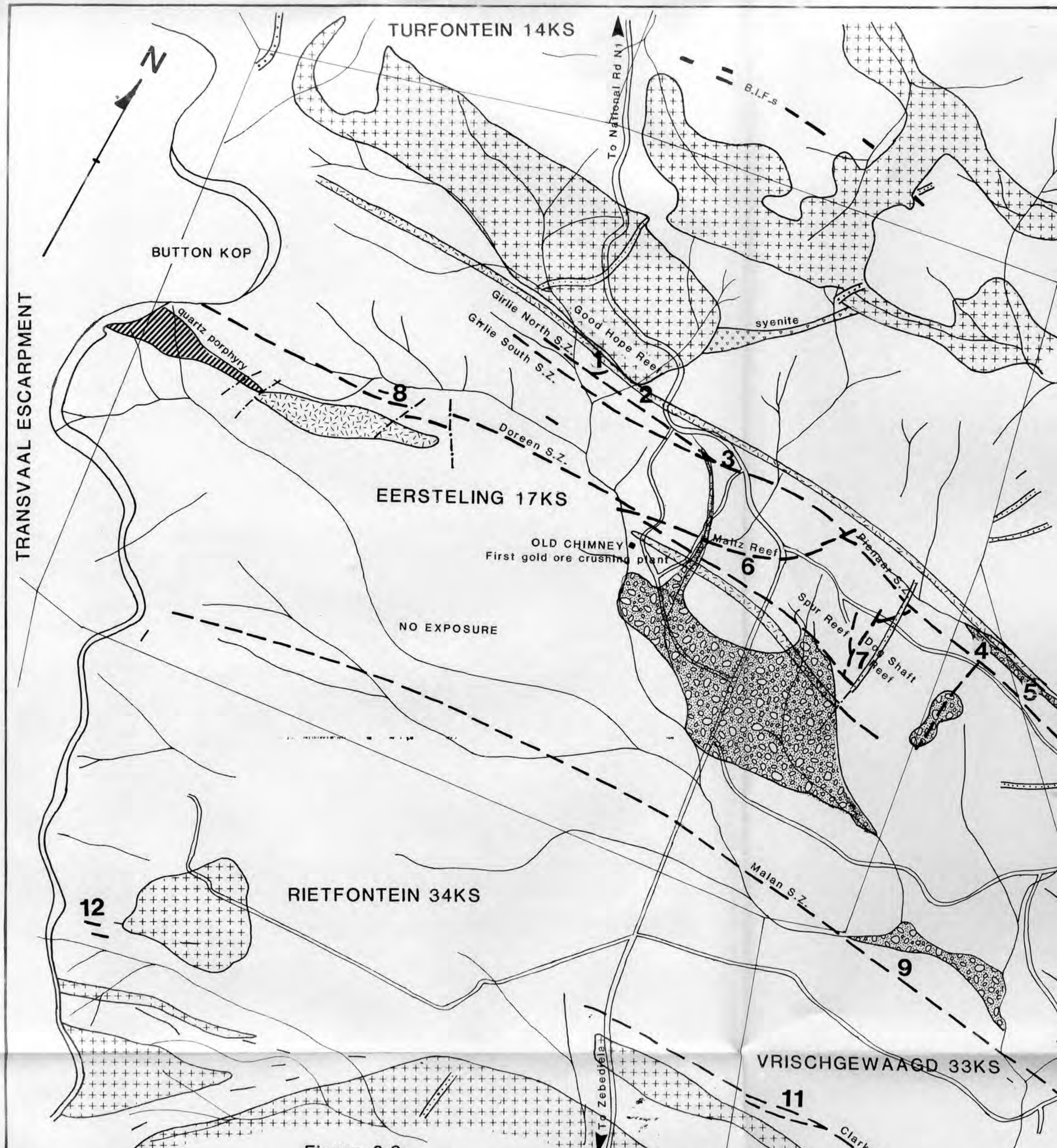
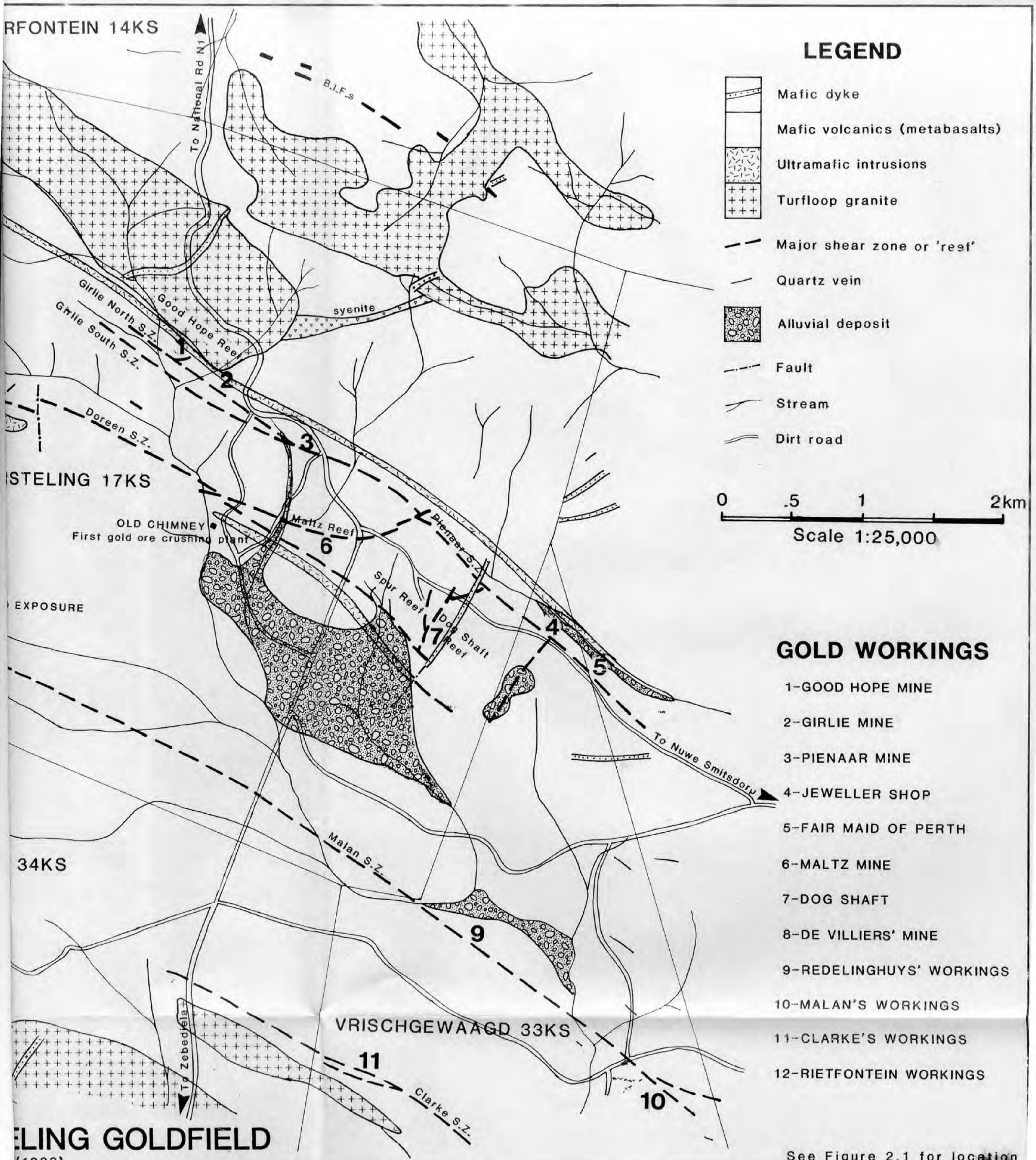


Figure 2.3

GEOLOGY OF THE EERSTELING GOLDFIELD

Modified from WILLEMSE(1938)



ELING GOLDFIELD

(1938)

See Figure 2.1 for location