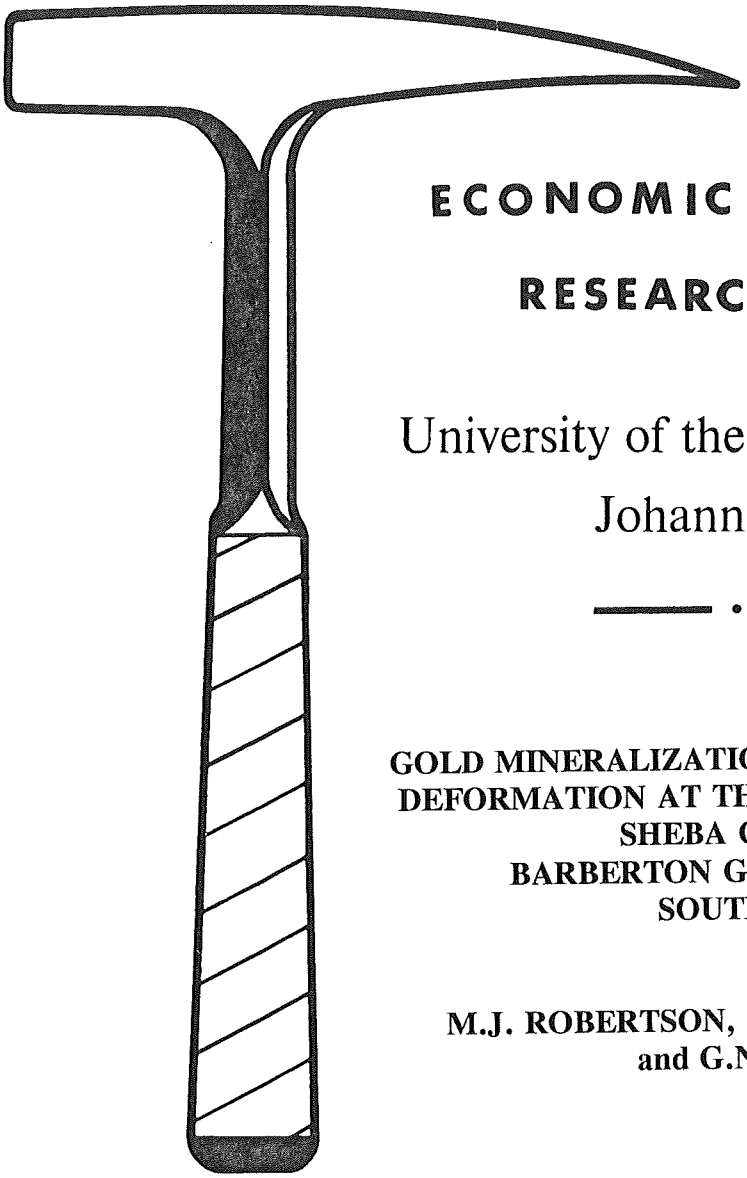

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GOLD MINERALIZATION DURING PROGRESSIVE DEFORMATION AT THE MAIN REEF COMPLEX, SHEBA GOLD MINE, BARBERTON GREENSTONE BELT, SOUTH AFRICA

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by

M.J. ROBERTSON[1], E.G. CHARLESWORTH[2] and G.N. PHILLIPS[3]
([1]P.O. Box 80363, Olympia, Windhoek 9000, Namibia.
[2]Department of Geology, University of the Witwatersrand,
P.O. WITS 2050, Johannesburg, Republic of South Africa.
[3] Key Centre in Economic Geology, James Cook University,
Townsville 4811, Queensland, Australia)

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ABSTRACT

Gold mineralization in the Main Reef Complex at Sheba Gold Mine is hosted within shear zones in a sequence of shales and greywackes of the Fig Tree Group. Competency contrasts between these rocks and a steeply dipping chert unit provided a locus for the development of a right lateral system of steeply dipping subparallel shear zones. A set of flatter dipping shear zones crosscut these and their intersections define a system of en échelon ore shoots.

Mineralization is both of vein type and disseminated strata-controlled replacement type, the latter mainly occurring within the wall rocks to the shear zones. Arsenopyrite and pyrite are the major ore minerals with arsenopyrite being largely confined to greywacke beds and pyrite to the more iron-rich shale units. Gold was introduced together with minor sphalerite, pyrrhotite, chalcopyrite and early arsenopyrite towards the end stages of a first pyrite phase. The mineralizing fluids were introduced along dilated cleavage planes and produced a series of replacement fronts. Mineralization was syn- to late- tectonic and occurred under conditions of progressive deformation resulting in sulphides being concentrated in the hinges of shear-related folds and semi-massive sulphides within tension fractures having been folded, attenuated and fractured.

An analysis of the structures shows a sequence of events with an initial ductile simple shear event with reverse movement being succeeded by a more brittle strike-slip event. Mineralization is temporally related to the latter. The evolution in style to strike-slip tectonics was probably related to reactivation of the Sheba Fault as a transcurrent fault during emplacement of large granitoid bodies.

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INTRODUCTION

Sheba Gold Mine is situated in the Sheba Hills, some 12 km northeast of Barberton within the Archaean Barberton Greenstone Belt (Fig. 1). Gold was first discovered in the Sheba Hills at the Golden Quarry by Edwin Bray in 1885. The initial assay results from this lode deposit yielded 250 g/t of free gold (Anhaeusser, 1986) and during its history, this deposit has produced 2840 kg of gold. The discovery of this rich strike led to a surge of prospecting and mining in the district and for the next half century, at least 20 companies produced gold from individual deposits within the present Sheba holdings area. The Sheba Company was established in 1886 and in 1953, together with several of the then-existing small companies and syndicates, was incorporated to form the Eastern Transvaal Consolidated Mines Ltd., a subsidiary of Anglovaal Ltd. (Wagener and Wiegand,1986).

Sheba Mine is the largest gold producer in the Barberton Greenstone Belt, having produced 24 percent of the 300 tons of gold mined in the belt up to 1983 (data from Anhaeusser, 1986). The mine has been in continuous operation for the last 108 years and has exploited numerous ore zones over a wide areal extent (Fig. 2). Currently, three sections of the mine are being exploited, namely; the Main Reef Complex (MRC), Zwartkoppie Section and Royal Sheba. Underground development of the MRC began in 1977 from a prediction of the extensions of ore zones in the adjacent Fairview Mine to the west (Fig.2) and the MRC presently forms one of Sheba Mine's major ore reserves.

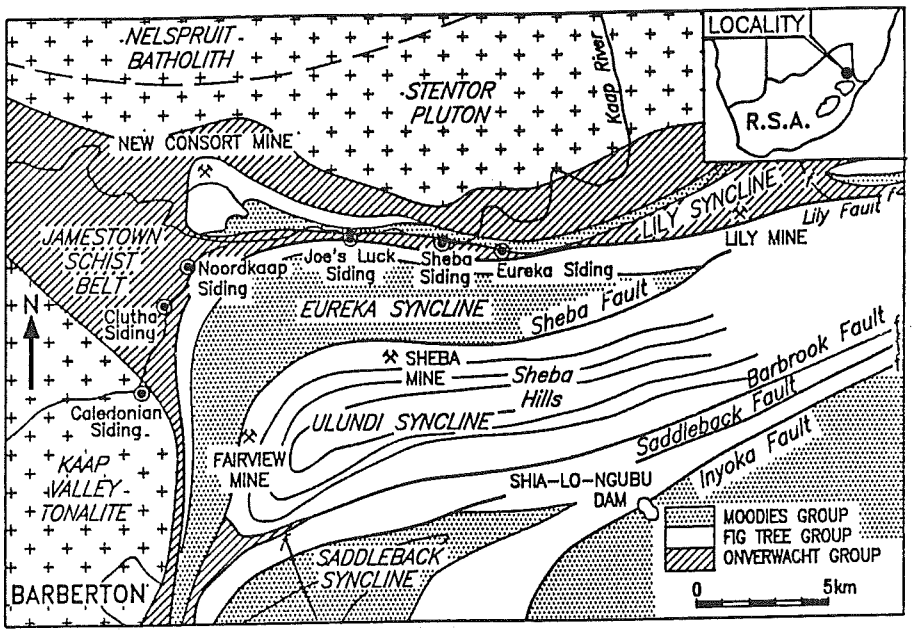

Figure 1: Geological map of the Sheba Hills area, northwestern flank of the Barberton Greenstone Belt (modified after Anhaeusser, 1976).

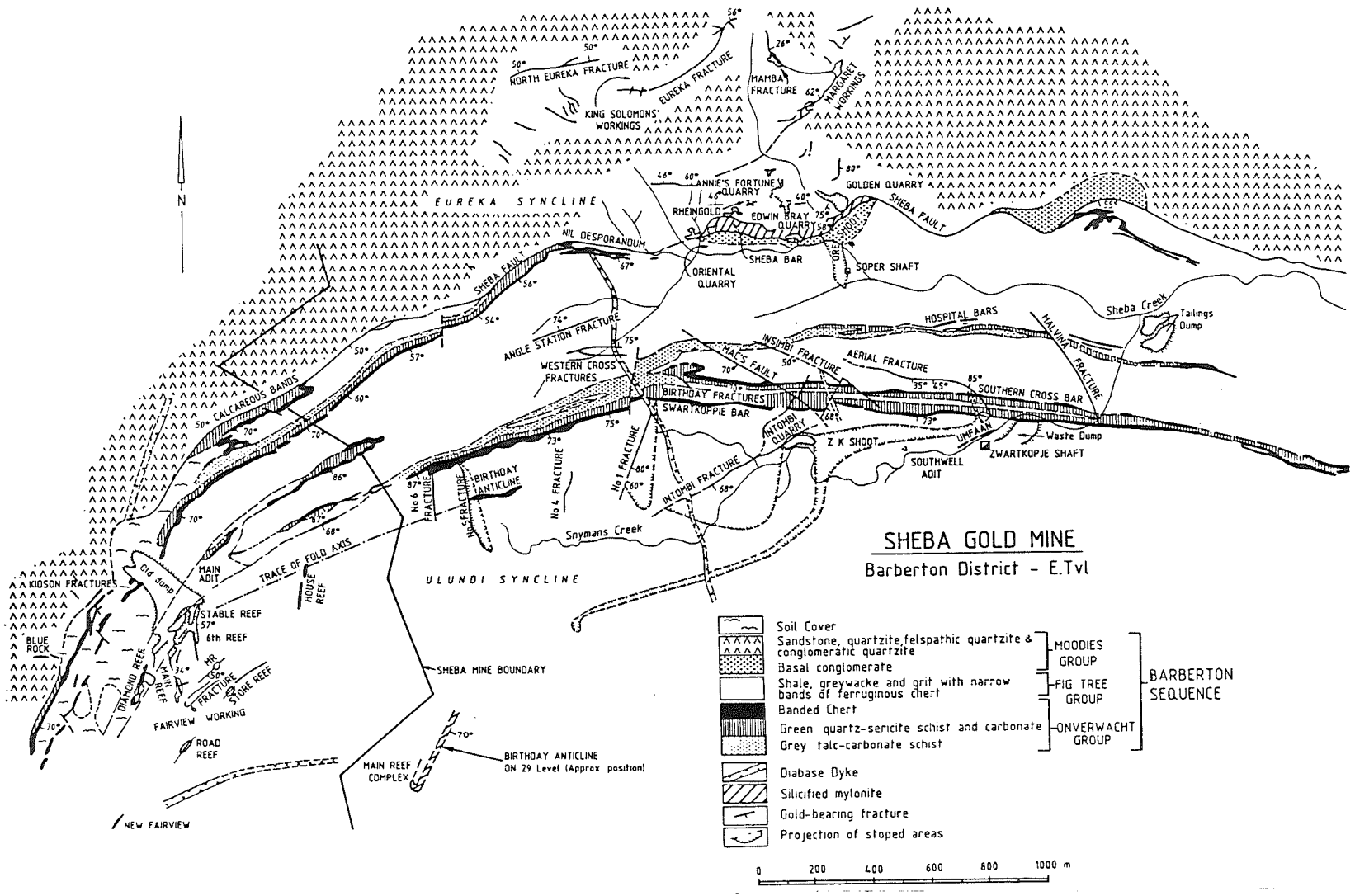

Figure 2: Geological map of the Sheba Gold Mine (modified after Wagener and Wiegand, 1986)

Aspects of the structural geology and associated mineralization at Sheba Mine have been described by Ramsay (1963) and Anhaeusser (1965). In addition, both Van den Berg (1984) and Wagener and Wiegand (1986) documented the occurrence of a wide variety of ore bodies which are, generally, steeply plunging ore shoots within and adjacent to fractures and shear zones in a zone some 2 km wide and over a strike length of approximately 6 km (Fig.2). Within the MRC, detailed mineralogical, lithological and geochemical investigations have been carried out by Schouwstra (1985) and Schouwstra and De Villiers (1988) with a view to defining zones of potential ore grade. Only minimal structural information at the MRC, however, has been gathered by these authors and by Van den Berg and Eaton (1984). The purpose of this paper is to present new data on the structural controls of gold mineralization in the MRC at Sheba Mine.

REGIONAL SETTING

Situated in the eastern part of the Kaapvaal craton, the Barberton Greenstone Belt consists of supracrustal volcanic and sedimentary rocks, metamorphosed to lower greenschist or at some localities to amphibolite grade, preserved in a granitic terrane with intrusive or structurally modified granite-greenstone contacts. In a recent review of the geochronology from the Barberton Mountain Land, Kamo and Davis (1991) provide evidence that the granitic terrane which surrounds the Barberton Greenstone Belt comprises a variety of granitic rocks which were emplaced episodically over a protracted time span of about 800 Ma. In particular, the granitic terrane along the northern flank of the greenstone belt is dominated by the occurrence of large plutonic and batholithic masses (Fig.1). The Kaap Valley pluton which lies to the west of the Sheba Hills, has an emplacement age of 3227 $\pm$ 1 Ma (U-Pb zircon age, Kamo et al.,1990, Kamo and Davis, 1991) and the extensive Nelspruit batholith together with the Stentor pluton which occur along the northern contact of the greenstone belt have been dated at 3106 $\pm$ 3 Ma and 3106 +6/-4 Ma respectively (U-Pb zircon ages, Kamo et al.,1990, Kamo and Davis,1991).

The Barberton Greenstone Belt is composed of rocks of the Barberton Sequence comprising three stratigraphic units, namely, the basal Onverwacht Group, followed by the overlying Fig Tree and Moodies Groups (SACS, 1980) and represents one of the internationally recognized type areas for the Archaean. The Onverwacht Group comprises a predominantly volcanic assemblage of ultramafic, mafic and felsic units with minor chert. This group is overlain by greywackes, shales and chemical sediments comprising the dominantly argillaceous Fig Tree Group which, in turn, is succeeded by the largely arenaceous Moodies Group consisting of conglomerates, quartz arenites, shales, jaspilites and minor volcanics. Detailed stratigraphic classifications of the Barberton Sequence have been presented by Viljoen and Viljoen (1969) and Anhaeusser (1976) and together with the pioneering work of Hall (1918), Van Eeden (1941), Visser et al. (1956) and Ramsay (1963), are reviewed by SACS (1980). More recent contributions with stratigraphic implications include the work of De Wit et al. (1987) and Lowe (1982, 1991).

Recent geochronological evidence presented by Kamo and Davis (1991) provides a U-Pb zircon age of 3470 Ma for the komatiitic units of the lower Onverwacht Group, whereas sedimentary units of the Fig Tree Group are considered to be deposited in the time span 3259 to 3225 Ma.

(U-Pb zircon ages), corresponding to the time of emplacement of the large tonalitic plutons e.g. Kaap Valley tonalite. Although the age of deposition of the Moodies Group is not tightly constrained, an age of c. 3227 Ma is suggested by Kamo and Davis (1991). This age is suggested from the recognition that the Moodies Group was deposited as a result of tectonism associated with the emplacement of the Kaap Valley pluton and thrusting of the supracrustal rocks at about 3227 Ma. Gold mineralization has been bracketed between 3126 $\pm$ 21 Ma and 3084 $\pm$ 18 Ma by De Ronde et al. (1991) from U-Pb ages of zircon and rutile from Fairview Gold Mine (Fig. 2), although these U-Pb ages may be imprecise.

GEOLOGY OF THE SHEBA MINE AREA

The Sheba Hills are dominated by two fold structures of post-Moodies age, namely the Eureka and Ulundi Synclines (Ramsay, 1963). These moderately plunging, steeply inclined, northerly verging folds are separated by an extensive strike fault, the Sheba Fault. Both the fold structures and the Sheba Fault have been subsequently deformed about a northwest-trending axis to produce the prominent arcuate fold structure flanking the Kaap Valley tonalite (Fig. 1). To the north of the Sheba Fault, the westerly plunging Eureka Syncline consists of arenaceous Moodies Group lithologies. To the south of the fault, lower Fig Tree Group lithologies and Zwartkoppie Formation assemblages (uppermost Onverwacht Group) form the easterly plunging Ulundi Syncline. Within the Ulundi Syncline, Zwartkoppie banded cherts and talc-carbonate schists delineate large-scale, tight to isoclinal folds locally referred to as the Sheba anticlines. These comprise the Hospital, Zwartkoppie, Eldorado and Birthday Anticlines (Figs. 2 and 3) whose axial planes dip steeply to the south and fold axes plunge betwen 10° and 40° to the east. The Birthday Anticlines, locally named Birthday Nos. 1 and 2 (of which only Birthday No.1 crops out in the Sheba mine area), close both to the east and west and form tight to isoclinal, doubly-plunging folds with a possible sheath-like geometry. These isoclinal fold structures probably occurred as a result of a pre-Moodies deformation event (De Wit, 1982, Robertson, 1989, Tomkinson and King, 1991). Within the Sheba mine area, however, because of the fold geometries and the superimposed deformation, the effects of the pre-Moodies deformation and the later post-Moodies deformation are difficult to separate. Tomkinson and Philpot (1990) and Tomkinson and King (1991), however, have presented evidence from areas south of Barberton to support a pre-Moodies age for these anticlinal structures.

Gold mineralization within the Sheba mine area has been exploited from approximately 25 fracture-hosted ore zones which occur on either side of the Sheba Fault. Most of the mineralization is hosted by fractures which dip steeply to the southeast and southwest forming a crude herringbone pattern (Fig.2), and which are associated with the isoclinal Sheba anticlines, south of the fault. More specifically, the mineralization is spatially associated with the lithological contact between greywackes and shales of the Fig Tree Group and the more competent Zwartkoppie banded cherts of the Onverwacht Group. Gold occurs together with pyrite and arsenopyrite within quartz-carbonate veins along the fractures and as disseminations in the adjacent wall-rocks.

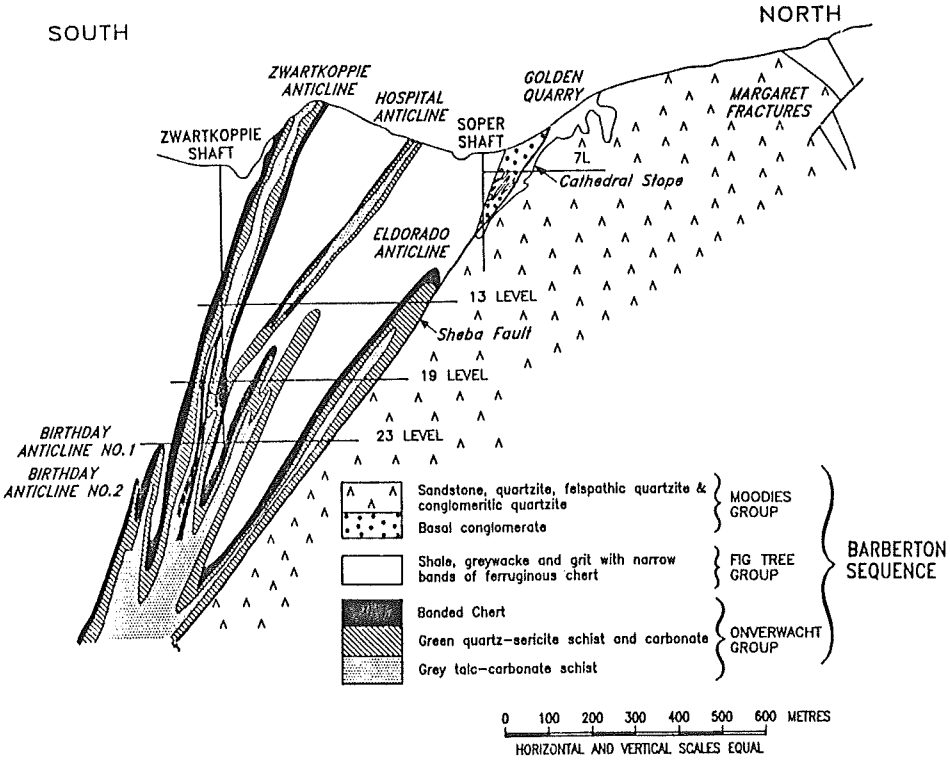

Figure 3: North-south section through the Zwartkoppie and Soper shafts showing the simplified structure of the Sheba Mine area (modified after Wagener and Wiegand, 1986).

MAIN REEF COMPLEX

The Main Reef Complex is situated in the most westerly section of the Sheba Mine within Fig Tree greywackes and shales in the vicinity of the southwesterly plunging fold closure of the doubly-plunging Birthday No.2 Anticline (Figs. 2,3 and 4). The ore body is characterized by three sets of shear zones. The first set, referred to in this paper as Main shear zones, comprises three subparallel shear zones, locally termed the Number 1, 2 and 3 Fractures, which strike northeast and dip approximately 55° to the southeast (Fig.4). These are interconnected by a set of narrow, steep, southerly dipping shear zones , or "Steep" shear zones locally called steep fractures. Both sets are crosscut by an en échelon set of shallow-dipping "Cross" shear zones (Fig.4).

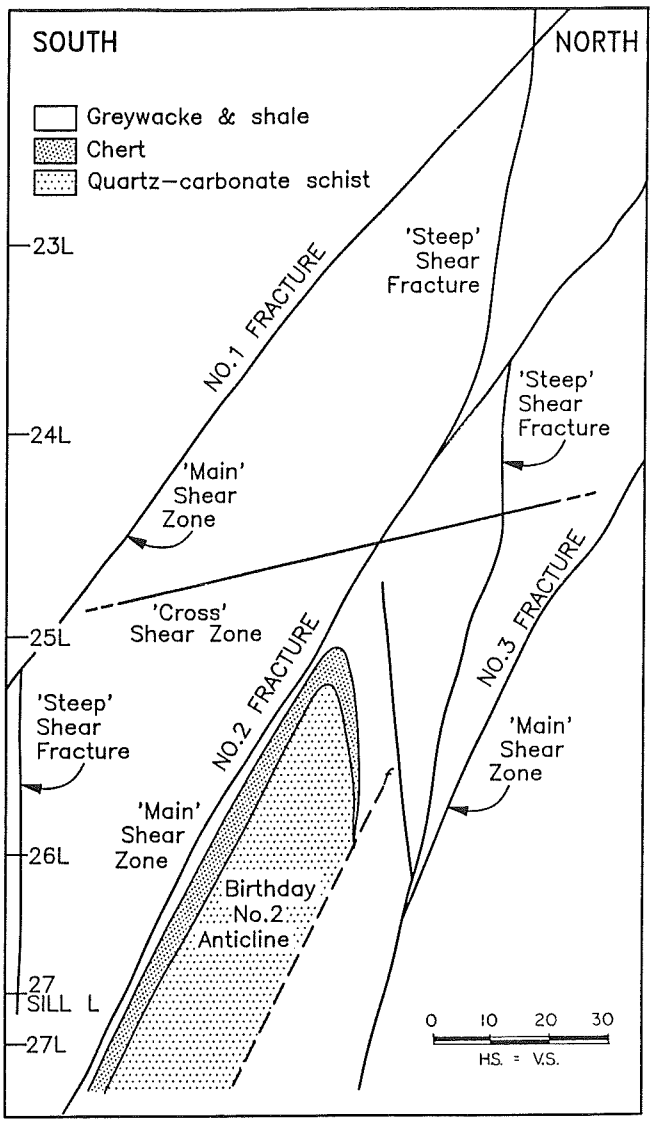

Figure 4: Cross-section through the Main Reef Complex, Sheba Mine.

Main Shear Zones

The Main shear zones comprise a central, narrow, shear zone up to 70 cm wide with a strike length up to 240m and smaller subparallel and anastomosing shear fractures collectively forming a zone 2 to 10 m wide. An example of detailed mapping showing many of the shear zone characteristics is presented as Figure 5. Within the shear zone, the subsidiary anastomosing shear fractures typically occur as conjugate sets. The central shear zone comprises a mélange of schistose shale with vugs and stringers of quartz, carbonate and ubiquitous pyrite forming a friable mass (Figs. 5 and 6). This zone of brittle-ductile deformation is characterized by a prominent crenulated schistosity. Boudinaged and intrafolial folded remnants of chert and quartz-carbonate vein material are ubiquitous and are deformed by the phase of ductile deformation as the foliation wraps around them (Fig.5). Deformation in the shear zones is accompanied by an increased carbonate content in the greywacke and shale components, with the more permeable greywacke containing up to 70%

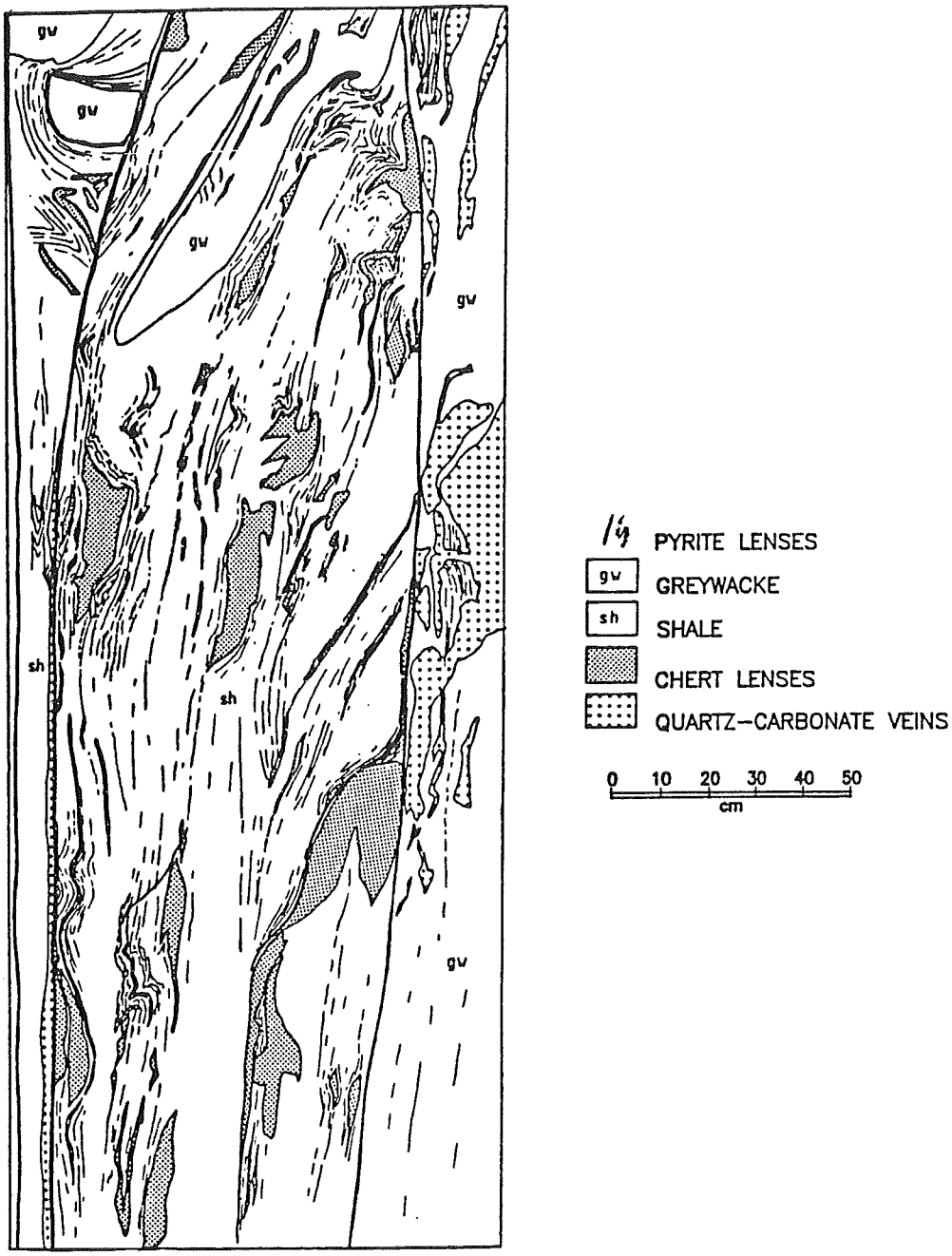

Figure 5: Sidewall map of part of the Main No. 2 shear zone as exposed in a cross section on 27 Sill Level, MRC. The zone of ductile deformation comprises schistose shale and attenuated and folded quartz-carbonate veins. Brittle fractures bound the zone of ductile deformation and cut across the schistosity within the zone. The shear zone dips 66° on 130°.

siderite and ferroan dolomite. A characteristic feature of these shear zones is that brittle fractures bound the zone of ductile deformation (Figs. 5 and 6) and persist along the entire length of the shear zone. The schistosity which is clearly evident in the zones of ductile deformation is truncated by these subsequently developed brittle fractures. Quartz-carbonate vein material fills the narrow fractures, usually by multiple stages of in-filling and, characteristically, sub-horizontal slickensides are commonly developed on graphitic fracture surfaces. These Main shear zones horsetail at their terminations and individual fractures display evidence of a more brittle behaviour and are in-filled with quartz and carbonate. A notable decrease both in sulphide and gold content occurs in the termination zone.

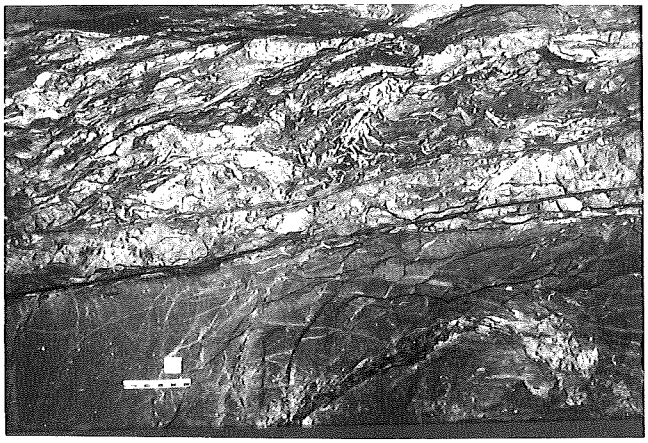

Figure 6: Main No. 2 shear zone comprising intensely deformed shale bounded by brittle, vein-filled fractures. Locality, 26 Level, MRC.

Steep Interconnecting Shear Zones

This set of shear zones occurs as steep, southerly dipping shears which interconnect with the Main shear zones (Fig.4). Deformation within the Steep shear zones is mainly restricted to a narrow, 3 to 10 cm wide, zone comprising schistose shale and narrow, subparallel, quartz-carbonate veinlets developed parallel to the walls of the shear zone. A lithological control on shear zone development is evident. Where the shear zone passes through massive greywacke it is typically narrow and comprises mainly vein material. In contrast, the shear zone is relatively wider in shale units, and drag effects are evident along shear zone boundaries where material is incorporated into the shear zone.

Shallow-dipping Cross Shears

A set of relatively shallow, southerly dipping shear zones is developed at a high angle to the Main shears and to bedding (Fig.4) and has strongly influenced the structure and mineralization in the MRC. The Cross shears differ from the Main shears in terms of morphology and style of mineralization. On both a mine and stope scale, the Cross shear

fractures undulate, split-up and in places occur subparallel to a well-developed joint set. The Cross shear zones range from 2 to 30 cm in width and consist predominantly of coarsely crystalline vein material which is usually zoned with quartz cores and carbonate rims. A common feature within these shear zones is the occurrence of small fragments of greywacke and shale which display a well-developed schistosity and occasionally are well mineralized. Drag effects of the wall-rock are observed along the shear zone boundaries and a chloritic alteration halo results in a slight olive-green discolouration of the wall-rock greywackes. In contrast to the Main shears, which are generally sub-parallel to bedding, the Cross shears crosscut the greywacke-shale bedding at approximately 70°. The intersection of the Cross and Main shear zones results in a zone of increased deformation and structural complexity. The resulting lines of intersection between these shear zones plunge at between 20° and 50° towards the east and northeast (Fig.7) and are of major importance in defining the geometry of the ore shoots.

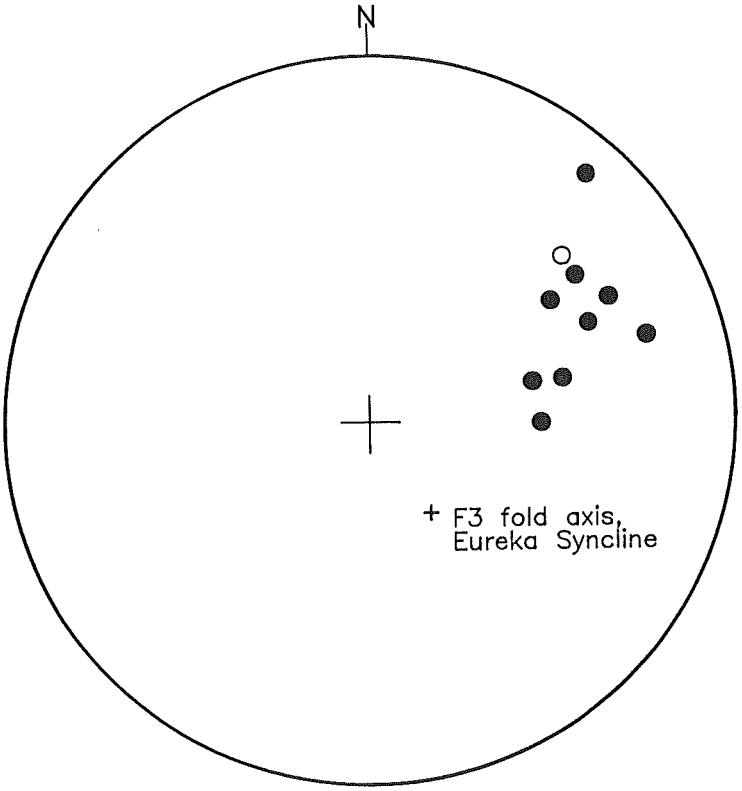

Figure 7: Stereoplot of the lines of intersection between Main and Cross shear zones. The average ore shoot orientation is shown by the open circle. Schmidt net, lower hemisphere projection.

Geometric Data on Shear Fractures

Within the Main shear zones, the majority of individual shear fractures are subparallel and dip between 40° and 70° to the southeast (Fig.8). However, a number of the shear fractures dip steeply to the southwest and west. Although not apparent in this composite plot, stereoplots constructed for fracture data for each mine level clearly indicate the conjugate nature of the shear fractures. Steeply orientated shear fractures are common and vary in orientation with a large number dipping to the northwest and west (Fig.8). In addition, the set of extensional Cross shear fractures dip at 30° to 40° to the northeast,

although they frequently undulate along strike resulting in a wide distribution of polar plots (Fig.8). These shear fractures are well correlated between mine levels and in plan transect the Main shear zones at approximately 50°.

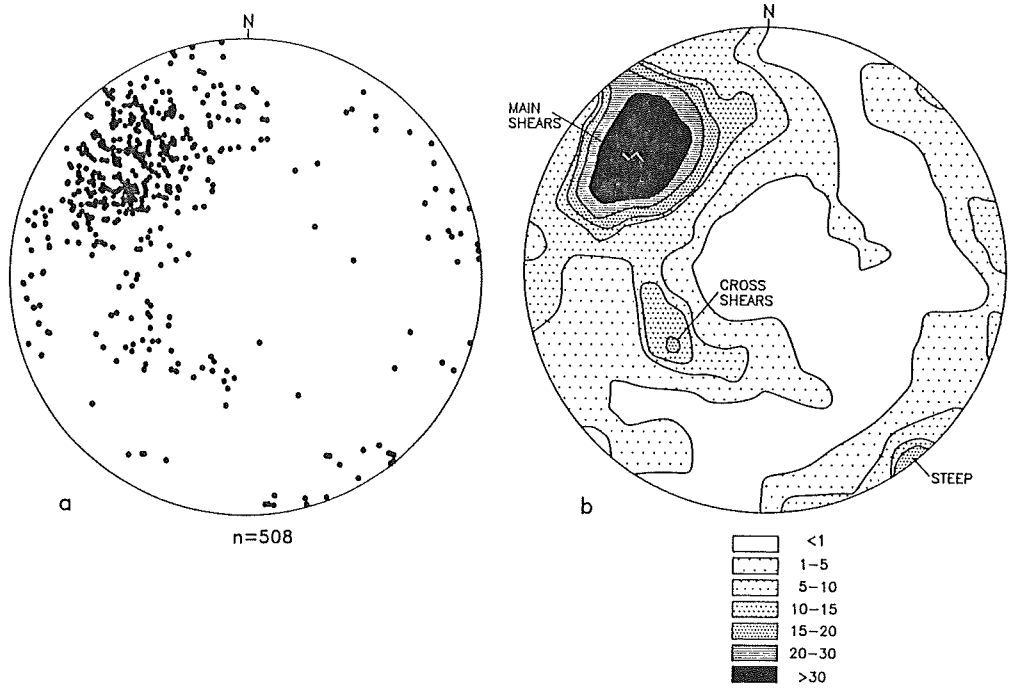

Figure 8a. Poles to shear fractures (n = 508), Levels 25-28, MRC. Schmidt net, lower hemisphere projection.

8b. Composite contour plot of the above data. Contours 1, 5, 10, 15, 20, and 30% per 1% area.

STRUCTURE OF THE ORE ZONES

Mineralization within the MRC was originally considered to be developed as a broad tabular zone surrounding the Main No.2 shear zone (Fig.4). This study has revealed, however, that the ore body comprises at least nine en échelon ore shoots which plunge consistently at 32° on 050° (Fig.7).

This is depicted in a three dimensional projection of the MRC from 25 to 28 Levels as Figure 9. Construction of this projection is based on detailed structural mapping carried out at a scale of 1:200 for each mine level. An accurate representation of the grade distribution over the five mine levels was achieved by plotting and contouring approximately 6000 gold values from development sampling carried out every 2m along the strike of the orebody. By combining the assay data with the structural data, large-scale structural controls on mineralization are evident. Zones of high-grade gold mineralization associated with areas

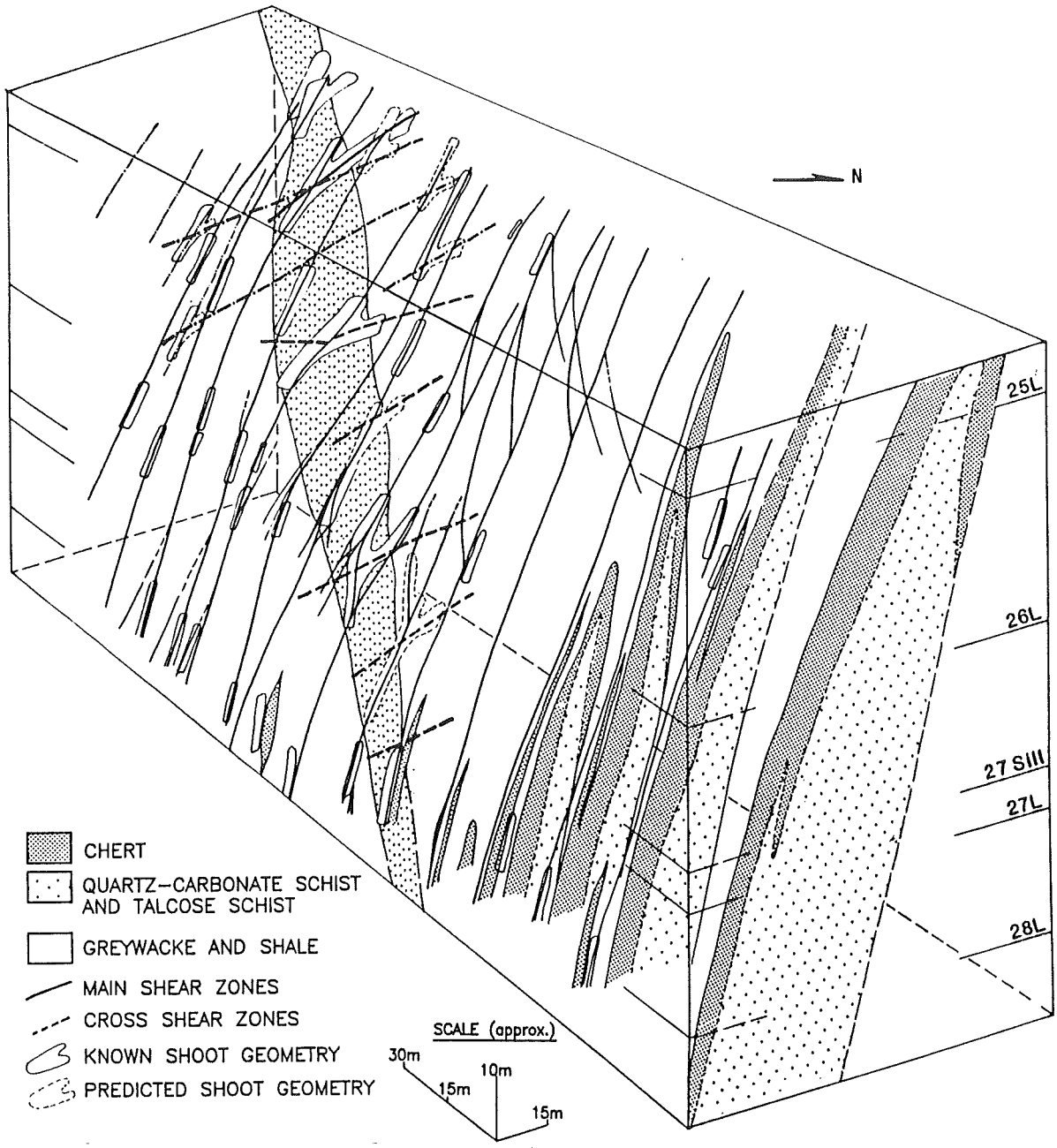

Figure 9: Schematic block diagram showing the three-dimensional projection of the Main Reef Complex from 25 to 28 Level. The Birthday No. 2 anticline plunges steeply to the southwest, the southern limb of this fold forms the locus for the development of the No. 2 Main shear zone. The intersection of the Main and Cross shear zones defines the orientation of the ore shoots in the MRC. A typical ore shoot which plunges to the northeast is indicated by ornamentation. Orientation data for various ore shoots are presented in Figure 7.

of arsenopyrite and pyrite enrichment can be traced from level to level through the MRC. The ore zones are clearly defined as a halo of high-grade mineralization which occurs at the

intersection of the Main and Cross shear zones and which extends up to 30m from the intersection along the shear zones forming a 3-pronged zone of enrichment. The mineralization halo extends up to 5m on either side of these shear zones and, in places, follows smaller fractures which splay from these zones. On a stereoplot, the average ore shoot orientation coincides with a plot of linear intersections between the Main and Cross shear zones (Fig.7). The Steep interconnecting shear zones do not appear to have any significant control on the distribution of high-grade mineralization. An examination of the geometry of individual ore shoots from level to level in the mine indicates that whereas some shoots tend to narrow others tend to broaden with depth.

Mineralization.

Gold mineralization occurs in the form of haloes along the three Main shear zones and the shallow-dipping Cross shear zones. These haloes are up to 5m wide on either side of the Main shear zones but are more sporadically developed along the Cross shears. The mineralization associated with the steep interconnecting shear zones is sub-economic. Within the preferentially mineralized ore shoots, the mineralization is controlled by local structures such as cleavage, folds and also by host lithology. Two styles of mineralization are observed, namely a disseminated stratabound type which occurs in the wall-rocks to the shear zones and which predominates over a second type which comprises vein-hosted sulphides. Gold is mainly associated with the stratabound type where it occurs in conjunction with abundant arsenopyrite and pyrite.

Well-mineralized host-rocks constitute finely interbedded greywacke and shale showing abrupt changes in sedimentary grain size. Arsenopyrite is almost exclusively restricted to greywacke and coarse-grained laminae within shale units, where it forms disseminated, euhedral, acicular crystal forms, typically occuring in small clusters. Pyrite is largely restricted to black shale units and to coarser layers rich in ferroan dolomite and siderite. A strong lithological control on mineralization is thus indicated. Although normally disseminated, arsenopyrite and pyrite may also form semi-massive layers within the ore shoots.

Structural controls to mineralization are indicated by mineralized en échelon veins occupying dilated cleavage planes which crosscut the bedding at 40° to 60° (Figs.10 & 11). Sulphide replacement fronts emanating from these veins and from hairline fractures parallel to the veins can be traced outwards along the bedding (Fig.12). In particular, where the veins contain semi-massive arsenopyrite and crosscut thick greywacke beds, the greywacke contains a high proportion of disseminated arsenopyrite. The replacement fronts are often asymmetrically developed about the fracture (Fig.12). Where veins and hairline fractures occur in close proximity, the replacement fronts intertongue producing long continuous bands of sulphide. No evidence exists for overprinting relationships between stratiform and cleavage-parallel mineralization.

In contrast with the Main shear zones where the associated mineralization is notably disseminated in the wall-rocks, the Cross shear zones are characterized by locally developed zones of high gold grades associated with the abundance of arsenopyrite. Arsenopyrite forms

Figure 10: Typical strata-controlled replacement mineralization from an ore shoot on 25 Sill Level. Pyrite is mainly confined to shale beds whereas arsenopyrite is confined to greywacke beds. En échelon pyrite veins occupy the dilated cleavage planes which are orientated at a high angle to bedding.

Figure 11: Specimen of high-grade mineralization from an ore shoot on 25 Sill Level. Pyrite is mainly confined to shaley beds in the left part of the specimen and arsenopyrite to greywacke beds in the right side of the specimen. Strata-controlled mineralization is inclined to the left. Arsenopyrite and pyrite also occur as bands along dilated cleavage traces and fractures, inclined to the right in the specimen. Note the occurrence of a small fold of pyrite at the bottom left of the specimen.

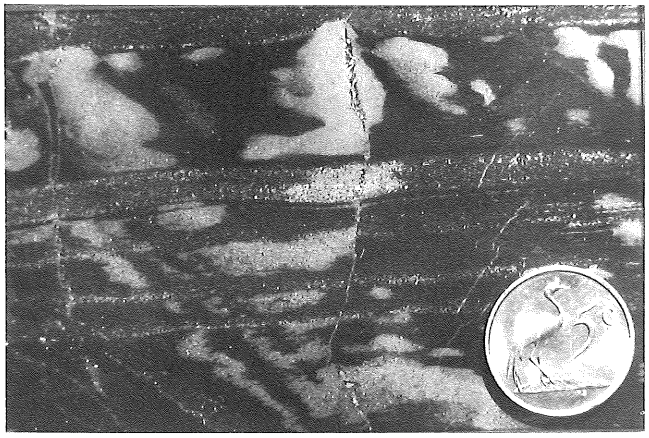

Figure 12: Strata-controlled replacement pyrite mineralization. Note that the asymmetric pyrite blooms that replace bedding can be traced from mineralized cleavage planes in the lower half of the photograph and from small fractures in the upper half.

semi-massive clusters in the quartz-carbonate vein material and as a replacement phase in greywacke fragments incorporated within the vein material. Pyrite is ubiquitous within all quartz-carbonate veins where it occurs as single euhedral crystals and as aggregates. Outside of the mineralized ore shoots pyrite occurs within greywacke as rounded aggregates of subhedral to euhedral crystals forming a characteristic spotted pattern and is not associated with economic gold mineralization. Arsenopyrite, however, is mainly confined to the shear zones.

Ore Paragenesis

Mineralization took place in a number of stages. Microscopic investigations indicate at least four stages of pyrite and two stages of arsenopyrite growth, shown as a paragenetic sequence in Figure 13. The first stage of pyrite growth is characterized by sieve-textured, "spongy" pyrite which is overgrown by a relatively void-free phase, both forming subhedral to euhedral crystals. This pyrite is spatially associated with minor structures such as cleavage planes and other small fractures and occurs as replacement phases along bedding planes. Minor sulphides and gold introduced towards the end stages of spongy pyrite growth predates the pyrite overgrowths. Minor chalcopyrite, pyrrhotite, sphalerite, pentlandite and gold preferentially filled the larger voids near the edges of spongy pyrite grains and were also deposited along the boundary between the two pyrite phases (Fig.14). Arsenopyrite postdates the spongy pyrite and is poikilitically enclosed as small euhedra within the second-stage pyrite. It is coeval with the pyrite overgrowths and continued to grow as larger euhedral crystals after cessation of pyrite growth. This stage represents the main phase of arsenopyrite mineralization with the euhedral acicular forms comprising 50 percent of the sulphides in the orebody. This arsenopyrite contains considerable submicroscopic gold (Schouwstra, 1985; Schouwstra and De Villiers, 1988). A second stage of arsenopyrite overgrew the pyrite and was also deposited along fractures in pyrite. Overgrowth textures are defined by anhedral arsenopyrite enveloping earlier pyrite and to a lesser extent by euhedral arsenopyrite growing on pyrite surfaces. Sphalerite was again introduced during

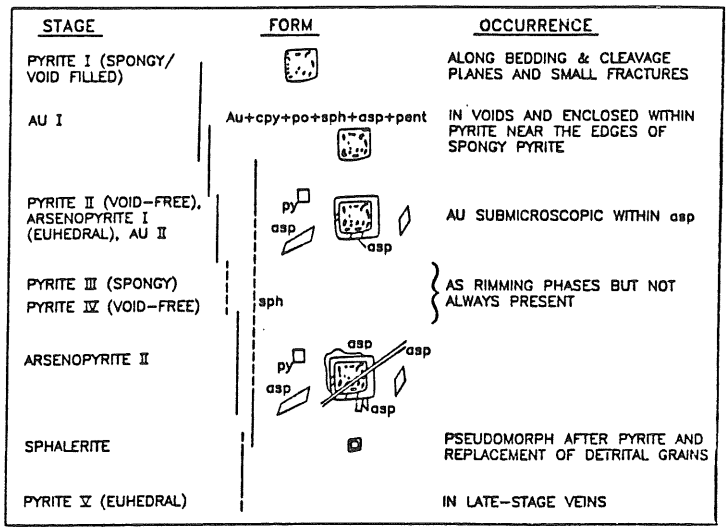

Figure 13: Paragenetic sequence of ore mineral deposition based on samples examined from the MRC.

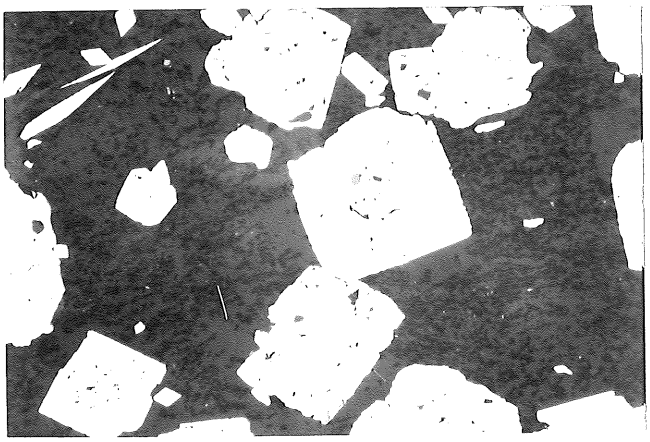

Figure 14: Euhedral to subhedral pyrite with clear rims enclosing spongy cores comprising chalcopyrite, pyrrhotite and sphalerite. Gold occurs with these minerals in the core filling larger voids and also in microscopic voids and cracks near the edges of the spongy pyrite. Note the occurrence of acicular arsenopyrite at the top left.

the late stages of the ore mineral paragenesis as it is disseminated throughout the mineralized rocks, partially replacing euhedral and round pyrite grains. A late-stage void-free, euhedral pyrite is found in late-stage quartz-carbonate veins which commonly crosscut stratabound mineralization.

Structural Controls on Mineralization

Both lithology and structure played a major role in the control and distribution of sulphides and gold. Differences in the style of mineralization reflect the influence of the host-rock during the mineralization event. This is most clearly evident where pyrite is concentrated in the more iron-rich shale and arsenopyrite in the greywacke (Fig. 15). In addition, lithological competency contrasts controlled the siting of bedding-parallel shear zones and fractures, influencing the setting for mineralization. On a large scale, this is evident where the No.2 Main shear zone is, in part, preferentially developed along the southern limb of the Birthday No.2 Anticline (Fig.4). This mineralized shear zone is developed along or close to the contact between the more competent Onverwacht cherts and less competent Fig Tree greywacke and shales. On a smaller scale, subsidiary shear zones are generally confined to the less competent shale units which cap individual turbiditic cycles in the Fig Tree stratigraphy. Within these cyclic units, deformation effects increase upwards with a corresponding increase in quartz-carbonate-pyrite vein material (Fig.15). The most intense deformation effects and veining are associated with the black shale beds.

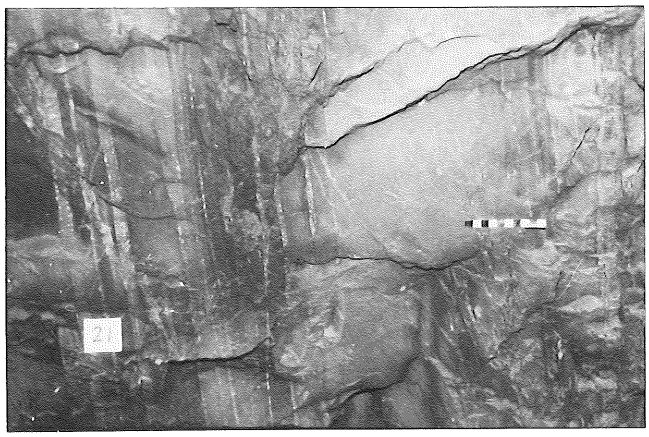

Figure 15: Preferentially sheared and carbonatized greywacke and shale. The coarser-grained greywacke contains more carbonate than the shale. The latter, relatively more incompetent shale, has acted as a locus for ductile deformation.

Stratabound mineralization accounts for most of the sulphides and occurs in association with narrow cross-cutting veins and fractures and within dilated cleavage planes (Figs. 10 & 16). The dominant cleavage is orientated at approximately 45° to bedding and shear zones and corresponds to the dilation plane of the strain ellipse for right lateral strike-slip movement along this shear zone (Fig.16).

Replacement-type pyrite and arsenopyrite mineralization in shear-related folds is traceable around fold hinges in beds which range from 1mm to 50 cm in thickness. A hand specimen illustrating folded sulphide layers related to progressive shear deformation is shown in Figure 17. Detailed mapping indicates that pyrite is restricted to folded shale beds and

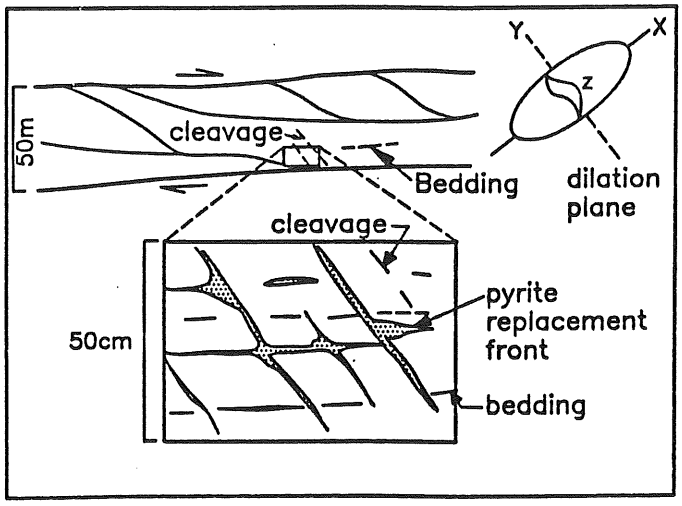

Figure 16: Schematic diagram showing dilation of cleavage planes which are favourably orientated with respect to the dilation plane of the strain ellipse in a right lateral shear system. Sulphide replacement fronts move out along bedding planes from the dilated cleavage planes.

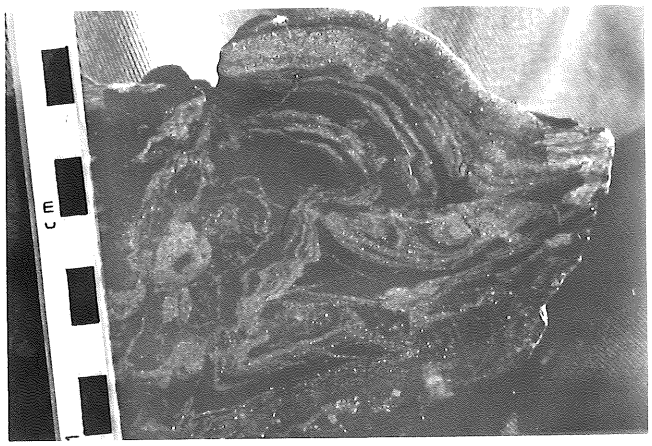

Figure 17: Folding and deformation of sulphide layers comprising arsenopyrite and pyrite.

assumes a uniform thickness, whereas arsenopyrite is confined to greywacke and is concentrated towards the fold closures with some fold closures containing arsenopyrite injection structures (Fig.18). Sulphide mineralization, in some instances, is also concentrated along axial planar cleavages of these shear-related folds. Examples of open-space filling include quartz-pyrite filled, sigmoidal, en échelon, tension gashes developed under lateral movement (Fig.19).

Figure 18: A deformed and mineralized fold within a ductile shear zone. The fold consists of deformed quartz and sulphide material which acted as a more competent block within the surrounding shale. Locality, 26 Level, MRC.

Figure 19: Pyrite-filled en échelon tension gashes showing a concentration of pyrite in the low pressure areas. Locality, 26 Level, MRC.

The recognition that mineralization is preferentially concentrated at the intersections of the Main and Cross shear zones to form the prominent and consistently orientated ore shoots (Fig.9), is clear evidence of the structural control on mineralization. The highest gold grades recorded are associated with areas of intense fracturing, folding and veining characteristic of these intersection zones. In particular, zones of anastomosing fractures, where smaller fractures splay-off and rejoin the Main shear zone, are associated with anomalously high sulphide contents and gold values. In addition, local fracture confluences are common sites for improved mineralization, particularly with respect to arsenopyrite. Both

the major intersection zones and the minor fracture confluences reflect zones of greater structural permeability allowing greater fluid penetration resulting in a direct correlation between the degree of mineralization and intensity of fracturing. Evidence for progressive deformation during and subsequent to mineralization is provided by the common occurrence within shear zones of mineralized tectonic clasts and blocks surrounded by barren schistose shale and greywacke material (Fig.18). In some instances the blocks containing the stratabound mineralization have been rotated in the shear zone. Furthermore, semi-massive sulphides are locally folded and attenuated and are indicative of ductile deformation processes. These deformation effects are typically developed in the Cross shear zones. In addition to sulphide deformation, microscopic investigation of associated quartz and carbonate crystals forming vein material in the Cross shears show undulose extinction, kink-banding, and subgrain formation.

Petrographically, the ore minerals show minor deformation textures such as fractures in pyrite, quartz pressure shadows around pyrite and microboudinage of acicular arsenopyrite crystals. Durchbewegung textures, indicative of penetrative deformation by fracturing and brecciation are recorded in semi-massive pyrite. Similar metamorphic textures of stratabound ores from Fairview, Sheba and Consort Mines have been described by Maiden (1984).

Geomechanical Interpretation of the Deposit

The structural setting and geometry of the shear zones and associated fractures are important to understanding the mechanisms of emplacement and relative timing of the mineralization. The Sheba Fault originated as a subhorizontal or low-angle thrust fault early in the history of the greenstone belt (Daneel,1987; Robertson, 1989; Tomkinson and King,1991) and was later reactivated during post-Moodies deformation during the emplacement of the Kaap Valley tonalite, Nelspruit batholith and the Stentor pluton. During progressive deformation and arcuation of the post-Moodies folds (viz. Eureka and Ulundi Synclines) against the Kaap Valley tonalite, the Sheba Fault underwent strike-slip movement. Evidence for right lateral movement has been documented by Visser et al. (1956), Anhaeusser (1965) and Robertson (1989).

The pattern of fracture zones which occur on both sides of the Sheba Fault (Fig. 2) is typical for a strike-slip model with the Shear Fault representing the principal displacement shear and the mineralized shear zones representing second and third order structures. Rose diagram plots for the shear fractures from each mine level mirror this pattern (Fig.20). Throughout the MRC there is little change in the inferred maximum principal compressive stress. The maximum principal stress, defined as the bisector of the angle between the R and R′ shears (Hancock, 1985), has a consistent west-northwest to east-southeast trend (Fig.20). The sets of en échelon shears correspond to those predicted in the revised summary model of Hancock (1985) and indicated in Figure 20 (insert). The right lateral movement recorded on the Sheba Fault (Anhaeusser, 1984) corresponds to a right lateral movement on the R, P and Y shears (Robertson, 1989). The Main shear zones correspond to Y-shears, whereas the conjugate shear fractures associated with them correspond to R and P shears. Together these shear fractures form the typical braided pattern of a strike-slip zone. The Cross shear zones correspond to the high-angle antithetic (R′) shears, and as predicted in the model have a left lateral shear sense and are more extensional structures than the R, P and Y shears. The shear

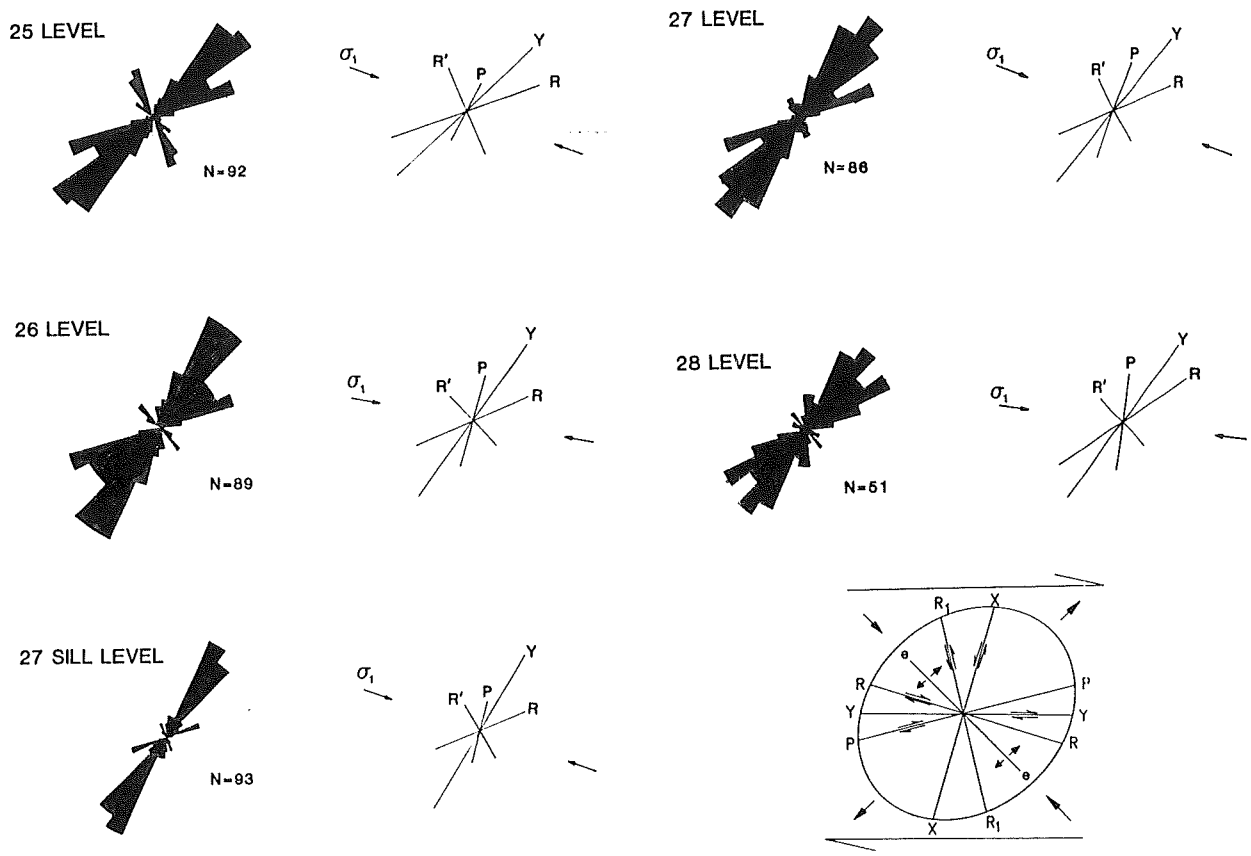

Figure 20: Rose diagram plots of the shear-fracture trends from 25 to 28 Levels, MRC. The right hand diagrams, in each case, represent the interpretation of the measured data. Insert shows the theoretical array of shear fractures from the summary model of Hancock (1985).

zones in the MRC represent a second to third order fracture geometry where the Nos. 1, 2 and 3 Main shear zones are considered to represent the principal displacement shears. This would be analagous to the Riedel- within- Riedel model of Tchalenko (1970). Most gold mineralization is, therefore, associated with second and third order structures which were active towards the end of post-Moodies deformation.

The MRC is characterized by brittle-ductile shear zones typical of vein-type gold deposits in greenstone belts elsewhere (Colvine et al.,1984, 1988; Cox et al.,1986, 1991; Harris,1987; Hodgson,1989; Roberts, 1987). Within the MRC, thick shale units preserve subvertical lineations on bedding subparallel shears, indicative of thrust movement. The ductile fabric in the shale is truncated by shear fractures on which lineations range from horizontal to moderately plunging orientations. On a stereographic projection (Fig.21), these lineations plot in a broad band coinciding with the cyclographic trace of the dominant shear zones. The transition from thrusting to strike-slip movement is viewed as a function of progressive deformation. Such a transition is by no means unusual; for example Kerrich and Allison (1987),in a study of vein geometry and mineralization in the Yellowknife greenstone

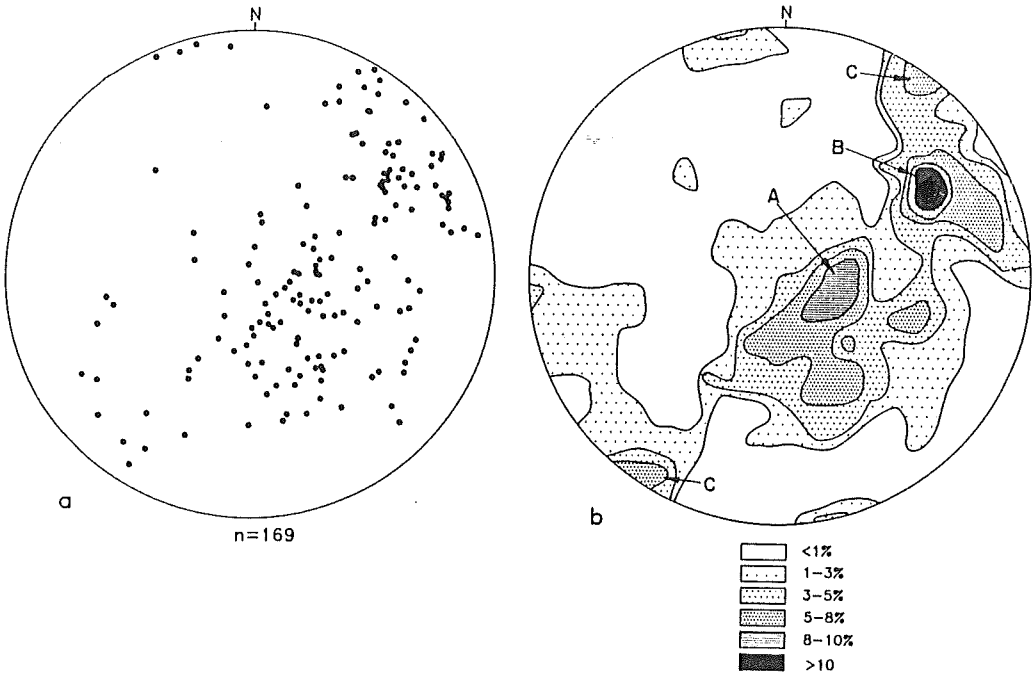

Figure 21: *a. Stereoplot of slickenside lineations (n = 169) from 25 to 28 Level. Schmidt net, lower hemisphere projection.*
b. Contoured plot of the above data, three distinct populations evident in the field data are indicated (i) a set of subvertical lineations, A, (ii) a set of shallow-dipping lineations, B, and (iii) a set of subhorizontal lineations, C. Contours: 1, 3, 5, 8 and 10% per 1% area.

belt of Canada,also record an early period of thrusting during ductile deformation which was postdated by a brittle deformational event involving fracturing and the introduction of vein material.

According to Tchalenko (1970), in a shear system formed under progressive deformation, the Riedel shears R and R$^{/}$ form and propagate in an en échelon manner during peak strength. Restraining P shears develop in a thrust attitude after peak strength and principal displacement shears characterize the shear zone towards residual strength. In the MRC, the progressive development of the shear zones is indicated by the fact that no direct offsetting occurs in the intersection zones; rather the Main and Cross shear zones change in orientation as they converge towards one another, with the latter flattening out considerably.

Evolution of Fluids

Gold was transported in an arsenic-sulphur-bearing fluid that contained small amounts of copper and antimony (Schouwstra, 1985; Schouwstra and De Villiers, 1988). According to these authors, gold deposition in the MRC took place at a temperature in the range 300° to 500° C. The formation of the shear zones was continuous and the evolution of the fluids

progressive through the later stages of shear zone development. Similar conclusions have been advocated for similar deposits, e.g. Guha et al. (1983) for the Henderson 2 Mine, Quebec. During the early compressive thrust event, fluid movement was restricted as shown by narrow, boudinaged quartz veins, whereas the evolution to strike-slip faulting resulted in dilation- contraction phenomena and the ingress of fluids. Most of the quartz-carbonate-pyrite veining is associated with later fracturing and, thus, it is inferred that the mineralizing fluids were channnelled through these fractures during the late stages of post-Moodies deformation. At this time, second-order strike-slip structures were evolving throughout the mine area and fluids utilizing the Sheba Fault as a pathway were concentrated in these minor structures. It is envisaged that fluid movement was controlled by seismic pumping where fluid movement and hence mineralization took place episodically resulting in the paragenetic sequence shown in Figure 13. These fluid pulses were probably concomitant with increments of shear displacement along the shear fractures (see Sibson et al., 1975). Field evidence to support this assertion is in the form of zoned polyphase quartz-carbonate veins and the multiple stages of ore mineral growth. Fluids were ultimately concentrated in late-stage structural traps during the progressive development of these second to third-order shear zones. Cox et al. (1986) have also drawn attention to the fact that many vein-hosted deposits are developed along relatively small, discontinuous and easily sealed fault and fracture zones. In these second and third-order fracture zones permeability seals are formed, promoting the build-up of supralithostatic fluid pressures, fracturing and subsequent deposition of sulphide material. In contrast, larger first-order regional fault structures, such as the Sheba Fault, tend to have a high fracture permeability and would be leaky structures.

CONCLUSIONS

The MRC at Sheba Mine is a typical Archaean lode gold deposit, formed during late-stage reactivation of the Sheba Fault as a strike-slip fault. The shear zones hosting mineralization were developed largely along zones of high competency contrast. The geometry of the shear zones conforms to that predicted for a region undergoing strike-slip deformation.

Mineralization is dominantly of strata-controlled replacement type and shows a strong lithological and structural control. Mineralization is syn- to late- tectonic and took place in an environment of progressive deformation. This is evident from:

1) Open-space filling of tension gashes and sigmoidal arrays;

2) The dilation and infilling of cleavage planes by quartz, carbonate and sulphide minerals;

3) Deformation within shear zones, of blocks containing pre-existing strata-controlled mineralization; and

4) Deformation of sulphide minerals and all stages of quartz-carbonate veins.

The distribution of gold and sulphides occur preferentially in minor structures towards the end stages of strike-slip deformation. It is of interest to note that the Sheba Fault is poorly mineralized, as are also, to a lesser extent, the second order Main shear zones. It is clear that mineralization moved out from all of the major channelways and was finally concentrated in higher-order, small-scale, structural traps towards the end stages of progressive deformation.

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REFERENCES

Anhaeusser, C.R. 1965. Wrench faulting and its relationship to gold mineralization in the Barberton Mountain Land. Inform. Circ. Econ. Geol. Res. Unit, Univ. Witwatersrand, Johannesburg, **24**, 20 pp.

Anhaeusser, C.R. 1976. The geology of the Sheba Hills area of the Barberton Mountain Land, South Africa, with particular reference to the Eureka Syncline. Trans. Geol. Soc. S. Afr., **79**, p. 253-280.

Anhaeusser, C.R. 1986. Archaean gold mineralization in the Barberton Mountain Land. *In:* Mineral Deposits of Southern Africa, vol.1, p. 113-154. *Edited by* C.R. Anhaeusser and S.Maske. Geol. Soc. S. Afr., 1020 pp.

Colvine, A.C., Andrews, A.J., Cherry, M.E., Durocher, M.E., Fyon, A.J., Lavigne, M.J., MacDonald, A.J., Marmont, S., Poulsen, K.H., Springer, J.S. and Troop, D.G. 1984. An integrated model for the origin of Archaean lode gold deposits. Ontario Geol. Surv., Open File Rep. 5524, 98 pp.

Colvine, A.C., Fyon, J.A., Heather, K.B., Marmont, S., Smith, P.M. and Troop, D.G. 1988. Archean lode gold deposits in Ontario. Ontario Geol. Surv., Miscellaneous Paper **139**, 136 pp.

Cox, S.F., Etheridge, M.A. and Wall, V.J. 1986. The role of fluids in syntectonic mass transport and the localization of metamorphic vein-type ore deposits. Ore Geology Reviews, **2**, p. 65-86.

Cox, S.F., Wall, V.J., Etheridge, M.A. and Potter, T.F. 1991. Deformation and metamorphic processes in the formation of mesothermal vein-hosted gold deposits-examples from the Lachlan Fold Belt in central Victoria, Australia. Ore Geology Reviews, **6**, p. 391-423.

Daneel, G.J., 1987. The structural controls of gold mineralization in the Moodies Hills which surround the Agnes Gold Mine, Barberton Greenstone Belt. Unpubl. M.Sc. thesis, Univ. Natal, Durban, 129 pp.

De Ronde, C.E.J., Kamo, S., Davis, D.W., De Wit, M.J. and Spooner, E.T.C. 1991. Field, geochemical and U-Pb isotopic constraints from hyperbyssal felsic intrusions within the Barberton greenstone belt, South Africa: implications for tectonics and the timing of gold mineralization. Precambrian Res., **49**, p. 261-280.

De Wit, M.J., 1982. Gliding and overthrust nappe tectonics in the Barberton Greenstone Belt. J. of Struct. Geol., **4**, p. 117-136.

De Wit, M.J., Armstrong, R.J., Hart, R.J. and Wilson, A.H. 1987. Felsic igneous rocks within the 3.3 to 3.5 Ga Barberton Greenstone Belt: high crustal-level equivalents of the surrounding tonalite-trondhjemite terrain, emplaced during thrusting. Tectonics, **6**, p. 529-549.

Guha, J., Archambault, G. and Leroy, J. 1983. A correlation between the evolution of mineralizing fluids and the geomechanical development of a shear zone as illustrated by the Henderson 2 Mine, Quebec. Econ. Geol., **78**, p. 1605-1618.

Hall, A.L., 1918. The geology of the Barberton gold mining district. South Africa Geol. Surv. Memoir, **9**, 347 pp.

Hancock, P.L., 1985. Brittle microtectonics: principles and practice. J. Struct. Geol., **7**, p. 437-457.

Harris, L.B., 1987. A tectonic framework for the Western Australian shield and its significance to gold mineralization: a personal view. *In:* Recent advances in understanding Precambrian gold deposits, p. 1-27. *Edited by* S.E. Ho and D.I. Groves. Geology Department and University Extension Unit, Univ. Western Australia, Publ. 11, 368 pp.

Hodgson, C.J., 1989. The structure of shear-related, vein-type gold deposits: a review. Ore Geology Reviews, **4**, 231-273.

Kamo, S.L., Davis, D.W. and De Wit, M.J. 1990. U-Pb geochronology of Archean plutonism in the Barberton region, South Africa: 800 m.y. of crustal evolution. Geological Society of Australia, Abstracts, **27**, 53 pp.

Kamo, S.L. and Davis, D.W. 1991. A review of geochronology from the Barberton Mountain Land. *In:* Two Cratons and an Orogen - Excursion Guidebook and Review Articles for a Field Workshop through selected Archaean Terranes of Swaziland, South Africa and Zimbabwe, IGCP Project 280, p. 59-68. L.D.Ashwal (Ed.), Dept. Geology, Univ. Witwatersrand. 312 pp.

Kerrich, R. and Allison, I. 1978. Vein geometry and hydrostatics during Yellowknife mineralization. Can. J. Earth Sci., **15**, p. 1653-1660.

Lowe, D.R. 1982. Comparative sedimentology of the principal volcanic sequences of Archean greenstone belts in South Africa, Western Australia and Canada: implications for crustal evolution. Precambrian Res. **17**, p 1-29.

Lowe, D.R. 1991. Geology of the Barberton Greenstone Belt: An overview. *In:* Two Cratons and an Orogen-Excursion Guidebook and Review Articles for a Field Workshop through selected Archaean Terranes of Swaziland, South Africa and Zimbabwe, IGCP Project 280, p. 47-58. L.D.Ashwal (Ed.), Dept. Geology, Univ. Witwatersrand. 312 pp.

Maiden, K.J. 1984. Metamorphic features of stratiform gold ores in the Barberton Greenstone Belt, Eastern Transvaal. *In:* Gold '82: The Geology, Geochemistry and Genesis of Gold Deposits. R.F.Foster (Ed.), Geological Society of Zimbabwe, 754 pp.

Ramsay, J.G. 1963. Structural investigations in the Barberton Moutain Land, eastern Transvaal. Trans. Geol. Soc. S. Afr. **66**, p. 353-401.

Roberts, R.G. 1987. Ore deposit models No.11. Archean lode gold deposits. Geoscience Canada, Vol. 14, No.1, p.37-52.

Robertson, M.J. 1989. The structural geology and gold mineralization of the Main Reef Complex, Sheba Gold Mine, Barberton Greenstone Belt. Unpubl. M.Sc. thesis, Univ. Witwatersrand, Johannesburg, 127 pp.

Schouwstra, R.P. 1985. Kontroles van goudmineralisasie by die Sheba-goudmyn, Barbertondistrik. Unpubl. M.Sc. thesis, Rand Afrikaans Univ., Johannesburg, 15pp.

Schouwstra, R.P. and De Villiers, J.P.R. 1988. Gold mineralization and associated wallrock alteration in Main Reef Complex at Sheba mine, South Africa. Trans. Inst. Min. and Metall. (Sect.B: Applied earth science), 97, pp. B158-B170.

Sibson, R.H., Moore, J. McM. and Rankin, A.H. 1975. Seismic pumping - a hydrothermal fluid transport mechanism. J. Geol. Soc. London, **131**, p. 653-659.

South African Committee for Stratigraphy (SACS), 1980. Stratigraphy of South Africa. Part 1. *In:* Lithostratigraphy of the Republic of South Africa, South West Africa/Namibia, and the Republics of Bophuthatswana, Transkei and Venda: L.E.Kent (Compiler). Handbk. Geol. Surv. S. Afr., **8**, 690 pp.

Tomkinson, M.J. and Philpot, H.G. 1990. Fault bounded tectonostratigraphic units in the northern portion of the Barberton Greenstone Belt and evidence for more than one phase of greenstone belt development. Abstrs. Tectonics. Div. Geol. Soc. S. Afr. 6th. Ann. Conf., Pretoria.

Tomkinson, M.J. and King, V.J., 1991. The tectonics of the Barberton Greenstone Belt - an overview. *In:* Two Cratons and an Orogen - Excursion Guidebook and Review Articles for a Field Workshop through Selected Archaean Terranes of Swaziland, South Africa and Zimbabwe, IGCP Project 280, p.69-83. L.D.Ashwal (Ed.), Dept. Geol., Univ. Witwatersrand, Johannesburg. 312 pp.

Tchalenko, J.S. 1970. Similarities between shear zones of different magnitudes. Bull. Geol. Soc. Amer., **81**, p. 1625-1640.

Van den Berg, M.A. 1984. The geological setting of gold mineralization at the Sheba Mine. *In:* Archaean Gold, Barberton Centenary Symposium, Abstracts. and Guidebook. T.N. Pearton (Ed.), Geol. Soc. S. Afr., 93 pp.

Van den Berg, M.A. and Eaton, B.G. 1984. Sheba Mine tour guide. *In:* Archaean Gold, Barberton Centenary Symposium, Abstracts and Guidebook. T.N.Pearton (Ed.), Geol. Soc. S. Afr., 93 pp.

Van Eeden, O.R. 1941. Die geologie van die Shebarante en omstreke, distrik Barberton. Unpubl. D.Sc. thesis, Univ. Stellenbosch.

Viljoen, R.P. and Viljoen, M.J. 1969. The geological and geochemical significance of the upper formations of the Onverwacht Group. Spec. Publ. Geol. Soc. S. Afr., **2**, p. 113-151.

Visser, D.J.L., (Compiler), Van Eeden, O.R., Joubert, G.K., Söhnge, A.P.G., Van Zyl, J.S., Roussouw, P.J., Tajaard, J.J., Visser, D.J.L. 1956. The geology of the Barberton area. Spec. Publ. Geol. Surv. S. Afr., **15**, 242 pp.

Wagener, J.H.F. and Wiegand, J. 1986. The Sheba Gold Mine, Barberton Greenstone Belt. *In:* Mineral Deposits of Southern Africa, vol.1, p. 155-161. C.R. Anhaeusser and S. Maske (Eds.), Geol. Soc. S. Afr., 1020 pp.

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