

Declaration

I declare that this research dissertation is my own work. It is being submitted for the Degree of Master of Science in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

A handwritten signature in black ink, appearing to be 'MR', is written above a horizontal line.

(Signature of candidate)

18TH day of March 2011

Abstract

The area around New Consort Gold Mine (NCGM) is complexly deformed during at least 5 distinct events named $D_{1NC} - D_{5NC}$. $D_{1NC} - D_{3NC}$ events involve progressive shearing and folding linked to the 3250-3225 Ma accretionary history of the Barberton greenstone belt (D_{1NC} and D_{2NC}), and subsequent 3105 Ma emplacement and doming of surrounding batholiths (D_{3NC}). During D_{3NC} the area experienced intense strain partitioning with the development of a network of shear zones, which envelop structural domains characterized by locally unique deformation histories. Around NCGM, D_{3NC} events involved early shearing (D_{3aNC}) along the Consort Bar followed by two episodes of 600m scale folding (D_{3bNC} and D_{3cNC}) resulting in a complex fold interference pattern. Pegmatites intruded during D_{3NC} . D_{4NC} structures comprise a network of extensional brittle-ductile shear fractures and associated kink bands and crenulation folds that formed concomitant with gold mineralization after all the D_{3NC} structures had fully developed, marking a clearly separate event. The D_{4NC} fractures are distributed along 100-200m wide corridors as 10-100m scale, en-echelon, Riedel, anti-Riedel and P-shear arrays. D_{5NC} structures represent late reverse faults of unknown age.

The critical structures controlling gold mineralization are the D_{4NC} fracture zones. The distribution of high-grade ore zones is controlled by the intersection orientation of D_{4NC} fractures and suitable host lithologies, mainly the silicified hinge zones of D_{1NC} folds and the laminated chert of the Consort Bar. Because these host lithologies were complexly folded in D_{1NC} - D_{3bNC} - D_{3cNC} fold interference patterns, the 3-D distribution of ore zones is highly discontinuous and complex.

Kinematics analysis and stress inversion using Bingham tensor solutions and an optimized dihedron method, of mineralized D_{4NC} fractures along old gold workings at NCGM, consistently indicate a vertical σ_1 , and a horizontal NW-SE

directed σ_3 , within a pure extensional stress regime indicating that gold mineralization occurred in an extensional tectonic setting. Results for the nearby Clutha, Albion and Woodstock mines are similar. This study suggests that gold mineralization in the NCGM area can be linked to an extensional event that may have developed separately from the accretionary events shaping the craton and may have coincided with the opening of Dominion Group basins.

Table of Contents

Declaration	i
Abstract	ii
Table of Contents	iv
List of Figures	viii
List of Tables	xvii
1. Introduction	1
1.1 General statement	1
1.2 Study Locality.....	3
1.3 Research Aims and Objectives	6
1.4 Methodology.....	7
1.5 Review of the regional geological setting.....	8
1.5.1 Introduction	8
1.5.2 Stratigraphy.....	10
1.5.2.1 Onverwacht Group	12
1.5.2.2 Fig Tree Group.....	14
1.5.2.3 Moodies Group.....	16
1.5.3 Granitoids of the Barberton Greenstone Belt	19
1.5.3.1 Ancient Gneiss Complex (>3600 Ma)	19
1.5.3.2 Tonalite Trondhjemite-Granodiorite (TTG) Gneiss Plutons (3600 – 3200 Ma).....	20

2.	Structural architecture, tectonic evolution and gold mineralization of the Barberton Greenstone Belt	23
2.1	Introduction	23
2.2	Structural Domains	28
2.2.1	Domain I	29
2.2.1.1	Deformation History	31
2.2.2	Domain II	32
2.2.2.1	Deformation History	32
2.2.3	Domain III	34
2.2.3.1	Deformation History	35
2.2.4	Domain IV	40
2.2.4.1	Deformation History	41
2.2.5	Domain V	45
2.2.5.1	Deformation History	46
2.2.6	Domain VI	46
2.2.6.1	Deformation History	47
2.3	Gold mineralization in the BGB	52
2.3.1	Sheba – Fairview Gold deposits	52
2.3.2	NCGM Gold deposits.....	55
3.	Geology of the New Consort Gold Mine	59
3.1	Onverwacht Group	59
3.1.1	Amphibolite	60

3.1.2	Tremolite-talc schist.....	61
3.1.3	Carbonate-talc-chlorite schist.....	63
3.1.4	Serpentinite	64
3.2	Consort Bar.....	64
3.3	Fig Tree Group.....	65
3.3.1	Greywacke and Shale.....	66
3.3.2	Felsic dacitic tuffs and agglomerates (Schoongezicht Formation)	69
3.4	Moodies Group.....	72
3.4.1	Conglomerate	72
3.4.2	Quartzite	73
3.4.3	Sandstone (Arkose)	74
4.	Structural setting of the NCGM	75
4.1	: D _{1NC} (pre-Moodies upright folding and thrusting)	75
4.2	: D _{2NC} (Post-Moodies upright folding and thrusting)	78
4.3	: D _{3NC} (Development of constrictional shears and folds)	79
4.4	: D _{4NC} (Late kink-folding and normal faulting)	89
4.5	: D _{5NC} (Late stage shear zones).....	98
5.	Palaeo-stress Analyses	100
5.1	Reduced moment tensor (Win-TENSOR)	101
5.2	Bingham distribution tensor (FaultKin Win)	102
5.3	Selection of faults for kinematic analysis.....	105

5.4 Results of kinematic analyses	106
5.4.1 Bingham tensor solutions in FaultKin.....	109
5.4.2 Reduced Moment Tensor method in Win-TENSOR	111
6. Discussion and conclusion	113
6.1 Deformation history	113
6.2 Palaeo-stress analyses.....	118
6.3 Structural controls and 3-D geometry of gold mineralization at the NCGM	119
6.4 Can D _{4NC} gold bearing fractures be associated with the extensional detachment faulting reported in the southern part of the BGB?	120
6.5 Is gold mineralization in the NCGM orogenic or does it post-date orogenic stages?.....	121
7. Acknowledgements	122
8. References	124
Appendix A –Paper published in Cratonic extension and Archaean gold mineralization in the Sheba-Fairview mine, Barberton greenstone belt, South Africa	
Appendix B- Paper submitted for publication: Archaean gold mineralization during post-orogenic extension in the New Consort Gold Mine, Barberton Greenstone Belt, South Africa	

Appendix C - Old gold workings

Appendix D – Structural Data Used

List of Figures

Figure 1.1: Geological map showing rock groups (Onverwacht, Fig Tree and Moodies Groups), plutons, anticlines, synclines, major faults (shear zones) and gold deposits that are found in the Barberton Greenstone Belt (BGB). JSB = Jamestown Schist Belt, SF = Saddleback Fault and IF = Inyoka Fault (after Anhaeusser, 1969).	2
Figure 1.2: Satellite image showing locations of the New Consort (NCGM), Albion, Clutha, Woodstock, Sheba and Fairview gold mines in relation to the Barberton town in Mpumalanga Province, South Africa (http://www.earth.google.com/images).....	4
Figure 1.3: Map showing distribution of rock units, structures, and major gold workings (No. 1-8) in the New Consort Gold Mine area. Grid blocks on the map are 1000m wide (Modified after Viljoen, 1964).	5
Figure 1.4: Stratigraphic columns showing rock groups, formations and their thicknesses, and correlations between rock units in the Northern, Central and Southern parts of the BGB (after Brandl <i>et al.</i> , 2006).....	11
Figure 1.5: Stratigraphic columns showing formations of the Onverwacht, Fig Tree and Moodies Groups. Inserts include estimated thicknesses, plutons, horizon markers and timing of formations (after Ward, 1999 based on work of Viljoen and Viljoen, 1969).	13

Figure 2.1: Structural geology map of the Barberton greenstone belt with inserted terranes and allocthons, and relative transport directions defined by de Ronde and de Wit (1994). The map also shows faults interpreted as shear zones, thrusts faults and strike-slip faults developed during four different phases of deformation. The top right insert diagram shows the locations of Saddleback and Inyoka faults that resulted from accretionary tectonics, which separate the northern and southern terrane of the BGB (after De Ronde and De Wit, 1994).
D₁, D₂ and D₃ mentioned in the figure refer to those in Table 2.1.....25

Figure 2.2: Simplified tectonostratigraphy of the Barberton Greenstone Belt showing groups, formations, horizon markers, plutons and the timing of deformation events within the belt. The age related to gold mineralization has also been inserted (adopted from Brandl *et al.*, 2006 after de Ronde and de Wit, 1994, modified from Armstrong *et al.*, 1990).26

Figure 2.3: Map showing the plutons, synclines (outstanding dots), faults and structural domains I-VI described in the text. The relatively thick solid lines mark major shear zones acting as boundaries between different structural domains. KF- Komati Fault, KRMF-Kromberg Fault, KMF – Kamhlabane Fault, Granville Grove Fault, MBF- Mbema Fault, IF – Inyoka Fault, MF- Moodies Fault, SAF – Saddleback Fault, BF- Barbrook Fault, LF – Lily Fault, SF- Sheba Fault, LF – Lily Fault, AF – Albion Fault, KRF – Kaap River Fault.

(a) = Weergevonden area, (b) = Tjakastad schist belt and (c) = Stolzburg schist belt in the Onverwacht Anticline (Modified from Lowe *et al.*, 1999).30

Figure 2.4: Geological map of the western part of Domain III in figure 2.3.

Abbreviations: P.R.S- Powerline Road Syncline, M.M.S – Maid of the Mist Syncline, E.M.F. – Eucalptus Mill Fault, A.V.F. – Auber Villiers Fault. Teeth structures show the hangingwall of 24-Hour Camp Fault. Lines A-A'', B-B'', C-C'' and N-S are lines of sections that are shown in Figures 2.5 & 2.6 (after Lowe *et al.*, 1999).36

Figure 2.5: Cross sections from section lines shown in figure 2.4. Sections show

tight to isoclinal folds (D_{2}^{III} folds) in the Onverwacht and Fig Tree Group, unconformably overlain by D_{3}^{III} folds in the Moodies Group (after Lowe *et al.*, 1999).38

Figure 2.6 Cross section (N-S) through the Maid of the Mist Syncline (M.M.S)

from Figure 2.4. The D_{2}^{III} tight to isoclinal folds structures in Fig Tree Group are bounded to the north by the 24-Hour Camp Fault, which is folded during D_{3}^{III} . The M.M.S that is composed of Moodies Group in the hanging wall of the fault, represents a typical structure formed during D_{3}^{III} (Lowe *et al.*, 1999).39

Figure 2.7: Geological map of the Sheba Hills, showing tight to isoclinal folds

(F_{1}^{IV}) preserved in the Onverwacht and Fig Tree Groups, which are unconformably overlain by agglomerate and rocks of the Moodies Group folded by F_{2}^{IV} . Inserted top right diagram shows mineralized

fractures of D^{IV}_4 that cross-cut earlier ductile structures (after Dirks <i>et al.</i> , 2009 based on Anhaeusser, 1976).	42
Figure 2.8: Cross-section A-B indicated in Figure 2.7, showing tight to isoclinal folds (F^{IV}_1) in the Fig Tree and Onverwacht Groups, unconformably overlain by the southern limb of the Eureka Syncline (F^{IV}_2). Legend similar to that of figure 2.7 (after Dirks <i>et al.</i> , 2009).....	43
Figure 2.9: Map showing the geology of the Jamestown Schist belt (JSB), plutons, faults and locations of the gold mines in the study area; New Consort, Albion, Woodstock and Clutha Mines. IF = Inyoka Fault, SF = Sheba Fault and LF = Lily Fault (Modified from Ward, 1999; Anhaeusser, 1969; Viljoen, 1964).....	48
Figure 2.10: A mineralized altered porphyry dyke, beneath the pen, that intruded a mineralized shear zone, above the pen, at the Nil Desporandum Mine in the Sheba area (Fig. 2.7; GR 311515 - 7155284).	54
Figure 2.11: A sample of the quartz porphyry dyke from Fairview Mine, which was dated by de Ronde <i>et al.</i> (1991) at 3126 ± 18 Ma.....	55
Figure 2.12: Map showing trends of major faults, e.g. Ivaura and MMR Faults, and ore shoots, which have been projected from underground workings in the NCGM. Grid spacing is a 1000 meters. (adjusted from Voges, 1986).	56

Figure 3.1: Foliated amphibolite occurs in the lower part of the Weltevreden Formation, preserved in the northern NCGM area. Quartz-plagioclase aggregates make up the white bands (GR 307206-7162465).	61
Figure 3.2: Thin section from what is known as the Footwall Lens. Minerals include tremolite (trm), hornblende (hbl), pyroxene (pyrx), plagioclase (plag), biotite (btt) and quartz (qtz).....	62
Figure 3.3: Carbonate-talc schist showing kink-folded S0 (foliation) crosscut by extensional shear fractures filled with magnesite. Outcrop occurs along a rail-line to the south of the Kaap River Fault (GR 307970-7159190).	63
Figure 3.4: A silicified, mylonitised and lineated Consort Bar, which marks the contact between the Onverwacht and Fig Tree Groups (GR 37288-7162072). White dotted lines are parallel to mylonitic stretching lineations in the Bar.	65
Figure 3.5: Greywacke showing bedding plane (S0) crosscut by chert-rich veins (GR 307513-7161014).	66
Figure 3.6: A shale unit of the Fig Tree Group occurs with a sharp contact with tremolite-talc schist of the Onverwacht Group, around No. 3 Shaft, east of the NCGM (GR 305493-7161575). Cleavage planes (S1) in the shale unit are almost parallel to the bedding plane (S0).	67
Figure 3.7: Garnet bearing greywacke unit interbedded with chert-rich units (GR 307523-7161049).	68

Figure 3.8: Coarse- to medium-grained felsic dacitic tuff, which comprises the lower part of the Schoongezicht Formation (GR 307958-7161315).	69
Figure 3.9: Agglomerate of the Schoongezicht Formation composed of dacitic clasts and dark grey tuffaceous matrix (GR 305466-7161270).	70
Figure 3.10: Deformed agglomerate showing elongated and lenses-like dacitic clasts (GR 307879-7160258).	71
Figure 3.11: A polymictic conglomerate of the Moodies Group, consisting of flattened quartz and chert pebbles in a medium-grained sandy matrix (GR 305437-7161281).	72
Figure 3.12: Alternating quartzite and shale units, which overly the conglomerate of the Moodies Group (GR 305290-7161340).	73
Figure 4.1: Map of the NCGM area showing anticlines, synclines and fold axial traces formed during the main deformation events described in the text. Lithology as indicated in Figure 1.3, and grid spacing is 1000 meters.	76
Figure 4.2: (a) Consort Bar consists of silicified vein-quartz and shale fragments (GR 307500-7161392); (b) An example of a bedding (S_0) - cleavage (S_{INC}) relationship in greywacke of the Fig Tree Group in the NCGM area (GR 307514-7161018).	78
Figure 4.3: Map of the triple junction between the JSB and the BGB showing a network of major D_{3NC} shear zones, and associated orientations of mylonitic lineations (L_{3aNC}) indicated by arrows and plunge angles. Solid daggers are placed in the block that is moving up.	80

Figure 4.4: A typical example of a D_{3aNC} shear zone in the NCGM area. The shear zone marks the contact between the Onverwacht greenstones and the overlying Fig Tree shale. Consort Bar and intruded, mylonitised pegmatite characterises the shear zone (GR 307280-7162207).	81
Figure 4.5: (a) Mylonitised Consort Bar intruded by mylonitic to (b) folded ultra-mylonitic pegmatite (GR 307385-7162560)	81
Figure 4.6(a-f): Thin sections, viewed under cross polars light, of a mylonitised pegmatite along the sheared Consort Bar (GR 307258-7162074). Mineral constituents include deformed grains (porphyroclasts) of plagioclase, quartz, microcline, biotite, muscovite and sericite. Porphyroclasts show a top to the NW sense of movement along some parts the Consort Bar, and is consistent with the movement also indicated by mica-fish and S-C structures elsewhere.	82
Figure 4.7: Map showing the dome-crescent-mushroom (Type 2) fold interference pattern. Orientation diagrams are presented of folded shear planes (S_{3aNC}) and mylonitic lineations (L_{3aNC}) developed during early stages of D_{3NC} (see text for full explanation). The fold axial plane (S_{3bNC}) and fold axis (F_{3bNC}) are indicated, deduced from D_{3bNC} , and S_{3cNC} and F_{3cNC} from the D_{3cNC} folds. A and B represent major structural domains symmetric about the S_{3cNC} planes of the D_{3cNC} fold, and 1, 2 and 3 indicate sub-domains defined along axial planes (S_{3bNC}) of D_{3bNC} fold, such that A1, A2, A3 and B1, B2, B3	

represent limbs of folds, with the respective orientation data
presented as Schmidt lower hemisphere projections.84

Figure 4.8: Schmidt lower hemisphere projections showing (a) orientations of
fold axes collected from a zone (GR 307700-7161500) that records
interference between D_{3bNC} , and D_{3cNC} folds, and (b) orientation of
pebble elongation L_{3cNC} collected from agglomerate and
conglomerate in the core of a D_{3cNC} fold.86

Figure 4.9: Deformation structures associated with D_{3cNC} in the NCGM area.
Open D_{3cNC} folds in the (a) Schoongezicht Formation, (b, c)
conglomerate of the Moodies Group (GR 307875-7160201); (d)
Elongated conglomerate pebbles in Moodies Group, defining L_{3cNC}
(GR 305437-7161281).87

Figure 4.10: Deformation structures associated with D_{4NC} event; (a) D_{4NC} kink
folds crosscut by D_{4NC} brittle-ductile shear fractures (GR 307970-
7159190); (b) A mineralized, D_{4NC} shear zone, cross-cuts steeply
dipping sandstone (see Figures 1.3 for old workings locations); (c)
Mineralized D_{4NC} shear zone (SZ) cross-cutting talc-schist in the
Albion Gold Mine (GR 302120-7160337); (d) D_{4NC} shear fractures
crosscut the complexly folded Consort Bar, gold workings have been
developed parallel to the fractures (GR 307348-7162505).90

Figure 4.11: Slickensided surface with quartz fibre growth on a D_{4NC} fault
indicating a normal sense of movement (a) (MRC ore body at 24
level in Sheba Mine) and (b) Mine Manger quarry in the NCGM area.91

Figure 4.12: Map of the Mine Manager Quarry found in the most-eastern part of the ENE corridor. The quarry has been mainly developed in the complexly folded Consort Bar. Inserts include plot of mineralized fractures and averaged trends of $\sigma_{\min. \text{ horizontal}}$ (open arrows) and $\sigma_{\max. \text{ horizontal}}$ (closed arrows).	94
Figure 4.13: Map of WNW, NNW and ENE mineralized corridors constructed from mineralized brittle-ductile shear fractures found in NCGM gold workings. (a) Schmidt lower hemisphere projection plots indicating mineralized fracture planes with arrows showing direction of hanging wall displacement, (b) stress diagrams indicating averaged trends of $\sigma_{\min. \text{ horizontal}}$ (open arrows) and $\sigma_{\max. \text{ horizontal}}$ (closed arrows) and (c) Results of fault slip inversions for palaeo-stress shown as ‘beach balls’ (grey areas for tension dihedrons).	95
Figure 4.14: Maps showing mineralized corridors, gold workings and brittle-ductile shear fractures that are found in Clutha, Woodstock and Albion Mines, maps show 100m grid spacing. (a) Schmidt lower hemisphere projection plots indicating mineralized fracture planes with arrows showing direction of hanging wall displacement, (b) stress diagrams indicating averaged trends of $\sigma_{\min. \text{ horizontal}}$ (open arrows) and $\sigma_{\max. \text{ horizontal}}$ (closed arrows) and (c) Results of fault slip inversions for palaeo-stress shown as ‘beach balls’ (grey areas for tension dihedrons).	97

Figure 4.15: One of the ore zones of the Albion Gold Mine. The red lines outline the steeply dipping shear fractures associated with mineralization and black lines show the traces of shallowly dipping fractures. The white lines outline the relationship between the S and C fabrics. The half arrows indicate the deduced sense of movement based on both S-C fabrics and shear fractures characteristics.99

Figure 5.1: Schmidt lower hemisphere projections showing the results of the reduced moment tensor method using Win-TENSOR (Delvaux and Sperner, 2003). For all sites a plot of the fault planes and slip vectors is provided together with the orientation of the principle stress axes (S1 – S3), the principle horizontal ($\sigma_{\text{min. horizontal}}$ = open arrows; $\sigma_{\text{max. horizontal}}$ = closed arrows) and a histogram of deviation angles (α). A measure of the input data quality (QRw and QRt), stress regime R and homogeneity of the dataset (F5) is also presented. Locations of gold workings are shown in Figure 1.3. Results are presented Tables 5.1 and summarized in Table 5.3.103

List of Tables

Table 2.1: Summary of the major geological events affecting the Barberton greenstone belt (after de Ronde and de Wit, 1994), with a comparison to more locally relevant deformation schemes proposed by Lowe *et al.* (1999), Dirks *et al.* (2009), Anhaeusser (1976), Viljoen (1964),

Tomkinson and Lombard (1990) and Harris <i>et al.</i> (1995). To prevent confusion, the subscript “NC” for ‘New Consort’ has been added to the deformation scheme proposed in this study.	27
Table 4.1: Stereoplots of D _{4NC} mineralized brittle-ductile shear fractures and associated mineral lineation from individual mines that are found in the NCGM area (Fig. 1.3).	92
Table 5.1: Results of fault-slip inversions for palaeo-stress shown as ‘beach balls’ (grey areas for tension dihedrons), and as stress diagrams ($\sigma_{\min.}$ horizontal = open arrows; $\sigma_{\max.}$ horizontal = grey arrows). Detailed results are listed in Tables 5.2 and 5.3.	107
Table 5.2: Summary of results from fault slip inversion for palaeo-stress by calculating a linked Bingham fault plane solution using FaultKin (Allmendinger, 2001). Eigenvalues (ev) for the calculated moment tensors have been used to obtain a stress ratio ($Rev = [ev2-ev3]/[ev1-ev3]$)., (σ) represents stress axes and Rev' is an adjusted stress ratio (see text for explanation) to estimate the stress regime. Refer to Figures 4.13 and 4.14 for localities of mineralized corridors.	110
Table 5.3: Summary of results from fault slip inversion for palaeo-stress by using the optimized, iterative, right dihedral approach in TENSOR after Delvaux and Sperner (2003). ‘nt’ is the total number of measurements; ‘n/nt’ the percentage of measurements used in the final calculation and (σ) represents stress axis. The average deviation angle (α), standard deviation and maximum slip deviation angle	

(Max.) are given together with an indication of data quality (QRw),
stress ratio (R) and stress regime (R'). See text for explanation.112

1. Introduction

1.1 General statement

Lode gold deposits are an important type of gold mineralization found in orogenic settings distributed world-wide and through time (e.g. Goldfarb *et al.*, 2001). They are structurally controlled, have been linked to second-order structures near major brittle-ductile shear zones (Condie, 1981; Groves *et al.*, 1998; Robb, 2004), and are common in Archaean greenstone belts (Condie, 1981; Robb, 2004). The formation of lode gold deposits has been linked to tectonically active plate boundary zones (Groves *et al.*, 1998; Goldfarb *et al.*, 2001), with controlling thrusts and strike-slip faults formed in accretionary settings (Lowe, 1994; de Ronde and de Wit., 1994). Mineralized shears are commonly reactivated repeatedly to give rise to complex mineralization patterns (Sibson, 2001, 2004).

The 3.6-3.1 Ga Barberton Greenstone Belt (BGB) in the Kaapvaal Craton of South Africa (Fig. 1.1), is a typical example of an Archaean greenstone terrane interpreted as an accretionary arc sequence (e.g. de Ronde and de Wit, 1994), hosting numerous gold deposits (Fig. 1.1; Anhaeusser 1969, 1976; Ward 2000). Since 1885, the belt has produced more than 345 tons of gold (Dirks *et al.*, 2009), leaving behind numerous old workings, pits and shafts providing excellent outcrops for detailed studies on mineralization controls. Gold in the BGB has been linked to large accretionary thrust zones that were reactivated as brittle-ductile, strike-slip faults and thrusts during the emplacement of large granite plutons such as the 3106 Ma Nelspruit Batholith (Anhaeusser, 1976; de Ronde and de Wit., 1994; Harris *et al.*, 1995; Ward 2000), presumably during the last accretionary stages of the BGB (de Ronde and de Wit., 1994). In contrast, Dirks *et al.* (2009) and work presented in this thesis show that mineralization in the Sheba-Fairview-New Consort area, including the world class Sheba and Fairview deposits, was controlled by a network of normal brittle-ductile shear fractures / faults that formed in an intra-cratonic, post-orogenic, extensional environment. Dirks *et al.* (2009) suggest that these controlling brittle-ductile shear fractures were related to the opening of

intracratonic basins, which post-date the accretion period of the greenstone sequence (see Appendix A).

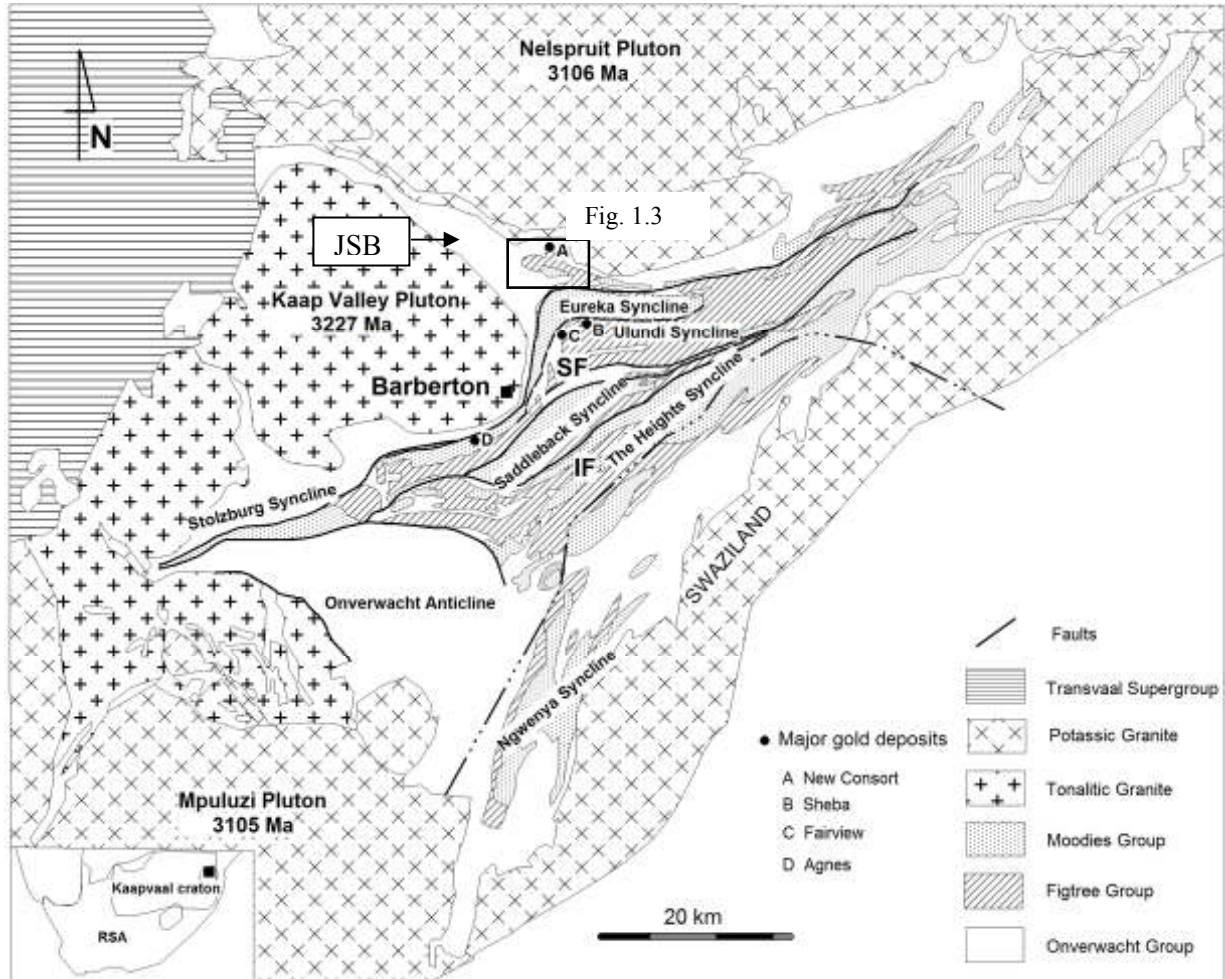


Figure 1.1: Geological map showing rock groups (Onverwacht, Fig Tree and Moodies Groups), plutons, anticlines, synclines, major faults (shear zones) and gold deposits that are found in the Barberton Greenstone Belt (BGB). JSB = Jamestown Schist Belt, SF = Saddleback Fault and IF = Inyoka Fault (after Anhaeusser, 1969).

The bulk of gold mined in the BGB comes from four mines: Agnes, New Consort, Fairview and Sheba Gold Mines (Fig. 1.1), which collectively produced 80% of all gold mined in the BGB (Dirks *et al.*, 2009). The New Consort Gold Mine (NCGM), which forms the focus of this study is located in a triple junction area, where greenstones of the

Jamestown Schist Belt (JSB) merge with the main BGB (Fig. 1.1). Gold mineralization in the NCGM is generally high grade (12-15g/t), and ore zones are complex and commonly discontinuous, and affected by several generations of overprinting folds, brittle-ductile shear zones, faults and pegmatite intrusions, all of which influenced the ore body geometry (e.g. Viljoen, 1964; Anhaeusser, 1976; Voges, 1986; Harris *et al.*, 1995). This complexity has made mine-scale predictive modelling extremely difficult. As a contribution towards establishing a feasible mine model, this research is aimed at constraining the geometry of ore bodies, by establishing the structural controls of gold mineralization in the NCGM. The results of this research are presented in this thesis and have been submitted to the South African Journal of Geology for publication (Appendix B).

1.2 Study Locality

The New Consort Gold Mine (NCGM) is one of four currently operating gold mines in the BGB (Fig. 1.1). It is located 15 kilometers north of Barberton and 3 kilometers north of the Noordkaap railway siding in Mpumalanga Province, South Africa (Fig. 1.2; Voges, 1986). The research studies were conducted on surface outcrops focussing on old gold workings that are scattered in the hills around the NCGM area. These workings are in a form of shafts, adits, tunnels, and shallow and deep pits. Many of these workings are accessible and contain mineralized zones, which are clearly observed in stopes left behind as pillars for support purposes during former mining activities. Mine adits and pits are generally developed parallel to these mineralized zones.

Gold workings considered in the NCGM area during the course of this research are mainly found in the northern and central parts of the mine area. These include, from north to south, MMR, MMR South, Bluejackets, Mine Manager, Betty, Witkoppies, PC, Hard Cash, Hand Cash and No. 1, 3 and 6 Shafts (Fig. 1. 3; Appendix C). Gold workings considered outside the NCGM area include those that are found in the Woodstock, Clutha and Albion Gold Mines (Fig. 1.2).

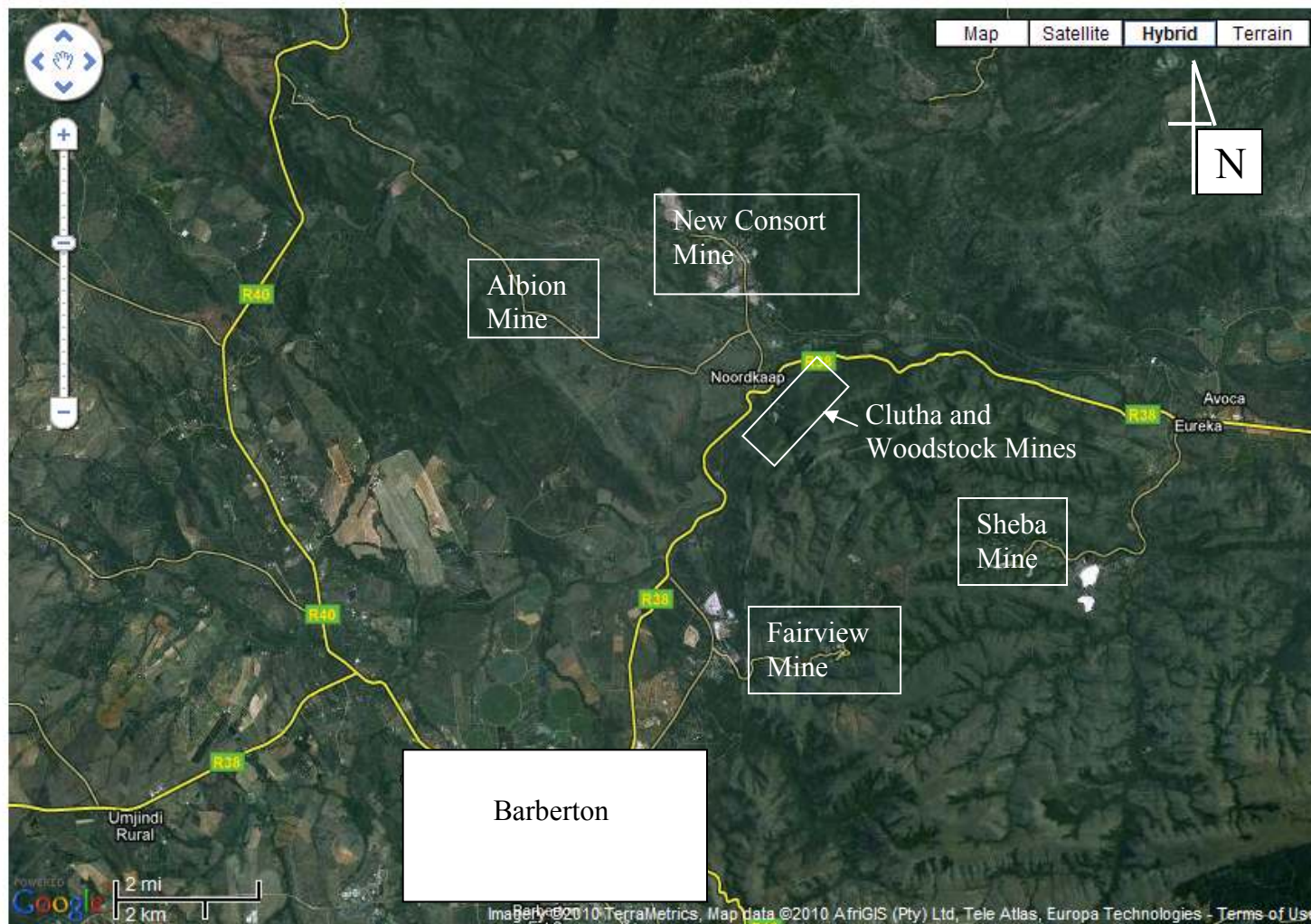


Figure 1.2: Satellite image showing locations of the New Consort (NCGM), Albion, Clutha, Woodstock, Sheba and Fairview gold mines in relation to the Barberton town in Mpumalanga Province, South Africa (<http://www.earth.google.com/images>).

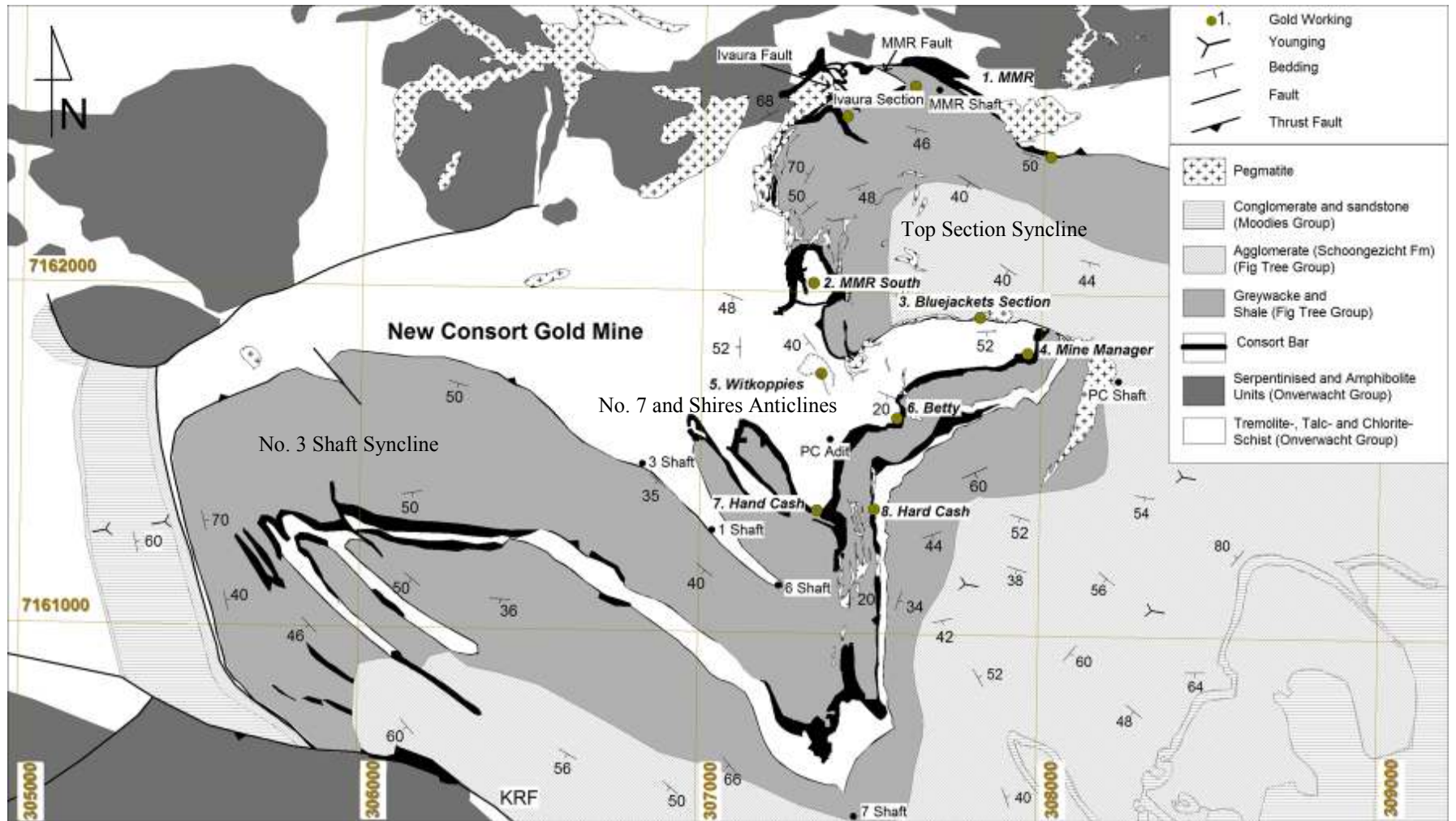


Figure 1.3: Map showing distribution of rock units, structures, and major gold workings (No. 1-8) in the New Consort Gold Mine area.

Grid blocks on the map are 1000m wide (Modified after Viljoen, 1964).

1.3 Research Aims and Objectives

In the NCGM area, gold has been structurally linked to thrusts and strike-slip faults associated with the Shires Shear Zone (SSZ) that developed in an orogenic environment (Viljoen, 1964; Voges, 1986; Tomkinson and Lombard, 1990; Harris *et al.*, 1995; Otto *et al.*, 2007). This link between gold deposits and orogenic structures has been interpreted to conform to regional interpretation by de Ronde and de Wit (1994), linking gold deposits in the belt with accretionary shear zones. In the past, similar orogenic structures were linked to the gold deposits in the Sheba area, south of NCGM (Anhaeusser, 1976).

The aim of this study is to investigate and test, in the NCGM area, the previously proposed structural controls of gold mineralization and associated tectonic environment under which they were formed. The investigation has been established in the Sheba area, where results have been published in Dirks *et al.* (2009) (Appendix A). The following objectives for the NCGM area were set in this study:

- To provide a detailed analysis of the structural history of the NCGM area, focussing on the sequence of ductile and brittle-ductile deformation events that resulted in the complex architectural framework hosting mineralization.
- To compare structures that controlled gold mineralization in the NCGM with those in the surrounding areas such as Albion, Woodstock, Clutha and Sheba Mines.
- To conduct kinematic studies of mineralized shear zones to determine the nature of the palaeo-stress environment during which the shears were infiltrated by gold-bearing fluids.
- To test the hypothesis that the NCGM mineralization is controlled by a late tectonic fracture system, which occurs as en-echelon arrays of riedel and anti-riedel shear systems, rather than earlier orogenic structures.
- To constrain the tectonic setting for gold mineralization.

1.4 Methodology

The aims of the project were achieved through detailed surface geological mapping conducted in the NCGM area. Prior to the mapping of the NCGM area, geological mapping was conducted in the Sheba area, which is characterized by gold deposits that are similar to those in the NCGM area, but underlain by less complex folded basement geology. Sheba mapping was aimed at understanding the structures that controlled gold mineralization in the area (Dirks *et al.*, 2009). Geological mapping of the NCGM area was done concurrently with a literature review of pre-existing data, which include information on structural geology, metamorphism and mineralization in the NCGM and the entire BGB. Various sources including the GIS unit at the University of the Witwatersrand, Johannesburg, South Africa, were accessed for pre-existing data sets such as both structural and lithological maps. The NCGM geological database, which includes maps and Anglovaal reports containing information about the nature of ore bodies, were also accessed.

Detailed mapping of the NCGM involved analysing the complex deformation history preserved in the area. Geological structures produced by different deformation events were identified and structures of the same event were grouped. Overprinting relationships and available geochronological data were used to group structures into deformation events. This classification of geological structures enabled the identification of the structures or mineralized shear fractures that controlled gold during mineralization processes. These mineralized fractures zones are well exposed in old gold workings, which are scattered in the hills around the NCGM area, as shafts, adits and open cast workings. In places, gold workings have been mapped in detail outlining fracture zones that are associated with gold.

The mineralized zones observed in stopes commonly contain discrete shear fractures, which contain slickensided surfaces. These surfaces were used for fracture kinematic studies, aimed at determining the sense of movement and the types of fractures or faults that host gold mineralization.

Fault kinematic studies were coupled with palaeo-stress studies to constrain the type of tectonics that governed the mineralization process. The techniques used in fault slip analysis and palaeo-stress reconstruction in these studies, are largely based on the early work of Angelier (1989, 1994) and subsequently modified by Allmendinger (2001, 2002) and Delvaux (2009, 1993). Investigations were carried out using stress inversion techniques, which allow the input of fault kinematic data such as orientation of the fault plane, slip direction and sense of movement. The techniques give an output of moment tensors with calculated orientations of stress axes, which can be used to determine tectonic environments linked to the input data.

FaultKin tensor by Allmendinger (2001) and WIN-TENSOR by Delvaux (1993, 2009) are the two different stress inversion computerised programmes, which have been used in this research to determining the averaged stress axes associated with mineralized structures in the NCGM and surrounding areas.

Other computerised programmes used in this research include MapInfo (v.9.5), which was used to generate geological maps that have been presented in this report. A Garmin, etrex GPS was used in collecting reference points presented as XY coordinates. These coordinates have been given in UTM, WGS, 84, southern hemisphere, zone 35.

1.5 Review of the regional geological setting

1.5.1 Introduction

The BGB is located south to southeast of Nelspruit in Mpumalanga Province, South Africa, covering a surface area of approximately 7000 km² of the Kaapvaal Craton (Anhaeusser, 1969; Ward, 1999) (Fig. 1.1). The belt, dated between 3600 - 3100 Ma, is composed of ultramafic- to mafic-, meta-volcanic and clastic supracrustal rocks that are surrounded by intrusive granitoid bodies (Viljoen, 1964; Anhaeusser, 1976; Ward, 1995, 1999). These supracrustal rock units have been interpreted to represent the remnants of early oceanic and continental crust (Viljoen and Viljoen, 1969; Condie, 1981; Lowe and Byerly, 2007). The granitoids have been classified into two groups; the trondhjemite-

tonalite-granodiorite (TTG) group and granite-monzonite-syenite (GMS) group (Lowe and Byerly, 2007). The supracrustal units and the GMS typically form high relief mountainous landscapes in contrast to the relatively flat-lying shallow areas underlain by the TTG bodies in the belt (Lowe and Byerly, 2007).

The BGB is a strongly deformed dome and keel-like structure that is 130 kilometers long, striking in a north-easterly direction (Fig. 1.1; Anhaeusser, 1964). Geophysical evidence shows that the belt is about 8 kilometres in thickness (de Beer *et al.*, 1988). The keel preserves a triangular outcrop pattern in the southern part of the belt attaining a maximum width of 51 kilometres, and tapers to 8 kilometres in the far north-eastern part of the belt (Fig. 1.1; Anhaeusser, 1964, 1976).

The keel structure is made up of a series of north-northeast trending open synformal and tight-antiformal structures that are separated by faults (Anhaeusser, 1969; Lowe *et al.*, 1999). Typical example of synclinal structures include Eureka, Ulundi, Stolzburg, Saddleback, The Heights, and Ngwenya Synclines (Fig1.1; Lowe *et al.*, 1999).

The bounding faults have been interpreted as thrusts that were commonly reactivated as strike-slip faults during later events (Anhaeusser, 1976; de Ronde and de Wit, 1994; Lowe *et al.*, 1999). These faults bound terranes, which are characterized by different deformational and metamorphic histories (Lowe *et al.*, 1999). A typical example is the Inyoka-Saddleback fault system, which divides the belt into a northern and a southern terrane, which are characterized by different stratigraphic, structural and metamorphic histories (de Ronde and de Wit, 1994; Lowe and Byerly, 1999; Lowe *et al.*, 1999).

In constraining the structural history of the belt, de Ronde and de Wit (1994) proposed a scheme of four regional deformation events, considered to represent a structural framework for the belt. More recent research has added few adjustments to the proposed structural framework of the belt (Lowe *et al.*, 1999; Schoene *et al.*, 2008; Dirks *et al.*, 2009).

Associated with the four deformation events are three episodes of metamorphism of which regional or burial metamorphism, characterized by greenschist-amphibolite facies assemblages, is the dominant (Cloete, 1999; Diener *et al.*, 2006). The belt is rich in gold, which has been structurally linked to brittle-ductile structures developed during the deformation history of the belt (de Ronde and de Wit, 1994; Dirks *et al.*, 2009). Other mineral deposits in the belt include barite, haematite, chrysolite, asbestos, cinnabar, magnesite, talc, stibnite and verdite (Voges, 1986; Ward, 1999).

1.5.2 Stratigraphy

Stratigraphically, the Archaean rocks exposed in the BGB are collectively known as the Barberton Supergroup (SACS, 1980; Brandl *et al.*, 2006). The supergroup has been dated the oldest in South Africa and is composed of three groups, which, from oldest to youngest, are the Onverwacht, Fig Tree and Moodies Groups (Fig. 1.4) (Visser, 1956; Viljoen and Viljoen, 1969; SACS, 1980; Brandl *et al.*, 2006). The Onverwacht Group forms the base of the stratigraphic sequence and consists of ultramafic- to mafic-lavas and chert (Visser 1956; Viljoen and Viljoen, 1969; Lowe and Byerly, 1999, 2007) (Fig. 1.4).

The Fig Tree Group, which partly conformably overlies the Onverwacht Group, is composed of meta-sedimentary rocks such as greywacke and shale, and volcanic units (Viljoen and Viljoen, 1969; Anhaeusser, 1969; Kohler and Anhaeusser, 2002; Lowe and Byerly, 1999) (Fig. 1.4). Clastic sediments such as conglomerate and quartzite of the Moodies Group unconformably overlie the Fig Tree Group (Fig. 1.4; Visser, 1956; Viljoen and Viljoen, 1969; Anhaeusser, 1969; Lowe and Byerly, 1999).

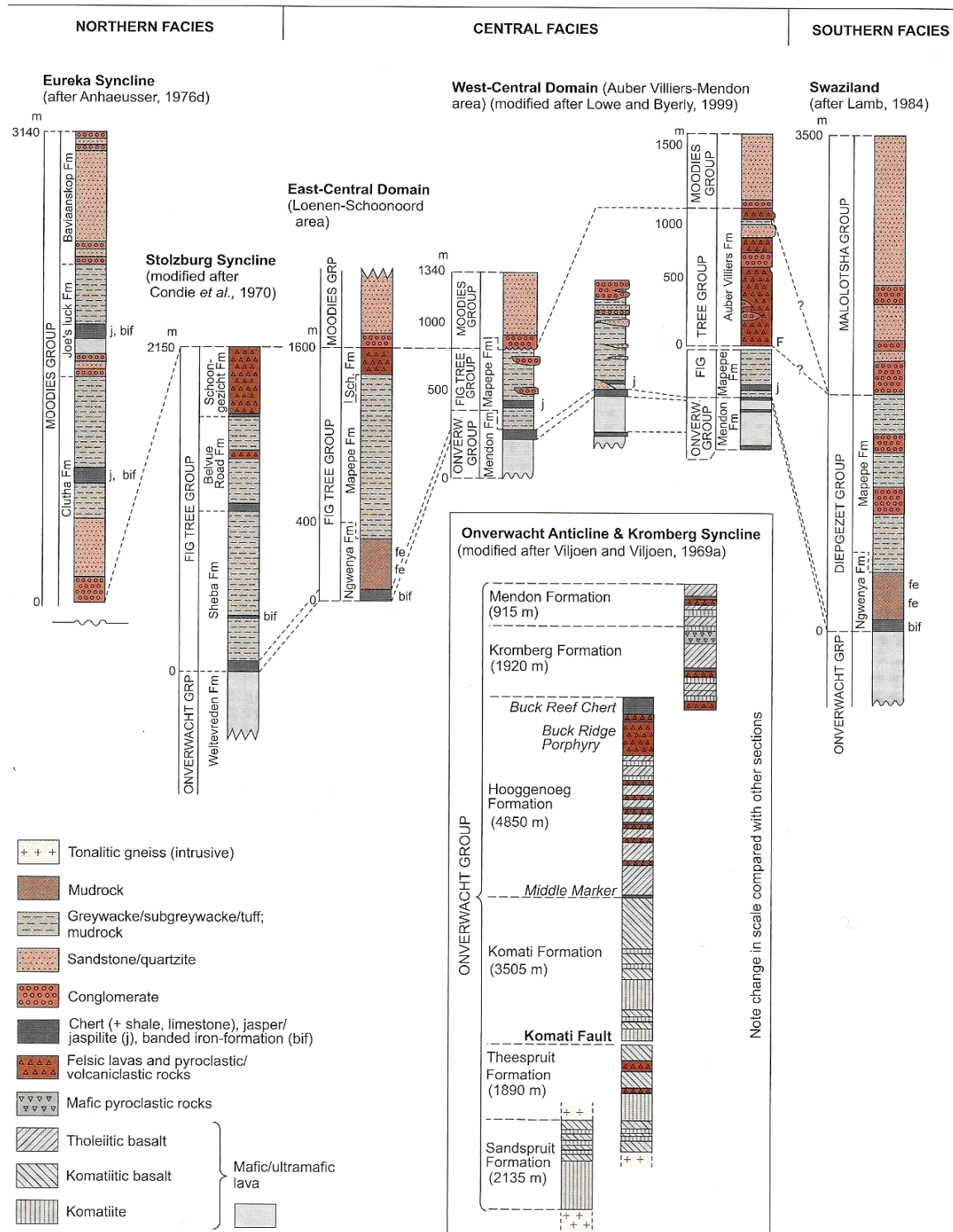


Figure 1.4: Stratigraphic columns showing rock groups, formations and their thicknesses, and correlations between rock units in the Northern, Central and Southern parts of the BGB (after Brandl *et al.*, 2006).

The next section describes in detail the stratigraphy of the BGB. Since the study location is found in the northern part of the belt, and the interests of the project are structurally related, only those rock formations and intrusions that are found in proximity to the study area have been discussed in detail.

1.5.2.1 Onverwacht Group

The Onverwacht Group is composed of metavolcanic, basaltic lavas with a predominance of komatiites of ultramafic in composition in the lower part of the group and tholeiitic basalts of more felsic composition towards the top of the group (Viljoen and Viljoen, 1969). These basalts are mainly rich in iron-magnesium, and contain minerals such as olivine, pyroxene and plagioclase (Viljoen and Viljoen, 1969). In the southern part of the BGB, Viljoen and Viljoen (1969) divided the group into six formations including the Sandspruit, Theespruit, Komati, Hooggenoeg, Kromberg and Zwartkoppie Formations from oldest to youngest (Figs. 1.4, 1.5). A characteristic sedimentary chert unit called the Middle Marker separates the Komati and Hooggenoeg Formations (Fig. 1.5; Viljoen and Viljoen, 1969). The Hooggenoeg and Kromberg Formations are separated by another silicified unit known as the Buck Reef Chert (Fig. 1.5; Viljoen and Viljoen, 1969). Lowe and Byerly (1999) proposed that the Mendon Formation forms the top part of the group in the southern part of the belt and interpreted the overlying chert-rich Zwartkoppie Formation, which marks the contact with the overlying Fig Tree Group, as a separate unit resulted from tectonic activities.

In the northern part of the belt, the rocks belonging to the Onverwacht Group are mainly found as isolated extrusive and intrusive rock lenses surrounded by schist units in the northwest trending Jamestown Schist Belt (Fig. 1.1; Anhaeusser, 1969). These rock units have been termed the Weltevreden Formation, and are considered the youngest formation of the Onverwacht Group dated at 3286 ± 29 Ma (Nd Isochron, Lahaye *et al.*, 1995; Lowe and Byerley, 1999).

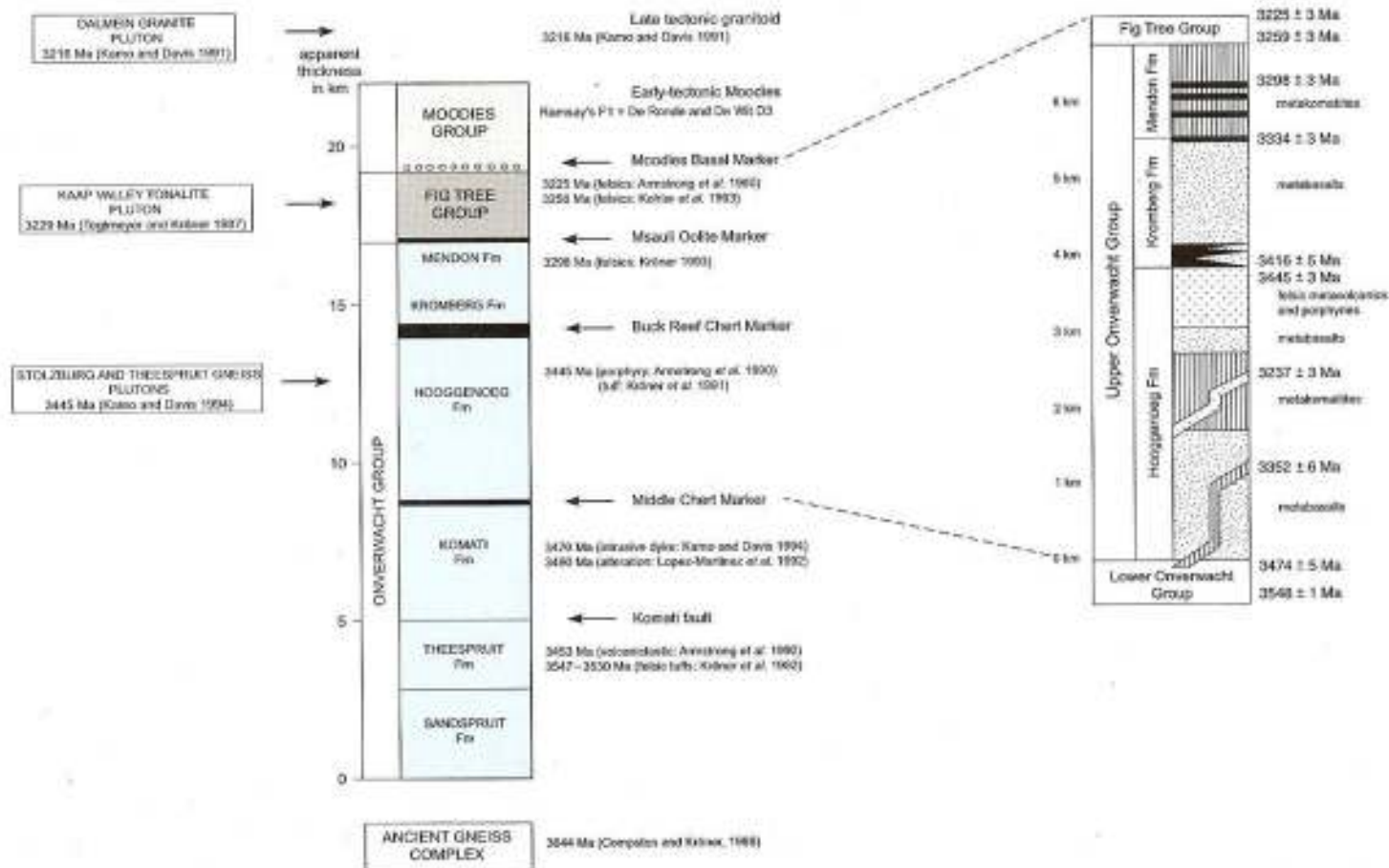


Figure 1.5: Stratigraphic columns showing formations of the Onverwacht, Fig Tree and Moodies Groups. Inserts include estimated thicknesses, plutons, horizon markers and timing of formations (after Ward, 1999 based on work of Viljoen and Viljoen, 1969).

The Weltevreden Formation consists of serpentinitised, komatiitic rocks, altered peridotitic layered intrusive rocks, serpentinitised komatiitic tuff, and black and banded chert (Lowe and Byerly, 1999). Komatiitic basalts occur as talc-carbonate, talc-chlorite, and talc-chlorite-tremolite-actinolite schist (Viljoen, 1964). The Weltevreden Formation has been correlated with the Mendon Formation in the southern parts of the belt based on the similarities in lithological units (Lowe and Byerly, 1999).

In the southern part of the belt, Viljoen and Viljoen (1969) have estimated a thickness of 20 kilometres for the Onverwacht Group; however, Lowe and Byerly (1999) indicated the existence of thrusts and tight folds within the group, interpreted to have duplicated the formations; hence, the estimated thickness may not be correct.

1.5.2.2 Fig Tree Group

A silicified unit marks the contact between the rocks of Onverwacht and Fig Tree Groups (Ward, 1999; Voges, 1986; Ramsay, 1963). This unit has been described in the Sheba and New Consort areas as a laminated or banded chert unit with distinctive carbonate ultramafic rocks, black shale and banded iron formation (Ramsay, 1963; Viljoen and Viljoen, 1969; Voges, 1986; Ward, 1999; Brandl *et al.*, 2006). In the Sheba and NCGM areas, the unit has been termed the Zwartkoppie and the Consort Bars respectively (Viljoen, 1964; Ramsay, 1963; Anhaeusser, 1969). The unit is the equivalent of the chert-rich Zwartkoppie Formation of Viljoen and Viljoen (1969).

The Fig Tree Group has been divided into the northern and southern facies in the northern and southern terranes on either side of the Inyoka-Saddleback fault system (Figs. 1.3, 1.4; Viljoen and Viljoen, 1969; Heinrichs and Reimer, 1977; Brandl *et al.*, 2006). The northern facies attains a thickness of 1500 meters and comprises what has been interpreted as deep water sediments (Hofmann, 2005) in contrast with the shallow water sediments of the southern facies (Condie *et al.*, 1970; Heinrichs and Reimer, 1977).

The northern facies consists of the Ulundi, Sheba, Belvue Road, Bien Venue and Schoongezicht Formations (Fig. 1.4; Condie *et al.*, 1970; Reimer, 1983; Lowe and Byerly, 1999; Kohler and Anhaeusser, 2002; Hofmann, 2005; Brandl *et al.*, 2006;). The Ulundi Formation marks the base of the Fig Tree Group and is composed of carbonaceous and pyritic shale units, and banded chert layers (Hofmann, 2005). The Ulundi Formation forms the Ulundi Syncline in the northern parts of the belt (Anhaeusser, 1976). The Sheba Formation succeeded the Ulundi Formation and is composed mainly of turbiditic sandstone (siltstone and greywacke) with interbeds of shale and BIF units (Kohler and Anhaeusser, 2002; Hofmann, 2005).

The Sheba Formation is overlain by the Belvue Road Formation, which is composed of carbonaceous shale with a few intercalations of greywacke, BIF and dacitic, epiclastic rocks (Kohler and Anhaeusser, 2002; Hofmann, 2005). Succeeding the Belvue Road Formation is the Bien Venue Formation consisting of quartz-muscovite schist, banded chert, phyllite and biotite-chlorite schist (Kohler and Anhaeusser, 2002). Coarse- to fine-grained tuff of the Schoongezicht Formation overlies the Bien Venue Formation (Fig. 1.4; Reimer 1967; Condie *et al.*, 1970; Heinrichs, 1980; Ward 1999; Hofmann, 2005).

In an area between the Eureka and Ulundi synclines (Fig. 1.1), the Schoongezicht Formation is thinly developed and composed mainly of tuff and agglomerate accompanied by shale, grit, chert and BIF attaining a maximum thickness of approximately 100 meters (Visser, 1956; Anhaeusser, 1976; Ward, 1999). Some authors have interpreted the Schoongezicht Formation in this area as feldspathic tuffaceous greywacke and greywacke-conglomerate (Anhaeusser, 1969). Porphyritic andesite observed at 6th level adit in the Clutha Central Gold Mine has been interpreted as the top part of the Schoongezicht Formation (Strauss, 1948; Ward, 1999)

In the southern parts of the belt (southern facies), the Fig Tree Group is represented by four formations, the Loenen, Ngwenya, Mapepe, Auber Villiers and Schoongezicht Formations (Fig. 1.4; Hofmann, 2005; Brandl *et al.*, 2006). The rock units of the Loenen Formation mark the base of the group and are composed of laminated carbonaceous and

ferruginous shale with silicified tabular sand to siltstone beds (Hofmann, 2005). The Ngwenya Formation, composed of layers of jaspilitic banded-iron-formation, overlies the Loenen Formation (Hofmann, 2005). The Mapepe Formation, composed of conglomerate and sandstones, succeeds the Ngwenya Formation (Nocita and Lowe, 1990). The Auber Villiers Formation consisting of dacitic volcanoclastic, ferruginous sedimentary units interlayered with conglomerate and greywacke, overlies the Mapepe Formation (Lowe and Byerly, 1999). The Schoongezicht Formation forms the top of the Fig Tree Group in the southern parts of the belt (Heinrichs, 1980; Lowe and Byerly, 1999).

1.5.2.3 Moodies Group

The Moodies Group unconformably overlies the Fig Tree Group in the southern part and unconformably in the northern part of the belt (Figs. 1.1, 1.4; Eriksson *et al.*, 1988; Lowe and Byerly, 1999; Dirks *et al.*, 2009). The rocks of the Moodies Group occur as structurally isolated blocks bounded by faults (Lowe and Byerly, 1999). These outcrops include rocks in the Lily, Eureka, Moodies, Stolzburg and Saddleback Synclines (Lowe *et al.*, 1999). The Moodies Group is composed of medium- to coarse-grained clastic sediments such as conglomerate, sandstone, quartzite and quartz arenite with minor shale (Anhaeusser, 1976; Heubeck and Lowe, 1994; Lowe and Byerly, 1999, 2007). In most rock packages of the Moodies Group, a conglomerate unit marks the base of the group (Lowe and Byerly, 1999).

The Eureka Syncline, which bounds the triple junction structure, south of the study area, is a classic structure that exposes the rocks of the Moodies Group. Anhaeusser (1976) classified the Moodies Group rocks in the syncline into three formations, from oldest to youngest, Clutha, Joe's Luck and Bavianaankop Formations (Fig. 1.4). Eriksson (1977) correlated the three formations to those he observed in the Saddleback Syncline (Fig. 1.1), located in the central parts of the belt. Anhaeusser (1976) has interpreted these formations as fining-upward sequences with each sequence marked by a conglomerate unit at the base and capped by a banded-iron formation. However, Dirks *et al.* (2009) suggested that the sequences are coarsening-upward and are tectonically duplicated.

Below is the summary of the formations as observed by Anhaeusser (1976), and used in this report in outlining the rock units of the Moodies Group.

Clutha Formation

The base of the Clutha Formation is marked by a conglomerate unit that occurs as pebble bands separated by immature sandstone. Pebbles of variable composition including chert, banded jaspilite, quartz and feldspar porphyries, quartzite, granite, greywacke and fuchsitic schist characterise the conglomerate. The conglomerate is overlain by medium-grained units of sandstone including calcareous quartzite, feldspathic quartzite, quartzo-feldspathic sandstone, massive pure and impure quartzite and minor shale units. Common mineral assemblage includes quartz, chert, albite, sericite, microcline, muscovite, perthite and carbonate. The sandstone units are well bedded and show cross-bedding and graded-bedding that can be used to determine facing directions (Anhaeusser, 1976).

A finely banded and reddish-brown shale unit succeeds the sandstone sequence. This shale is associated with a band of magnetic shale and jaspilitic iron formations. The shale unit envelopes the banded iron-formation and becomes more arenaceous towards the top of the formation. A basalt lava band caps the magnetic ferruginous shale in the Eureka and Stolzburg Synclines (Reimer, 1967; Anhaeusser, 1976; Lowe and Byerly, 1999).

Joe's Luck Formation

A quartzite unit, which can be traced in both limbs of the Eureka Syncline, marks the base of the formation. In contrast to the quartzite on the northern limb, the quartzite on the southern limb is generally thicker. This quartzite is steeply dipping (at least 50°), forming prominent ridges that can be traced on aerial photographs (Anhaeusser, 1976).

The unit consists of massive, well-bedded quartzite with some conglomerate lenses and gravel beds. In places, the quartzite shows cross-bedding and graded bedding where younging directions can be deduced. Mineralogically, the unit is mainly composed of

rounded to sub-angular quartz with minor feldspar, magnetite and biotite (Anhaeusser, 1976).

Shale and basaltic lava, which are poorly exposed, overly the quartzite unit. The shale unit is mainly red-brown, magnetic and banded. This shale unit is slightly different from that in the Clutha Formation in a sense that this unit contains lenses of shaley quartzite and siliceous argillites (Anhaeusser, 1976). The amygdaloidal basalt is best preserved in the nose of the Eureka Syncline. Actinolite and chlorite are the main minerals found in the unit with minor quantities of biotite, carbonate, plagioclase, iron oxides, sulphides, tourmaline, sericite and quartz (Anhaeusser, 1976).

Bavianskop Formation

A quartzite unit, which overlies the shale and basaltic lavas of the Joe's Luck Formation, marks the base of Bavianskop Formation. This unit forms prominent elevated ridges that are also traceable on areal photographs. The quartzite unit occurs as pure to impure quartzite with grits and shaley units that are interbedded with a locally developed conglomerate unit in places. The quartzite unit is mainly hard, massive, cross-bedded, pale grey, white or buff in colour. Mineral constituents of this quartzite include quartz with minor quantities of feldspar and magnetite. Impure quartzite shows higher amounts of feldspar, chlorite, iron oxides and sulphides including pyrite (Anhaeusser, 1976).

A shale unit, which forms the top part of the formation, overlies the quartzite unit. This shale unit occurs with sub-greywacke, carbonaceous argillite, argillaceous quartzite, grit and sandstone. Though some shale units in the formation are strongly magnetic, they do not quite compare to the iron-formations in the Clutha and Joe's Luck Formations. The red coloured jasper bands found in the other formations are missing in the Bavianskop Formation (Anhaeusser, 1976).

1.5.3 Granitoids of the Barberton Greenstone Belt

Granitoid bodies associated with the belt include the Ancient Gneiss Complex forming a basement, intrusive TTG granite suites and various younger granitoids (Robb *et al.*, 1986; Ward, 1999). The Ancient Gneiss Complex shows an age that is greater than 3500 Ma (Robb *et al.*, 2006). The TTG bodies have an age range from 3600 Ma to 3200 Ma while, the younger granitoids have been dated between 3200 Ma and 2800 Ma (Lowe, 1991; Ward, 1999; Robb *et al.*, 2006). Some of these TTG gneisses and granitoids have been linked to the dome and keel structure of the belt, and gold mineralization - particularly the Nelspruit Batholith (Ramsay, 1963; Anhaeusser, 1969; Anhaeusser, 1975; de Ronde and de Wit, 1994; Harris *et al.*, 1995). A review of the intrusive bodies that have been associated with the deformational history of the belt, is presented in the following section.

1.5.3.1 Ancient Gneiss Complex (>3600 Ma)

The oldest rock units preserved near the BGB occur within the Ancient Gneiss Complex located in the Piggs Peak area, Swaziland, to the southeast of the BGB (Robb *et al.*, 2006). The Ngwenya Gneiss located near the border between South Africa and Swaziland, forms part of the Ancient Gneiss Complex (Robb *et al.*, 2006). The complex consists of banded tonalite gneiss, which in places, contains mafic remnants (Robb *et al.*, 2006). U-Pb dating method on zircon grains from the gneiss gave an age of 3644 ± 4 Ma (Compston and Kroner, 1988). Xenocrystic zircon found in the Ngwenya Gneiss gave an age of 3683 ± 10 Ma (Robb *et al.*, 2006). The presence of the Ancient Gneiss Complex has been interpreted to represent the continental fragment of the Kaapvaal Craton prior to the development of the BGB (Robb *et al.*, 2006).

1.5.3.2 Tonalite Trondhjemite-Granodiorite (TTG) Gneiss Plutons (3600 – 3200 Ma)

3500 to 3400 Ma TTG Plutons

These TTG gneisses generally occur as relatively small, discrete plutons emplaced mainly to the south of the belt (Fig. 1.1; Robb *et al.*, 2006). The average maximum diameter reached by these gneisses is about 6 kilometres (Robb *et al.*, 2006). Sheared, sharp contacts between the granitoids and surrounding rocks are commonly preserved (Robb *et al.*, 2006). The TTG gneisses are mainly light to dark-grey and medium- to coarse-grained (Robb *et al.*, 2006). Mineral assemblages include quartz, plagioclase, and biotite (Robb *et al.*, 2006). The plutons often preserve good foliation and mineral stretching lineations, defined by quartz and plagioclase crystals (Robb *et al.*, 2006). Plutons are commonly less deformed in their centres than their margins, which are characterized by sheared contacts with surrounding rocks, showing structural emplacement of the plutons into the surrounding rocks (Robb *et al.*, 2006). Greenstone xenoliths are common and found with their long axes parallel to the trends of local granite-greenstone contacts (Robb *et al.*, 2006).

Typical examples of this generation of TTG plutons include the Stynsdorp (3505±10 Ma to 3509±8 Ma – single zircon, U-Pb, SHRIMP, Kroner *et al.*, 1996), Stolzburg (3450±3 Ma – single zircon, U-Pb, SHRIMP, Kamo and Davis, 1994) and Theespruit Batholiths (3443±2 Ma - single zircon, U-Pb, SHRIMP, Kamo and Davis, 1994; Robb *et al.*, 2006).

3230 Ma TTG Plutons

The 3230 Ma old TTG plutons are found along the west and northwest flanks of the BGB (Robb *et al.*, 2006). They are generally larger than the older TTG plutons and also characterized by sheared contacts with the surrounding rocks (Robb *et al.*, 1986; Robb *et al.*, 2006). Examples include the Kaap Valley (Fig. 1.1), Nelshoogte and Stentor Plutons (Robb *et al.*, 2006). The Kaap Valley Pluton, which occurs along the western boundary of the study area, has been described below.

Kaap Valley Pluton

The Kaap Valley Pluton is found in the northern part of the BGB bordering the Eureka Syncline to the east and Jamestown Schist Belt to the north. The pluton is the largest intrusive body in the northern part of the belt. This pluton is tonalitic in composition, characterized by minerals such as plagioclase, quartz and hornblende with minor quantities of biotite (Robb *et al.*, 1986). Hornblende is typically euhedral and mainly poikilitic containing small inclusions of quartz and feldspar (Robb *et al.*, 1986). The plagioclase also occurs as euhedral grains that show sericitization and epidotization (Robb *et al.*, 1986). Accessory minerals include microcline, apatite, zircon and titanite (Robb *et al.*, 1986). Towards the contact with the surrounding rocks, the pluton shows a well-developed alignment of minerals defining a planar fabric that is parallel to the contact (Robb *et al.*, 1986). In places, the planar fabrics display a mineral lineation, which are similar orientated to those found in the surrounding greenstones (Robb *et al.*, 1986). The pluton has been dated at 3226 ± 14 Ma (WR Rb-Sr, Armstrong *et al.*, 1990) and at 3227 ± 2 Ma (U-Pb zircon SHRIMP, Kamo and Davis, 1994).

Younger Granitoids (<3200 – 2800 Ma)

Younger granitoids (3200 – 2800 Ma) are found in the southern and northern parts of the belt, and include granodiorite, monzogranite and syenogranite. They are dominantly metaluminous to slightly peraluminous I-type granites (Robb *et al.*, 2006). The granitoids of this age are medium to high potassic rocks (Robb *et al.*, 2006; Lowe, 1991). Examples include the Nelspruit, Mpuluzi (Fig. 1.1), Berlin, Heerenveen, Piggs's Peak and Salisbury Kop Batholiths (Robb *et al.*, 2006). The Nelspruit Batholith has been reviewed below (Robb *et al.*, 2006).

Nelspruit Pluton

The Nelspruit Pluton is found to the north of the BGB, flanking the eastern boundary of the study area and the Stentor Pluton, which occurs as an elongated intrusion between the

BGB and the Nelspruit Pluton (Fig. 1.1). The Nelspruit Pluton extends for about 80 km to the north of the BGB, covered by Transvaal and Karoo Supergroup rock units to the west and east respectively (Robb *et al.*, 2006). Around the study area, the batholith is in contact with the greenstones of the JSB (Viljoen, 1964; Anhaeusser, 1969; Lowe and Byerly, 1999). A sheared and mylonitised contact between the pluton and the greenstones of the Weltevreden Formation is preserved (Viljoen, 1964; Anhaeusser, 1969). The granite preserves a gneissic texture, whilst greenstones in close proximity to the contact show a schistose texture (Anhaeusser, 1969).

The pluton is a grey-white, medium- to coarse-grained biotite granodiorite mainly composed of quartz, microcline, plagioclase, perthite and biotite (Viljoen, 1964; Robb *et al.*, 2006). A gneissic texture found in the pluton is defined by bands composed of alternating layers of biotite and felsic minerals such as plagioclase (Viljoen, 1964). The Nelspruit Pluton, which has been dated at 3106 ± 3 Ma (Zircon, U-Pb SHRIMP, Kamo and Davis, 1994), has been linked to gold mineralization in the belt and intrusive pegmatite units found in the JSB (Viljoen, 1964; Harris *et al.*, 1995). The pegmatites were interpreted to have formed from a same magmatic fluid as the pluton (Harris *et al.*, 1995).

2. Structural architecture, tectonic evolution and gold mineralization of the Barberton Greenstone Belt

The aim of this chapter is to outline the deformation history of the belt, and compare structural characteristics in the study area with those found in other parts of the belt. The comparison of structural events and their characteristics has enabled the link between deformation schemes to be established and ultimately, their associations with gold mineralization.

2.1 Introduction

The BGB has been affected by a series of deformation events that have produced a number of major structural features, which include 5-10 km-scale antiforms and synforms separated by shear zones (Fig. 1.1). Synforms, mainly defined by rocks of the Fig Tree and Moodies Groups, are well developed and contain steeply dipping limbs that are overturned in places (Ramsay, 1963; Anhaeusser, 1964). Typical examples of these synforms include the Ngwenya, The Heights, Stolzburg, Saddleback, Ulundi and Eureka Synclines (Fig. 1.1; Anhaeusser, 1964). Antiforms between the synforms are less clearly developed, however, some better developed examples include the Steynsdorp Anticline in the Komati River valley, the Onverwacht Anticline (Fig. 1.1) of the southern BGB and the Stentor Anticline to the SE of BGB (Anhaeusser, 1964; Lowe and Byerly, 1999; Brandl *et al.*, 2006). The Onverwacht Anticline is bounded to the west and southeast by the Stolzburg and Ngwenya Synclines respectively (Fig. 1.1; Anhaeusser, 1964).

Early tectonic models proposed for the BGB include that of Viljoen and Viljoen (1969), who interpreted the belt as a series of synformal structures characterized by a layer-cake stratigraphy, cut across by the Saddleback-Inyoka fault system (e.g. Viljoen and Viljoen, 1969). Detailed structural mapping, sedimentary analysis and recent high-resolution age dating methods have revealed a more complex deformational history for the BGB (Armstrong *et al.*, 1990; Kamo and Davis, 1994; de Ronde and de Wit, 1994; Lowe *et al.*,

1999). This has included the recognition of early thin-skinned thrusting preceding upright folding accompanied by further generations of thrusting events (e.g. Tomkinson and King, 1991; de Ronde and de Wit, 1994; Lowe *et al.*, 1999, Schoene *et al.*, 2008). Recent work by Lowe and Byerly (2007) suggests that the models based on a layer-cake stratigraphy, younging towards the north still hold in some parts of the belt, mainly in the south.

The commonly used deformation scheme representing the deformation history of the BGB is that proposed by de Ronde and de Wit (1994). They produced a detailed structural map of the southwest BGB, which they used as a basis to interpret the overall deformation pattern for the belt (Fig. 2.1). De Ronde and de Wit (1994) divided the belt into a northern and a southern terrane separated by the Saddleback-Inyoka fault system and have provided a tectonic summary for the evolution of the BGB (Fig. 2.2). The authors place the locally complex, polyphase deformation history of the belt in a simple deformation scheme with comparisons to modern plate tectonic settings (Table 2.1).

Following the deformation scheme of de Ronde and de Wit (1994), the earliest events, D_0 , (3490-3450 Ma) represent alteration processes near oceanic volcanic spreading centres (ridges; <3460Ma) and involved extension (Table 2.1). Associated with D_0 was sea floor metamorphism (M_0), interpreted to have started during the emplacement of the Onverwacht Oceanic Plateau about 3472 Ma ago and ending around 3449 Ma during D_1 (Table 2.1). D_1 (thermo-tectonic events), between 3450-3416 Ma, involved subduction-like processes with the emplacement of proposed ophiolite allochtons in intra-oceanic environments and emplacement of TTG plutons (Fig. 2.2). A second phase of subduction-accretion, D_2 , between 3260-3225 Ma, likened to an Andean-type margin, was accompanied by inter-arc deformation and culminated in accretion of unrelated arc systems after 3225 Ma with the Saddleback-Inyoka fault system as the dominant suture (Fig. 2.2). D_2 was linked with regional metamorphism (M_1) associated with loading of sediments over the Onverwacht Oceanic Plateau (Brandl *et al.*, 2006). Rocks affected by sea-floor and regional metamorphism preserved primary textures, sea-floor alteration, a greenschist facies overprint, and a lack of tectonic fabric (Cloete, 1999).

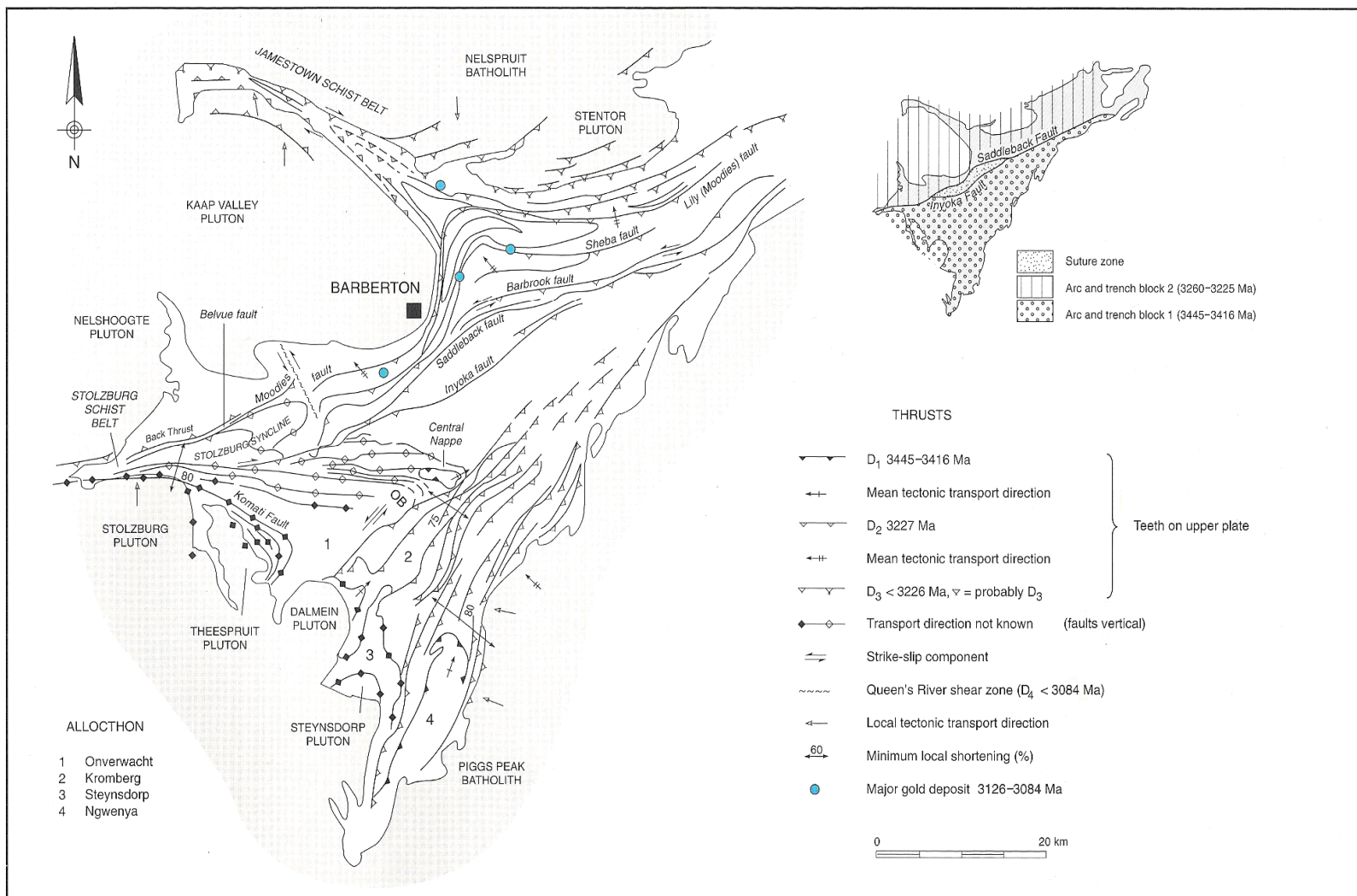


Figure 2.1: Structural geology map of the Barberton greenstone belt with inserted terranes and allochthons, and relative transport directions defined by de Ronde and de Wit (1994). The map also shows faults interpreted as shear zones, thrusts faults and strike-slip faults developed during four different phases of deformation. The top right insert diagram shows the locations of Saddleback and Inyoka faults that resulted from accretionary tectonics, which separate the northern and southern terrane of the BGB (after De Ronde and De Wit, 1994). D₁, D₂ and D₃ mentioned in the figure refer to those in Table 2.1.

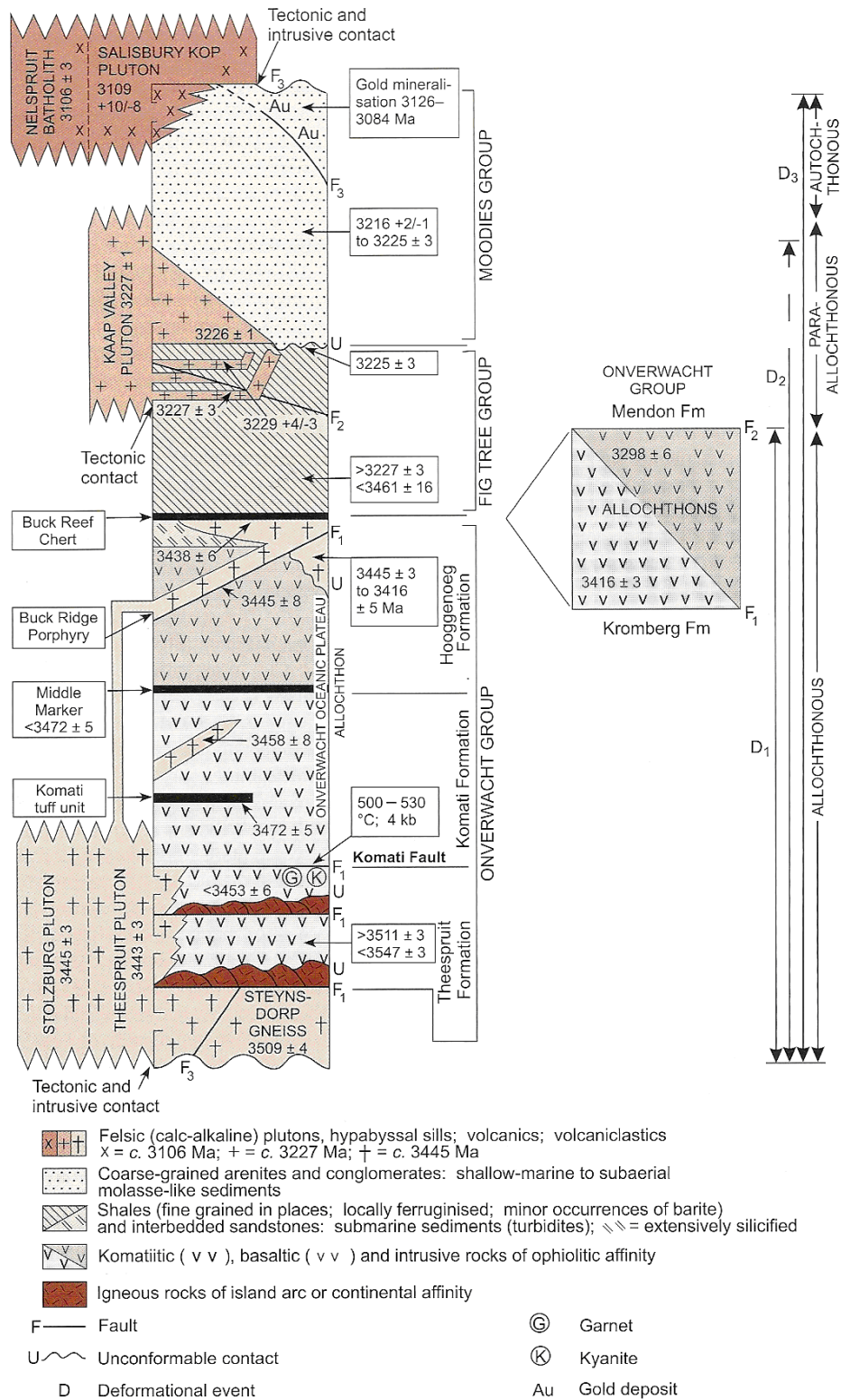


Figure 2.2: Simplified tectonostratigraphy of the Barberton Greenstone Belt showing groups, formations, horizon markers, plutons and the timing of deformation events within the belt. The age related to gold mineralization has also been inserted (adopted from Brandl *et al.*, 2006 after de Ronde and de Wit, 1994, modified from Armstrong *et al.*, 1990).

Table 2.1: Summary of the major geological events affecting the Barberton greenstone belt (after de Ronde and de Wit, 1994), with a comparison to more locally relevant deformation schemes proposed by Lowe *et al.* (1999), Dirks *et al.* (2009), Anhaeusser (1976), Viljoen (1964), Tomkinson and Lombard (1990) and Harris *et al.* (1995). To prevent confusion, the subscript “NC” for ‘New Consort’ has been added to the deformation scheme proposed in this study.

Tectonic event description (after de Ronde and de Wit, 1994)		de Ronde & de Wit (1994) Regional	Lowe <i>et al.</i> (1999) South of Barberton Town	Ramsay (1963) & Anhaeusser (1976) Sheba Hills	Dirks <i>et al.</i> (2009) Sheba Hills	Viljoen (1964) Consort Area	Harris <i>et al.</i> (1995) Consort Area	This study
Formation of oceanic crust; ocean floor type metamorphism (~3.55 Ga)	Deposition of Lower Onverwacht Group	D ₀						
Subduction-accretion of immature island arc systems (3.55-3.45 Ga)	Deposition of Lower Onverwacht Group	D ₁						
Subduction-accretion in a Cordilleran-type subduction system (3.26-3.22 Ga)	Accretion of Upper Onverwacht Group and deposition of Fig Tree Group	D ₂	D ₂ Folding of Onverwacht and Fig Tree rocks	D _{1s} Folding and thrusting of Onverwacht Fig Tree and Moodies Groups	D _{1s} Folding of the Onverwacht and Fig Tree Groups. Development of S1	D ₁ Folding and thrusting of Onverwacht, Fig Tree and Moodies Group. Formation of Lily Syncline	D ₁ Recumbent isoclinal folds and tectonic slides. Development of S1 cleavage	D _{1NC} Folding of the Onverwacht and Fig Tree Groups. Development of S _{1NC}
Terrane accretion and deposition of coarse clastics, with collisional amalgamation followed by transcurrent faulting (3.26-3.16)	Deposition of Moodies Group sediments	Early D ₃	D ₃ Thrusting of Moodies onto Fig Tree D ₄ Folding of Moodies Group D _{5a} Upright folding D _{5b} Emplacement of Kaap Valley pluton and foliation development	D _{2s} Formation of regional cleavage with emplacement of Kaap Valley pluton	Late D _{1s} Deposition of the Moodies Group D _{2s} Folding of the Moodies Group and development of Eureka Syncline	D ₂ Formation of regional cleavage with emplacement of Kaap Valley pluton		Late D _{1NC} Deposition of the Moodies Group D _{2NC} Folding of the Moodies Group and development of Eureka Syncline
Gold mineralization; shift from transpression to transensional deformation (~3.1 Ga)	Deposition of Moodies Group sediments	Late D ₃	D _{3c} Refolding	D _{3s} Refolding Eureka syncline with dextral thrusting on Sheba fault followed by gold mineralization	D _{4s} Normal faulting Gold Mineralization	D ₃ Refolding of the SW plunging folds such as the Lily Syncline Formation of Consort SE plunging folds. Gold Mineralization	D ₂ Development of north-south to NW-SE trending vertically dipping shear zones Development of SSZ Intrusion of Consort pegmatites. Later NW-SE trending SW dipping faults displacing ore shoots. Dextral strike-slip faults.	D _{4NC} Normal faulting Gold Mineralization
Strike-slip and normal faulting; emplacement of alkaline batholiths (~3.1 Ga)		D ₄		D _{4s} Formation of conjugate recumbent crenulation and chevron folds	D _{3s} Refolding of the F2 folds	D ₄ Development of intermediate size folds with horizontal fold axial planes, crenulation, conjugate and flat lying kink- bands. Normal faulting	D ₃ Normal faults displacing ore shoots.	D _{3NC} Refolding of the F2 folds

The D₂ event was also linked to the occurrence of high-pressure, intermediate-temperature, metamorphic mineral assemblages in greenstones and tonalites in the southern BGB (Diener *et al.*, 2006). P-T estimates in these rocks vary between 9-12 kbar at 650°C – 700°C, 6 kbar at 490°C and 7.4 kbar at 580°C (Diener *et al.*, 2006). Diener *et al.* (2006) concluded that these amphibolite facies assemblages resulted from deep burial associated with D₂ crustal shortening, exposed during extensional events.

D₃ involved post accretionary, transpressional events grouped as early-D₃ (Table 2.1), between 3225-3126 Ma, and resulted in the NE-trending map pattern of the BGB and the formation of strike-slip faults linked to gold mineralization (Figs. 1.1, 2.2; de Ronde *et al.*, 1991; Ward, 1999). Regional extensional collapse, termed D₄ (De Ronde and de Wit, 1994), around 3100 Ma accompanied by the emplacement of potassic granite batholiths preceded cratonic stabilization (Table 2.1).

2.2 Structural Domains

Lowe *et al.* (1999) proposed a more detailed subdivision of the BGB into structural blocks guided by stratigraphy, structure, geochronology and geochemistry within shear zone bounded blocks or terranes. The subdivisions have been considered in detail in the central parts of the belt. Unlike the two terranes and four local deformation events proposed by de Ronde and de Wit (1994) (Table 2.1), the structural terranes or domains of Lowe *et al.* (1999) address the changes in stratigraphy and structural characteristics from one terrane to another. Amongst other things, the domains explain the difference in the Fig Tree Group rock facies and the occurrence of the Mendon Formation, which is only observed to the north of the Granville Grove Fault (Lowe *et al.*, 1999; Lowe and Byerly, 1999, 2007).

In order to understand the deformation pattern of the belt, a review of the structural domains proposed by Lowe *et al.* (1999) has been provided. The work of Lowe *et al.* (1999) focused on the central BGB, and this study describes the deformation pattern preserved in the southern and northern parts of the belts, including areas such as Sheba

and New Consort. Major shear zones that bound the domains in this thesis include the Komati Fault- KF, Kromberg Fault-KRMF, Kamhlabane Fault - KMF, Granville Grove Fault - GGF, Mbema - MBF, Inyoka Fault - IF, Moodies Fault - MF, Saddleback Fault - SAF, Barbrook Fault - BF, Lily Fault -LF, Sheba Fault - SF, Kaap River Fault - KRF and Albion Fault - AF (Fig. 2.3). It should be noted that these bounding structures are brittle-ductile shear zones. The use of the term “fault” for these structures has been retained to avoid confusion and maintain consistency with pre-existing terminology.

At least six domains, Domain I to IV, can be identified in the BGB (Fig. 2.3). Information outlined in each domain includes geology, deformation history and geochronology. Structural information in Domain IV, which forms part of the study area, has been integrated with metamorphic details of the area. In the descriptions of these domains, the letter “D” indicates the deformation. The superscript indicates the domain number, and subscript indicates the deformation event.

2.2.1 Domain I

Domain I occurs in the southwestern part of the BGB and is bounded to the south by the Mpuluzi Batholith and to the north by the Komati Fault (Fig 2.3). This domain is composed of rock units of the Sandspruit and Theespruit Formations, forming part of the Onverwacht Anticline (Figs. 1.4, 1.5; Lowe and Byerly, 2007). Parts of the Sandspruit and Theespruit Formations represent the oldest stratigraphic units in the domain (Figs. 1.4, 1.5; Viljoen and Viljoen, 1969). These rock units were intruded by the Steynsdorp, Stolzberg and Theespruit plutons (Fig. 2.3; Lowe and Byerly, 2007). The Steynsdorp Pluton consists of older tonalite-trondjemite-gneiss and relatively younger foliated granodiorite (Kisters and Anhaeusser, 1995).

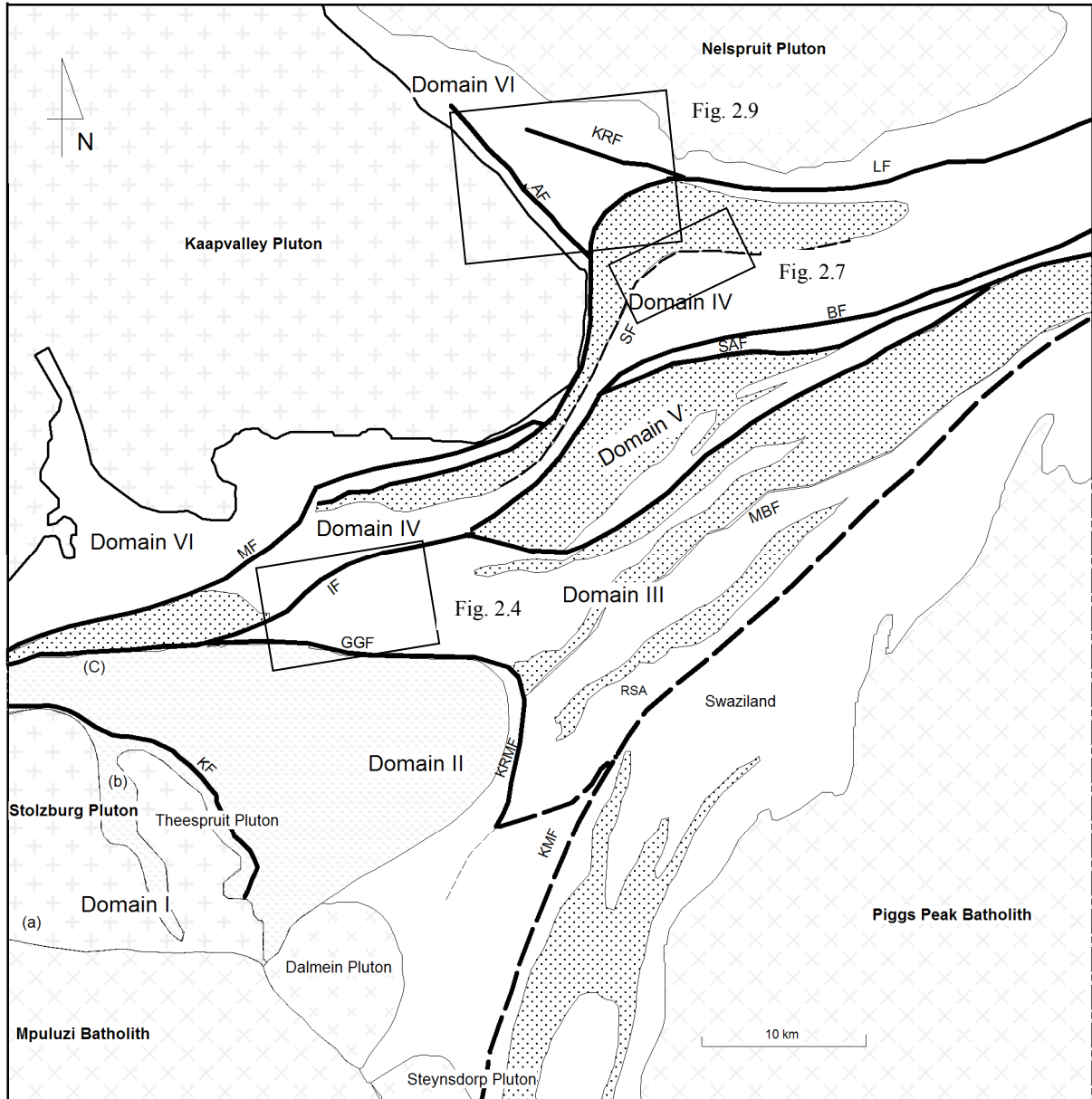


Figure 2.3: Map showing the plutons, synclines (outstanding dots), faults and structural domains I-VI described in the text. The relatively thick solid lines mark major shear zones acting as boundaries between different structural domains. KF- Komati Fault, KRMF-Kromberg Fault, KMF – Kamhlabane Fault, Granville Grove Fault, MBF- Mbema Fault, IF – Inyoka Fault, MF- Moodies Fault, SAF – Saddleback Fault, BF- Barbrook Fault, LF – Lily Fault, SF- Sheba Fault, LF – Lily Fault, AF – Albion Fault, KRF – Kaap River Fault. (a) = Weergevonden area, (b) = Tjakastad schist belt and (c) = Stolzburg schist belt in the Onverwacht Anticline (Modified from Lowe *et al.*, 1999).

2.2.1.1 Deformation History

In Domain I, the BGB is characterized by the presence of schistose greenstone xenoliths and a gneissic layering recorded within early plutons such as the Theespruit Pluton (Kisters *et al.*, 2003). The xenoliths are aligned parallel to the contact between plutons and host rocks (Kisters and Anhaeusser, 1995).

D_1^I structures occur in the xenoliths within the Weergevonden area ((a) in Fig. 2.3). The structures include inclined to recumbent folds that verge to the south, and pinch and swell structures with internal boudin axes that trend in an easterly direction (Kisters and Anhaeusser, 1995). The shapes of the folds are periclinal or domal, plunging moderately to the east (Kisters and Anhaeusser, 1995). The occurrences of westerly plunging folds have been noted in places within Domain I (Kisters and Anhaeusser, 1995). Other D_1^I structures in the xenoliths include minor S and Z folds, sheath folds, tight pinch cusps and N-S trending boudins (Kisters and Anhaeusser, 1995).

In the N-S trending Tjakastad schist belt ((b) in Fig. 2.3), D_1^I structures include steeply plunging, isoclinal, upright folds (Kisters and Anhaeusser, 1995). Large folds dominate the central parts of the Tjakastad schist belt and plunge moderately to steeply towards the northeast (Kisters and Anhaeusser, 1995). Poorly foliated to massive amphibolite and ultramafic serpentinite around the central Tjakastad schist belt are commonly boudinaged along a north-south trend (Kisters and Anhaeusser, 1995). Duplication of the rock sequence and unusual rock thickening in the Tjakastad schist belt has been linked to upright folding (Kisters and Anhaeusser, 1995).

The Tjakastad schist belt has been stratigraphically correlated with the Theespruit Formation of the Onverwacht Group (Anhaeusser, 1978). The development of the above structures has been interpreted to be associated with diapirism of the Theespruit and Stolzburg plutons between 3460 Ma and 3440 Ma (Kisters and Anhaeusser, 1995).

2.2.2 Domain II

Domain II covers the area in which the Onverwacht Anticline occupies a central portion. This domain is bounded by the Komati Fault, Inyoka Fault, Granville Grove Fault and Kromberg Fault to the south, north, northeast and east respectively (Figs. 1.1, 2.3). The stratigraphic units in this domain include the Komati, Hooggenoeg, Kromberg Formations and the basal part of the Mendon Formation (Fig. 1.4; Lowe and Byerly, 2007).

2.2.2.1 Deformation History

At least four deformation events (D^{II}_1 - D^{II}_4) were noted within Domain II (de Wit, 1982; de Wit *et al.*, 1983; Kisters *et al.*, 2003; de Vries and Touret, 2006). The deformation history in Domain II is most completely described from the Stolzburg schist belt in the western limb of the Onverwacht Anticline ((c) in Fig. 2.3) (Fig. 1.1) (de Wit, 1982; de Ronde and de Wit, 1994; Kisters *et al.*, 2003; de Vries and Touret, 2006).

The first deformation event D^{II}_1 is an extensional deformation that was observed in the Buck Ridge Chert (BRC) volcano-sedimentary-complex (de Vries and Touret, 2006). The deformation event was deduced from intraformational fold and fault patterns, block rotations, thickness variations and local unconformities (de Vries and Touret, 2006). Growth faulting causing offset of layers in the BRC decreases up-stratigraphy, with no offset of the upper most unit of the BRC (de Vries and Touret, 2006). Significant thickness variations in the stratigraphy across the fault structures are common in the BRC and in some of the overlying strata (de Vries and Touret, 2006). This was interpreted to have resulted from syn-depositional faults (de Vries and Touret, 2006). The fault structures, which are folded by NE trending structures, have been interpreted as west-block-down, listric, normal faults (de Vries and Touret, 2006). D^{II}_1 was interpreted to have occurred between 3472 ± 5 Ma and 3416 ± 5 Ma, which are the ages for rock deposition in Domain II.

D_{II}^2 deformation involves recumbent nappe structures, downward-facing sequences and shear zones described by de Wit (1982) and de Wit *et al.* (1983). De Wit (1982) indentified lower, upward-younging, and upper, downward-younging sedimentary structures in the chert that marks the core of a major recumbent fold in the western limb of the Onverwacht Anticline. The shear zones trend NW-SE and separate a series of ultramafic-mafic autochtons (de Wit, 1982; de Wit *et al.*, 1983; de Ronde and de Wit, 1994;Lowe and Byerly, 2007). Rocks of the Hooggenoeg Formation in the domain are affected by faulting that is not preserved in the overlying strata of the Kromberg Formation (Lowe and Byerly, 2007). The faulting was interpreted to record the effects of D_{II}^2 deformation (Lowe and Byerly, 2007). The Komati Fault has been interpreted as a typical example of D_{II}^2 fault structures, and is a thrust (de Ronde and de Wit, 1994).

The D_{II}^2 event has been interpreted to be caused by thrusting involving crustal shortening before 3240 Ma (Table 2.1, Fig. 2.2; de Wit, 1982; de Wit *et al.*, 1983; de Ronde and de Wit; 1994). De Ronde and de Wit (1994) considered D_{II}^2 events to be regional and marking the onset of a first accretionary episode (de Ronde and de Wit; 1994). Lowe and Byerly (2007) however, suggested this deformation was only localized in the west limb of the Onverwacht Anticline. The age of the Hooggenoeg Formation (3445 ± 3 Ma) and the overlying Kromberg Formation (3416 ± 5 Ma) have been suggested to bracket the time of D_{II}^2 deformation; since faulting in the Hooggenoeg Formation is not preserved in the overlying Kromberg Formation (de Ronde and de Wit, 1994).

A third deformation event (D_{II}^3) involved thrusting and the formation of upright tight to isoclinal folds (de Wit *et. al.*, 1983; de Ronde and de Wit, 1994). These upright folds refold D_{II}^2 recumbent folds and are associated with a penetrative axial planar cleavage best developed in the hinges of the folds (de Wit, 1982; de Wit *et al.*, 1983).

D_{II}^3 events are thought to represent part of the second accretionary period proposed by de Ronde and de Wit (1994), and have been linked to regional sub-horizontal compression around 3230 Ma (Table 2.1; de Wit *et al.*, 1983). D_{II}^3 events have been interpreted to have initiated before deposition of the Moodies Group (Tomkinson and King, 1991).

A fourth deformation event (D_4^{II}) involved the formation of an extensional detachment resulting in exhumation of deeper crustal rocks, interpreted to have been caused by extensional collapse (Kisters *et al.*, 2003). The characteristic features of this event, such as mylonitic textures and a sharp metamorphic gradients, were observed along the contact between the Stolzberg Pluton and the Stolzberg schist belt (Kisters *et al.*, 2003) (Fig. 2.3). The sense of movement determined from shear sense indicators along the fault indicate that the top block of the detachment moved to the northeast (normal) (Kisters *et al.*, 2003).

The timing of the event was constrained using ages of high-grade metamorphosed amphibolite dated at 3219 ± 9 Ma (U-Pb zircon SHRIMP Kisters *et al.*, 2003) and emplacement of the cross-cutting Dalmein Pluton dated at 3216 ± 2 Ma (Kamo and Davis, 1994) (Fig. 2.3). The amphibolites are considered to represent the foot wall rocks of the detachment whilst, the pluton, which cuts all structures, is considered to provide an upper age limit for D_4^{II} (Kisters *et al.*, 2003).

2.2.3 Domain III

Domain III is bounded by the Inyoka Fault to the north and Granville Grove Fault to the south (Fig. 2.3). The eastern boundary is an arbitrary line along the boundary between RSA and Swaziland connected from the Kromberg Fault (Fig. 2.3). The easternmost parts of the domain were considered a separate domain by Lowe *et al.* (1999) and Lowe (1990), but since this area contains stratigraphy and structure that is not different from the western part in the domain (Lowe *et al.*, 1999), it is considered here to be a single domain. Rock units in this domain include the characteristic Mendon Formation of the Onverwacht Group, the southern facies of the Fig Tree Group and the Moodies Group (Figs. 1.4 and 2.3) (Lowe and Byerly, 1999, 2007). The Fig Tree Group rocks include greywacke and shale of the Mapepe and Auber Villiers Formations (Fig. 1.4) (Lowe and Byerly, 2007). Rocks in the easternmost parts of the domain include mainly tuffaceous layers, shale, turbiditic lithic sandstone and conglomerate of the Mapepe Formation (Lowe *et al.*, 1999).

Two felsic tuff layers of Fig Tree Group rocks located north of the Granville Grove Fault and immediately south of the Inyoka Fault were dated at 3258 ± 3 Ma and 3243 ± 4 Ma respectively (Pb-Pb zircon SHRIMP Byerly *et al.*, 1996; Pb-Pb zircon Kroner *et al.*, 1991). A tuff layer of the Schoongezicht Formation, which provides an upper age bracket of the Fig Tree Group in this domain, was dated at 3227 ± 4 Ma (Pb-Pb zircons Kroner *et al.*, 1991). Thus above ages bracket deposition of the Fig Tree Group within Domain III between 3258 Ma and 3227 Ma. It was also noted that there are no rocks older than the Mendon Formation north of the Granville Grove Fault (Lowe and Byerly, 2007).

2.2.3.1 Deformation History

The first deformation event in Domain III was linked to early faulting and folding preserved in the domain (de Ronde and de Wit, 1994; Lowe *et al.*, 1999). D^{III}_1 produced major faults including the Granville Grove, Eucalyptus Mill, Auber Villiers, Schultzenhorst and Inyoka Faults that divide the domain into structural blocks (Fig. 2.4). These faults were folded during D^{III}_2 and are mainly vertical to steeply dipping structures that merge with the Inyoka Fault (Fig. 2.4). Repetition of rock units of the Mendon Formation occurs within the fault-blocks (Lowe and Byerly, 2007). Rock units separated by these faults occur as isolated and rotated blocks (Lowe *et al.*, 1999).

Tight- to isoclinal, strongly asymmetric, synclinal structures are found in the isolated structural blocks (de Ronde and de Wit, 1994; Lowe *et al.*, 1999). These formed during the second deformation event (D^{III}_2) interpreted to have resulted from thrusting around 3230 Ma (Table 2.1; de Ronde and de Wit, 1994). The fold structures contain complete and thick southern limbs and thin disrupted northern limbs (Lowe *et al.*, 1999). A series of tight fold structures are preserved in the Msauli Chert and komatiites of the Mendon Formation along the western limb of the Onverwacht Anticline (Lowe *et al.*, 1999).

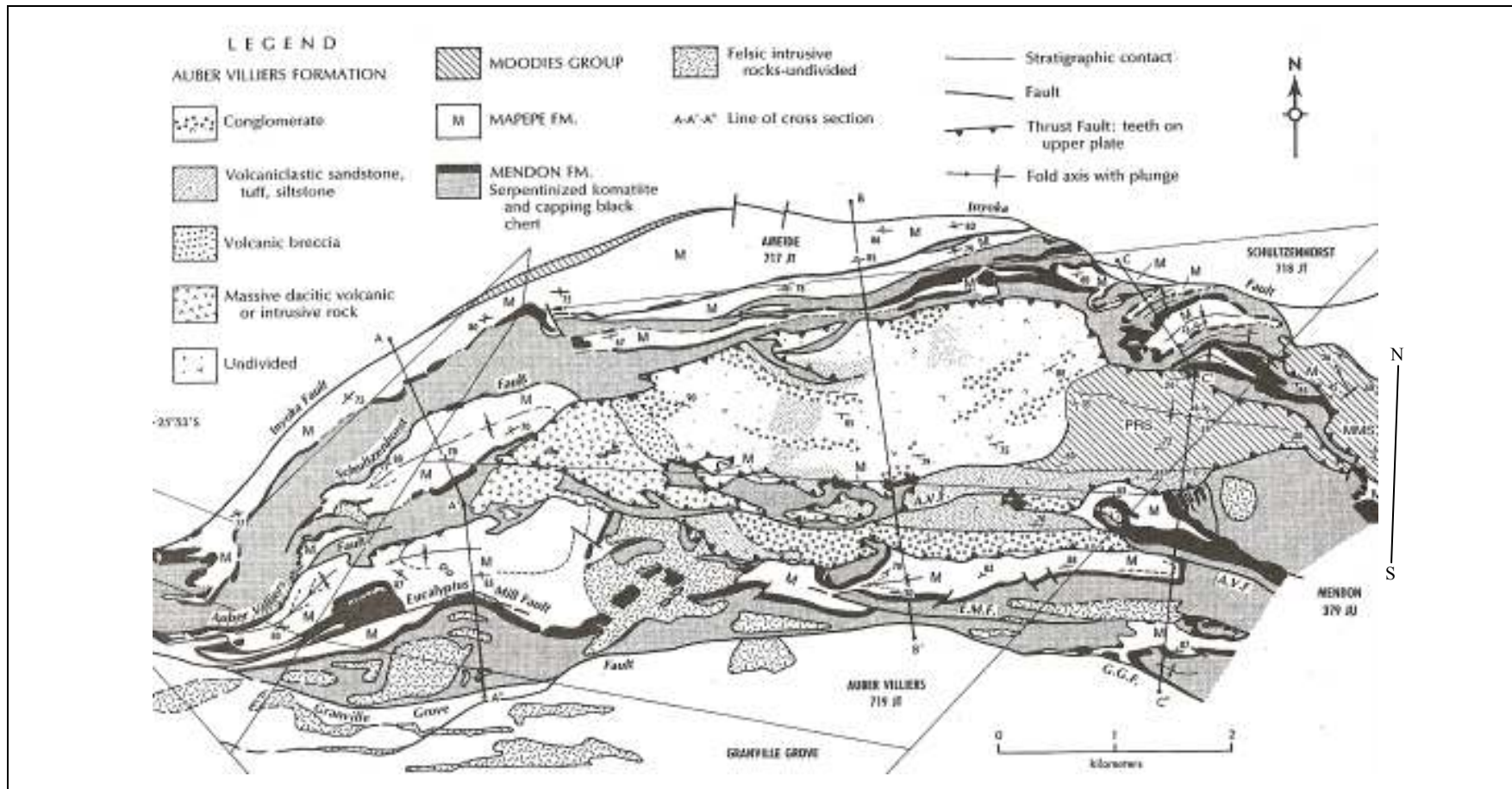


Figure 2.4: Geological map of the western part of Domain III in figure 2.3. Abbreviations: P.R.S- Powerline Road Syncline, M.M.S – Maid of the Mist Syncline, E.M.F. – Eucalptus Mill Fault, A.V.F. – Auber Villiers Fault. Teeth structures show the hangingwall of 24-Hour Camp Fault. Lines A-A'', B-B'', C-C'' and N-S are lines of sections that are shown in Figures 2.5 & 2.6 (after Lowe *et al.*, 1999).

The plunge direction of the folds in the western part of the domain is to the west; whilst fold plunges in the eastern part of the domain are to the east (Lowe *et al.*, 1999).

Ages for D^{III}_2 events have been constrained using hypabyssal feldspathic porphyries that propagated along D^{III}_1 faults (Lowe *et al.*, 1999). These deformed and undeformed porphyries intruded the Fig Tree Group (de Ronde *et al.* 1991; de Ronde and de Wit, 1994) and were dated at 3240 ± 5 Ma to 3230 Ma (Table 2.1; Lowe *et al.*, 1999; Kroner *et al.*, 1991; U-Pb zircon De Ronde *et al.*, 1991). The D^{III}_2 event was interpreted to have been caused by horizontal shortening (de Ronde and de Wit, 1994). The Moodies Group is partly interpreted to have been deposited during the last stages of the D^{III}_2 (de Ronde and de Wit, 1994).

A third deformation event (D^{III}_3) progresses from D^{III}_2 thrusting and deformed the Moodies Group during deposition (de Ronde and de Wit, 1994; Lowe *et al.*, 1999). The Moodies Group sedimentary units terminate against fault surfaces (Figs. 2.5, 2.6; Lowe *et al.*, 1999). Sediments are thicker and coarser closer (southeast) to the faults and thinner away (east) from the faults (Lowe *et al.*, 1999). It has been suggested that the changes in facies and variation in thickness in the lower Moodies Group indicate faulting that occurred during deposition (Lowe *et al.*, 1999).

D^{III}_3 was also responsible for folding of the Moodies Group sediments into large isoclinal synclinal structures that contain thick, relatively non-deformed south limbs and heavily sheared north limbs (Figs. 2.5, 2.6; Lowe *et al.*, 1999). Some of these synclinal structures are tight, locally overturned to the north and doubly plunging (Lowe *et al.*, 1999). The type examples of the latter synclines include two synclines known as the Powerline Road Syncline and Maid of the Mists Syncline (Figs. 2.5, 2.6; Lowe *et al.*, 1999). Later faults such as the 24-hour Camp Fault, developed during this event and truncate synclinal structures (Lowe *et al.*, 1999). D^{III}_3 folding has been linked to accretion processes (de Ronde and de Wit, 1994; Lowe *et al.*, 1999), and also linked to the emplacement of the Kaap Valley Pluton (Table 2.1; de Ronde and de Wit, 1994) dated at 3227 ± 1 Ma (U-Pb zircon SHRIMP Kamo and Davis, 1994).

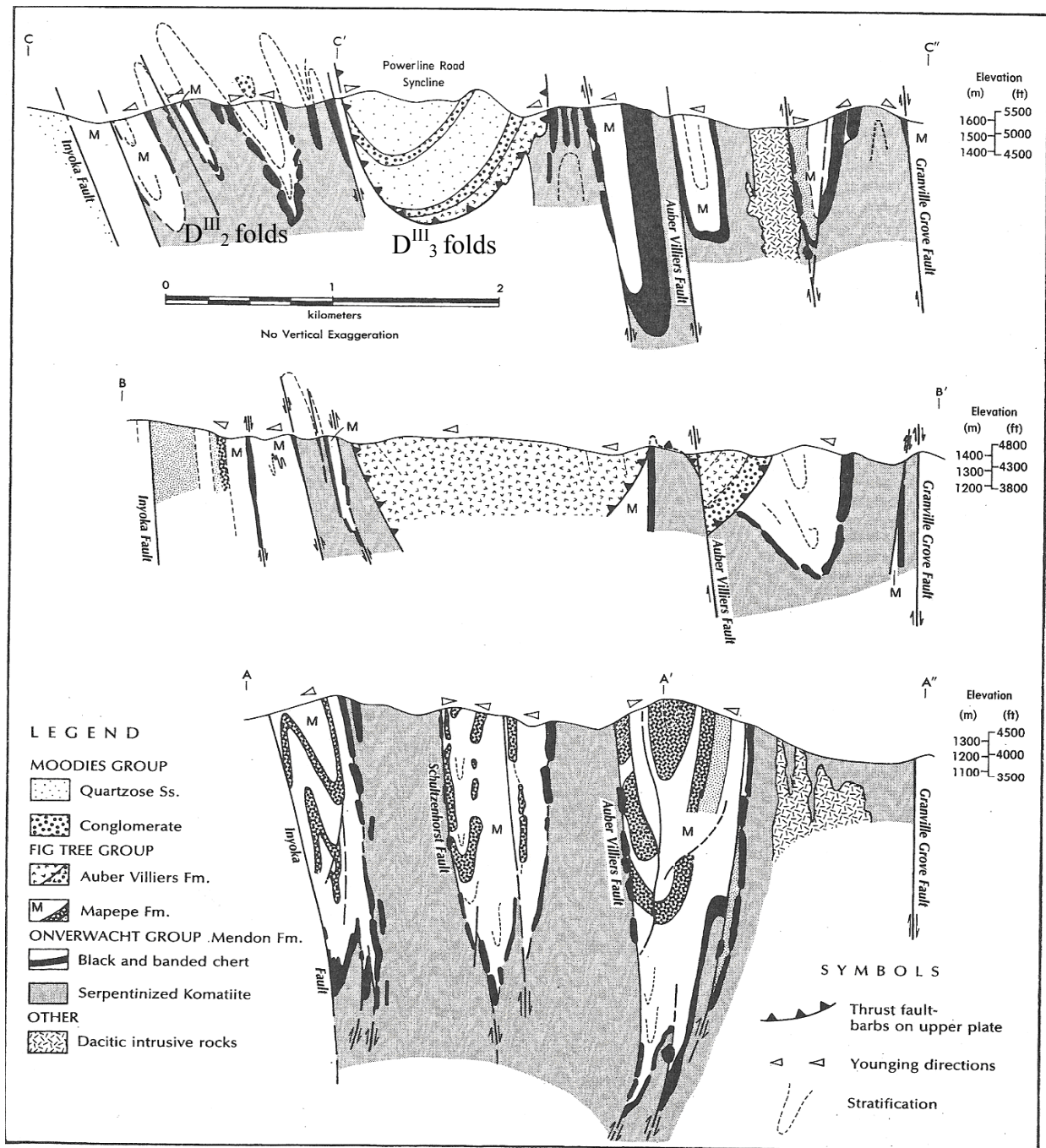


Figure 2.5: Cross sections from section lines shown in figure 2.4. Sections show tight to isoclinal folds (D_{III}^2 folds) in the Onverwacht and Fig Tree Group, unconformably overlain by D_{III}^3 folds in the Moodies Group (after Lowe *et al.*, 1999).

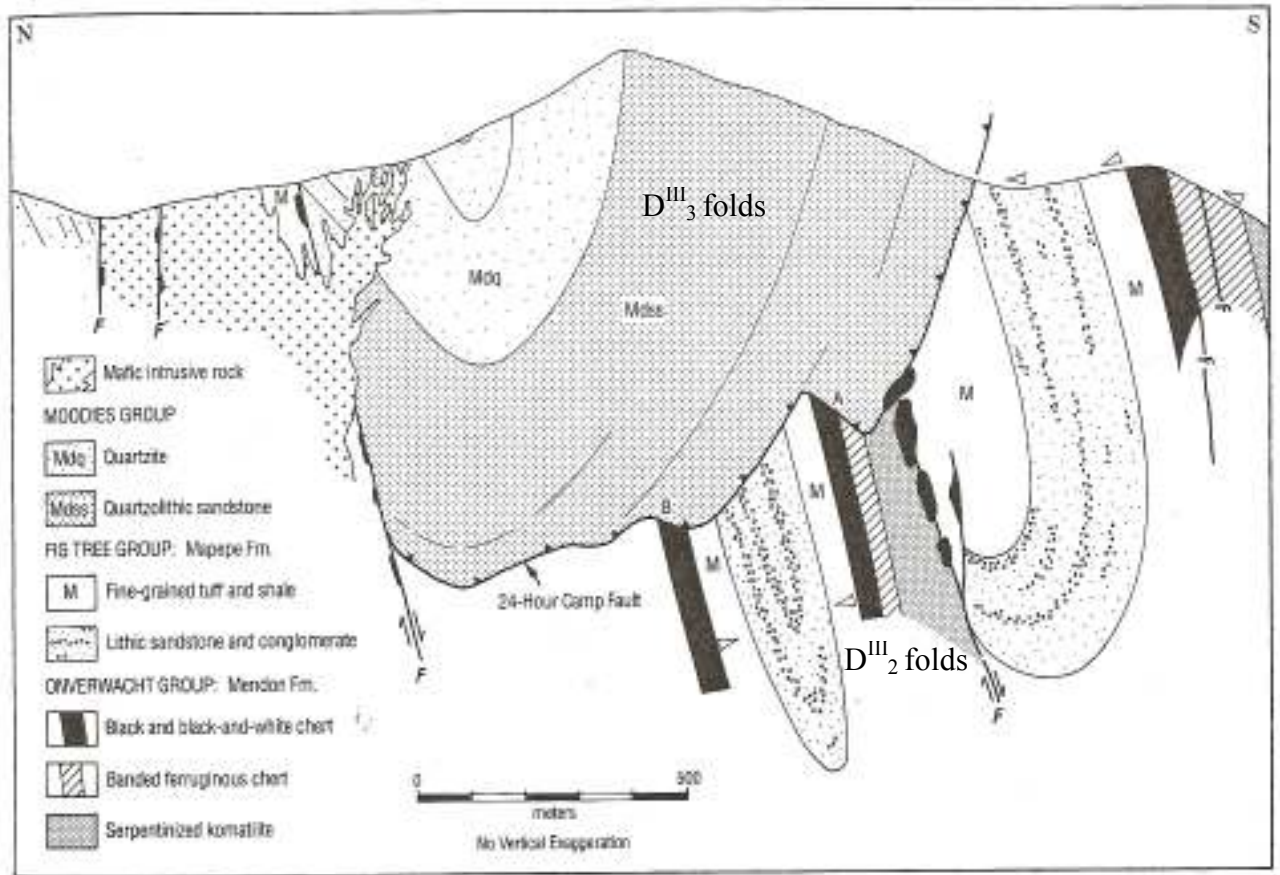


Figure 2.6 Cross section (N-S) through the Maid of the Mist Syncline (M.M.S) from Figure 2.4. The D^{III}_2 tight to isoclinal folds structures in Fig Tree Group are bounded to the north by the 24-Hour Camp Fault, which is folded during D^{III}_3 . The M.M.S that is composed of Moodies Group in the hanging wall of the fault, represents a typical structure formed during D^{III}_3 (Lowe *et al.*, 1999).

A fourth deformation event, D^{III}_4 , has been linked to the rotation, refolding and tightening of the D^{III}_3 folds (Lowe *et al.*, 1999). The synclinal structures developed during D^{III}_3 are overturned and rotated in a northerly direction, due to D^{III}_4 thrusting (Lowe *et al.*, 1999). NE-SW striking, open synclinal structures with tight antiforms and strike-slip faults developed during this event (Lowe *et al.*, 1999; de Ronde and de Wit, 1994). In the easternmost parts of the domain, tight, overturned, north verging anticlinal and synclinal structures that plunge northeast and southwest are common (Lowe *et al.*, 1999). Cleavage planes related to D^{III}_4 are poorly developed, and where developed are sub-parallel to bedding planes (Lowe *et al.*, 1999).

South-to southeast directed thrusting has been linked to south-to-southeast verging D_{4}^{III} folds (Lowe *et al.*, 1999). D_{4}^{III} was interpreted to account for the NE-SW outcrop pattern of the BGB (de Ronde and de Wit, 1994) and to represent the main shortening period in the BGB linked to $D_2 - D_3$ of de Ronde and de Wit (1994) (Table 2.1; Lowe *et al.*, 1999).

2.2.4 Domain IV

Domain IV is bounded to the south by the Inyoka and the Barbrook Faults, merging with the Saddleback Fault in the central BGB. The northern boundary is the Lily Fault that merges with the Moodies Fault in the southwestern BGB (Fig. 2.3). The domain is composed of rock units of the Onverwacht, Fig Tree and Moodies Groups (Figs. 1.1 and 1.4) (Anhaeusser, 1969; Ramsay, 1963). The Onverwacht Group is represented by layers of fuchsite and talc schist and banded chert of the Weltevreden Formation (Lowe *et al.*, 1999; Anhaeusser, 1976; Ramsay, 1963). The Fig Tree Group comprises the Ulundi, Sheba, Belvue Road and Schoongezicht Formations. The greywacke and shale units of the Fig Tree Group are the main constituents of the Ulundi Syncline and clastic sediments of the Moodies Group form the Eureka Syncline (Fig. 1.4; Anhaeusser, 1976, 1969).

Major structures within the domain include the Stolzberg Syncline, Ulundi Syncline, Eureka Syncline (Fig. 1.1), Moodies Fault, Saddleback Fault, Lily Fault and Sheba Fault (Fig. 2.3). The Lily Fault, which is one of the main faults, extends from Louw's Creek westwards towards Noordkaap, then continues on the outer arc of the Eureka Syncline through Clutha Gold Mine extending southwards merging with the Moodies Fault (Fig. 2.3; Anhaeusser, 1976). Domain IV has been further subdivided into a southwestern and a northern part. The southwestern parts include structures such as the Stolzberg Syncline, Inyoka and Moodies Faults. The northern parts include structures such as the Ulundi and Eureka Synclines, Sheba Fault, Saddleback Fault and Barbrook Fault (Anhaeusser, 1976).

2.2.4.1 Deformation History

The first deformation event, D^{IV}_1 , produced faults and tight to isoclinal folds (F^{IV}_1) restricted to rock units of Onverwacht and Fig Tree Groups (Lowe *et al.*, 1999; Dirks *et al.*, 2009) (Figs. 1.4 and 2.7). The folds contain an axial planar cleavage that is penetrative (Lowe *et al.*, 1999; de Ronde and Kamo, 2000; Dirks *et al.*, 2009). In the south-western parts of the domain, the rocks are isoclinally folded and the cleavage planes are orientated almost parallel to bedding (de Ronde and Kamo, 2000). The isoclinal folds contain hinges that plunge in various directions with a variable pitch (de Ronde and Kamo, 2000). Anticlinal structures are isoclinal, parallel folds with minor hinge thickening (Lowe *et al.*, 1999). The Sheba Formation in the area defines synclines that are separated by tight to isoclinal faulted anticlines. The anticlines are composed of less competent serpentinite and thin layers of shale and chert of the Ulundi Formation. A typical fault structure that developed during the D^{IV}_1 is the Belvue Fault, which strikes northeast-southwest (de Ronde and Kamo, 2000).

In the NE part of Domain IV, the tight to isoclinal folds (F^{IV}_1) are mainly preserved in greywacke and shale of Fig Tree Group in the Ulundi Syncline (Figs. 2.7, 2.8). Bedding and cleavage relationships in the Fig Tree Group lithologies show the existence of several tight folds indicated by changes in facing direction of the antiforms on a scale of 10's of meters (Dirks *et al.*, 2009). The development of silicified contacts between the Onverwacht and Fig Tree Groups in the Sheba area is linked to D^{IV}_1 . The typical examples of these units include the Zwartkoppies Bar described by Ramsay (1963) in the Sheba area. The structures of D^{IV}_1 have been linked to thrust processes (Table 2.1).

D^{IV}_2 involved folding of Schoongezicht and Moodies Group, and produced large synclinal structures that are bounded by faults (Lowe *et al.*, 1999; Dirks *et al.*, 2009).

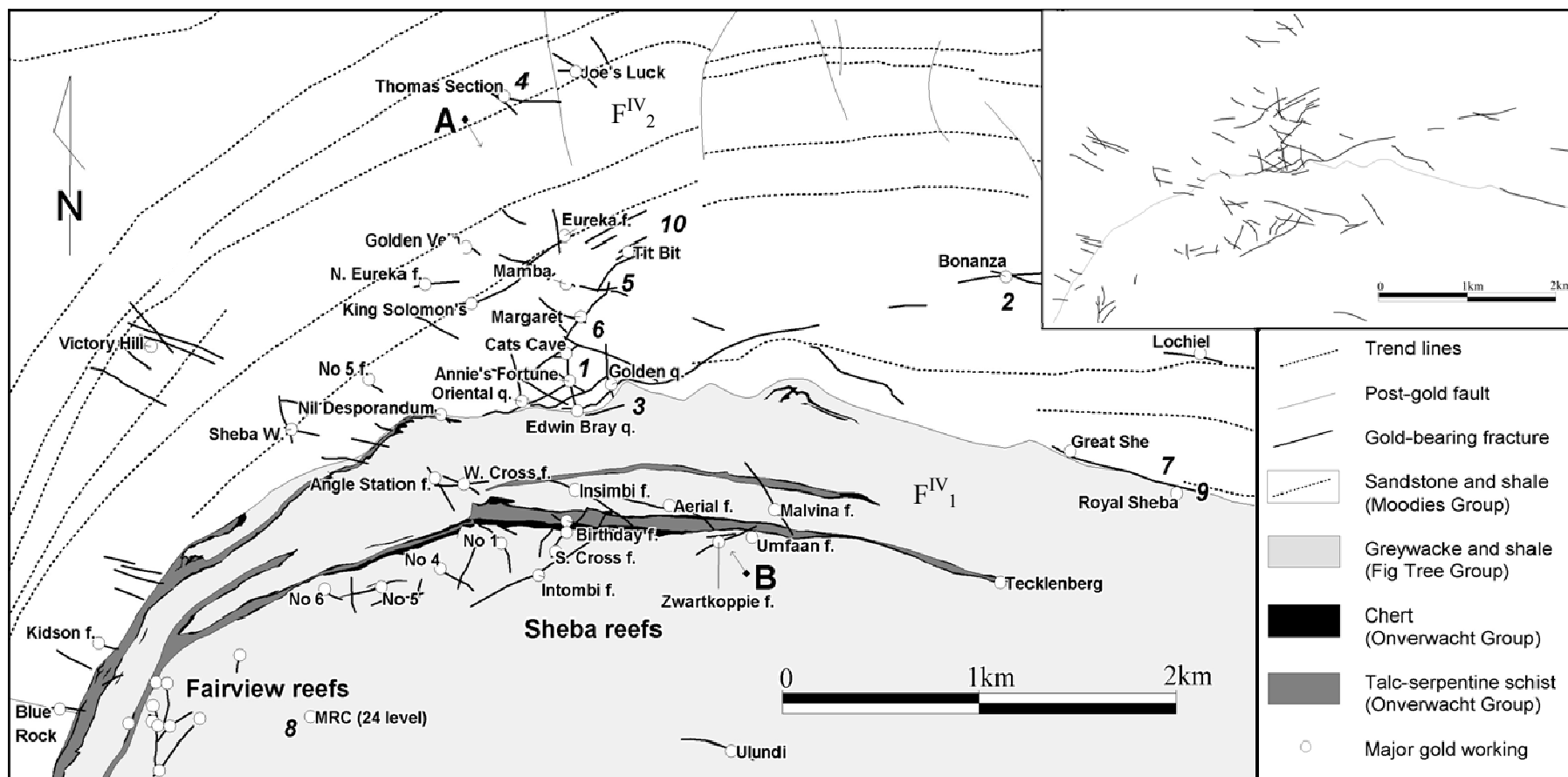


Figure 2.7: Geological map of the Sheba Hills, showing tight to isoclinal folds (F^{IV}_1) preserved in the Onverwacht and Fig Tree Groups, which are unconformably overlain by agglomerate and rocks of the Moodies Group folded by F^{IV}_2 . Inserted top right diagram shows mineralized fractures of D^{IV}_4 that cross-cut earlier ductile structures (after Dirks *et al.*, 2009 based on Anhaeusser, 1976).

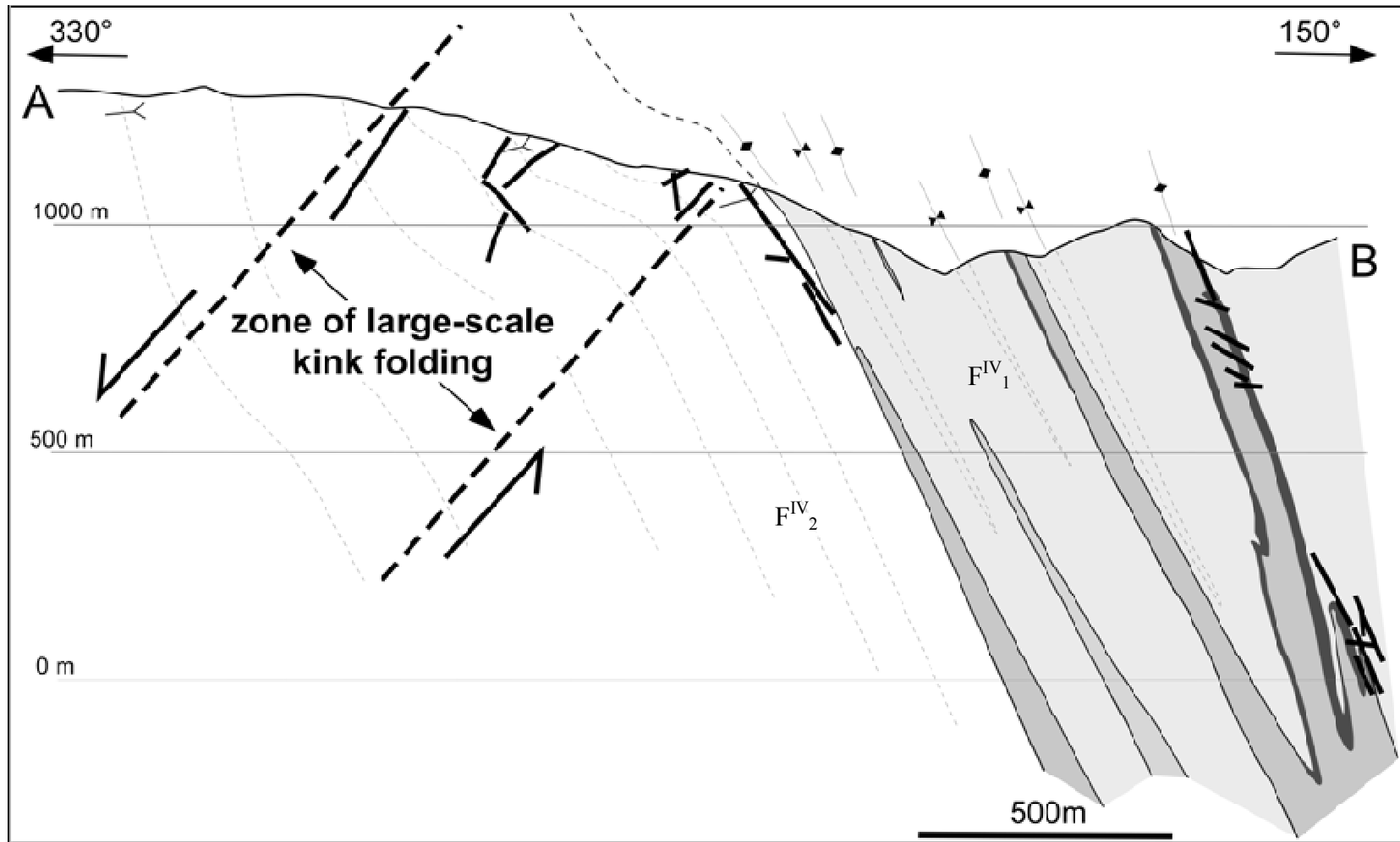


Figure 2.8: Cross-section A-B indicated in Figure 2.7, showing tight to isoclinal folds (F^{IV}_1) in the Fig Tree and Onverwacht Groups, unconformably overlain by the southern limb of the Eureka Syncline (F^{IV}_2). Legend similar to that of figure 2.7 (after Dirks *et al.*, 2009).

The D^{IV}_2 structures tightened D^{IV}_1 structures and produced synclines (F^{IV}_2) (Figs. 2.7, 2.8), in which the southern limbs are thicker and overturned to the north, and northern limbs are narrow, upright and heavily sheared (Lowe *et al.*, 1999). A typical example in the south-western part of the domain includes the Stolzberg Syncline that youngs and plunges to the southwest (Visser, 1956; de Ronde and Kamo, 2000). The Stolzberg Syncline is a vertical, antiformal syncline, bounded to the south and the north by the Inyoka and Moodies Faults, respectively (Lowe *et al.*, 1999). The Moodies Fault was interpreted to be a thrust fault with a strike-slip component that has been formed during D^{IV}_2 (de Ronde and Kamo, 2000).

In the NE part of Domain IV, large synclinal structures have been interpreted to be sheared out on the margins by faults (Ramsay, 1963; Anhaeusser, 1976). The Eureka Syncline is a typical example of a large D^{IV}_2 synclinal structure (Fig. 2.8; Anhaeusser, 1976). The syncline has a curving axial plane that dips steeply to the south, southeast or east (Ramsay, 1963; Anhaeusser, 1976). Shear zones interpreted to have sheared-out the limbs of the synclines include the Lily and Sheba Faults (Ramsay, 1963; Anhaeusser, 1976). These shear zones were interpreted to be thrusts that were reactivated as strike-slip faults during later deformation events (Ramsay, 1963; Anhaeusser, 1976). The D^{IV}_2 deformation in the NE part was linked to the emplacement of the Kaap Valley Pluton at 3227 Ma (Table 2.1; Ramsay, 1963; Anhaeusser, 1969).

A third deformation event, D^{IV}_3 , in Domain IV involved refolding and tightening of D^{IV}_2 structures (Lowe *et al.*, 1999; de Ronde and Kamo, 2000). The refolding event was accompanied by strike-slip faulting (Anhaeusser, 1969). In the south-western part of Domain IV, cleavage planes, S^{IV}_3 , associated with D^{IV}_3 are poorly developed. S^{IV}_3 is sub-vertical and dips steeply towards the NE or SW (Lowe *et al.*, 1999). D^{IV}_3 in the south-western part also produced series of fault structures that have been interpreted as strike-slip faults, possibly reactivating earlier thrusts (de Ronde and Kamo, 2000). These faults occur as splays off D^{IV}_2 faults (de Ronde and Kamo, 2000). The D^{IV}_3 faults show a sinistral sense of shear and have been interpreted to be associated with hydrothermal alteration and gold mineralization (de Ronde and Kamo, 2000).

In the NE part of Domain IV, D^{IV}_3 is manifested by mainly southeast trending large- and small-scale fold structures that refolded the D^{IV}_2 structures (Ramsay, 1963; Anhaeusser, 1976). The D^{IV}_3 event refolded the Eureka Syncline into a southeast plunging structure (Ramsay, 1963; Anhaeusser, 1976). The Lily and Sheba Faults were refolded during D^{IV}_3 and now dip steeply to the south, southeast or east (Anhaeusser, 1969).

The fourth deformation event, D^{IV}_4 , has been linked to the formation of chevron folds, crenulation, and conjugate fold structures associated with brittle-ductile normal faulting (Ramsay, 1963; Anhaeusser, 1969; de Ronde and de Wit, 1994; Dirks *et al.*, 2009). These fault structures cross-cut all the rock units that are preserved in the BGB (de Ronde and de Wit, 1994). Faults are commonly observed in competent rocks such as quartzite of the Moodies Group (Anhaeusser, 1976).

Anhaeusser (1976) linked D^{IV}_4 structures to a final episode of diapirism, possibly related to the rise of the Nelspruit Pluton (Anhaeusser, 1969). De Ronde *et al.* (1992) and de Ronde and de Wit (1994) interpreted D^{IV}_4 to post-date gold mineralization in the BGB, and linked D^{IV}_4 to extensional collapse after the emplacement of the Nelspruit Pluton at 3106 ± 3 Ma (U-Pb zircon SHRIMP Kamo and Davis, 1994). However, Dirks *et al.* (2009) indicated in the Sheba area that the brittle-ductile normal faults of D^{IV}_4 event do not overprint gold mineralization, but are the controlling structures of gold mineralization (Appendix A).

2.2.5 Domain V

Domain V is bounded to the north and south by the Saddleback Fault and Inyoka Fault respectively (Fig. 2.3). The domain is composed of Fig Tree Group and Moodies Group rocks (Fig. 1.4; Lowe and Byerly, 1999). The main structure in the domain is the Saddleback Syncline (Fig. 1.1; Lowe and Byerly, 1999). The domain was considered by Lowe *et al.* (1999) as part of the Domain IV due to similarity in stratigraphy and deformation history. This report considers Domain V as a separate entity because it is

wedged between the Inyoka and Saddleback Faults considered by de Ronde and de Wit (1994) to delineate a major terrane boundary.

2.2.5.1 Deformation History

The deformation events that are preserved in the Saddleback Syncline are similar to those in the Stolzburg Syncline in Domain IV (Lowe *et al.*, 1999). The first deformation event, D^V_1 , involved folding that produced the Saddleback Syncline (Lowe *et al.*, 1999). The Saddleback Syncline is a fault-bounded syncline that is composed of an overturned southern limb and faulted northern limb (Lowe *et al.*, 1999).

The second deformation event, D^V_2 , has been ascribed to refolding of D^V_1 structures (Lowe *et al.*, 1999). The D^V_2 events tightened and rotated D^V_1 structures and produced northwest-verging fold structures with axial planes that dip steeply to the east or southeast (Lowe *et al.*, 1999). D^V_2 folds plunge moderately to the northeast, southwest or both (Lowe *et al.*, 1999). The Saddleback Fault, which is mainly a vertical structure, was interpreted to have formed during D^V_2 (Lowe *et al.*, 1999). The fault structure merges with the Inyoka Fault in the western part of the domain (Fig. 2.3).

2.2.6 Domain VI

Domain VI is bounded to the south by the Lily Fault and Moodies Fault (Fig. 2.3). The northern and western bounds are the Nelspruit and Kaap Valley Plutons, respectively (Fig. 1.1). The domain, which consists of two parts, represents all the rocks to the NW of the Lily-Moodies fault system (Fig. 2.3). The north-western part of Domain VI covers the Jamestown Schist Belt (Fig. 1.1), including the study location, whilst the southern part occurs north of the Moodies Fault (Fig. 2.3). Rocks of Onverwacht, Fig Tree and Moodies Groups, and granitic intrusions comprise lithological units of the domain (Figs. 1.1 and 1.4). Rocks of the Weltevreden Formation represent the Onverwacht Group in Domain VI (Fig. 1.4; Lowe and Byerly, 1999).

The Fig Tree Group is represented by greywacke, shale and feldspathic-tuffaceous agglomerate, which belongs to the Schoongezicht Formation (Fig. 1.4; Viljoen, 1964; Anhaeusser, 1969). The Moodies Group in the domain is composed of conglomerate, calcareous quartzite, impure sandstone, and feldspathic quartzite (Viljoen, 1964). Intrusions in the domain include the Kaap Valley and Nelspruit Plutons, and porphyry bodies and muscovite-bearing pegmatite, geochemically linked to the Nelspruit Pluton (Anhaeusser, 1969; Harris *et al.*, 1995). The pegmatite bodies are common along the folded Consort Bar and the northern extremities of the JSB towards the margin of the Nelspruit Pluton (Harris *et al.*, 1995).

2.2.6.1 Deformation History

The deformation history of Domain VI, which is not covered by the work of Lowe *et al.* (1999), is best described in the JSB (Fig. 2.9). The JSB is a long, narrow, wedge-shaped greenstone septa between the Nelspruit and Kaap Valley Plutons (Fig. 1.1; Anhaeusser, 1969). The JSB is characterized by lensoidal-shaped ultramafic- to mafic intrusions, including the Handsup and Mundts Concessions, which is surrounded by green schist units (Anhaeusser, 1969). This belt has been described as a complexly folded and faulted anticlinal structure that trends northwest (Anhaeusser, 1969). Major faults in the belt include the Albion and the Kaap River Faults that trend northwest (Figs. 2.3, 2.9; Anhaeusser, 1969). The Albion Fault acts as a detachment plane below the Handsup fold (Anhaeusser, 1969). The Kaap River Fault connects from the eastern part of the JSB to an area north of Noordkaap and cuts across the Lily Syncline (Viljoen, 1964; Anhaeusser, 1969).

The deformation history of the JSB has been described in detail around the New Consort Gold Mine area (Fig. 1.3) by Viljoen (1964), updating the work by Ramsay (1963). Tomkinson and Lombard (1990) have published, an abstract with a few adjustments to the deformation history, based on internal mine reports (Table 2.1).

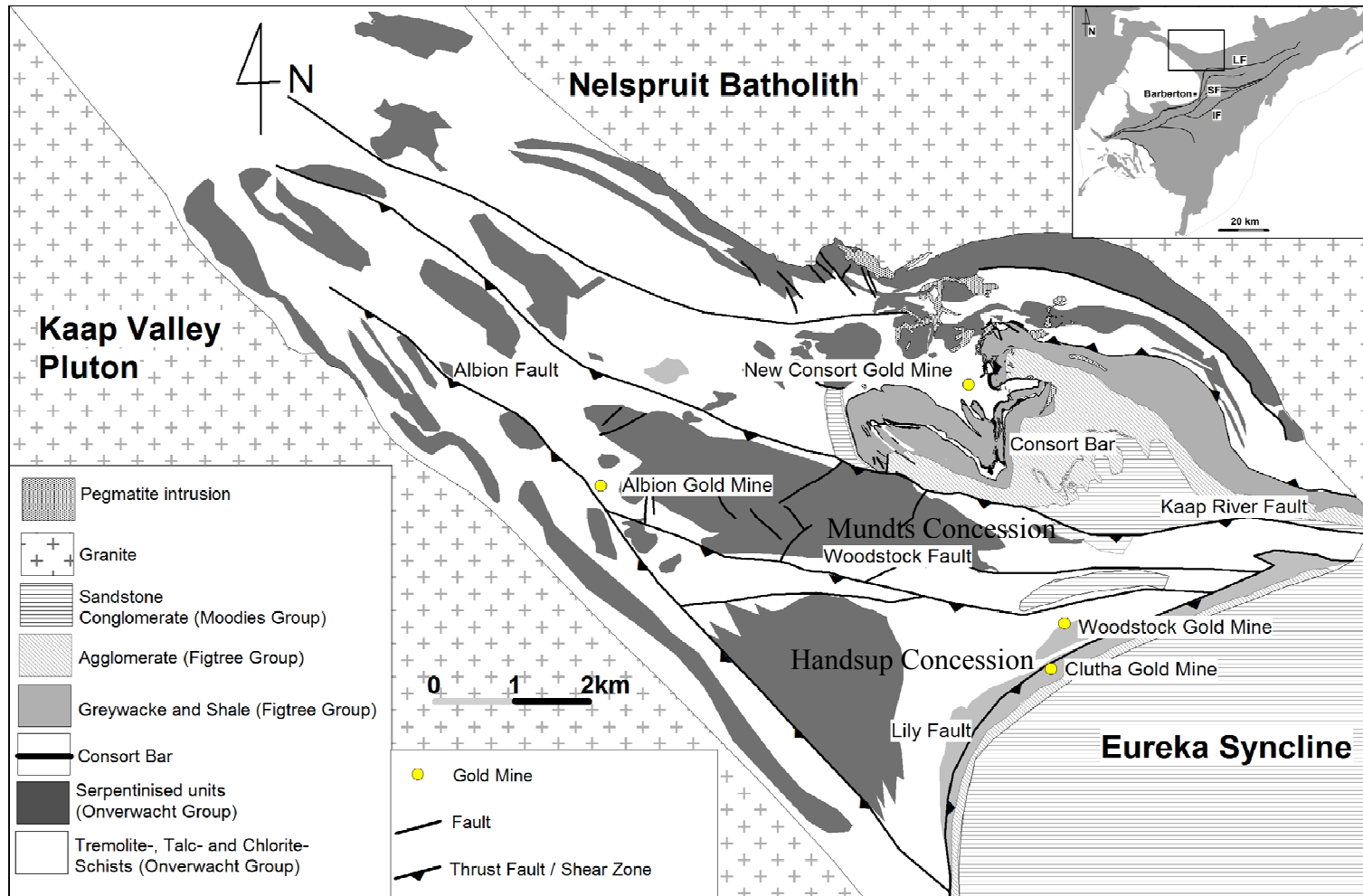


Figure 2.9: Map showing the geology of the Jamestown Schist belt (JSB), plutons, faults and locations of the gold mines in the study area; New Consort, Albion, Woodstock and Clutha Mines. IF = Inyoka Fault, SF = Sheba Fault and LF = Lily Fault (Modified from Ward, 1999; Anhaeusser, 1969; Viljoen, 1964).

Dziggel *et al.* (2007), Otto *et al.* (2007) and Harris *et al.* (1995) adopted the adjustments made by Tomkinson and Lombard (1990) and discussed the relationship between metamorphism and gold mineralization in the area.

The deformation history of the NCGM as outlined by previous authors has been described below. New details about the deformation history and mineralization around the New Consort Gold Mine are presented in Chapter 4.

The NCGM area is complexly folded and faulted to form a large synclinorium, which according to Voges (1986) plunges to the southeast. This synclinorium is composed of the Top Section Syncline, located towards the north of the mine, the No. 3 Shaft Syncline, located to the south of the mine, and several smaller anticlines between No. 3 Shaft and the Top Section Synclines (Fig. 1.3; Viljoen, 1964; Voges, 1986; Ward, 1999). The anticlines between the synclines are collectively known as the No. 7 Shaft and Shires anticlines (Fig. 1.3). Parasitic folds occur along the Consort Bar (Voges, 1986; Ward, 1999).

Viljoen (1964) described D^{VI}_1 as a folding event that deformed rock units of Onverwacht, Fig Tree and Moodies Groups (Table 2.1; Viljoen, 1964). The folding produced steeply dipping axial planes near vertical folds such as Lily Syncline (F^{VI}_1) that is located east of the NCGM (Viljoen, 1964; Anhaeusser, 1969). The folding was linked to the formation of the Eureka Syncline in the Sheba area where a southwest plunge associated with these folds was deduced (Ramsay, 1963; Anhaeusser, 1976).

The area around NCGM has been variably affected by several metamorphic events that vary in grade across the shear zone-bounded domains around the mine. This includes peak metamorphic conditions (M^{VI}_1), achieved during D^{VI}_1 in the Onverwacht Group schist near the southern margin of the Stentor Pluton and north of the Consort Bar (Dziggel *et al.*, 2006). The peak conditions have been variably reported as 600-700 °C, 5+/- 1 kbar (Dziggel *et al.* 2006) and 600-700 °C, 6-8 kbar (Otto *et al.*, 2007) for garnet-sillimanite-bearing metapelitic and garnet-hornblende-clinopyroxene-bearing metabasic

assemblages, respectively. Peak conditions drop sharply to 510-530 °C, 4 kbars in Fig Tree Group rocks west of No 3 shaft.

D^{VI}_2 structures include a pronounced penetrative cleavage that was interpreted to cut obliquely through the rocks of Onverwacht, Fig Tree and Moodies Groups and local F^{VI}_1 folds (Viljoen, 1964; Table 2.1). The cleavage stands out prominently in the shale units and is penetrative in places (Viljoen, 1964). The cleavage occurs at a low angle (about 4°) to bedding of the host rocks and is associated with a stretching lineation visible along the cleavage planes (Viljoen, 1964). Elongation of pebbles in the conglomerates found in the F^{VI}_1 synclines, has been linked to the D^{VI}_2 . The slaty cleavage and elongation of pebbles have been described in detail by Anhaeusser (1976). Dziggel *et al.* (2007) provided kinematic information for D^{VI}_1/D^{VI}_2 fabrics interpreted as N-up shear fabrics linked to doming of the Stentor Pluton.

D^{VI}_3 involved complex folding of the Consort Bar to form a large synclinorium (F^{VI}_3) (Viljoen, 1964). Plunge directions of the F^{VI}_3 folds are to the southeast and southwest, with southeast the most common (Viljoen, 1964; Voges, 1986). The folds refolded the F^{VI}_1 folds to southeast plunging structures (Table 2.1; Viljoen, 1964; Anhaeusser, 1976). Viljoen (1964) proposed that the refolding of the F^{VI}_1 folds and the formation of the F^{VI}_3 folds are linked to the rise of the Nelspruit Pluton and probably refolded the Eureka Syncline (Table 2.1).

Viljoen (1964) also suggested that gold mineralization in the NCGM area to D^{VI}_3 event and the emplacement of the Nelspruit Batholith. The diapirism of the batholith has also been associated with the intrusion of pegmatites that are found in most parts of the NCGM area (Harris *et al.*, 1995). Tomkinson and Lombard (1990) linked gold to steeply dipping NE-SW trending shear zones, activated during the rise of the Nelspruit Batholith. A network of these shear zones, termed the Shires Shear Zone (SSZ), was interpreted to be the controlling structure of gold mineralization (Tomkinson and Lombard, 1990; Harris *et al.*, 1995). The observation of the SSZ is based on underground exposures, and

no such shear zones have been mapped or observed on surface, and the validity of this structure is unclear (see also Chapter 4).

A second metamorphic event (M^{VI}_2) around the mine is represented by contact metamorphism, noted by Viljoen (1964), who indicated contact metamorphic aureole affecting rocks along the northern margin of the JSB. This event is also associated with an increase in grade from No 3 shaft in the SW to PC shaft in the NE from 530 $\pm$ 20 °C at 4-5 kbar to 590 $\pm$ 20 °C at 4-5 kbar respectively (Dziggel *et al.*, 2006; Otto *et al.*, 2007). (M^{VI}_2) was tentatively linked to shearing along the Consort Bar and gold mineralization (Dziggel *et al.*, 2006; Otto *et al.*, 2007), and to the emplacement of pegmatite veins (Harris *et al.*, 1995). Dziggel *et al.* (2007) interpret mylonite along the Consort Bar as syn- D^{VI}_3 , and suggested it formed during extension allowing rapid exhumation of higher metamorphic grade rocks from below the Consort Bar.

Regional fractionation trends in lithium-rich pegmatites reflect increased metamorphic conditions at deeper levels in the mine and towards the NE, with crystallisation conditions reported at 500-650 °C and 3-4 kbar, to coincide with the gold mineralization (Harris *et al.*, 1995)

D^{VI}_4 involved folding that produced brittle-ductile normal faults / shear fractures and intermediate size folds with almost horizontal fold axes and horizontal fold axial planes (near recumbent folds) (Table 2.1; Viljoen, 1964). These folds mainly occur in well foliated talc-chlorite- and sericite-schist (Viljoen, 1964; Anhaeusser, 1976). Minor crenulation folds, conjugate folds and flat lying kink-bands related to this deformation occur in greywacke and shale and greenstones layers (Viljoen, 1964; Anhaeusser, 1969). Normal faults in the area include the Bluejackets Fault, which has been interpreted to overprint gold mineralization (Viljoen, 1964; Harris *et al.*, 1995). M^{VI}_3 , a third, retrograde, lower greenschist facies metamorphic event has been linked to alteration assemblages along late, cross cutting D^{VI}_4 faults.

2.3 Gold mineralization in the BGB

Outside of the Witwatersrand Basin, the BGB is the foremost gold producing area in South Africa. Since the discovery of gold in the BGB in 1883, more than 345t of gold have been produced from the BGB, with the bulk of production coming from the Sheba (123.7t), Fairview (63.4t) and New Consort (68.5t) mines (Fig. 1.1), which continue to produce 2.5-3t of gold per year at average grades of ~10-12 g/t (Dirks *et al.*, 2009) .

Gold in the BGB is hosted by second-order brittle-ductile shear zones, which overprint different lithological units and earlier complexly folded ductile structures (de Ronde and de Wit, 1994; Dirks *et al.*, 2009). De Ronde and de Wit (1994) interpreted these mineralized brittle-ductile shear zones as D₃ strike-slip and thrust faults (Table 2.1), and classified gold in the BGB as orogenic gold. However, Dirks *et al.* (2009) in the Sheba-Fairview area indicate that gold mineralization postdates all orogenic periods. Below is a summary review of the setting of gold deposits in the Sheba-Fairview and NCGM deposit.

2.3.1 Sheba – Fairview Gold deposits

In the Sheba Hills, gold is hosted by all rock types, with no preferential host lithology (Robertson *et al.*, 1994; Ward, 1999, 2002). Mineralization occurs in two types of ore bodies: 1. quartz vein deposits with free milling gold in fractures transecting quartzite units of the Moodies Group, and 2. disseminated sulphide ore zones in Fig Tree shale and greywacke (Wiggett *et al.*, 1986; Robertson *et al.*, 1994). Mineralized vein deposits include the Blue Rock, Kidson, Victory Hill, Golden Quarry, Annie's Fortune, Mamba, Tit Bit, Joe's Luck and Thomas deposits amongst others (Fig. 2.7; Anhaeusser, 1976; Wagener and Wiegand, 1986; Wiggett *et al.*, 1986; Dirks *et al.*, 2009). Disseminated sulphide deposits include the main ore bodies at both Fairview and Sheba mines (*e.g.* the MRC ore body).

At Sheba mine, ore zones occur along the intersections of flat and steeply-dipping SSW-trending shear fractures, with competent greywacke horizons of the Fig Tree and chert bars at the top of the Onverwacht Group forming the locus of mineralization. Ore fluids penetrated host rocks along dilated planes. Arsenopyrite is the dominant sulphide in greywacke with pyrite dominant in iron-rich shale (Robertson *et al.* 1994).

Complex ore parageneses have been linked to several phases of arsenopyrite and pyrite growth, and numerous phases of overlapping veins, indicating progressive deformation and fluid infiltration during mineralization (*e.g.* Schouwstra and DeVilliers, 1988; Robertson *et al.*, 1994). In spite of great complexity at a detailed scale, de Ronde *et al.* (1991, 1992) noted that the fluid composition (H₂O, CO₂, NaCl) from gold deposits across the northern BGB is homogeneous with gold being deposited from the same ore-bearing parental fluid, which was probably derived external to the greenstone belt.

Alteration associated with mineralization includes widespread silicification, such as quartz vein stockworks in the hangingwall of the Golden Quarry deposit referred to as the Sheba Bar (Anhaeusser, 1976; Dirks *et al.* 2009). Potassic alteration, carbonatization, sulphidization (mostly pyrite, arsenopyrite with minor stibnite) and tourmaline growth have also been noted (Schouwstra and DeVilliers, 1988; Schouwstra, 1995). Arsenopyrite, in particular, shows a close correlation with gold values.

Dirks *et al.* (2009) indicate that gold mineralization in the Sheba-Fairview area occurs along a network of complexly interconnected D^{IV}₄ brittle-ductile normal shear fracture zones that cross-cut all earlier ductile structures including the D^{IV}₃ constrictional fold structures that have been linked to doming of the Kaap Valley Pluton and Nelspruit Batholith (Harris *et al.*, 1995; Anhaeusser, 1976). On a 10m-scale, these fractures anastomose and are arranged in en-echelon fashion. On 10m to 100m scales the mineralized fractures are arranged in overlapping Riedel, P-shear and anti-Riedel shear arrays defining mineralized corridors, which dominantly trend NE to ENE, WNW and NNW with variable, moderate dips. These fractures were dominantly formed in an

extensional environment in which σ_1 was vertical and σ_3 orientated in a horizontal NW-SE direction (Dirks *et al.*, 2009).

Dirks *et al.* (2009) also indicate that gold mineralization was accompanied by D^{IV}_4 kink folding, porphyry dyke intrusions (Fig. 2.10) and extensive silicification, which dominantly occurs as a halo around mineralized areas. The best estimate for the age of gold mineralization in the Sheba-Fairview and NCGM regions comes from a quartz porphyry dyke in Fairview Mine dated at 3126 ± 26 Ma (de Ronde *et al.*, 1991). Rutile dated at 3084 ± 18 Ma from this porphyry (de Ronde *et al.*, 1991) was linked to hydrothermal alteration thought to have resulted in gold mineralization (Fig. 2.11). Dirks *et al.* (2009) concluded that mineralization occurred in an extensional environment involving silicification and the emplacement of porphyries, which occurred after the formation of all regional ductile structures including structures related to the emplacement of all major batholiths; *i.e.* after 3106 Ma (Dziggel *et al.*, 2010).



Figure 2.10: A mineralized altered porphyry dyke, beneath the pen, that intruded a mineralized shear zone, above the pen, at the Nil Desporandum Mine in the Sheba area (Fig. 2.7; GR 311515 - 7155284).



Figure 2.11: A sample of the quartz porphyry dyke from Fairview Mine, which was dated by de Ronde *et al.* (1991) at 3126 ± 18 Ma.

2.3.2 NCGM Gold deposits

Gold mining in the NCGM area started in 1886 on the Ivaura, and MMR sections (Fig. 1.3). In the early days of mining, numerous surface workings were developed, mainly on small and discontinuous ore zones, resulting in tens of small workings scattered around the NCGM area. As mining progressed, activity concentrated on a limited number of major shoots including the Seven Shaft, the Ivaura, the MMR and PC shoots (Fig. 2.12), which have been mined down to 1600 m level (Voges, 1986), resulting in a total production to date of 68.5 tons of gold (Dirks *et al.*, 2009).

The complexity of the geology around the NCGM has resulted in several interpretations for gold mineralization, and its timing. All studies agree that gold mineralization in the NCGM was structurally controlled (e.g. Viljoen 1964; Voges, 1986; Harris *et al.*, 1995; Dziggel *et al.*, 2007), but there remains a paucity of detailed structural information on the exact controls.

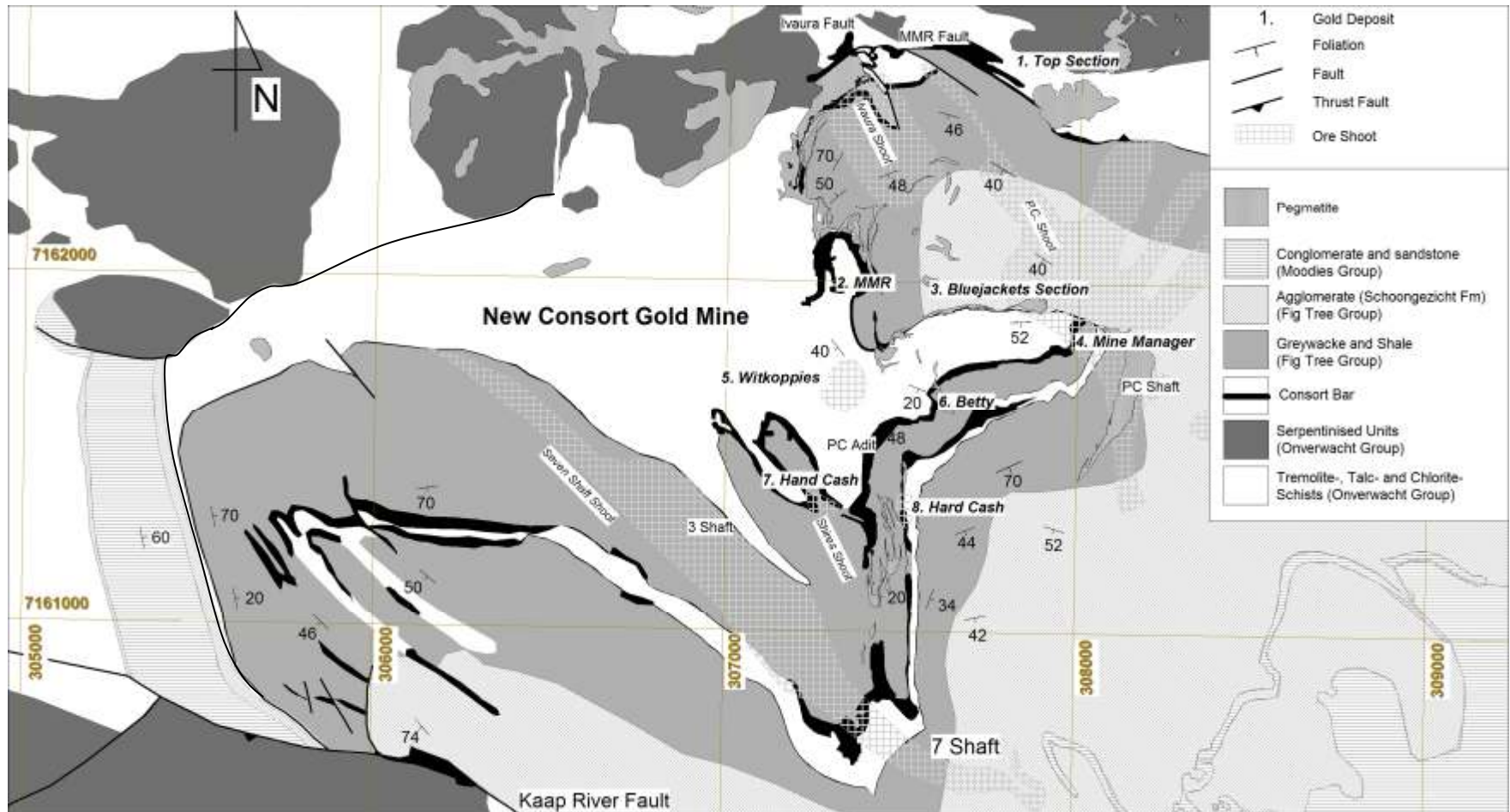


Figure 2.12: Map showing trends of major faults, e.g. Ivaura and MMR Faults, and ore shoots, which have been projected from underground workings in the NCGM. Grid spacing is a 1000 meters. (adjusted from Voges, 1986).

The main ore shoots occur in amphibolitic schist of the Onverwacht Group in the immediate footwall of the folded Consort Bar and along the bar itself (e.g. No7, Ivaura, MMR and PC shoots), with minor ore shoots occurring in Fig Tree meta-greywacke and chert units in the hanging wall of the Consort Bar (e.g. Hard Cash, Shires and Betty's Quarry shoots), as well as in schist and deformed felsic porphyry deeper into the footwall (e.g. Witkoppies and Bluejackets ore shoots; Voges, 1986; Ward, 1999; Fig. 2.12). Ore bodies occur as 10-80 m wide, SE and SW plunging ore shoots that are sub-parallel to the orientation of the Consort Bar, and in places transgress the bar. Some ore envelopes have been traced down plunge as near-continuous ore zones to depths of up to 1600 meters (Voges, 1986; Ward, 1999), and consist of irregular, discontinuous ore shoots cut and displaced by pegmatite bodies.

Otto *et al.* (2007) classified mineralization in the NCGM into two types, in which, Type 1 was linked to the amphibolites (clinopyroxene-hornblende-garnet-k-feldspar-biotite) formed during D^{VI}_1 , implying the occurrence of an early stage of gold mineralization associated with D^{VI}_1 (e.g. Otto *et al.*, 2007). Type 2 mineralization has been linked to D^{VI}_3 and the Shires Shear zone. In general, mineralization is thought to be late and related to the dominant D^{VI}_3 fold and shear structures (e.g. Tomkinson and Lombard, 1990; Voges, 1986; Viljoen, 1964), and mineralising fluids were linked to pegmatite intrusions (e.g. Harris *et al.*, 1995), even though some of the main ore shoots such as the PC and MMR shoots are known to be intruded and displaced by late pegmatite bodies (Voges, 1986; Harris *et al.*, 1995).

A direct date for gold mineralisation of 3027 ± 7.5 Ma has been reported from the NCGM for hydrothermal titanite that formed part of the alteration assemblage in the "footwall lens" ore body (Dziggel *et al.*, 2010). This date is consistent with a poorly constrained Rb-Sr age of 3040 ± 84 Ma reported by Harris *et al.* (1995) for a pegmatite in NCGM interpreted to be emplaced during mineralisation. An ~ 3030 Ma age of mineralisation appears to postdate accretionary events (at ~ 3230 Ma) and subsequent advective overturn and thermal and mechanical stabilisation of the craton (by ~ 3100 ; e.g. deRonde and deWit, 1994; Schoene *et al.*, 2008) by a considerable time period.

The most detailed information on geological controls on mineralization is contained in a series of exploration reports compiled by Anglovaal in the late 1980's and early 1990's (Marchini, 1987; Voges, 1989; Tomkinson, 1989). These reports make mention of the ribbon-like, irregular nature of the ore shoots along the Consort Bar, and suggest this geometry reflects a control by later cross-cutting faults, similar to what has been described in the Sheba-Fairview area (e.g. Dirks *et al.*, 2009).

These faults are thought to have introduced the fluids resulting in arsenopyrite-pyrrhotite alteration and gold mineralization as well as retrograde quartz-biotite-chlorite alteration. These controlling faults such as the Ivaura and MMR Faults (Fig. 1.3) have been described for the MMR and PC shoots (Voges, 1989), but also occur along the orebody near No. 3 and No. 6 Shafts (Marchini, 1987) and in the Witkoppies Quarry where they overprint mylonitised pegmatite zones (Tomkinson, 1987). The MMR Fault is reported to be shallow and split into a series of listric fault segments, where it transects the Consort Bar possibly resulting in dilation and ingress of mineralization along the intersection of the faults and the Consort Bar (e.g. Anglovaal Ltd Report 1989 ETC/AVE/88/329; Anglovaal Ltd Report 1989 ETC/AVE/87/232).

3. Geology of the New Consort Gold Mine

The New Consort Gold Mine (NCGM) is located in a triple junction area of the BGB, in Domain VI (Fig. 2.3), where the NW trending Jamestown Schist Belt (JSB) merges with the NE trending main branch of the BGB (Figs. 1.1, 2.3). The 3106 ± 3 Ma Nelspruit Batholith (Kamo and Davis, 1994), including gneisses of the 3107 ± 5 Ma Stentor pluton (Kamo and Davis, 1994), and the 3227 ± 1 Ma Kaap Valley Pluton (Kamo and Davis, 1994), bound this triple junction to the N and SW respectively (Figs. 1.1, 2.9). These plutons have acted as buttresses between which the complex constrictional structures that characterise the NCGM were formed (Anhaeusser, 1976). To the SE, the triple junction area is bounded by a thick sequence of clastic sediments belonging to the Moodies Group that have been folded to form the Eureka Syncline (Fig. 1.1). The NCGM area is transected by a series of major faults including the Lily, Albion, Woodstock and Kaap River Faults (Figs. 2.3, 2.9), which act as boundaries to structural domains with distinct deformation and metamorphic histories (e.g. Anhaeusser, 1976; Dziggel *et al.*, 2007). The Kaap River Fault forms the southern boundary of the complexly folded greenschist to amphibolite grade rocks that host the gold mineralization around the NCGM (Figs. 2.3, 2.9).

Rocks of the Onverwacht, Fig Tree and Moodies Groups have been preserved in an area around the NCGM (Fig. 1.3), and their stratigraphy has been described in detail by Viljoen (1964) and Anhaeusser (1976) (Fig. 1.4). This stratigraphy conforms closely with that observed in the Sheba area to the south of the Lily Fault (e.g. Anhaeusser, 1976; Dirks *et al.*, 2009).

3.1 Onverwacht Group

Onverwacht Group rocks constitute the bulk of the JSB and comprise komatiitic and tholeiitic meta-basalts intruded by layered intrusive mafic-ultramafic complexes collectively grouped as the 3286 Ma Weltevreden Formation (Fig. 1.4; Byerly *et al.*, 1996; Lowe and Byerly, 1999). These rocks have been deformed and metamorphosed

resulting in a complex patchwork of massive, relatively undeformed, lensoidal bodies of ultramafic rocks, including dunite and pyroxenite, surrounded by highly strained, schistose units of variable composition ranging from serpentinite, via talc-carbonate-chlorite schist to amphibolite (Fig. 1.3; Viljoen, 1964). Amphibolites are common near the contact between the greenstones and the Nelspruit Batholith reflecting an amphibolite facies contact metamorphic aureole along the N margin of the JSB (Viljoen, 1964).

Below are the descriptions of rock units that represent the Weltevreden Formation in the NCGM area. It must be noted that, due to several complex deformation events and high intensity of alteration affecting the Weltevreden Formation in the NCGM area, it is not clear what rocks constitute the original stratigraphy.

3.1.1 Amphibolite

Amphibolite mainly occurs to the north of the NCGM, forming parts of the elevated areas in the hills to the north of the Top Section Syncline (Fig. 1.3). The amphibolite that crops out near the Nelspruit Batholith is dominantly black- to dark-green with white flecks of feldspars in places (Fig. 3.1). This amphibolite unit attains a maximum thickness of approximately 60 meters and in places, occurs as xenoliths within the batholith (Viljoen, 1964). The mineral assemblage in the amphibolite includes radiating tremolite needles, plagioclase and hornblende with biotite, talc and phlogopite subordinately developed (Voges, 1986; Harris, 1992). Common accessory minerals include albite, carbonate, chlorite and minor quartz (Harris, 1992).

Amphibolite and amphibolite-quartz-feldspar alternate, defining a banding or foliation in the unit (Fig. 3.1; Viljoen, 1964). The banding is mainly parallel to the granite-greenstone contact that dips moderately to steeply to the south (Viljoen, 1964). The long axes and foliation of the xenoliths are also aligned parallel to the trend of the granite-greenstone contact (Viljoen, 1964). This amphibolite unit is commonly altered, with chlorite being the main alteration mineral, and weathers to a rough surface texture (Fig. 3.1). The amphibolite grades into a relatively thin serpentinite unit, which is in contact with a

tremolite-talc schist in the Top Section area, west of the Consort Bar (Fig. 1.3; GR 307311-7162499)



Figure 3.1: Foliated amphibolite occurs in the lower part of the Weltevreden Formation, preserved in the northern NCGM area. Quartz-plagioclase aggregates make up the white bands (GR 307206-7162465).

3.1.2 Tremolite-talc schist

Tremolite-talc schist is found throughout the NCGM area, commonly defining low elevated areas. Typical examples include areas around PC Shaft and along the Onverwacht Group rocks, commonly known as the Hangingwall Band (Harris, 1992), which is a tremolite-talc-schist unit bounded by rocks of Fig Tree Group in the central NCGM (Fig. 1.3). Tremolite-talc-schist units are dominantly light green, fine- to medium-grained and contain tremolite, talc, quartz, plagioclase, pyroxene and biotite with minor cummingtonite and antigorite. Antigorite, which occurs as specks, is known

to be common in areas where the tremolite schist grades into a serpentinite unit (Viljoen, 1964).

Tremolite grains occur as two generations, randomly-orientated and well-orientated needle-like grains. The well-orientated tremolite together with micas, define a schistose fabric and mineral lineation in the outcrops, e.g. around PC area, close to the Consort Bar (GR 307530-7161300). Tremolite grains attain a length between 2 to 5 mm and are at most, 1 mm in width. Around the Ivaura sections, the tremolite-schist unit occurs as banded units, which are commonly defined by actinolite and pyroxene (Viljoen, 1964).

A strong schistose fabric defined by biotite, abundant phlogopite, and the presence of zoisite, epidote, albite and chlorite, are common in close proximity to the Consort Bar (Voges, 1986; Harris, 1992). In places, tremolite-talc schist occurs as lensoidal bodies, which have been termed the Footwall Lens (Voges, 1986; Baumann, 1990). Thin section evidence shows that the Footwall Lens is a rather fine-grained amphibole-bearing rock, which contains sheared or deformed grains of tremolite, hornblende, plagioclase, quartz, biotite and pyroxene, which is the equivalent of a tremolite-talc schist (Fig. 3.2).

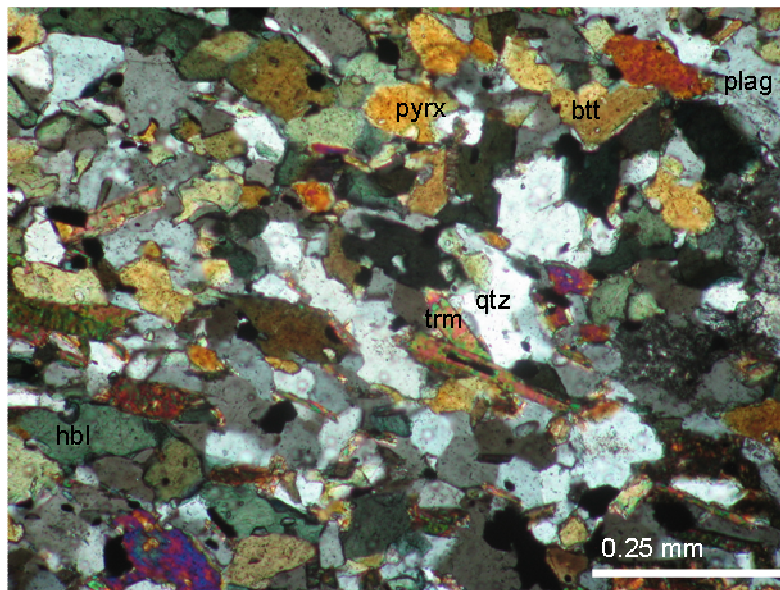


Figure 3.2: Thin section from what is known as the Footwall Lens. Minerals include tremolite (trm), hornblende (hbl), pyroxene (pyrx), plagioclase (plag), biotite (btt) and quartz (qtz).

3.1.3 Carbonate-talc-chlorite schist

Carbonate-talc-chlorite schist (talc schist) is dominantly developed to the south of the Lily Syncline along the Kaap River and partly in the Mundts Concession Intrusion to the south of the Kaap River Fault (Viljoen, 1964). Talc-chlorite schist is mainly medium- to coarse-grained, greenish to grey on fresh surfaces and dirty brown on weathered surface (Fig. 3.3; Viljoen, 1964). Common minerals include talc, chlorite, quartz, feldspars, magnesite and carbonates. In places, chlorite occurs as long elongated crystals that are aligned parallel to the foliation (S₀). Light green talc patches, amygdales and veins of magnesite are observed in the rock unit. Carbonate-talc-chlorite schist is well exposed along a rail-line, south of Kaap River Fault (GR 307970-7159190; Fig. 3.3)

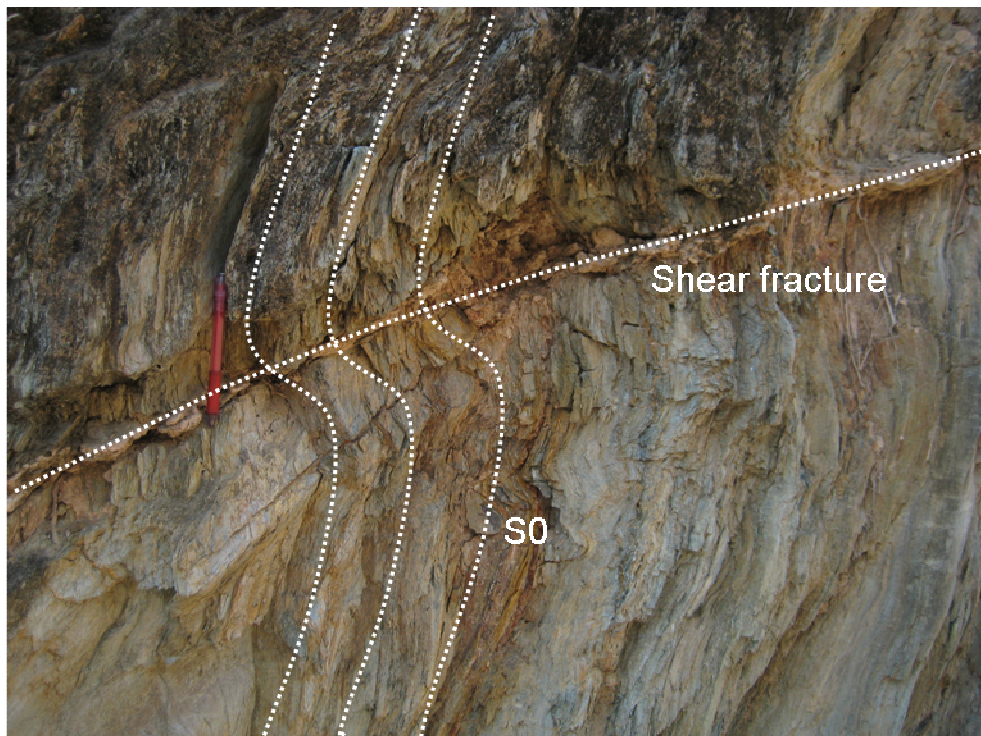


Figure 3.3: Carbonate-talc schist showing kink-folded S₀ (foliation) crosscut by extensional shear fractures filled with magnesite. Outcrop occurs along a rail-line to the south of the Kaap River Fault (GR 307970-7159190).

3.1.4 Serpentinite

Serpentinised units in the NCGM area commonly occur as lensoidal or rounded bodies, which, in places, form elevated areas. These are mainly found to the south of the NCGM area, including Handsup and Mundts Concession intrusions (Fig. 2.9.), and to the north of the NCGM, separating amphibolite from talc schist. Some of the fresh specimens of the serpentinised units are mainly dark-green to olive-green with sericite flakes, and weather to a brown colour. To the north of the NCGM, blue serpentinite is common (Viljoen, 1964). The mineral constituents of these units include serpentine, chlorite, talc, carbonate and magnetite with remnants of olivine, especially where massive serpentinite occurs (Harris, 1992; Hearn, 1943).

In the hills to the south of the NCGM, the massive serpentinised units preserve primary igneous layering. The primary layering dips shallowly to the SW and is defined by parallel planar surfaces of tens of meters in thickness. The rock is characterized by an equigranular texture defined by dark- to light-green olivine and pyroxene. Olivine occurs predominantly over pyroxene, and the units were dunitic (> 90% Olivine) in composition.

3.2 Consort Bar

The Consort Bar occurs between the rocks of the Onverwacht and Fig Tree Groups, and is the equivalent of the Zwartkoppie Formation in the Sheba Area (Anhaeusser, 1976). The unit is a fine-grained, banded, hard, cherty, dark brown (Fig. 3.4) rock ranging variably from 1 centimetre to 25 meters in width, with an average width of 0.5 to 2 meters (Hearn, 1943; Voges, 1986).

The mineral assemblage in the Consort Bar includes, quartz, biotite, muscovite, rutile, minor amounts of zoisite, apatite, sericite and green-brown tourmaline (Hearn, 1943; Harris, 1992). The unit is mylonitised, and biotite-muscovite flakes, and quartz are strongly aligned within the banding of the unit, defining a prominent mineral lineation. Diopside-rich skarn alteration characterise the bar's immediate footwall contact,

interpreted to have formed at least in part because of alteration and silicification of ultramafic rocks (Schouwstra and de Villiers, 1988). The greywacke and shale units of the Fig Tree Group conformably overlie the Consort Bar (Anhaeusser, 1964; Viljoen, 1964; Voges, 1986).



Figure 3.4: A silicified, mylonitised and lineated Consort Bar, which marks the contact between the Onverwacht and Fig Tree Groups (GR 37288-7162072). White dotted lines are parallel to mylonitic stretching lineations in the Bar.

3.3 Fig Tree Group

The Fig Tree Group is composed of alternating layers of metamorphosed greywacke and shale (Voges, 1986), and volcanoclastics of the Schoongezicht Formation, which includes dacitic tuff and agglomerate units (Anhaeusser, 1976). Note that for simplicity, and to retain the terminologies in the literature, this thesis refer to the Fig Tree Group units as greywacke, shale and mud, the prefix meta- is assumed.

3.3.1 Greywacke and Shale

Greywacke and shale units are found in most parts of the NCGM area and include the Top Section and No. 3 Shaft Synclines. These units are generally brown in colour and dominantly composed of quartz and plagioclase. Shale is relatively finer-grained in contrast to the medium- to coarse-grained greywacke (Figs. 3.5 and 3.6).

Inverse graded bedding that is defined by coarser-grained over finer-grained mud-rich layers, is preserved in some outcrops of the greywacke. These mud-rich layers, which are also rich in fine-grained biotite, are commonly thin and can reach up to 4 centimetres in thickness. A generally easterly younging direction has been deduced from the graded bedding preserved to the east of PC Shaft.



Figure 3.5: Greywacke showing bedding plane (S0) crosscut by chert-rich veins (GR 307513-7161014).

Common metamorphic mineral assemblages include quartz, plagioclase, tremolite, biotite, garnet, muscovite, chlorite and hornblende, representing amphibolite facies

assemblages. This mineral assemblage is commonly found in the greywacke units, but tremolite, which occurs as random and orientated grains, is also preserved in the mud-rich units. In the mud-rich units, tremolite occurs as needle-shaped radiating crystals that can reach 3mm in length. Garnet grains are dark-brown, rounded and, in places, attain a diameter between one and two millimetres. Garnet increases in abundance and size towards the Consort Bar.

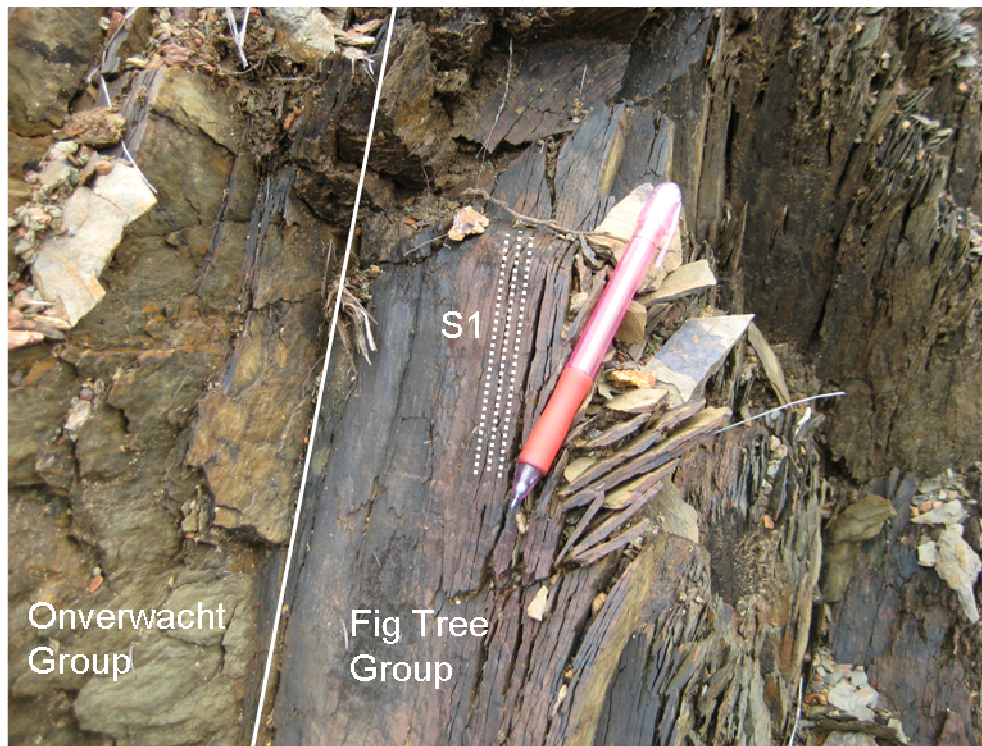


Figure 3.6: A shale unit of the Fig Tree Group occurs with a sharp contact with tremolite-talc schist of the Onverwacht Group, around No. 3 Shaft, east of the NCGM (GR 305493-7161575). Cleavage planes (S1) in the shale unit are almost parallel to the bedding plane (S0).

A penetrative cleavage is commonly observed in the greywacke and shale units, but more in the greywacke units. In most places, biotite grains are aligned parallel to these cleavage planes, defining a stretching mineral lineation trends that are present in the rock units. These cleavage planes are axial planar to tight folds that are present in the Fig Tree and Onverwacht Groups. Randomly orientated tremolite grains crosscut these cleavage

planes. Other bands of the greywacke-shale units contain large, irregular, randomly orientated andalusite crystals showing sieve-like textures with quartz and biotite inclusions (Viljoen, 1964).

Greywacke and shale layers are highly silicified near the Consort Bar, and are invariably dark-grey to brown units, which tend to resist weathering. In areas where greywacke-shale units are interbedded or crosscut by thin layers of chert, garnet grains are larger and more common (Fig. 3.7). In places, silicified greywacke-shale units occur as laminated (banded) layers with faint traces of the penetrative cleavage. Cordierite overgrowth on the silicified greywacke has been observed.



Figure 3.7: Garnet bearing greywacke unit interbedded with chert-rich units (GR 307523-7161049).

3.3.2 Felsic dacitic tuffs and agglomerates (Schoongezicht Formation)

The Schoongezicht Formation is exposed in the eastern and western parts of the NCGM (Fig. 1.3). To the west of the NCGM, the Schoongezicht Formation overlies a sheared serpentinitised unit of the Onverwacht Group, whilst, to the east of the mine, the formation unconformably overlies the greywacke-shale units of the Fig Tree Group. Around the Woodstock area, the Schoongezicht Formation overlies rocks of the Onverwacht Group (Fig. 2.9).

The Schoongezicht Formation is composed of cream-coloured to light grey, medium- to coarse-grained dacitic tuff units, and dark grey dacitic agglomerate. The tuff forms the basal part of the Schoongezicht Formation in the NCGM area, and consists of plagioclase, quartz, tremolite, hornblende and finer-grained micas (Fig. 3.8). Plagioclase is the dominant mineral in the unit, and hornblende and tremolite appear to be secondary minerals representing a metamorphic assemblage.



Figure 3.8: Coarse- to medium-grained felsic dacitic tuff, which comprises the lower part of the Schoongezicht Formation (GR 307958-7161315).

Plagioclase occurs as rounded to rectangular crystals, where long axes define a grain-shape preferred orientation. The felsic tuff grades to an agglomerate, commonly assigned to the upper Fig Tree Group.

The agglomerate unit is generally light- to dark-grey, consisting of clasts and rare cobbles in a medium-grained dark-grey to brown matrix (Fig. 3.9). The clasts are mainly of dacitic composition, characterized by white spots of plagioclase. These crystals range from euhedral, subhedral to angular, but euhedral to subhedral grains are most common (Viljoen, 1964). Other clasts include granite and rare black chert. The matrix is composed of plagioclase, quartz, biotite, muscovite, chlorite and rare tremolite, and preserved fused, gradational contacts with dacitic clasts more common (Fig. 3.9). Accessory minerals in the matrix include epidote, apatite, magnetite and calcite (Viljoen, 1964).



Figure 3.9: Agglomerate of the Schoongezicht Formation composed of dacitic clasts and dark grey tuffaceous matrix (GR 305466-7161270).

Microscopic studies of the matrix confirmed the existence of volcanic ash fragments within a mafic matrix (Reid, 1990). Tuffaceous fragments are composed of feldspar porphyry with twinned microcline and granitic fragments (Reid, 1990). The presence of amphibole, biotite and chlorite in the matrix, impose a dark colour on the rock (Reid, 1990). Amphiboles include actinolite and tremolite (Reid, 1990).

The clasts of the agglomerate have been deformed to form elongated, cigar-shape and lens-like structures (Fig. 3.10). These clasts attain a length of ten centimetres in places. Plagioclase crystals in the clasts are also elongated, parallel to the long axes of the clasts.



Figure 3.10: Deformed agglomerate showing elongated and lenses-like dacitic clasts (GR 307879-7160258).

A gradational contact exists between the agglomerate and overlying conglomerate unit of the Moodies Group. The contact is characterized by a change in composition of the matrix from a dacitic composition to a quartz-rich sandy matrix, and an increase in number of chert and granitic clasts observed up-stratigraphy.

3.4 Moodies Group

The Moodies Group in the NCGM area is composed of conglomerate, quartzite and sandstone (Figs. 1.3, 2.9). The rocks of the group outcrop to the east and west of the NCGM area, and are well developed in the eastern part (Viljoen, 1964; Ward, 2000). The Moodies Group in the NCGM and surrounding areas occurs in synclinal structures that are underlain by rocks of the Schoongezicht Formation. A conglomerate is found at the base of the group, overlain by quartzite and sandstone. To the southeast of NCGM, close to the Woodstock Gold Mine, the basal conglomerate is poorly developed and thin and the unit is dominated by quartzite, grading into sandstone.

3.4.1 Conglomerate

The conglomerate is polymict, matrix-supported and generally grey in colour (Fig. 3.11). In places, conglomerate units are relatively thin (one to 1.5 meters thick), and alternate with agglomerate of the Schoongezicht Formation, e.g. at location GR 305470-7161270.



Figure 3.11: A polymictic conglomerate of the Moodies Group, consisting of flattened quartz and chert pebbles in a medium-grained sandy matrix (GR 305437-7161281).

Pebbles within the conglomerate include chert, jasper, shale, fuchsite, granite and vein quartz. These pebbles are supported by a medium-grained sandy argillaceous matrix, which is composed of grains of quartz, plagioclase and shale fragments. As observed in the agglomerates of the Schoongezicht Formation, the pebbles in the Moodies Group conglomerate are strongly deformed into elongated pebbles aligned parallel to those of the agglomerates.

3.4.2 Quartzite

The conglomerate grades into a relatively thick quartzite, which grades into a thinner sandstone (arkosic) unit. The quartzite is dark-grey to brown, medium- to coarse-grained and composed of mainly rounded quartz with minor plagioclase, biotite and sericite. The quartzite beds are interbedded with shale units, which are dominantly fine-grained and dark-grey with a smooth, soapy texture (Fig. 3.12). The interbeds define graded bedding, which shows clear younging directions.



Figure 3.12: Alternating quartzite and shale units, which overly the conglomerate of the Moodies Group (GR 305290-7161340).

Typical examples are preserved in the synclinal structure to the west of NCGM (GR 305290-7161340). Planar and trough-cross bedding structures are common in the quartzite units. Laminated or planar stratifications are observed in the interbedded shale units. Silicification is common in the quartzite and, in places, involves crosscutting quartz- and chert- veins that occur as conjugate sets.

3.4.3 Sandstone (Arkose)

The arkose around the NCGM is medium-grained, brown to green in colour and has a sugary texture. The arkose occurs as an immature quartzite that weathers easily, and is crosscut by quartz veins. Trough and planar sedimentary laminations are preserved, but not as common as in the quartzite. The typical example of the arkose is well-exposed around the Kaap River Fault, in the eastern parts of NCGM (Figs. 1.3, 2.9) (GR 308145-7160159).

4. Structural setting of the NCGM

This chapter describes the new findings on the structural history of the New Consort Gold Mine and the surrounding areas. Following detailed mapping, the deformation history of the NCGM area has been redefined to a scheme that is composed of five deformation events, which have been termed, from the oldest to the youngest event, D_{1NC} to D_{5NC} (Table 2.1). The first three deformation events (D_{1NC} to D_{3NC}) involved thrusting and folding of rock units, producing folds and shear zones, which preserve a relatively complex ductile deformation history. The earlier folds were overprinted by a brittle-ductile extensional deformation event (D_{4NC}), producing shear zones, which are commonly represented by brittle-ductile normal faults and shear fractures associated with gold mineralization. D_{4NC} structures are overprinted by D_{5NC} brittle-ductile thrust faults.

The redefined deformation scheme has been linked to the events described from other parts of the belt including in the Sheba area and the southern parts of the BGB. These include the newly proposed deformation events by Dirks *et al.* (2009) around the Sheba Gold Mine and the scheme of Lowe *et al.* (1999) in the southern parts of the belt.

4.1 : D_{1NC} (pre-Moodies upright folding and thrusting)

D_{1NC} structures include tight- to isoclinal, upright- to inclined folds that are restricted to rocks of the Onverwacht and Fig Tree Groups. These folds are associated with a penetrative axial planar cleavage, S_{1NC} , which occurs throughout the NCGM area.

Around the NCGM, several tight D_{1NC} antiforms and synforms can be traced (Fig. 4.1) that are the equivalent of folds such as the Zwartkoppies antiform in the Sheba area (Dirks *et al.*, 2009). An antiformal hinge zone defined by an 80 m wide band of Onverwacht schist within Fig Tree rocks, occurs to the S of the NCGM (Fig. 4.1). The hinge zone, commonly known as the Hangingwall Band, is characterized by silicified contacts including the Consort Bar.

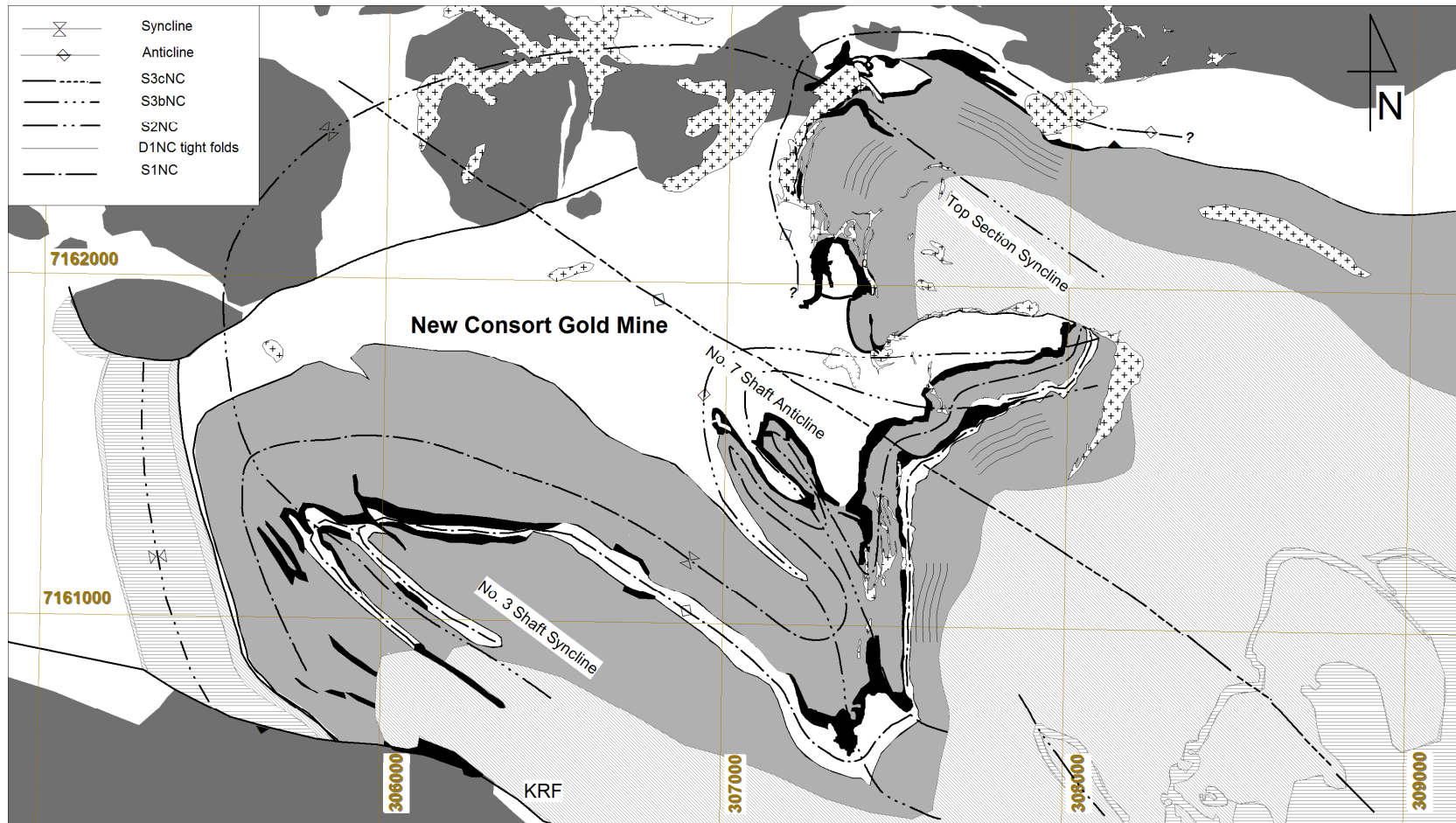


Figure 4.1: Map of the NCGM area showing anticlines, synclines and fold axial traces formed during the main deformation events described in the text. Lithology as indicated in Figure 1.3, and grid spacing is 1000 meters.

In places the Consort Bar is represented by fragments of vein-quartz and shale in a silicified fine-grained matrix (Fig. 4.2a). Individual fragments or clasts attain a length of 5 centimetres (Fig. 4.2a). Typical examples can be observed from the Hard Cash gold working (GR 307500-7161392). These silicified contacts were formed during this event, and probably originated during M_{INC} peak-metamorphism as a silica enrichment zone along the contact of Onverwacht ultramafic schist and silicic Fig Tree Group metasediment (Schouwstra and De Villiers, 1988; Dirks *et al.*, 2009).

The antiform exposing the Onverwacht Group is separated from the Consort Bar to the NW by a 100m scale synform positioned in Fig Tree Group schist, which can be traced using changes in the S_0 - S_{INC} cross cutting relationships (Fig. 4.2b). These S_0 - S_{INC} relationships in Fig Tree Group schist vary repeatedly on 10m scales (e.g. GR 307514-7161018; Fig. 4.1) indicating the presence of isoclinal vergence folds along the larger scale tight folds, such as the D_{INC} antiform (Fig. 4.1). The D_{INC} antiform of Onverwacht Group rocks within Fig Tree Schist pinches and merges with the main body of Onverwacht Group rocks north of the Bluejackets Fault, i.e. E and NE of the mine (Fig. 4.1) indicating that the fold hinge of the D_{INC} synform in Fig Tree Schist plunges in a SW direction.

D_{INC} folds are near-isoclinal and the traces of the fold axial planes of these folds are folded throughout the NCGM area (Fig. 4.1). In the central parts, axial planes mainly dip moderately to the east and southeast, where the Consort Bar is folded, whilst axial planes in the Top Section dip to the south, east and west (Fig. 4.1). The regional S_{INC} fabric is generally near parallel to the compositional layering S_0 , and average angles between S_0 and S_1 are between 2 and 10 degrees (Fig. 4.2b). The orientation of S_{INC} varies from a moderately NE, SE, S, SW and NW dip as it is traced along the Consort Bar. S_{INC} is defined by orientated tremolite, serpentine and mica grains in the greenstones and by a schistosity in the greywacke and shale units of the Fig Tree Group.

D_{INC} is the equivalent of the regional D_2 proposed by de Ronde and de Wit (1994) and D_{1s} proposed by Dirks *et al* (2009) (Table 2.1).

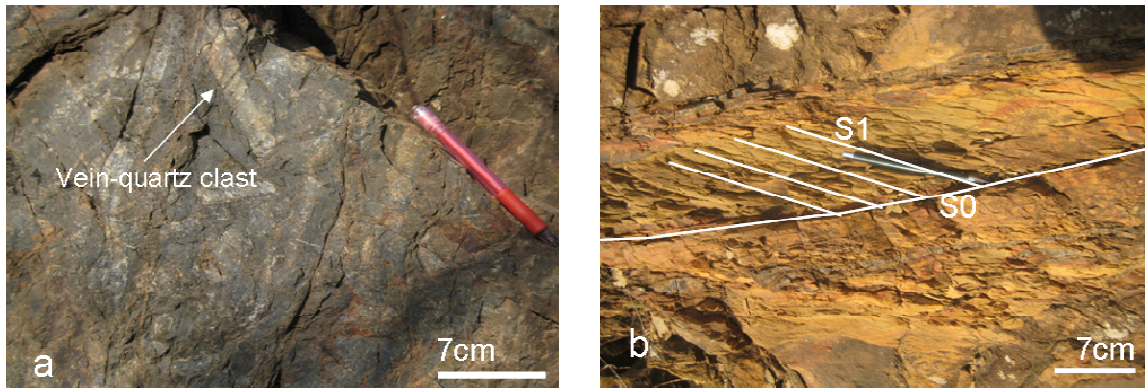


Figure 4.2: (a) Consort Bar consists of silicified vein-quartz and shale fragments (GR 307500-7161392); (b) An example of a bedding (S_0) - cleavage (S_{1INC}) relationship in greywacke of the Fig Tree Group in the NCGM area (GR 307514-7161018).

The event has been linked to large-scale thrusting between 3.25-3.22 Ga (de Ronde and de Wit, 1994) during the principle accretionary stages of the BGB.

4.2 : D_{2NC} (Post-Moodies upright folding and thrusting)

D_{1NC} folding and metamorphism of the Onverwacht and Fig Tree group rocks were followed by uplift and erosion and then deposition of the Schoongezicht Formation (3225 Ma) and Moodies Group rocks above an angular unconformity (Dirks *et al.*, 2009) that is well exposed W and S of NCGM.

Once deposited, the Schoongezicht Formation and Moodies Group rocks were shortened during D_{2NC} into a series of upright synforms, of which the Eureka synform to the south of NCGM is the largest most prominent example (Fig. 1.2). Older D_{1NC} structures were presumably tightened in the process (Lowe and Byerly, 1999; Dirks *et al.*, 2009). In the NCGM area, D_{2NC} folds are best preserved in synformal inliers as seen along a well-exposed river section of the Noordkaap River west of the NCGM (GR 305460-7161250) and along road and rail sections N of the Woodstock Mine (GR 308140-7159150) (Figs. 1.3, 2.9).

Along the Noordkaap River folded Schoongezicht Formation and Moodies Group rocks unconformably overlie strongly foliated serpentinite-talc schist of the Onverwacht Group to the W, NW and NE of the synform, and metapelitic schist of the Fig Tree Group to the SE. Agglomerate of the Schoongezicht Formation marks the base of the sequence, and grades into cross-bedded conglomerate and quartzite in the core of the fold. The units define a strongly asymmetric, upright synclinal synform, 290 m in width, with the E limb being much thicker at 180 m than the strongly attenuated W limb. Flattened pebbles in the agglomerate and conglomerate define an S_{2NC} fabric and an L_{2NC} stretching lineation. S_{2NC} parallels the axial plane of the syncline and trends N to NNW, dipping steeply to the E or W (Fig 4.1). S_{2NC} parallels the penetrative S_{1NC} fabric in underlying Fig Tree Schist suggesting D_{1NC} and D_{2NC} deformation were coaxial (see also Lowe and Byerly, 1999, and Dirks *et al.*, 2009).

D_{2NC} folds correlate with the large Eureka and Lily Synclines described south of NCGM (Ramsay, 1963; Anhaeusser, 1976; Dirks *et al.*, 2009), and similar large-scale synforms in Moodies Group rocks elsewhere in the BGB (e.g. Lowe and Byerly, 1999). The folds formed during the latter stages of accretion of the BGB (Table 2.1).

4.3 : D_{3NC} (Development of constrictional shears and folds)

D_{3NC} structures resulted from a series of progressive events that have been termed D_{3aNC} , D_{3bNC} and D_{3cNC} . These events include the development of a network of shear zones (Figs. 4.3, 4.4), which bound structural domains with diverse structural and metamorphic histories, and a series of 600m- scale tight reclined folds (eg Top Section Syncline, No. 7 Shaft Anticline and No. 3 Shaft Syncline). The shear zones form the skeletal framework of the triple junction structure and divide the area around NCGM in separate structural domains (Fig. 4.3), each characterized by slightly different deformational, metamorphic and exhumation histories (e.g. Dziggel *et al.*, 2007). Movement on the shear zones has been linked to the rise of the Nelspruit Batholith (Viljoen, 1964; Dziggel *et al.*, 2006) imposing a constrictional environment on the area.

Complex constrictional folds developed in between the principle shear zones and, in some domains, early D_{3NC} shear zones were progressively folded as illustrated by the mylonites of the Consort Bar (Fig. 4.3). D_{3NC} events transposed, refolded and tightened the D_{1NC} and D_{2NC} structures and fabrics, and formed concomitant with the large re-fold of the Eureka syncline S of the NCGM (Table 2.1; Anhaeusser, 1976).

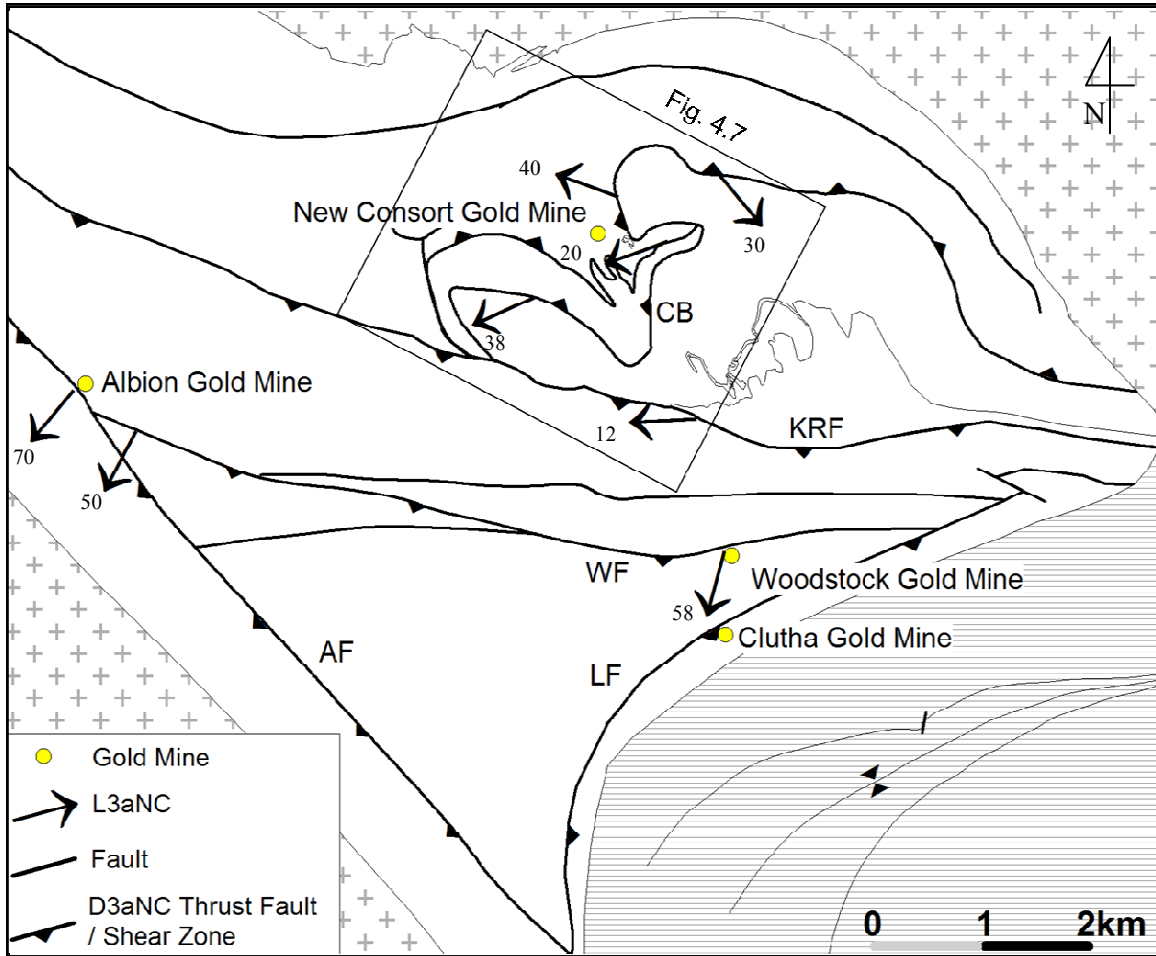


Figure 4.3: Map of the triple junction between the JSB and the BGB showing a network of major D_{3NC} shear zones, and associated orientations of mylonitic lineations (L_{3aNC}) indicated by arrows and plunge angles. Solid daggers are placed in the block that is moving up.

The earliest D_{3aNC} events in the triple junction area involved mylonitisation along a network of shear zones that include the Lilly, Albion, Woodstock and Kaap River Faults as well as the mylonites along the Consort Bar (Fig. 4.4). The shear zones are

characterized by mylonite (Figs. 4.5a, 4.6) and ultramylonite (Fig. 4.5b) with extensive silicification, which, in many places, takes the form of laminated chert (Figs. 4.4, 4.5a).

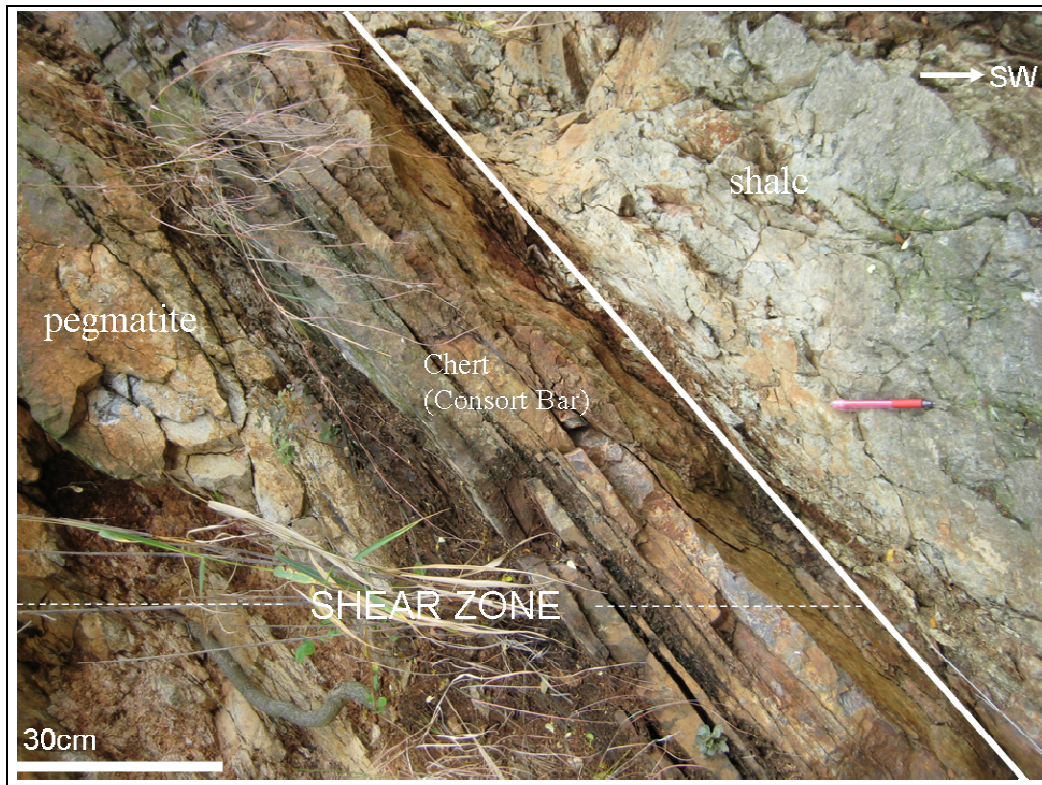


Figure 4.4: A typical example of a D3_{aNC} shear zone in the NCGM area. The shear zone marks the contact between the Onverwacht greenstones and the overlying Fig Tree shale. Consortium Bar and intruded, mylonitised pegmatite characterises the shear zone (GR 307280-7162207).

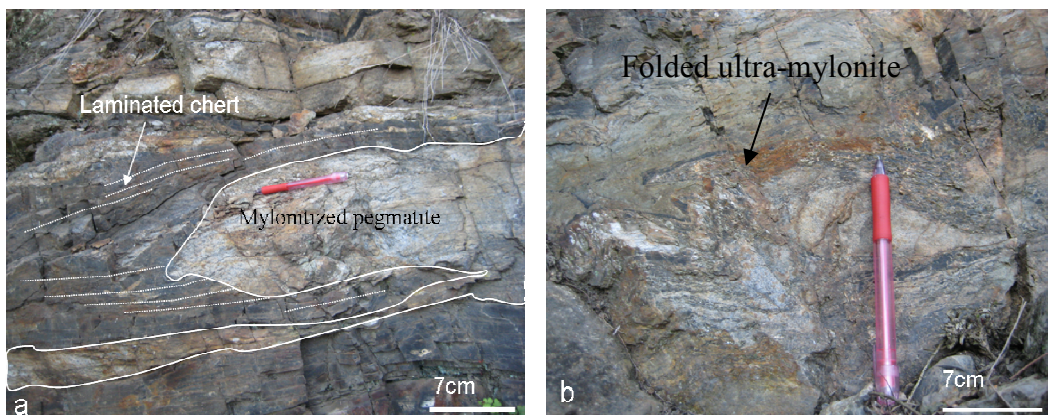


Figure 4.5: (a) Mylonitised Consortium Bar intruded by mylonitic to (b) folded ultra-mylonitic pegmatite (GR 307385-7162560)

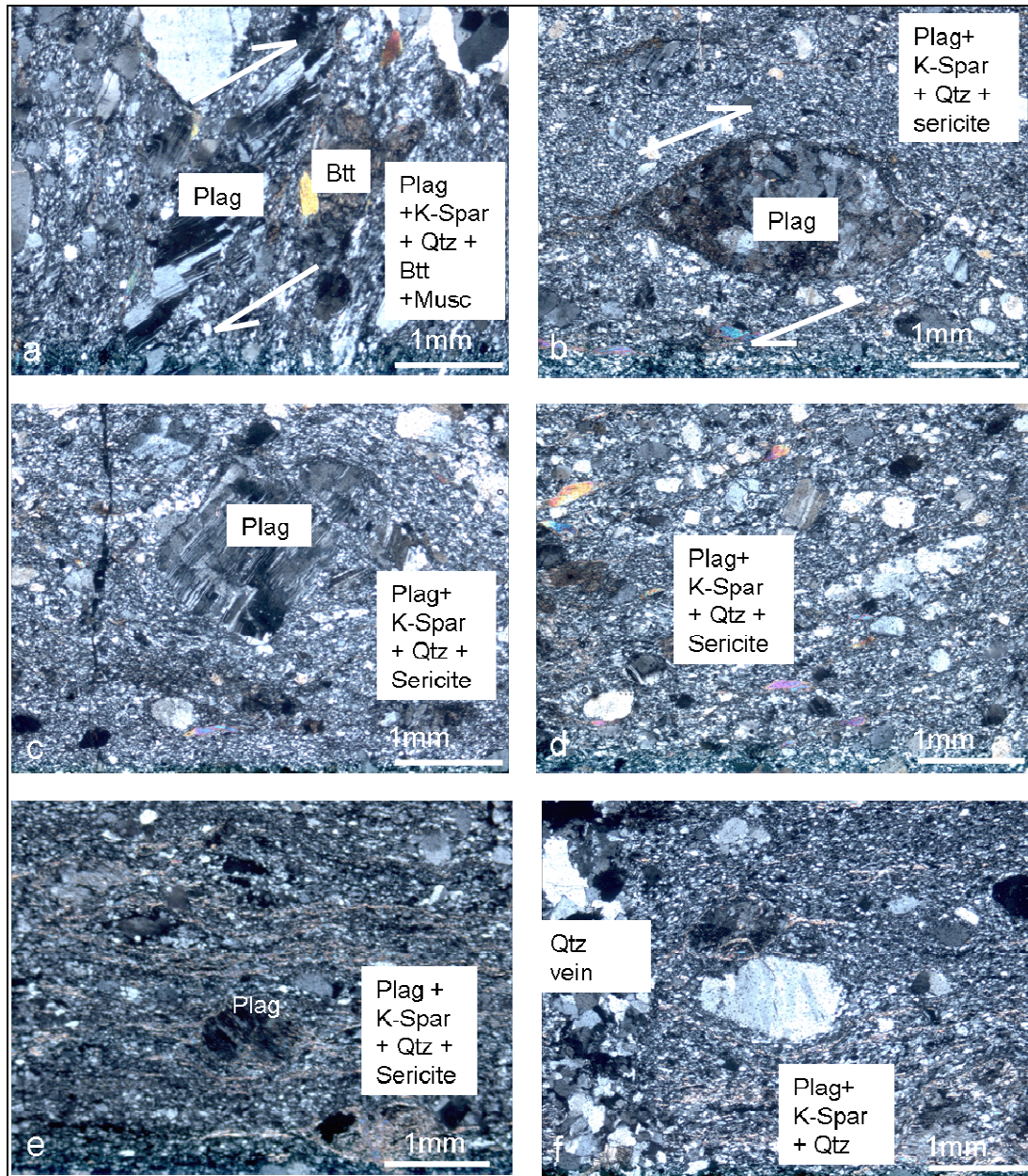


Figure 4.6(a-f): Thin sections, viewed under cross polars light, of a mylonitised pegmatite along the sheared Consort Bar (GR 307258-7162074). Mineral constituents include deformed grains (porphyroclasts) of plagioclase, quartz, microcline, biotite, muscovite and sericite. Porphyroclasts show a top to the NW sense of movement along some parts the Consort Bar, and is consistent with the movement also indicated by mica-fish and S-C structures elsewhere.

Where the shear zones transect ultramafic units, carbonate and fuchsite are common constituents, and mineral rodding, quartz stretching lineations and oriented amphibole growth defines an intense S_{3aNC} - L_{3aNC} fabric. Rotated porphyroclasts (Fig. 4.6) S-C and shear band fabrics are common, as are intrafolial folds, which in places assume sheath-like geometries with fold axes parallel to L_{3aNC} . Shearing along the Consort Bar coincided with the emplacement of an early generation of pegmatite veins along the shear zone. The pegmatites are mylonitised and show quartz and K-feldspar ribbon grains enveloping mantled feldspar porphyroclasts (Fig. 4.6a,b,c,e,f), many preserving monoclinic asymmetries.

Figure 4.7 shows the dominant orientation of L_{3aNC} and shear sense on the main D_{3aNC} shear zones around NCGM. The steeply S to SW dipping Albion, Woodstock and Kaap River Faults all preserve a steeply SW plunging L_{3aNC} lineation, and a SW-up, reverse sense of movement (Fig. 4.3). The movement sense on the Consort Bar is more complex due to later folding, which affected the orientation of S_{3aNC} and L_{3aNC} (Fig. 4.7). As the Consort Bar mylonite is traced around the complex folds near NCGM, S_{3aNC} and L_{3aNC} orientations vary (Fig. 4.7), e.g. east of the MMR ore shoot, L_{3aNC} plunges SE and the shear sense is normal sinistral, and SW of the MMR shoot, L_{3aNC} plunges NW on a moderately W to SW dipping mylonite surface, recording a NW-up, thrust sense of movement. In spite of this complexity, the movement sense consistently indicates that the younger hanging wall units of the Fig Tree Group moved down, relative to the older Onverwacht Group units (Fig. 4.7). This movement sense has been linked to a sharp metamorphic gradient across the fault with Onverwacht Group rocks preserving higher-grade mineral assemblages (e.g. Dziggel *et al.*, 2006).

The structural domain N of the Kaap River Fault, i.e. the area in the immediate vicinity of the NCGM, experienced complex folding during D_{3bNC} and D_{3cNC} events as illustrated by the contorted nature of the Consort Bar (Fig. 4.3). The Consort Bar is folded to produce a generally SE plunging synclinorium composed of several 600m-scale fold structures referred to in the mine from NE to SW as the “Top Section Syncline” the “No. 7 Shaft

Anticline”, and the “No. 3 Shaft Syncline” (Fig. 4.1; Voges, 1986), each associated with several ore bodies (Viljoen, 1964; Voges, 1986; Ward, 1999).

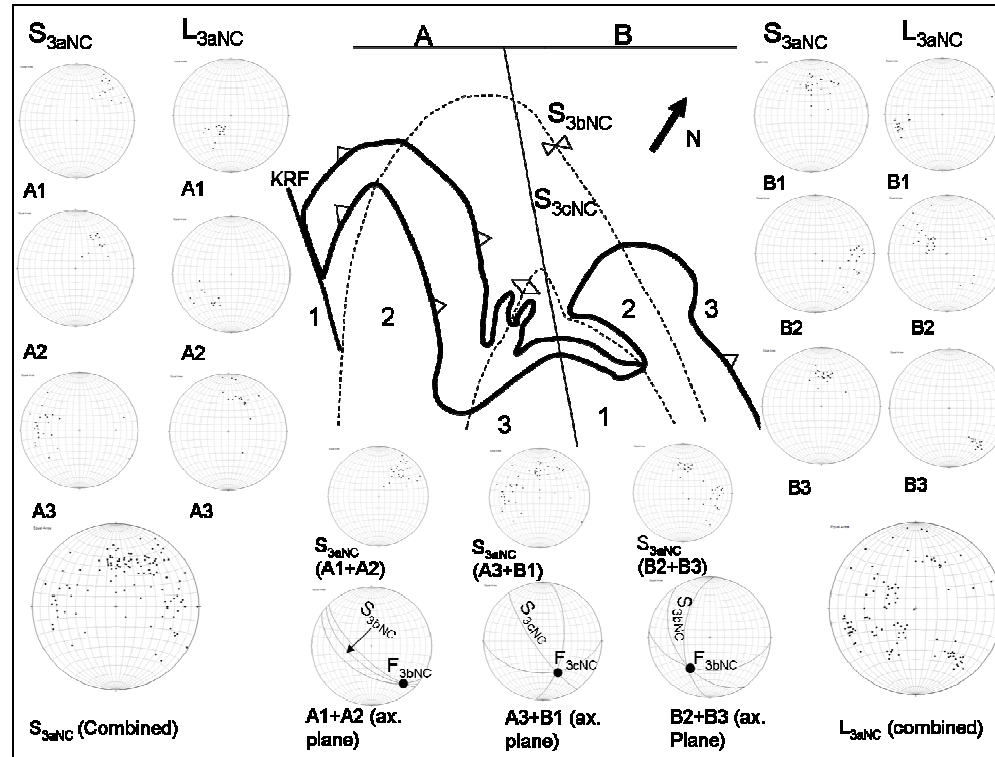


Figure 4.7: Map showing the dome-crescent-mushroom (Type 2) fold interference pattern. Orientation diagrams are presented of folded shear planes (S_{3aNC}) and mylonitic lineations (L_{3aNC}) developed during early stages of D_{3NC} (see text for full explanation). The fold axial plane (S_{3bNC}) and fold axis (F_{3bNC}) are indicated, deduced from D_{3bNC} , and S_{3cNC} and F_{3cNC} from the D_{3cNC} folds. A and B represent major structural domains symmetric about the S_{3cNC} planes of the D_{3cNC} fold, and 1, 2 and 3 indicate sub-domains defined along axial planes (S_{3bNC}) of D_{3bNC} fold, such that A1, A2, A3 and B1, B2, B3 represent limbs of folds, with the respective orientation data presented as Schmidt lower hemisphere projections.

By systematically mapping the orientation of L_{3aNC} and S_{3aNC} along the Consort Bar, it can be demonstrated that the synclinorium is not a single fold structure, but instead represents an interference fold pattern of D_{3bNC} and D_{3cNC} folds defining a type 2, dome-crescent-mushroom fold interference pattern (Fig. 4.7; Thiessen, 1986; Ramsay and Huber, 1987).

The interference pattern can be illustrated by the domainal nature of D_{3aNC} fabric elements on the different limb orientations of D_{3bNC} folds, as they bend around the younger D_{3cNC} structure. Each of the four D_{3bNC} fold limb domains preserves characteristic orientations of older fabric elements such as S_0 , S_{1NC} , S_{2NC} , S_{3aNC} , and L_{3aNC} (Fig. 4.7), which can be used to reconstruct the orientation of S_{3bNC} and S_{3cNC} and the regional plunge of the D_{3bNC} and D_{3cNC} folds (F_{3bNC} and F_{3cNC}) (Fig. 4.7). Thus, the orientation of the L_{2NC} mylonitic mineral lineation varies from SE to NW around the “Top Section Syncline” E of NCGM, SW around the “No 3 Shaft Syncline” SW of NCGM, and NE along the Hard Cash area representing the 4 main orientation concentrations in the area; S_0 and S_{2NC} display a similar four way distribution pattern (Fig. 4.7).

D_{3bNC} folds consist of asymmetric, NW-verging, upright, closed folds with a moderately SE dipping fold axial plane, and probably near horizontal fold axis. At least one, 600m-scale synform-antiform pair can be defined (Fig. 4.7) with smaller scale, vergence folds occurring on their limbs. D_{3bNC} folds were refolded by a single NW trending, steeply reclined closed, D_{3cNC} antiform with a steeply SW dipping fold axial plane and a SE plunging fold axes (Fig. 4.7).

A good example of a D_{3bNC} folds in outcrop is the reclined, SW plunging synclinal, vertical fold exposed along the road section south of the MMR shaft (GR307379-7162532) where the core of what is referred to as the “Top Section Syncline” is well exposed. The W limb of this structure dips moderately W to SW, whilst the E limb dips moderately S to define a moderately SW plunging fold axes ($F_{3bNC} = 225/40$; Fig. 4.7), and a SW dipping fold axial plane ($S_{3bNC} = 228/41$; Fig. 4.7).

The core of the D_{3cNC} fold occurs to the SE of Betty's Quarry (Fig. 2.12), where outcrops in the Schoongezicht Formation preserve complex fold interference patterns (e.g. GR 308670-7160500). D_{3cNC} fold axes plunge either to the NW or the SE and vary in orientation depending on the orientation of D_{3bNC} fold limbs, which they overprint (Fig. 4.8a). A SE plunge is dominant (Fig. 4.7) reflecting the asymmetric NW verging nature of the underlying D_{3bNC} folds, consistent with general stratigraphic younging to the SE. Excellent examples of D_{3cNC} folds and associated fabrics in outcrop occur in rocks of the Schoongezicht Formation and conglomerate of the Moodies Group S and E of No. 7 shaft (e.g. GR 307875-7160234).

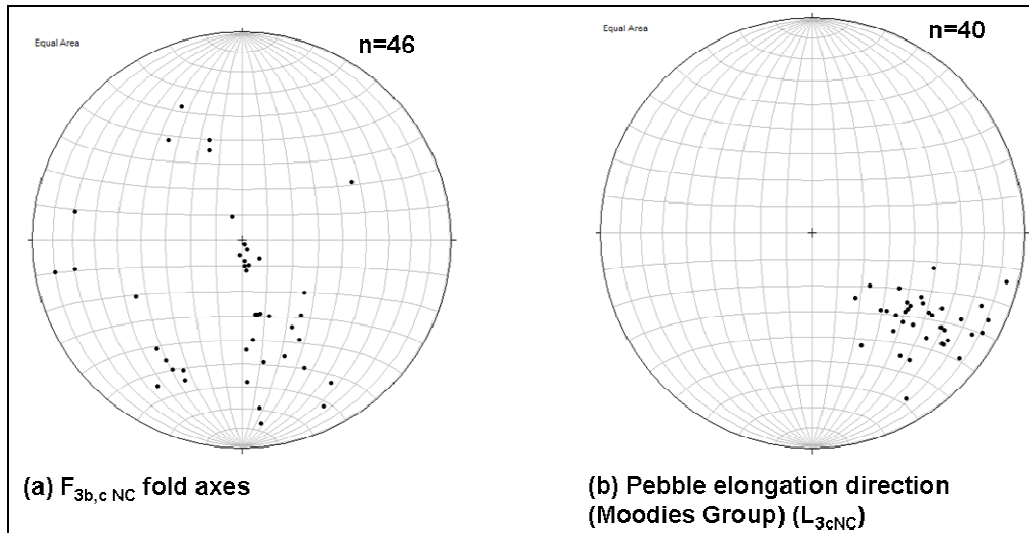


Figure 4.8: Schmidt lower hemisphere projections showing (a) orientations of fold axes collected from a zone (GR 307700-7161500) that records interference between D_{3bNC} , and D_{3cNC} folds, and (b) orientation of pebble elongation L_{3cNC} collected from agglomerate and conglomerate in the core of a D_{3cNC} fold.

D_{3cNC} folds are open, concentric folds associated with a weakly developed axial planar fabric (Fig. 4.9a,b,c).

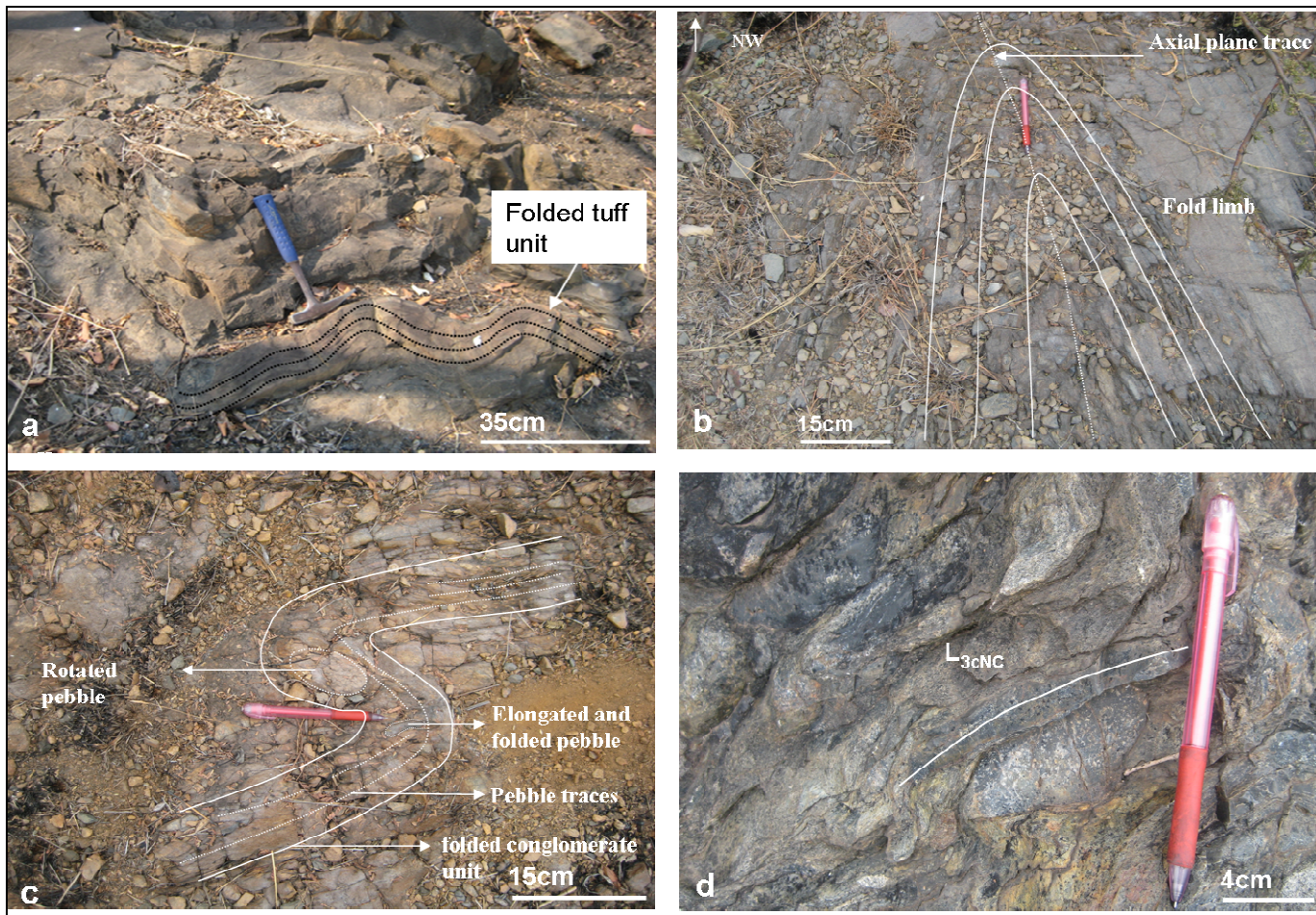


Figure 4.9: Deformation structures associated with D_{3cNC} in the NCGM area. Open D_{3cNC} folds in the (a) Schoongezicht Formation, (b, c) conglomerate of the Moodies Group (GR 307875-7160201); (d) Elongated conglomerate pebbles in Moodies Group, defining L_{3cNC} (GR 305437-7161281).

In conglomerate of the Moodies Group at GR 307875-7160201, pebbles have been flattened (Fig. 4.9d) under plane strain conditions to define a NW trending, steeply W-dipping axial planar fabric and a moderately SE plunging stretching lineation (Fig. 4.8b) that parallels the fold axes of 1-5 m scale folds (Fig. 4.9a,b).

The No.7 Antiform, between Witkoppies Quarry and No. 6 shaft, represents a package of tight, synclinal, D_{3bNC} folds that repeatedly fold, and thus duplicate D_{3aNC} mylonites along the Consort Bar. Underground drives crossing these folds, display a wide zone of D_{3aNC} mylonite as the Consort Bar is repeatedly crossed. This zone has been described as a discrete NW trending structure called the “Shires Shear Zone” (Tomkinson, 1989; Harris *et al.*, 1995), but this interpretation is not supported by surface outcrop.

4.4 : D_{4NC} (Late kink-folding and normal faulting)

D_{4NC} structures comprise shallowly dipping sets of conjugate kink folds that can be linked to a network of brittle-ductile shear zones with a normal sense of movement (Fig. 4.10; Anhaeusser, 1976; Dirks *et al.*, 2009; Table 2.1). D_{4NC} kink folds (Appendix C, Figs. C5 and C16) are typically about 2 to 4 meters in size and mainly trend SE and E, whose axial planes dip shallowly SW and S respectively. They occur as localised structures with crenulation cleavage and extensional brittle-ductile shear zones cutting across the cores of the kinks along the traces of axial planes (Fig. 4.10a) Fully developed conjugate pairs (e.g. GR 307869-7163737) with well-defined conjugate normal shears are common. Good examples of kink folds can be found in the Mine Manager Quarry (GR 308230-7159033) and along the railway siding (Fig. 4.10a; GR 307970-7159190) north of Woodstock Mine. In places (e.g. NW of MMR), the axial planes of kink folds are silicified and invaded by quartz veins and pegmatite units. On larger scales, kink folds produce flattening and steepening of rock units orientations. Typical examples include outcrops along a road cut from MMR through the Top Section Syncline (Fig. 1.3) where variations in dip angle of bedding planes are common.

The most prominent D_{4NC} structures are brittle-ductile extensional shear zones, commonly associated with quartz veining, sericitisation, silicification and biotite-chlorite alteration as well as sulphide growth. These brittle-ductile shear zones dominantly trend east-west with some trends to the north, northwest and northeast. D_{4NC} shear zones are always present in the old gold workings, and stoping commonly occurs along the shears suggesting a close association with gold mineralization (Figs. 4.10b,c,d). These shear zones commonly guide major trends of gold workings.

The most prominent of these faults have been named (e.g. the MMR and Ivaura Faults; Fig. 1.3). Gold workings are commonly found parallel to the traces of these brittle-ductile faults, which present themselves as discontinuous array of en-echelon shears connected by cross-shears.

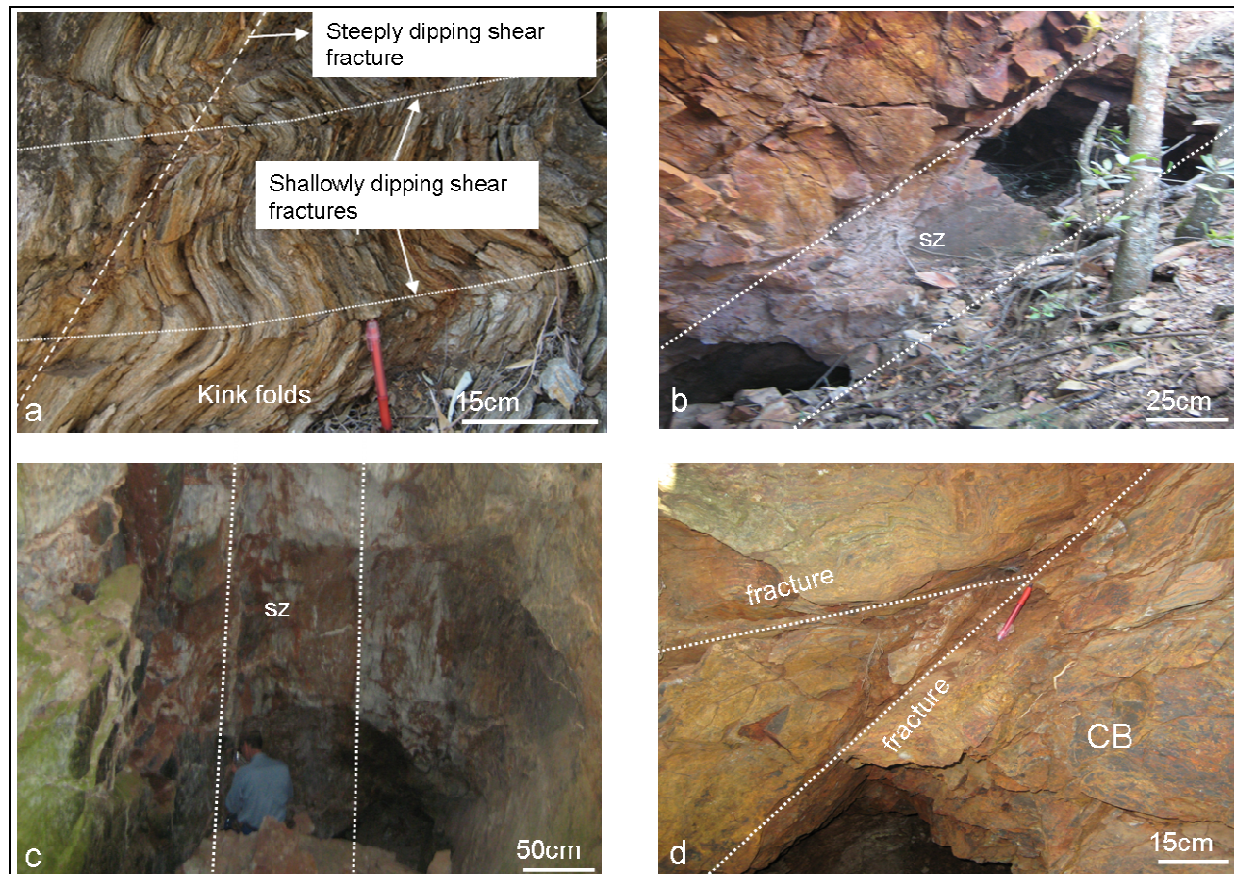


Figure 4.10: Deformation structures associated with D_{4NC} event; (a) D_{4NC} kink folds crosscut by D_{4NC} brittle-ductile shear fractures (GR 307970-7159190); (b) A mineralized, D_{4NC} shear zone, cross-cuts steeply dipping sandstone (see Figures 1.3 for old workings locations); (c) Mineralized D_{4NC} shear zone (SZ) cross-cutting talc-schist in the Albion Gold Mine (GR 302120-7160337); (d) D_{4NC} shear fractures crosscut the complexly folded Consort Bar, gold workings have been developed parallel to the fractures (GR 307348-7162505).

Good examples of mined, mineralized brittle-ductile shears can be found in the Witkoppies, Betty and Mine Manager Quarries (Fig. 1.3; Appendix C), and in large pits found in both Albion and Woodstock gold mines (Fig. 2.9). The shears typically occur as 25-30 cm wide zones (Fig. 4.10b) in which a strong foliation has developed defined by schistose micaceous zones that are sulphidised in places. This foliation is truncated by discrete, 5-7 mm-wide fracture planes (Fig. 4.10d) commonly associated with slickensided surfaces with secondary quartz and calcite overgrowth (Fig. 4.11a,b). Several generations of quartz veining including early black, cherty veins and later milky veins, are common and obvious alteration as expressed by quartz, calcite and chlorite growth with sulphidisation and silicification affecting the wall rock for several meters on either side of individual shear zones, with wider alteration zones occurring in areas of complex intersections between two or more shear zones. Fault planes contain clear striations and slickenfibres lineations, with steps indicative of a mostly normal sense of movement (Fig. 4.11a,b).

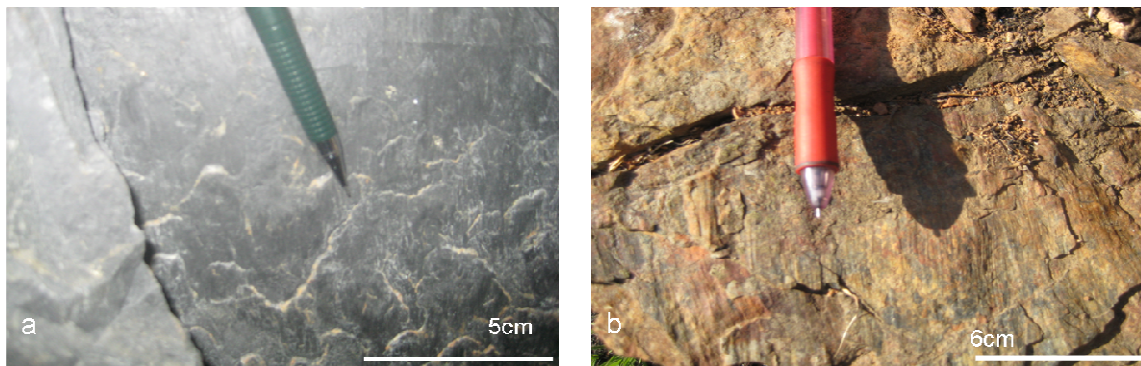
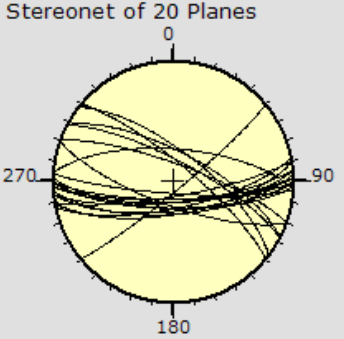
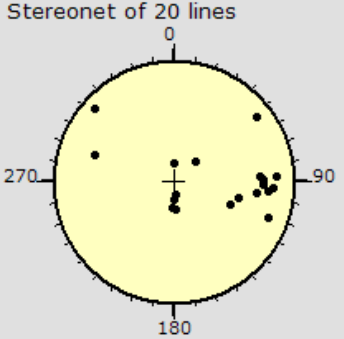
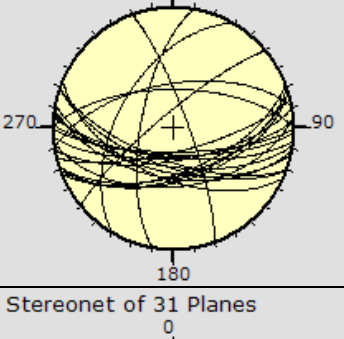
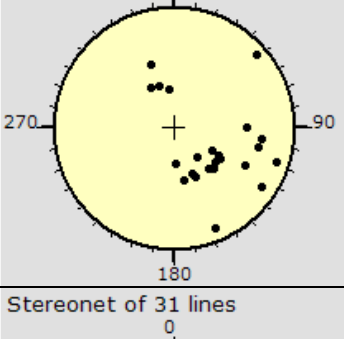
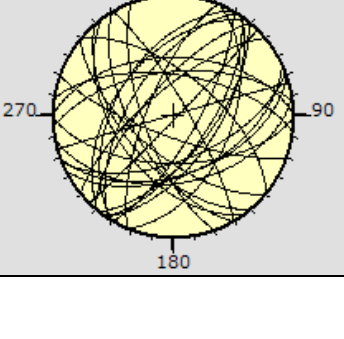
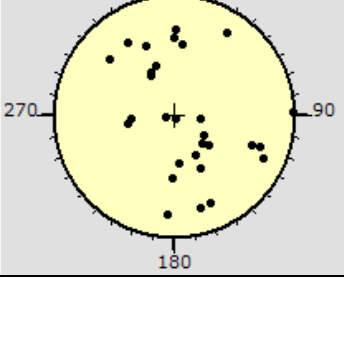


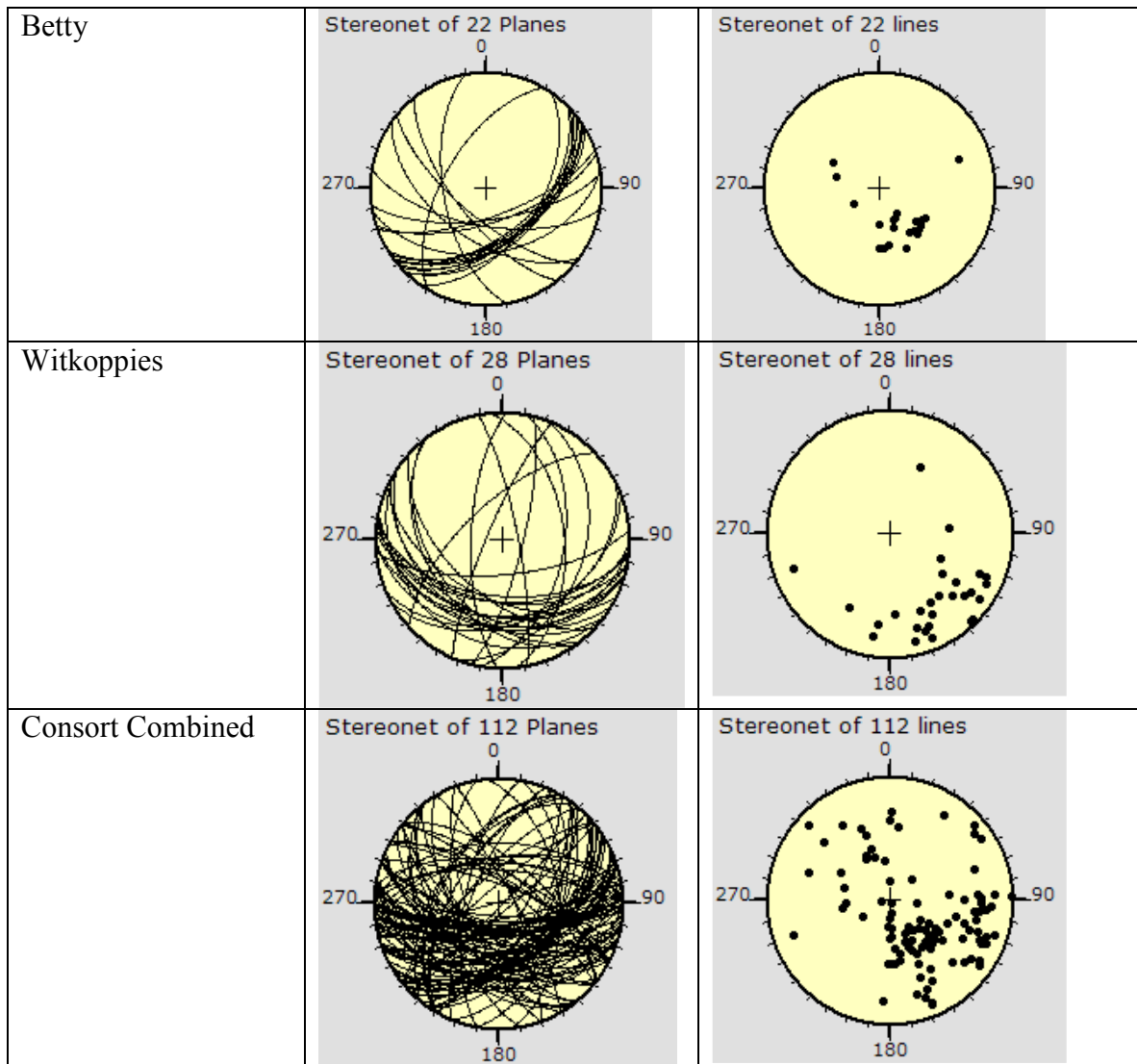
Figure 4.11: Slickensided surface with quartz fibre growth on a D_{4NC} fault indicating a normal sense of movement (a) (MRC ore body at 24 level in Sheba Mine) and (b) Mine Manager quarry in the NCGM area.

On the scale of individual workings such as the 100x100 m Witkoppies Quarry, a number of D_{4NC} shear zones can be traced that display a wide variety of orientations (Table 4.1; Appendix C) and complex cross-cutting relationships, although almost all of these shears accommodated a normal sense of movement. Individual shears in the Witkoppies Quarry can be traced for tens of metres and have moderate dips (30-60 degrees) to the SE, S or SW, and slickenline orientations that plunge predominantly at low to medium angles to

the SSE-SE (Table 4.1; Appendix C). Individual faults occur in en echelon and cross cutting arrays across the pit to define two roughly NNW and ENE trending fault corridors, which also define the shape of the open pit and distribution of surrounding adits. The fault pattern in the well exposed Witkoppies Quarry (Table 4.1) is also observed in other workings in the NCGM area, such as Mine Manager Quarry (Fig. 4.12).

Table 4.1: Stereoplots of D_{4NC} mineralized brittle-ductile shear fractures and associated mineral lineation from individual mines that are found in the NCGM area (Fig. 1.3).

Gold Working	Mineralized shear fractures	Mineral lineation
MMR	Stereonet of 20 Planes 	Stereonet of 20 lines 
MMR South	Stereonet of 23 Planes 	Stereonet of 23 lines 
Mine Manager	Stereonet of 31 Planes 	Stereonet of 31 lines 



Although near vertical NNW-trending strike-slip faults are observed, steeply S-dipping and ENE trending normal faults are dominant, see Consort Combined (Table 4.1), especially in pits along the MMR and PC shoots. The Mine Manger and Betty gold workings are dominated by NE-SW and NW-SE trends characterized by NW-SE trending mineral lineations (Table 4.1; Appendix C). As a mineralized fracture terminates, a new one starts up, commonly in a slightly displaced, but overlapping en-echelon manner, whilst cross fractures connect both shear zone strands.

By mapping individual faults in surface workings across the hills around NCGM, a larger scale pattern of mineralized brittle-ductile fractures arises (Fig. 4.13).

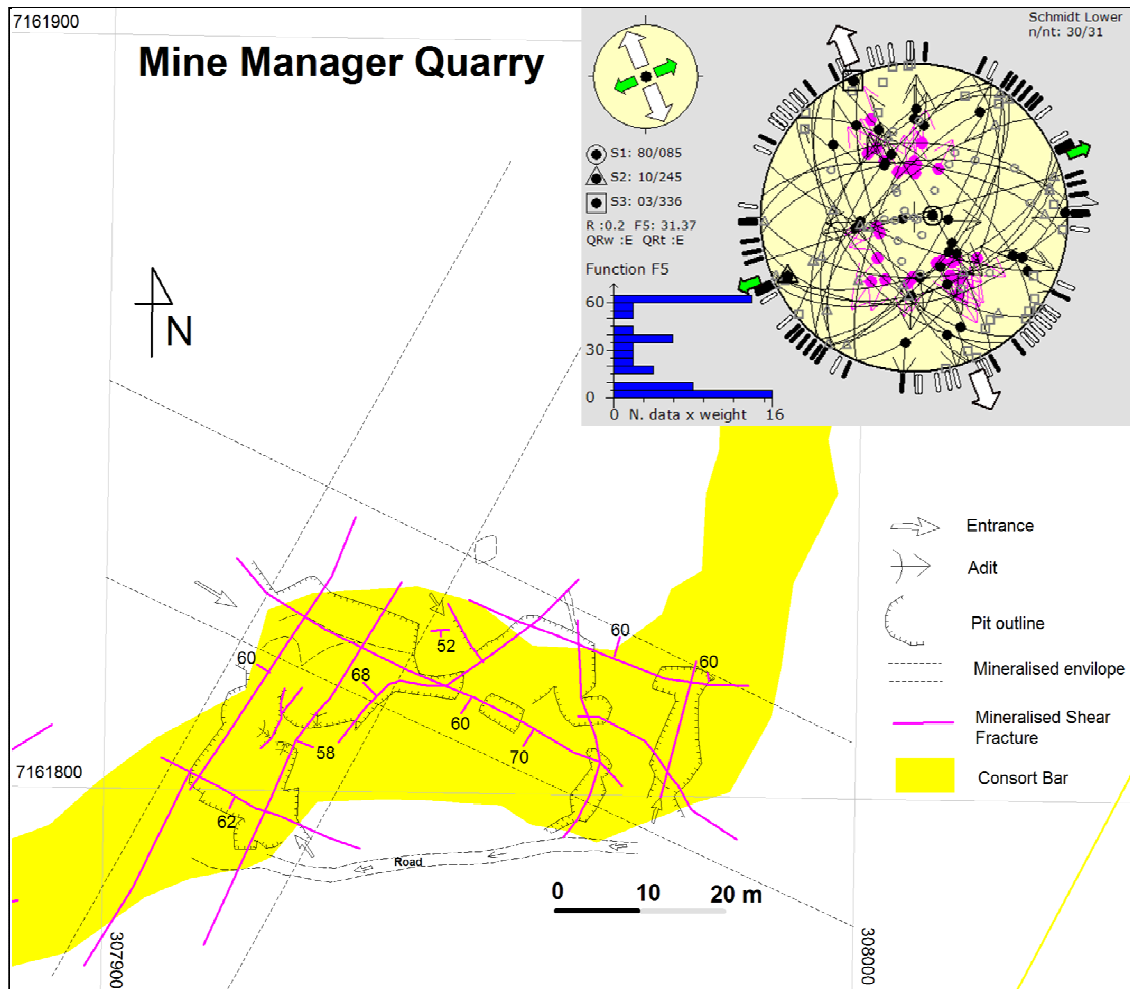


Figure 4.12: Map of the Mine Manager Quarry found in the most-eastern part of the ENE corridor. The quarry has been mainly developed in the complexly folded Consort Bar. Inserts include plot of mineralized fractures and averaged trends of $\sigma_{\min. \text{ horizontal}}$ (open arrows) and $\sigma_{\max. \text{ horizontal}}$ (closed arrows).

The pattern shows a 120 m wide central NNW trending corridor of fractures between the Ivaura workings in the NNW via the Witkoppies Quarry and Hard cash to the workings around 7 shaft in the SSE (Fig. 4.13). In each of these corridors, individual brittle-ductile shear zones can be traced for up to 100-140 m along which pits, shafts and trenches have been developed (Fig. 4.13).

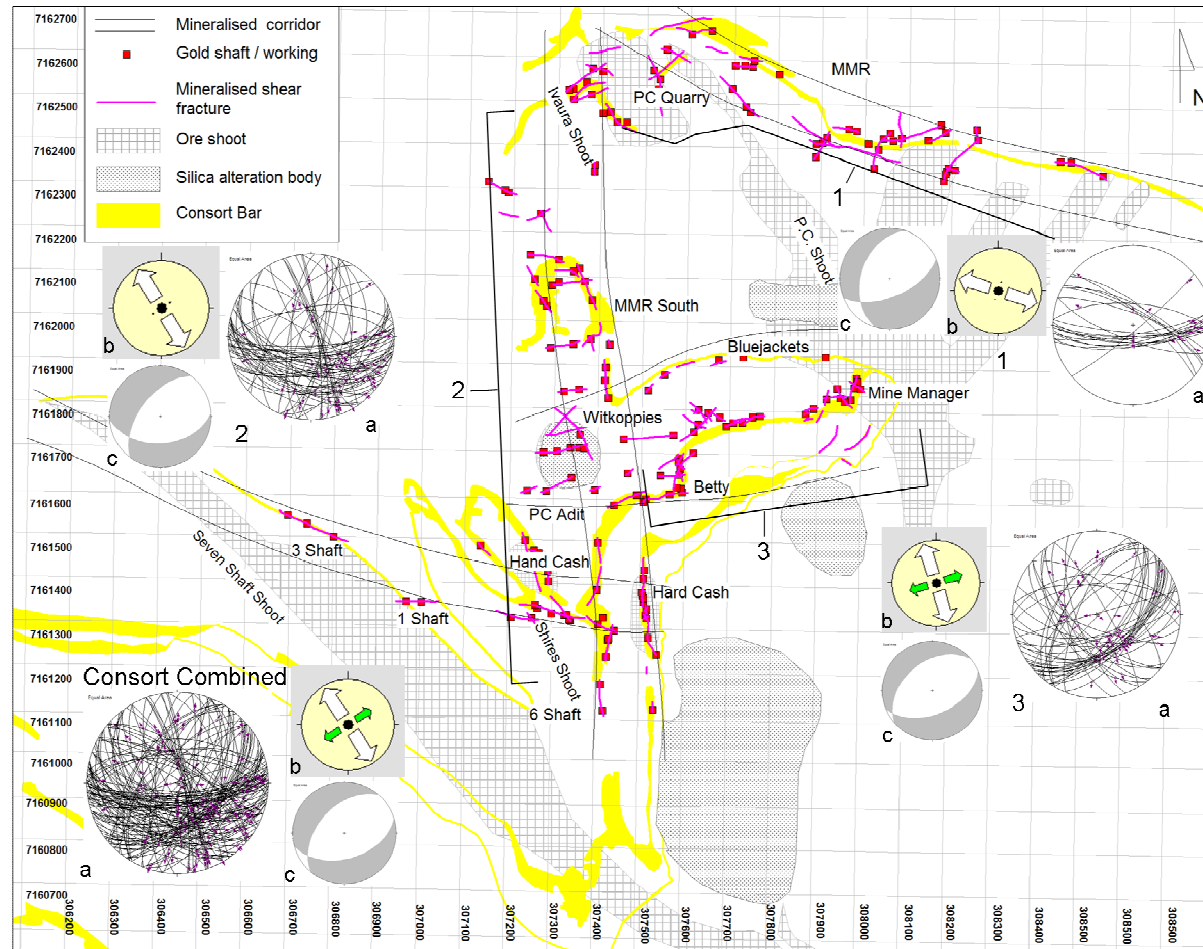


Figure 4.13: Map of WNW, NNW and ENE mineralized corridors constructed from mineralized brittle-ductile shear fractures found in NCGM gold workings. (a) Schmidt lower hemisphere projection plots indicating mineralized fracture planes with arrows showing direction of hanging wall displacement, (b) stress diagrams indicating averaged trends of $\sigma_{\min. \text{ horizontal}}$ (open arrows) and $\sigma_{\max. \text{ horizontal}}$ (closed arrows) and (c) Results of fault slip inversions for palaeo-stress shown as 'beach balls' (grey areas for tension dihedrons).

A major WNW trending corridor with mineralized fractures can be traced along the NE limb of the “Top Section Syncline” (Fig. 4.13). The corridor is 200-250 m in width, and contains NW-trending, mineralized fractures up to 250 m in strike length, and shorter SW trending cross fractures. The mineralized corridor dips moderately SSW to coincide with the orientation of projected ore shoots at depth as indicated by Voges (1989) (Fig. 4.13).

Another WNW trending corridor also occurs in the southern and western parts of the NCGM covering workings such as Hand Cash, PC, and No.1, No. 6 and No. 3 shafts found in the central to southwest of the mine (Fig. 4.13). The corridor averages 160 meters in width and mineralized fractures within the corridor are about 100 meters long. The fractures mainly trend parallel to the corridor with relatively few cross-fractures trending towards the southwest. This corridor coincide with the No. 7 shaft anticline. An ENE trending corridor covers the workings between Mine Manger and Witkoppies Quarries. This corridor is relatively wider with an average width of 300 meters (Fig. 4.13). The brittle-ductile shear zones in this corridor generally trend E-W and mineralized fractures within them dominantly show NE-SW and NW-SE trends explained above.

Extensional brittle-ductile shear zones in relation to gold mineralization also characterise the workings of nearby Albion, Woodstock and Clutha Mines (Fig. 4.14), and have been described from the workings in the Sheba-Fairview mine area (Dirks *et al.*, 2009). In the Woodstock Mine, workings occur along an ENE trending corridor that extends for a kilometre and for about 200 meters wide (Fig. 4.14). The corridor is composed of several, E-trending fractures arranged in an echelon fashion and cut by SE-trending cross fractures (Fig. 4.14).

NW trending corridors cover the workings found in the Albion and Clutha gold workings. The corridor found in the Clutha gold workings is about 250 meters wide, whilst that of the Albion gold workings averages approximately 50 meters in width. Mineralized fractures in the Albion gold workings define a northwest trending en-echelon arrangement connected by north-northwest trending cross fractures.

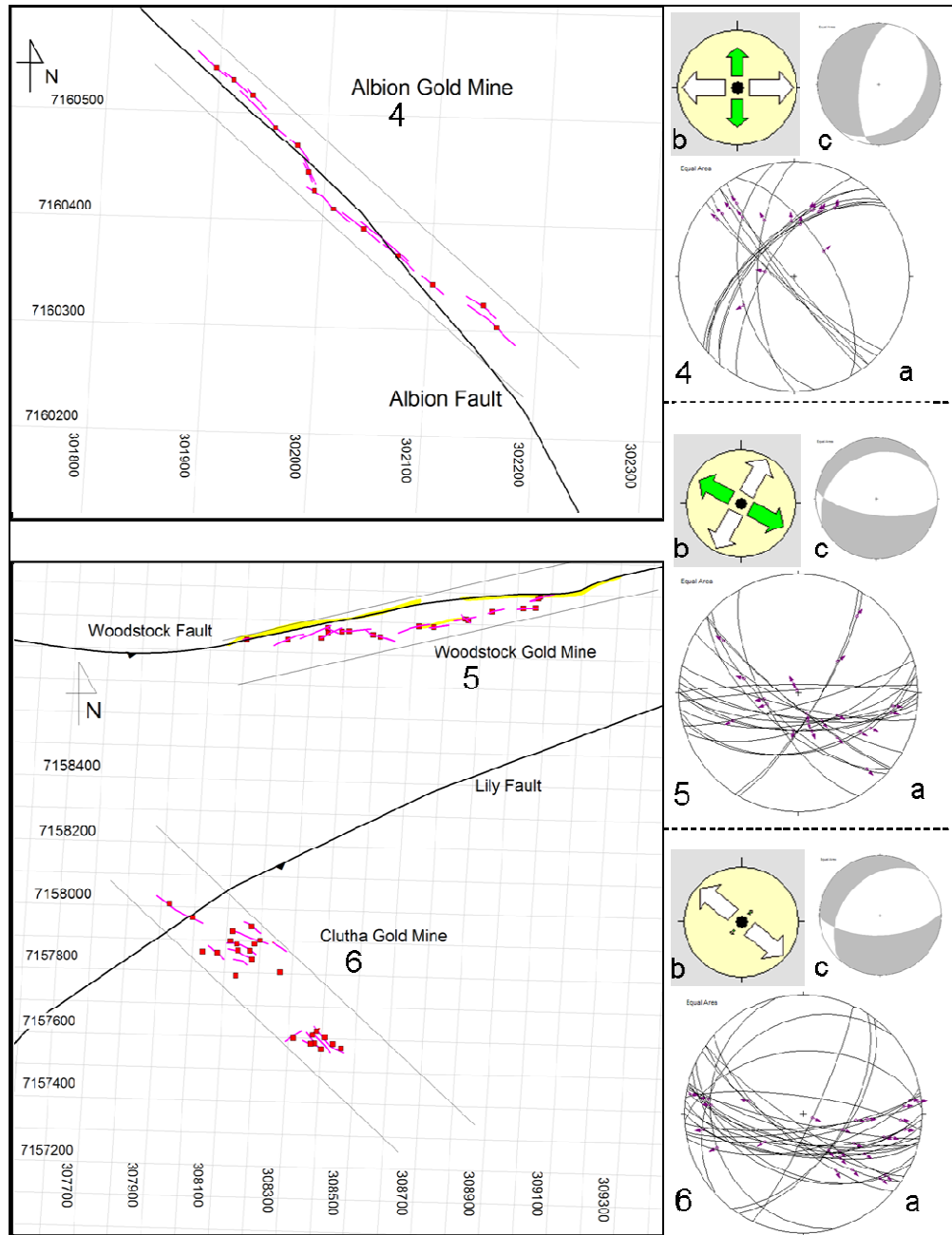


Figure 4.14: Maps showing mineralized corridors, gold workings and brittle-ductile shear fractures that are found in Clutha, Woodstock and Albion Mines, maps show 100m grid spacing. (a) Schmidt lower hemisphere projection plots indicating mineralized fracture planes with arrows showing direction of hanging wall displacement, (b) stress diagrams indicating averaged trends of $\sigma_{\min. \text{ horizontal}}$ (open arrows) and $\sigma_{\max. \text{ horizontal}}$ (closed arrows) and (c) Results of fault slip inversions for palaeo-stress shown as 'beach balls' (grey areas for tension dihedrons).

Gold-bearing shear zones are associated with silica alteration, involving quartz veining, and the development of larger silica alteration haloes. The alteration haloes are commonly found in close proximity to old gold workings and occur as massive bodies that are mainly elongated or rounded. These alteration zones are found in the hanging wall of mineralized horizons and form topographically pronounced features (Fig. 4.13) characterized by altered host rocks, locally invaded by stockworks of thin chert veinlets.

A good example of a silica alteration halo occurs in Woodstock Mine, where it consists of a complex, 10-30m wide stockwork zone of milky quartz veins accompanied by pervasive silica alteration resulting in a massive chert-like unit immediately adjacent to the sulphidic ore zone.

Although the old workings around the Woodstock gold workings are in places found in distal areas of the silica haloes, major workings tend to be concentrated in close proximity to large silica caps (Fig. 4.9, Appendix C). Large (600 x 300m) areas affected by pervasive silica alteration also characterise the area between PC and 7 Shafts (Fig. 4.13).

4.5 : D_{5NC} (Late stage shear zones)

D_{5NC} structures include brittle-ductile shear zones that accommodated a reverse sense of movement and crosscut the extensional shears associated with gold mineralization. D_{5NC} reverse shears have been observed in several gold workings with good examples in the Albion Mine, but their larger scale geometry is unclear (Fig. 4.15). They are indicative of reactivation of gold-bearing shears as thrusts, and are associated with carbonate and silica alteration including late-stage quartz veining. In the Albion Gold Mine, the reverse faults are about 5cm wide trending NE and NW dipping shallowly to moderately to the southeast and southwest (Fig. 4.15).

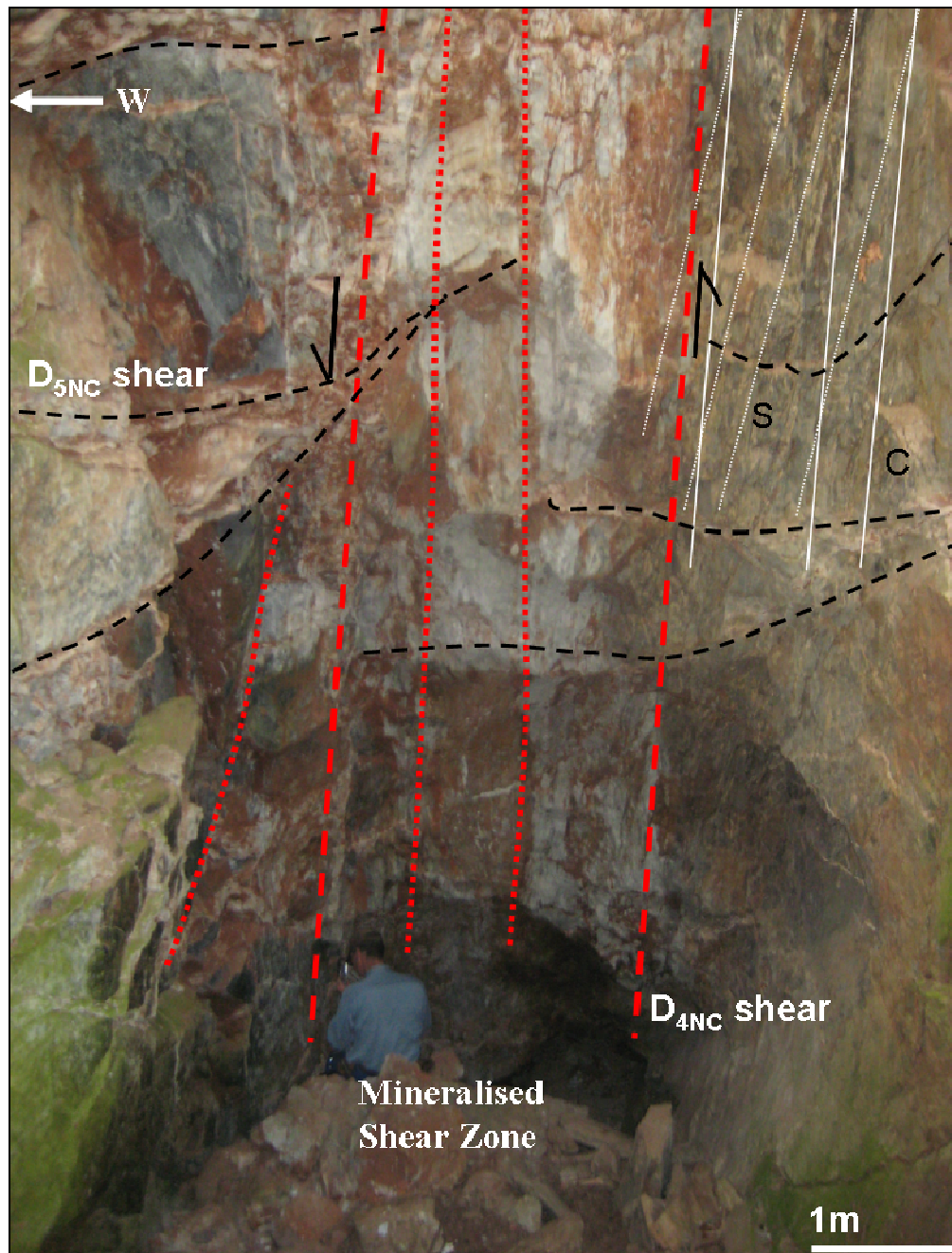


Figure 4.15: One of the ore zones of the Albion Gold Mine. The red lines outline the steeply dipping shear fractures associated with mineralization and black lines show the traces of shallowly dipping fractures. The white lines outline the relationship between the S and C fabrics. The half arrows indicate the deduced sense of movement based on both S-C fabrics and shear fractures characteristics.

5. Palaeo-stress Analyses

Field observations indicate that gold mineralization in the NCGM is spatially associated with D_{4NC} retrograde, extensional brittle-ductile shear zones that cross-cut a complex sequence of older, D_{1NC} - D_{3NC} ductile structures which impart a complex geometry on the area. The aim of this chapter is to further investigate the timing of mineralization and constrain the tectonic regime. This is achieved through reconstruction of the palaeo-stress, using inversion techniques on kinematic data from D_{4NC} brittle-ductile shear zones that are linked to gold mineralization. Kinematic data used from faults to reconstruct the palaeo-stress fields include the orientation of the fault plane, the slip direction visible as slickenlines, striations or gouge marks, and the sense of movement. This kinematic analysis of the D_{4NC} fractures was undertaken across the NCGM area and nearby mines, to determine the nature of the regional palaeo-stress field. The results of the analyses, which are presented below, have been published in Dirks *et al* (2009).

Generally, reconstruction of stress axes is complex and in some cases, considered impossible (Nemcok and Lisle, 1995; Arlegui-Crespo and Simon-Gomez, 1998). This is because calculations of stress vectors are estimates and rely on final orientations of fault planes, which might represent different deformation events, imposing different orientation and magnitudes of stress on fault planes (Ramsay and Lisle, 2000). In this chapter, reconstruction of palaeo-stress has been done in the realisation of the above-mentioned limitations, and for that reason, the author does not consider resolved stress axes as accurate vectors, but as vectors indicating general orientations of stress fields associated with the deformation of the D_{4NC} brittle-ductile shear fractures or faults. Several stress inversions techniques have been employed in reconstruction of stress axes vectors (e.g. Delvaux and Sperner, 2003). Amongst the foremost of the assumptions, inversion techniques assume that the slip direction is parallel to the determined shear stress on the fault plane, and that the set of faults used in the analysis, were active in response to the same stress field, i.e. stress is considered homogenous to the rock mass containing faults used in analyses (Ramsay and Lisle, 2000).

The inversion techniques invert fault-slip data to a reduced moment tensor with information on the direction of the principle stress axes and their relative (arbitrary) magnitude expressed as a stress ratio (Angelier, 1994; Delvaux and Sperner, 2003). This reduced stress tensor can be calculated using the P and T axes that bisect the fault plane and an auxiliary plane perpendicular to the fault, by using least-square minimization techniques of direction cosines (e.g. Marrett and Allmendinger, 1990) or iterative methods that test a variety of possible tensor solutions (e.g. Etchecopar *et al.*, 1981). Stress axes can also be determined graphically using the right dihedral method (Lisle, 1987; Delvaux and Sperner, 2003), which constrains the orientation of principle stress axes by determining the area of maximum overlap of compressional and extensional quadrants for a suite of faults. The right dihedral method requires fault plane data for one plane. A second plane (auxiliary plane) perpendicular to slip lineation on the fault plane is reconstructed, and the two planes are used to determine the quadrants (Ramsay and Lisle, 2000). Stress axes are better constrained when a number of faults with different orientations are used.

In analyzing the fault-slip data from gold workings around the triple junction I have used the 2009 Windows version of the programme Win-TENSOR (Delvaux, 1993; 2009), which uses an expanded right dihedral method described in Delvaux and Sperner (2003). Results have been compared with a linked Bingham distribution tensor calculated with the programme FaultKin (Allmendinger, 2001) following methods described by Marrett and Allmendinger (1990) and Cladouhos and Allmendinger (1993). The two independent methods are used to determine and constrain the palaeo-stress.

5.1 Reduced moment tensor (Win-TENSOR)

The WIN-TENSOR programme follows the basic numerical approach outlined by Angelier (1994). Principle stress axes (σ_1 , σ_2 and σ_3) and the ratio of principle stress differences ($R = (\sigma_2 - \sigma_3) / (\sigma_1 - \sigma_3)$) are determined using an improved version of the method of Angelier and Mechler (1977), optimized by minimizing deviation angles (α) between observed and predicted slip vectors on fault planes, and by maximizing the shear stress

magnitude (σ) on fault planes. This is done using an iterative procedure that involves successive rotations on σ_1 , σ_2 and σ_3 axes until an optimal fit is found (see Delvaux and Sperner, 2003). Misfits in the dataset can be identified and excluded in an interactive manner. A quality assessment for the data is provided following quality ranking schemes developed in the World Stress Map Project (*e.g.* Sperner *et al.*, 2003). This scheme combines assessments of the type and quality of data used, with quantitative assessments of the size of the data set, the distribution of slip and fault plane data and the average slip deviation between the observed and predicted slip vectors, to provide a quality ranking ranging from A (best) to E (worst) (Delvaux and Sperner, 2003). The type of stress regime can be expressed as a stress ratio R , which varies from constrictional ($R=1$ with $\sigma_1 = \sigma_2$) via plane ($R = 0.5$ with $\sigma_1 > \sigma_2 > \sigma_3$) to flattening stress ($R = 0$ with $\sigma_2 = \sigma_3$), and varies with the orientation of the principle stress axes. Delvaux and Sperner (2003) define a parameter R' to express the stress regime numerically as a number between 0 and 3 with $R' = R$ when σ_1 is sub-vertical (*i.e.* plunging steeper than 45° representing an extensional stress regime), $R' = 2 - R$ when σ_2 is sub-vertical (strike-slip stress regime) and $R' = 2 + R$ when σ_3 is sub-vertical (compressional stress regime). The parameters R and R' will be referred to with reference to gold mineralization in the NCGM area as well. The programme output is a diagram displaying the fault-slip data, a histogram of α values, a diagram showing the horizontal maximum and horizontal minimum stress axes, the orientation of σ_1 , σ_2 and σ_3 , the R value and a quality ranking (Fig. 5.1).

5.2 Bingham distribution tensor (FaultKin Win)

The FaultKin programme (Allmendinger, 2001) uses the distribution of P and T axes for a suit of faults (Angelier and Mechler, 1977) to calculate a Bingham axial distribution based on a least squares minimization technique for direction cosines. The auxiliary plane has been calculated assuming P is at 45° from the fault. The eigenvectors for the calculated Bingham axial distribution provide average orientations for the maximum, minimum and intermediate concentration direction of the P and T axes, and the eigenvalues provide a measure of the relative concentration of P and T axes.

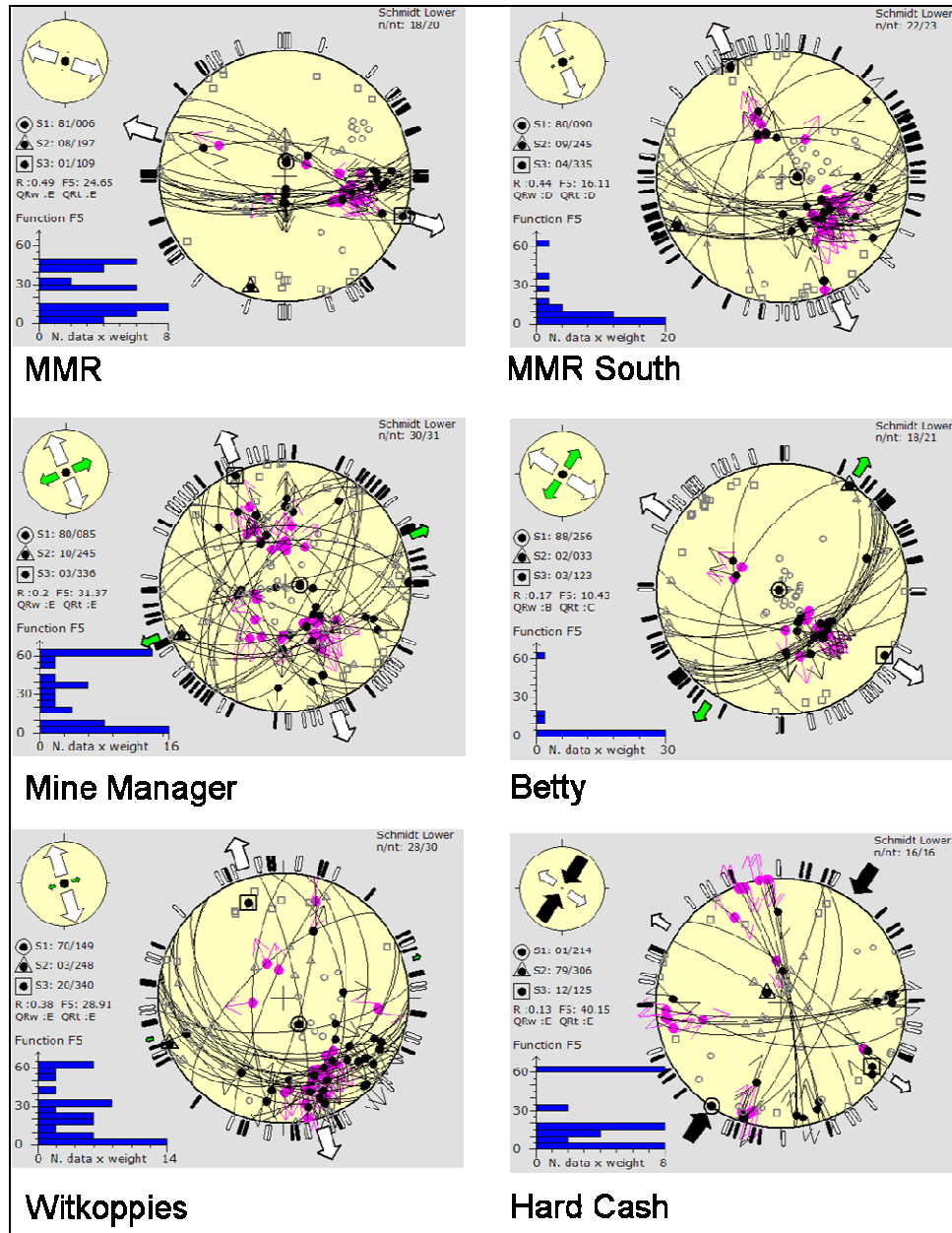


Figure 5.1: Schmidt lower hemisphere projections showing the results of the reduced moment tensor method using Win-TENSOR (Delvaux and Sperner, 2003). For all sites a plot of the fault planes and slip vectors is provided together with the orientation of the principle stress axes (S1 – S3), the principle horizontal ($\sigma_{\min}$, horizontal = open arrows; $\sigma_{\max}$, horizontal = closed arrows) and a histogram of deviation angles (α). A measure of the input data quality (QRw and QRT), stress regime R and homogeneity of the dataset (F5) is also presented. Locations of gold workings are shown in Figure 1.3. Results are presented Tables 5.1 and summarized in Table 5.3.

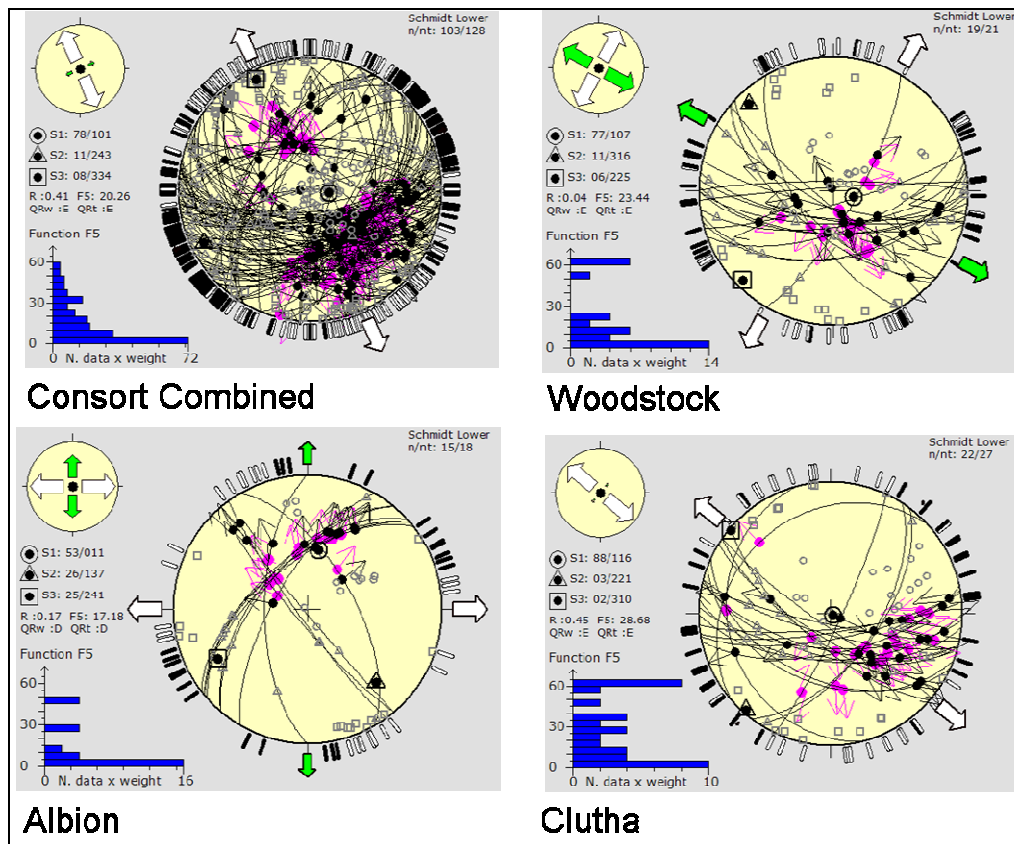


Figure 5.1 continue

These eigenvalues vary between -0.5 and +0.5, with maximum values reached when P and T axes are perfectly concentrated. Variations in the eigenvalues provide a measure of the distribution of the P and T axes. The FaultKin programme output is a plot of linked Bingham axes with eigenvalues and a related fault plane solution diagram displaying P and T quadrants in a manner similar to earthquake focal mechanisms (Table 5.1; Dirks *et al.*, 2009).

Results

Although stress analysis from fault slip data is widely applied, debate continues whether the obtained solutions represent a stress field or provide a measure of strain and strain rate (e.g. Molnar, 1983, Twiss and Unruh, 1998). Marrett and Allmendinger (1990) and Allmendinger (2001), using FaultKin, prefer to interpret the fault plane solutions as an

indicator of strain rather than stress, whilst the output of Win-TENSOR is presented in terms of stress regimes (Delvaux and Sperner, 2003; Sperner *et al.*, 2003). In spite of the difference in approach, the results of the FaultKin programme can be directly compared with the Win-TENSOR programme.

Because the same datasets to generate a linked Bingham fault plane solution through FaultKin and an improved right dihedron solution using an iterative approach in Win-TENSOR, I will interpret all results as an indication of the palaeo-stress field. In doing this, I am aware that faults, once formed, can interact in complex ways in response to an imposed stress-field due to scale-dependent strain partitioning, complex fault interactions, block rotations, and inhomogeneities in the rock mass (e.g. Twiss and Unruh, 1998). In spite of such limitations, the palaeo-stress analysis technique has been successfully applied in a wide variety of tectonic settings (e.g. Sperner *et al.*, 2003), and I believe that it provides valuable insights in the tectonic controls on gold mineralization in the NCGM and surrounding areas (see also Dirks *et al.*, 2009).

5.3 Selection of faults for kinematic analysis

In selecting faults for analyses I have focused on surface workings where stoping occurs along brittle-ductile shear zones that display slickensided surfaces and sulphide alteration (Figs. 4.10b,c,d, 4.11a,b). Support pillars left behind in stopes (e.g. Figs. 4.11b, c) provide excellent sites to observe the shears associated with the highest grade of mineralization and ensure that our data set can be linked to mineralization. Working on the assumption that gold mineralization occurred in response to a single late-tectonic phase in the evolution of the greenstone belt (e.g. de Ronde *et al.*, 1991; de Ronde and de Wit, 1994) this approach will ensure a relatively homogeneous input data set.

A common problem encountered in selecting data is that some mineralized fractures contain more than one lineation; commonly one steep- and one shallow-pitching lineation. It is generally not clear whether such overprinting lineations reflect separate events (e.g. D_{4NC} and D_{5NC} events) or form as a result of slip partitioning in a continuous

D_{4NC} event. To prevent subjective bias, both sets of lineations have been included in the data sets.

Misfits in the collected datasets may have resulted from observational errors or the mixing of unrelated data points. They can also be due to non-uniform stress fields as a result of fault interactions, anisotropies in the rock mass, block rotations or slip partitioning. In our analyses using Win-TENSOR we have kept manual cleaning of the data sets to a minimum considering that much of the pre-selection of the data was done in the field. In calculating a Bingham tensor solution using FaultKin all data points were included.

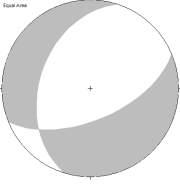
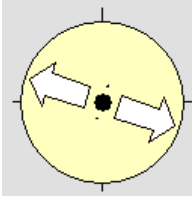
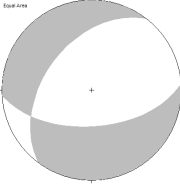
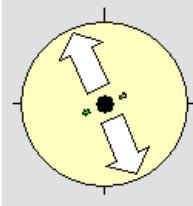
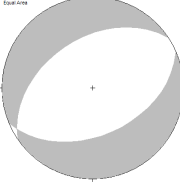
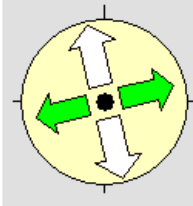
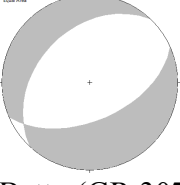
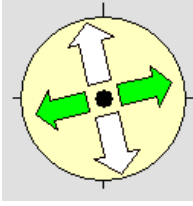
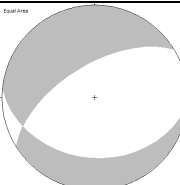
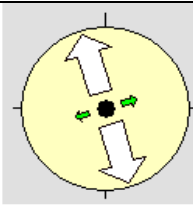
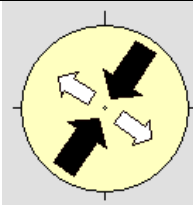
Data of several pits occurring along the same mineralization corridor (Fig. 4.13) have been grouped together to calculate an average solution for the palaeo-stress field. Because individual pits are commonly developed on a single fracture, or group of parallel fractures, measurements from such pits may place an undue emphasis on one particular fracture orientation (and corresponding palaeo-stress field). By combining pits within a mineralization corridor a wider variety of fracture orientations is included, and localised effects, or observational bias due to strain partitioning along any one fracture is reduced (Fig. 4.13).

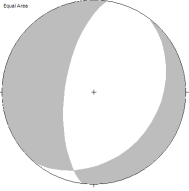
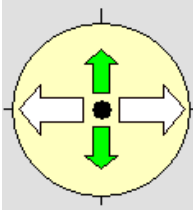
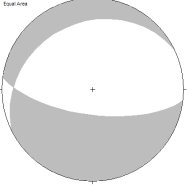
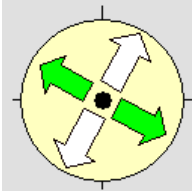
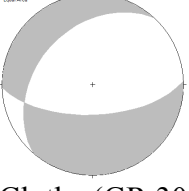
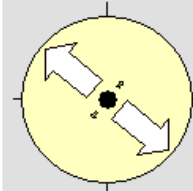
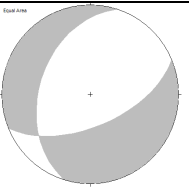
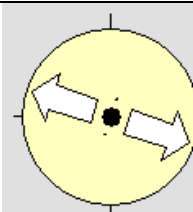
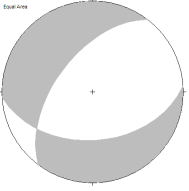
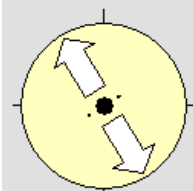
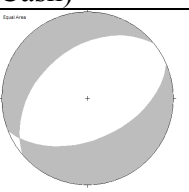
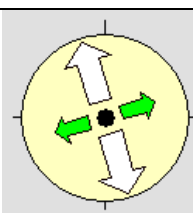
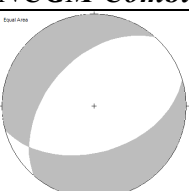
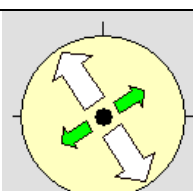
Thus, the data sets for the NCGM area have been identified as NNW, WNW and ENE trending corridors described above (Fig. 4.13). The data from individual corridors is compared with the total data set from NCGM and with data sets obtained from nearby workings at the Albion Mine, the Clutha Mine and the Woodstock Mine, to allow an assessment of the regional nature of the calculated stress field.

5.4 Results of kinematic analyses

The results of kinematic analyses from fracture planes in gold workings in the NCGM are presented in Tables 5.1, 5.2 & 5.3.

Table 5.1: Results of fault-slip inversions for palaeo-stress shown as ‘beach balls’ (grey areas for tension dihedrons), and as stress diagrams ($\sigma_{\min. \text{ horizontal}}$ = open arrows; $\sigma_{\max. \text{ horizontal}}$ = grey arrows). Detailed results are listed in Tables 5.2 and 5.3.

<i>Individual Gold Workings</i>	
Beach Balls (FaultKinWin)	Stress Diagrams (Win-TENSOR)
 MMR (GR 307520-7162532)	
 MMR South (GR307258-7162074)	
 Mine Manager (GR 308230-7159033)	
 Betty (GR 307565-7161632)	
 Witkoppies (GR 307368-7161745)	
 Hard Cash (GR 307500-7161392)	

 Albion (GR 302120-7160337)	
 Woodstock (GR 308503-7158852)	
 Clutha (GR 308135-7157869)	
<i>NCGM Corridors</i>	
 WNW (MMR)	
 NNW (MMR South, Witkoppies and Hard Cash)	
 ENE (Mine Manager and Betty)	
<i>NCGM Combined</i>	
	

5.4.1 Bingham tensor solutions in FaultKin

The Bingham tensor solutions (Table 5.1, 5.2) are consistent for all data sets with σ_1 being steep ($>60^\circ$) and variable around a vertical orientation, σ_3 being horizontal and directed along a 145° ($\pm 15^\circ$) trend and σ_2 being horizontal and directed along a 235° ($\pm 15^\circ$) trend. The results for the MMR workings along the WNW trending corridor display a pure extensional stress regime ($R = 0.51$, $R' = 0.51$) with σ_1 being near-vertical and σ_3 being horizontal and orientated at $136^\circ/10^\circ$. The results for the workings along the ENE trending corridor between the Mine managers Quarry and Witkoppies quarry are almost identical with a pure extensional stress regime ($R = 0.41$, $R' = 0.41$) and σ_1 near-vertical and σ_3 orientated at $149^\circ/04^\circ$. Results for the NNW trending corridor display pure extensional stress regime ($R = 0.60$, $R' = 0.60$) with σ_1 remaining near-vertical and σ_3 remaining horizontal and orientated at $330^\circ/06^\circ$ (Table. 5.2).

The combined result for the workings in the NCGM shows a near vertical σ_1 orientation, with σ_3 at $148^\circ/04^\circ$ and σ_2 at $238^\circ/17^\circ$ (Table 5.1). An indication for the stress regime as calculated from the eigenvalues suggests a pure extensional setting (Table 5.2). Results for the Albion, Clutha and Woodstock mines are similar (Table 5.2) with the latter two providing evidence for a more radial extensional setting.

Individual gold mines within the corridors show variable stress regimes associated with gold fractures. Pure and radial extensional stress regimes dominate in most gold workings. Pure extensional stress is indicated by all gold workings mapped in the NCGM, which include MMR, MMR South, Mine Manger, Betty and Witkoppies.

In places such as Hard Cash in the corridor, a trans-tensional environment stress regime is observed, supporting a compressional stress regime (Table 5.1). Albion and Woodstock gold mines show an R value that is close to zero, indicating a radial or multidirectional extension regime (Table 5.2).

Table 5.2: Summary of results from fault slip inversion for palaeo-stress by calculating a linked Bingham fault plane solution using FaultKin (Allmendinger, 2001). Eigenvalues (ev) for the calculated moment tensors have been used to obtain a stress ratio (Rev = [ev2-ev3]/[ev1-ev3]), (σ) represents stress axes and Rev' is an adjusted stress ratio (see text for explanation) to estimate the stress regime. Refer to Figures 4.13 and 4.14 for localities of mineralized corridors.

Individual Gold Workings											
#	Name	n	σ 1	σ 2	σ 3	ev1	ev2	ev3	Rev	Rev'	Stress regime
1	MMR	21	027\62	231\26	136\10	-0.2191	-0.0042	0.2233	0.51	0.51	Pure extensional
2	MMR South	23	052\62	247\27	154\06	-0.3798	-0.0112	0.3911	0.52	0.52	Pure extensional
3	Mine Manager	31	052\84	242\05	152\08	-0.2790	-0.0071	0.2861	0.52	0.52	Pure extensional
4	Betty	23	024\76	238\12	146\8	-0.4382	0.1047	0.3335	0.30	0.3	Pure Extensional
5	Hard Cash	17	043\7	174\80	313\8	-0.2924	0.0063	0.2861	0.48	0.48	Pure strikeslip
6	Witkoppies	30	110\68	248\17	343\14	-0.3154	0.0119	0.3034	0.47	0.47	Pure extensional
7	Albion	18	069\68	194\13	289\17	-0.3054	0.0582	0.2471	0.34	0.34	Radial extensional
8	Woodstock	21	032\65	272\13	176\21	-0.3011	0.0894	0.2117	0.24	0.24	Radial extensional
9	Clutha	27	041\63	255\23	160\14	-0.2560	0.0198	0.2362	0.44	0.44	Pure extensional
NCGM Corridors											
1	WNW (MMR)	21	027\62	231\26	136\10	-0.2191	-0.0042	0.2233	0.51	0.51	Pure extensional
2	NNW (MMR South, Witkoppies and Hard Cash)	70	071\63	237\27	330\06	-0.2566	-0.0367	0.2932	0.60	0.60	Pure extensional
3	ENE (Mine Manager and Betty)	54	033\80	240\09	149\04	-0.3429	0.0398	0.3032	0.41	0.41	Pure extensional
NCGM Combined											
	Consort Combined	145	057\72	238\17	148\04	-0.2673	-0.0112	0.2785	0.53	0.53	Pure extensional

5.4.2 Reduced Moment Tensor method in Win-TENSOR

Optimized dihedron Tensor results are presented in Figure 4.6 and Table 5.1 and 5.3. Generally, the results for the NCGM area show a near vertical σ_1 orientation with σ_3 being near horizontal along 334° ($\pm 15^\circ$) and σ_2 being near horizontal and trending at 243° .

The results for the MMR workings along the WNW trending corridor display a pure extensional stress regime ($R = 0.49$, $R' = 0.49$) with σ_1 being near-vertical and σ_3 being horizontal and orientated at $109^\circ/01^\circ$ (Table 5.3). The results for the workings along the ENE trending corridor between the Mine managers Quarry and Witkoppies quarry are almost identical with a dominant radial extensional stress regime ($R = 0.16$, $R' = 0.16$) and σ_1 near-vertical and σ_3 orientated at $342^\circ/01^\circ$ (Table 5.3). Results for the NNW trending corridor display a more trans-tensional pure extensional stress regime ($R = 0.54$, $R' = 0.54$) with σ_1 remaining near-vertical and σ_3 remaining horizontal and orientated at $372^\circ/09^\circ$ (Table 5.3).

The combined result for the workings in the NCGM shows a near vertical σ_1 orientation, with σ_3 at $318^\circ/06^\circ$ and σ_2 at $228^\circ/03^\circ$ (Table 5.3). An indication for the stress regime as calculated from the eigenvalues suggests a pure extensional setting (Table 5.3). Results for the Clutha, Albion and Woodstock mines are similar (Table 5.3) with the latter two providing evidence for a multidirectional extension setting. Generally, results from individual workings within the corridors conform to those indicated by Bingham tensor solutions in FaultKin.

Table 5.3: Summary of results from fault slip inversion for palaeo-stress by using the optimized, iterative, right dihedron approach in TENSOR after Delvaux and Sperner (2003). ‘nt’ is the total number of measurements; ‘n/nt’ the percentage of measurements used in the final calculation and (σ) represents stress axis. The average deviation angle (α), standard deviation and maximum slip deviation angle (Max.) are given together with an indication of data quality (QRw), stress ratio (R) and stress regime (R’). See text for explanation.

<i>Individual Gold Workings</i>															
#	Name	nt	n/nt	σ 1	σ 2	σ 3	R	α ave.	α Std. Dev	α Max.	Q Rw	σ h max	σ h min	R’	Stress regime
1	MMR	21	0.9	006\81	197\08	109\01	0.49	24.65	13	42.8	E	018	108	0.49	Pure extensional
2	MMR South	23	0.96	090\80	245\09	335\04	0.44	16.11	12.6	52.6	D	066	156	0.44	Pure extensional
3	Mine Manager	31	0.84	103\86	253\03	343\02	0.42	23.72	17.52	57.6	E	073	163	0.42	Pure extensional
4	Betty	23	0.93	256\88	033\02	123\03	0.17	10.43	11.6	51.1	C	036	126	0.17	Radial Extension
5	Witkoppies	30	0.93	149\70	248\03	340\20	0.38	28.91	19.97	81.4	E	073	163	0.38	Pure extensional
6	Hard Cash	17	1	214\02	116\75	305\15	0.24	32.21	38.02	338.5	E	034	124	1.76	Pure strikeslip
7	Albion	18	0.83	011\53	137\26	241\25	0.17	17.8	13.77	43.3	D	180	90	0.14	Radial extensional
8	Woodstock	21	0.9	107\77	316\11	255\06	0.04	23.44	19.63	60.3	D	119	029	0.04	Radial extensional
9	Clutha	27	0.81	116\88	221\03	310\02	0.45	28.68	17.2	95.7	E	040	130	0.45	Pure extensional
<i>NCGM Corridors</i>															
1	WNW (MMR)	21	0.9	006\81	197\08	109\01	0.49	24.65	13	42.8	E	018	108	0.49	Pure extensional
2	NNW (MMR South, Witkoppies and Hard Cash)	70	0.99	091\73	236\14	327\09	0.54	31.14	31.3	176.6	E	059	149	0.54	Pure extensional
3	ENE (Mine Manager and Betty)	54	0.98	087\81	252\09	342\01	0.16	22.83	21.99	81.7	E	074	164	0.16	Radial extension
<i>NCGM Combined</i>															
	Consort Combined	144	0.94	111\83	228\03	318\06	0.31	27.63	21.93	84.1	E	049	139	0.31	Pure extensional

6. Discussion and conclusion

6.1 Deformation history

The NCGM area, located in a triple junction between the Jamestown Schist Belt and the Barberton Greenstone Belt (BGB), exhibits a complex ductile structural history characterized by tight- to isoclinal, closed to open folds and shear zones, that have been formed during stages of accretion of the BGB (3.2 Ga and 3.1 Ga; de Ronde and de Wit, 1994; Lowe and Byerly, 1999). The ductile structures are crosscut by a network of brittle-ductile faults/ shear zones marking final deformation events in the area. Based on field observations from this study, the deformation history of the NCGM has been re-defined to at least five deformation events ($D_{1NC} - D_{5NC}$; Table 2.1).

The first three events ($D_{1NC} - D_{3NC}$) involve a range of shearing and folding events linked to the accretionary history of the greenstone belt (D_{1NC} and D_{2NC}), and subsequent doming of surrounding batholiths (D_{3NC}) (Schoene *et al.*, 2008). The deformation events are superimposed by D_{4NC} structures, which involved the formation of a network of extensional brittle-ductile shear zones and associated kink bands and crenulation folds and can be linked to gold mineralization, and D_{5NC} structures, which represent late reverse faults.

D_{1NC} is restricted to Onverwacht and Fig Tree Group rocks and produced a penetrative cleavage (S_{1NC}) axial planar to a series of tight antiforms and synforms (Table 2.1). Typical example of antiforms includes an 80 m wide band of Onverwacht Group schist within Fig Tree rocks, located to the S of NCGM (Fig. 1.3). The outcrop thickness of the band decreases from the south to the north of NCGM, where around the Bluejackets section; the unit appears to pinch-out and merges with the Onverwacht Group rocks, which make up the footwall to the greywacke-shale units comprising the Top Section Syncline (Fig 1.3). The presence and tightness of the antiform-synform pairs in the greenstones and greywacke-shale units has been determined using the cross cutting relationships between S_0 and S_{1NC} . Within larger synforms, S_0 - S_{1NC} relationships also

illustrate the presence of isoclinal vergence folds along the larger scale tight folds. In the Sheba area, antiform-synform pairs associated with D_{INC} are also found in the greenstones and greywacke shale units (Figs. 2.7, 2.8), some known as the Hospital Hill and Birthday Anticline (Dirks *et al.*, 2009).

The contact between the Onverwacht and Fig Tree Group rocks was strongly sheared and silicified resulting in a discrete, fine-grained, banded, hard, cherty, dark brown unit commonly known as the Consort Bar. The metamorphic mineral assemblages and the abundance of silica in the unit can be explained as products of alteration processes linked to peak metamorphism (M_{INC}), associated with D_{INC} . The contact probably served as a zone of silica enrichment during metamorphism. In places, the unit contains angular fragments of greywacke-shale and vein-quartz that are compacted together in a fine-grained silicified matrix, further providing evidence of a tectonic origin of the Consort Bar.

An angular unconformity separates the Fig Tree and Onverwacht Group rocks from the overlying volcanoclastic units of the Schoongezicht Formation and Moodies Group (Dirks *et al.*, 2009). Thus, Fig Tree and Onverwacht Group rocks were uplifted and eroded prior to deposition of the volcanoclastics. In the NCGM area, this unconformity is preserved to the west of the mine, as a sheared contact between greywacke-shale units and the overlying Schoongezicht Formation. Outside the NCGM, in the Woodstock area, the Schoongezicht Formation, which is overlain by a conglomerate unit, overlies rocks of Onverwacht Group.

D_{2NC} folding of the rocks in large synformal structures followed the D_{INC} event. This event tightened the D_{INC} structures and folded the Schoongezicht Formation and Moodies Group (Table 2.1). The Schoongezicht Formation is separated from the greywacke-shale units of the Fig Tree Group by an unconformity, does not contain an S_{INC} fabric, grades to the Moodies Group conglomerate, and folds with the Moodies Group. This evidence suggests that the Schoongezicht Formation is not part of the Fig Tree Group, but forms the basal part of the Moodies Group.

D_{2NC} structures trend parallel to the D_{1NC} folds and suggest that these events are part of a progressive compressional regime associated with accretion of the BGB. In the southern part of the belt, Lowe *et al.* (1999) noted that although separated by an unconformity, Moodies Group synclines and pre- Moodies Group tight to isoclinal folds show parallelism in strike-lines, suggesting a common directional source between the events. Dirks *et al.* (2009) have reported similar observations in the Sheba area.

D_{3NC} structures resulted from a series of progressive events that include the development of a network of shear zones, which divide the area around NCGM in separate structural domains, each characterized by slightly different deformational, metamorphic and exhumation histories (e.g. Dziggel *et al.*, 2006, 2007). Movement on the shear zones has been linked to the rise of the Nelspruit Batholith (Viljoen, 1964; Dziggel *et al.*, 2006) imposing a constrictional environment on the area. Around NCGM, complex fold interferences developed in between the principle shear zones. Early D_{3aNC} shear zones visible as mylonites along the Consort Bar were folded during D_{3bNC} and D_{3cNC} events, which also transposed, refolded and tightened the older D_{1NC} and D_{2NC} structures and fabrics. This happened simultaneously with the large refold of the Eureka Syncline S of NCGM (Table 2. 1; Anhaeusser, 1976).

D_{3bNC} folds consist of asymmetric, NW-verging, upright, closed folds with a moderately SE dipping fold axial plane, and probably near horizontal fold axis. At least one, 600m-scale synform-antiform pair can be defined around NCGM with smaller scale, vergence folds occurring on their limbs. D_{3bNC} folds were refolded by a single NW trending, steeply reclined closed, D_{3cNC} antiform with a steeply SW dipping fold axial plane and a SE plunging fold axis. This refolded-fold pattern is responsible for the complex distribution of the Consort Bar both on surface and underground (Voges, 1986). The complexity imposed by this refolded-fold pattern is further illustrated by more complex distributions of underground ore zones. Although common trends of ore zones are known from mined areas, the fold interference-pattern makes projections of ore shoots extremely difficult.

The complex fold interference pattern has resulted in confusing interpretations of the local geology. A good example is the Shires Shear Zone (SSZ), which has been described in mine reports (Tomkinson, 1989) and has been referred to as an important gold-bearing structures in papers like Otto *et al.* (2008), Dziggel *et al.* (2007) and Harris *et al.* (1995). The SSZ has been described underground from an area that coincides with the No.7 Antiform, between Witkoppies Quarry and No. 6 shaft. This package of tight, synclinal, D_{3bNC} folds, repeatedly fold and duplicate D_{3aNC} mylonite along the Consort Bar. Underground drives crossing these folds, display a wide zone of D_{3aNC} mylonite as the Consort Bar is repeatedly crossed, creating the impression of a wide shear zone, which I believe is the origin of the interpretation of this fold zone as the “Shires Shear Zone” (Tomkinson, 1989; Harris *et al.*, 1995). In the reports, e.g. Tomkinson (1989), there is a lack of evidence presented from surface geology that can be used to justify the existence of the Shires Shear Zone. The surface locations of this shear zone have been strongly influenced by projections, from underground workings, along the mylonitised Consort Bar. The projection of the zone appears to have ignored the structural complexity imposed by different deformation events, hence the existence and the location of such a shear zone in my opinion (Munyai *et al.*, 2010 submitted) has been misinterpreted and is invalid.

The Bluejackets Fault is also, another misinterpreted structure. The fault has been previously interpreted as a late brittle structure that crosscuts the complexly folded ductile structures (Viljoen, 1964; Voges, 1986; Tomkinson and Lombard, 1990; Harris, 1995). The presence of the Consort Bar, mylonitised pegmatite units, folded S_{3aNC} and L_{3aNC} (Fig. 4.7) along the previously considered fault zone, indicate that the zone is a continuation of the Consort Bar. There is also little evidence in the mine reports about the underground extension of the Bluejackets Fault. Further structural evidence from D_{4NC} event shows that the zone is cut by en-echelon brittle-ductile E-W trending D_{4NC} normal faults, which we believe is the origin of the large-scale normal fault indicated by previous authors. Similar to other D_{4NC} brittle-ductile normal faults or shear fractures, these faults are characterized by sizable gold workings along them.

These results contradict the consideration, by previous authors, of the Bluejackets Fault zone as a major normal fault zone, interpreted to post-date ductile structures and gold mineralization in the NCGM. The results show that the zone is not a large-scale normal fault, as it is commonly known, but a part of the folded Consort Bar crosscut by D_{4NC} brittle-ductile normal faults or shear fractures.

This study shows that gold mineralization can be linked to a network of extensional brittle-ductile shear zones that cross-cut the complex refolded fold patterns in the NCGM. These brittle-ductile shear zones are mineralized and can be observed in old gold workings. By mapping the individual brittle-ductile shear zones in surface workings across the hills around NCGM, a larger scale pattern of D_{4NC} brittle-ductile shear zones was obtained. These shear zones include a 120 m wide central NNW trending corridor of fractures between the Ivaura workings in the NNW via the Wikoppies Quarry and Hard Cash to the workings around No. 7 shaft in the SSE. This corridor is transected by several WNW and ENE trending fracture corridors including the line along the MMR workings in the N, the Witkoppies, Bluejacket, Mine Manager, Betty's and PC workings in the centre, and the No. 3-No. 6 workings to the SW of the NCGM. In each of these corridors, individual brittle-ductile shear zones can be traced for up to 100-140 m along which pits, shafts and trenches have been developed. As a mineralized fracture terminates, a new one starts up, commonly in a slightly displaced, but overlapping en-echelon manner, whilst cross fractures connect both shear zone strands.

Gold workings are concentrated where D_{4NC} extensional brittle-ductile shear zones crosscut the complexly folded laminated cherts of the Consort Bar, or the silicified mafic-ultramafic Onverwacht Group units in its immediate footwall, which possibly coincide with the location of D_{1NC} fold hinge areas. Relatively higher-grade ore-shoots, including PC, Ivaura and No. 7 shoots, are more pronounced where these fold hinges are complexly folded and transected by faults. In places, such as around No. 3 Shaft, northwest trending brittle-ductile faults have been reported to cross-cut the mineralized Consort Bar and silicified shale units (Marchini, 1987). The silicified banded shale contained arsenopyrite

grains that trend parallel to the fault plane (Marchini, 1987). In the very same area, gold has been reported to be closely associated with arsenopyrite (Marchini, 1987).

The introduction of the auriferous fluids may be linked to the magmatic fluids related to pegmatite emplacement as suggested by Harris *et al.* (1995), which themselves have been linked to emplacement and doming of the Nelspruit Batholith (Harris, 1992), which would have presumably occurred around 3106 Ma (Kamo and Davis, 1994). Pegmatites, however, are common along the northern margin of the BGB, and only around NCGM are they closely associated with gold mineralization. The alternative explanation for the introduction of auriferous fluids is that it was related to a magmatic event that post-dated emplacement of the Nelspruit Batholith possibly around 3084 $\pm$ 18 Ma (de Ronde *et al.*, 1992) and involving the emplacement of porphyry dykes in the area (Dirks *et al.*, 2009).

6.2 Palaeo-stress analyses

The two different stress inversion programmes, FaultKinWin tensor and Win-TENSOR, have produced similar results during palaeo-stress analyses performed in this study. This similarity partly suggests that the results from either program can be used with confidence, and reliance for the reconstruction of palaeo-stress. The minor difference between the results from the two programs is the R-value. Generally, the R-values indicated by Win-TENSOR are lower than those indicated by FaultKinWin (Tables 5.2 and 5.3). This is partly because of the way the two programs have been designed. The Win-Tensor assumes that an optimal position for a rock failure or fault slip is at 30° degrees to the principal stress axis, whilst the FaultkinWin assumes a 45° degrees angle position.

The results (Tables 5.2 and 5.3) from the NCGM area are near identical in many ways to the results from Clutha, Woodstock, Albion and those obtained in the Sheba area by Dirks *et al.* (2009). In all these gold workings, σ_1 is generally steep whilst σ_3 is shallowly directed along NW-SE directions. This suggests that all gold-bearing structures formed within the same extensional tectonic setting, and that the extensional stress field was probably of regional significance. Judging from the dominance of NW or SE directed slip

directions on the multitude of D_{4NC} fault plane directions, a pure extensional stress regime is most common as can also be seen from the calculated stress tensor results (Tables 5.2 and 5.3).

6.3 Structural controls and 3-D geometry of gold mineralization at the NCGM

D_{4NC} en-echelon brittle-ductile extensional shears, which occur as Riedel, anti-Riedel and P-Shear arrays in different corridors, are the critical controls of gold mineralization in the NCGM. These mineralized shears fractures constitute all the gold-bearing shoots known in the NCGM area. The gold shoots occur as complex patterns of arrays, which in larger scale (1000m), show trends that can be important tools to locate the next set of ore shoots. Major gold shoots are also common where these trends intersect or crosscut one another.

Generally, previous authors such as Harris *et al.* (1995) and Voges (1986), considered these gold-bearing shoots in the underground workings of the NCGM area as complex structures. The complexity of these shears is associated with the geology and the structural architecture that host these shoots. The results show that silica-rich units (Consort Bar) and greenstones are the main lithological units preferred for the precipitation of gold. This is in part indicated by a large amount of gold workings that are found along these units. Although a large number of gold workings is found on the Consort Bar, it must be noted that not the entire bar is mineralized, indicating the existence of an external control factor. This observation does not agree with what has been concluded by previous authors (e.g. Tomkinson, 1989; Harris *et al.*, 1995) about the bar being the main control of mineralization.

Precipitation of gold in the NCGM also appeared to have had higher affinity to the complexly folded zones. This is also illustrated by the presence high number of major gold workings in the cores of the fold interference of D_{1NC} - D_{3NC} folds. These complexly folded ductile structures, which include the Consort Bar and D_{1NC} hinge zones, appear to

have acted as zones of mineral enrichment, trapping mineralized fluids when cross-cut by the D_{4NC} normal brittle-ductile shear zones rich in gold mineralising fluids.

It is concluded that the distribution of high-grade ore zones in the NCGM is a function of the intersection orientation of the D_{4NC} fault zones with suitable host lithologies as chemical traps, which display a complex distribution pattern as a result of D_{1NC}-D_{3bNC}-D_{3cNC} fold interference patterns. The 3-D distribution of ore zones is therefore discontinuous and complex.

This conclusion does not agree with conclusions, see section 2.3, made by previous authors that considered gold in the NCGM to pre-date the D_{4NC} normal brittle-ductile shear zones. The results do not support the two types of mineralization indicated by Otto *et al.* (2007), and Tomkinson and Lombard (1990). Gold bearing fractures cross-cut all ductile structures including the skarns developed during D^{VI}₁; hence, the gold bearing fractures cannot be linked to the D^{VI}₁ event. Dziggel *et al.* (2007), Harris *et al.* (1995), Tomkinson and Lombard (1990) and Viljoen (1964) linked gold-bearing fractures to events that are the equivalent of D_{3NC}. It has been indicated in the previous chapters that gold fractures cross-cut the D_{3NC} events; hence, the conclusions from these authors raise a lot of concerns.

6.4 Can D_{4NC} gold bearing fractures be associated with the extensional detachment faulting reported in the southern part of the BGB?

The extensional detachment, which caused exhumation of deep crustal amphibolite facies rocks noted in the southern parts of the belt, occurred shortly after regional D₂ (Kisters *et al.*, 2003), which occurred between 3.26 Ga and 3.22 (de Ronde and de Wit, 1994). The detachment event has been interpreted to pre-date D₃ of de Ronde and de Wit, 1994, which comprises deposition, folding and re-folding of the Schoongezicht Formation and Moodies Group (Table 2.1). These age dates coupled with a fact that gold-bearing brittle-ductile shear-fractures in the NCGM and Sheba areas crosscut the structures associated with regional D₃ of de Ronde and de Wit (1994), outline clearly that gold mineralization

in the NCGM and Sheba areas cannot be linked to normal faulting associated extensional detachment outlined by Kisters *et al.* (2003).

6.5 Is gold mineralization in the NCGM orogenic or does it post-date orogenic stages?

Gold mineralization in granite-greenstone terranes is mostly categorized as mesothermal lode gold (Kerrick and Wyman, 1990; Robert *et al.*, 1991) or orogenic gold and linked to Cordilleran-type accretionary settings (Goldfarb *et al.*, 2001; Groves *et al.*, 2003). This implies that Archaean greenstone belts originated as accreted oceanic crust and oceanic arc sequences (*e.g.* de Ronde and de Wit, 1994), a commonly held, but certainly not universally accepted view considering that Archaean rocks preserve many unique characteristics not consistent with modern plate boundary processes (*e.g.* Bleeker, 2002). Gold deposits at Sheba-Fairview Mines have in the past been interpreted as orogenic gold deposits hosted by structures that originated as secondary faults due to dextral thrusting on the Sheba shear zone (Anhaeusser, 1986; de Ronde *et al.*, 1991; Robertson *et al.*, 1994; Otto *et al.*, 2007). In NCGM, gold has also been linked to thrusts and strike-slip faults associated with the accretionary period of the belt, implying that gold mineralization is orogenic (Tomkinson and Lombard, 1990; Harris *et al.*, 1995)

The results of this research indicate that the extensional D_{4NC} structures overprint all earlier ductile structures that can be linked to the 3260-3225 Ma accretionary stages of the BGB (*i.e.* D_{1NC}-D_{2NC} events; Table 2.1) or to events linked to emplacement and doming of the Nelspruit Batholith around 3106 Ma (*i.e.* D_{3NC} events; Table 2.1) (Schoene *et al.*, 2008). Mineralization can therefore be linked to an extensional event that may have developed separately from the accretionary events shaping the craton; *i.e.* after stabilisation of the craton had occurred. This is consistent with the age dates deduced by both Dziggel *et al.* (2010) and Harris *et al.* (1995), showing that gold mineralization occurred post accretionary period.

The presence of such an extensional event has been noted before (e.g. de Ronde and de Wit, 1994; Dirks *et al.*, 2009), and explained as extensional collapse of the craton possibly related to the opening of intracratonic basins in which volcanic and sediments of the Dominion Group were deposited shortly before 3074 ± 6 Ma (Armstrong *et al.*, 1991).

It is important to note that the ingress of auriferous fluids could have occurred after accretion and stabilisation of the craton. This indicates that classifying deposits like the NCGM as orogenic is misleading even though the lode-gold deposits are hosted by accretionary greenstone sequences. Instead, their tectonic position in time and space is better explained as extensional intracratonic.

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**Appendix A –Paper published in Cratonic extension
and Archaean gold mineralization in
the Sheba-Fairview mine, Barberton
greenstone belt, South Africa**

**Appendix B- Paper submitted for publication:
Archaean gold mineralization during
post-orogenic extension in the New
Consort Gold Mine, Barberton
Greenstone Belt, South Africa**

Appendix C - Old gold workings

Appendix D – Structural Data Used