

CRATONIC EXTENSION AND ARCHAEOAN GOLD MINERALISATION IN THE SHEBA-FAIRVIEW MINE, BARBERTON GREENSTONE BELT, SOUTH AFRICA

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ABSTRACT

Gold mineralisation in the world-class Sheba-Fairview mining district in the Barberton greenstone belt, South Africa, occurs along a fracture network that is arranged in overlapping Riedel, P-shear and anti-Riedel arrays on 10m and 100m scales. The mineralised fracture arrays overprint and fold the Sheba shear zone interpreted by previous workers as a major, strike-parallel thrust thought to have controlled mineralisation in the area. Our results indicate that mineralised structures did not result from movement on the Sheba shear zone, which is not a major thrust. Instead the Sheba shear zone is locally overprinted by the mineralised structures and reactivated as a sinistral normal fault. Mineralisation was accompanied by silicification and the emplacement of porphyries, and occurred after the ductile geometry of the greenstone belt was fully established, i.e. after the emplacement of late-tectonic, 3105 Ma potassic granites and associated doming and constrictional folding.

Kinematic analysis shows that the network of mineralising fractures formed in an extensional environment with σ_1 vertical and σ_3 orientated in a horizontal northwest to southeast direction. The stress regime was predominantly radial extensional, with σ_3 orientated at right angles to the long axes of the greenstone belt.

Greenstone hosted gold deposits such as the Sheba-Fairview deposits have been classified as orogenic gold deposits invoking a genetic link between mineralisation and compressional or transpressional, accretionary thrusts in a late tectonic environment likened to modern volcanic arcs. Our results suggest that mineralisation in the Sheba area formed in an extensional environment, related to structures that developed after cratonisation of the Kaapvaal Craton had occurred; i.e. the Archaean lode gold deposits at Sheba-Fairview mine are probably not related to orogenic processes linked to formation of the greenstone belt.

Introduction

Greenstone belts throughout the world are important sources of gold. Most Archaean greenstone belt gold occurrences have been classified tectonically as orogenic gold deposits (Groves et al., 1998; Goldfarb et al., 2001), but are referred to with a range of other names as well including lode gold, mesothermal gold, hydrothermal gold, shear-zone-hosted gold and quartz-carbonate vein gold. These names reflect the common association of orogenic gold deposits with shear zones, veining and low- to medium-grade metamorphic alteration within deformed and metamorphosed host rocks in active tectonic environments (Groves et al., 1998). Gold occurs as replacement-type mineralisation with quartz-carbonate-sulphide veins in lithologies of suitable composition and permeability. Orogenic gold deposits have been attributed to accretionary events in arc settings during the late stages of Cordilleran tectonics (e.g. Kerrich et al., 2000; Goldfarb et al., 2001; Groves et al., 2003; Groves et al., 2006; Bierlein et al., 2006). By grouping Archaean lode-gold deposits as orogenic

gold it is implicit that Archaean greenstone belts represent accretionary terrains; an interpretation supported by the common observation that orogenic gold deposits are spatially associated with secondary structures near major compressional and/or late-stage transpressional shear zones (e.g. Robert et al., 1991; Groves et al., 1998), which act as fluid pathways carrying mineralisation from greater depth.

The multi-staged nature of mineralisation in shear zones is commonly explained with a cyclic fault-valve model (Sibson, 2001; 2004). Impermeable rocks along the fault plane may act as barriers below which fluid-whole rock interaction is optimised to generate ore zones (e.g. Cox et al., 2001). Gold is trapped in complex arrays of dilatant, brittle-ductile structures interpreted as secondary structures to thrusts (e.g. Colvine et al., 1988; Robert et al., 1991), generally reactivated by subsequent strike-slip movement. During mineralisation, greenschist to amphibolite metamorphic conditions of 200 to 650°C and 1 to 5 kbar prevailed, with siliceous, carbonate and potassic alteration haloes, and a generally low salinity,

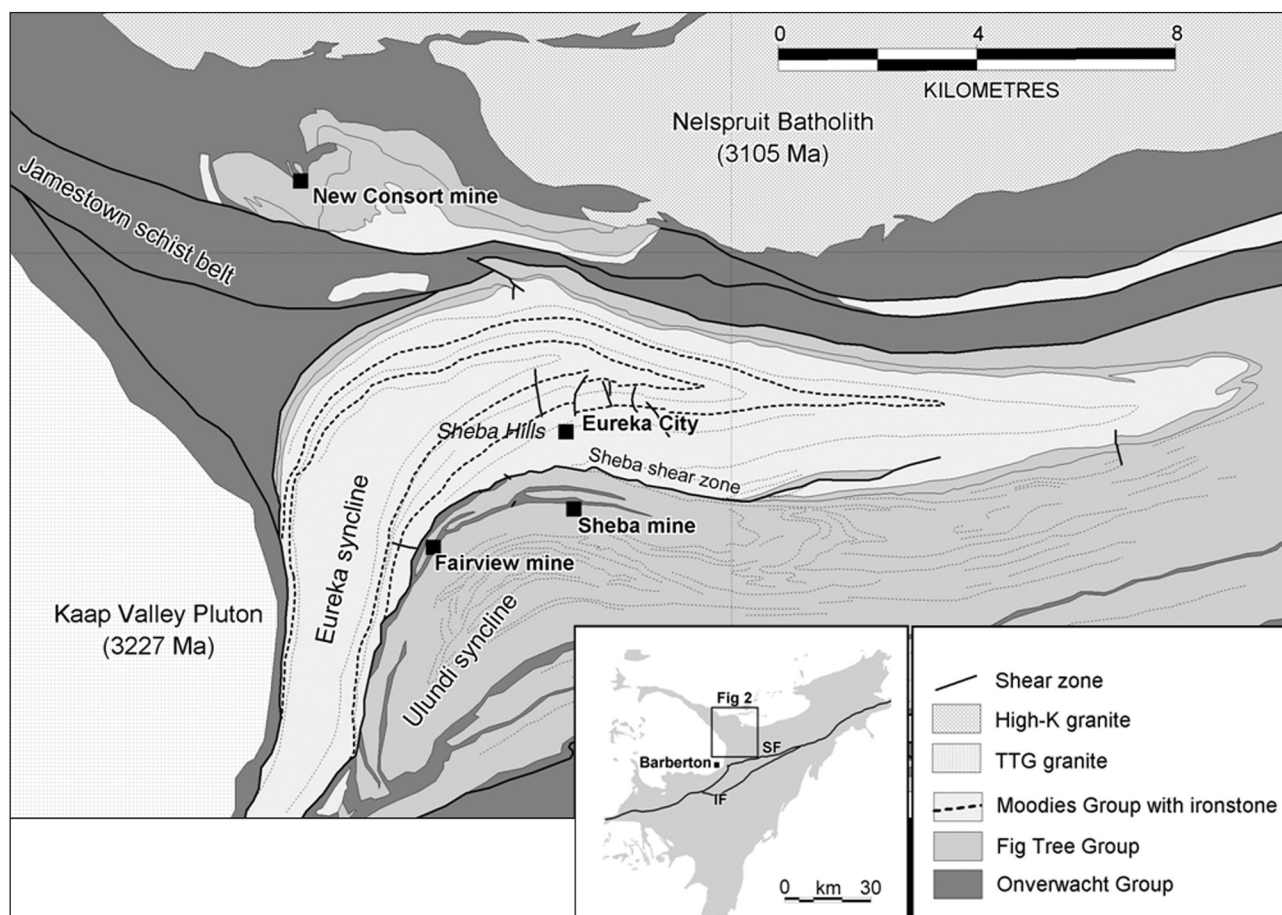


Figure 1. Geological map of the Sheba Hills area, Barberton greenstone belt, South Africa. The inset shows the extent of the greenstone belt and the position of the Saddleback (SF) and Inyoka (IF) faults.

CO₂ – rich mineralising fluid chemistry (De Ronde et al., 1992; Groves et al., 1998). The timing of mineralisation is generally syn- to late-tectonic and associated with late-stage accretionary events in volcanic arc type settings (De Ronde and De Wit, 1994; Groves et al., 1998; 2003; Goldfarb et al., 2001).

The strong emphasis placed in the literature on the link between Archaean orogenic gold deposits and large-scale accretionary thrusts has meant that many Archaean deposits including those in the Barberton Greenstone Belt (BGB) of South Africa are assumed to have formed in thrust-related accretionary environments (e.g. Ward, 2002). In the BGB, studies have been carried out on individual deposits concentrating on the mineralised fracture system at mine-scale (e.g. Anhaeusser, 1986; Voges, 1986; Wagener and Wiegand, 1986; Robertson et al., 1994; Otto et al., 2007; Dziggel et al., 2007). All these studies invoke a generic link between accretionary thrusts and mineralisation, but none demonstrates how mineralised fractures are related and interact regionally, and if they are indeed linked to the major thrusts in the belt. Almost without exception, there is a paucity of kinematic data recorded from mineralised shear fractures and nearby shear zones.

In this paper, we present for the first time a detailed study of the kinematics of mineralised gold-bearing shear fractures in the Sheba Hills that host the world-class Sheba-Fairview-New Consort Gold Mines (Figure 1). This study provides a significant insight into the structural controls of gold mineralisation and its timing in the tectonic development of the BGB and has implications for structural control on gold mineralisation in other greenstone belts.

Regional geological setting

The Barberton greenstone belt (BGB) represents one of the best preserved mid-Archaean supracrustal sequences in the world. The 40 x 120 km large belt consists of tectonically and stratigraphically interleaved, northeast-striking 3.55 to 3.22 Ga volcanic and clastic rocks surrounded by granite-gneiss domes ranging in age from 3.5 to 3.1 Ga (Lowe and Byerly, 2007; Figure 1).

The volcano-sedimentary sequence of the BGB has been subdivided into three lithostratigraphic units from bottom to top: the Onverwacht, Fig Tree and Moodies Groups (Brandl et al., 2006). The Onverwacht Group is composed of ultramafic to mafic volcanic rocks with minor felsic volcanic flows, tuff, and sediments, which formed in a shallow marine environment between

Table 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) and Anhaeusser (1976). To prevent confusion, the subscript "s" for 'Sheba' is added to the local deformation scheme of Anhaeusser (1976).

		Deformation Scheme		
Tectonic event description (after De Ronde and De Wit (1994))		De Ronde and De Wit (1994)	Lowe et al. (1999)	Ramsay (1963) and Anhaeusser (1976)
		Regional	South of Barberton Town	Sheba Hills
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 Cordillera-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
Terrain Accretion and deposition of coarse clastics, with collisional amalgamation followed by transcurrent faulting (3.26-3.16)	Deposition of Moodies Group Group sediments	Early D ₃	D ₃ Thrusting of Moodies onto Fig Tree D ₄ Folding of Moodies 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
Gold mineralisation; shift from transpression to transtensional deformation (~3.1 Ga)	Deposition of Moodies Group sediments	Late D ₃	D _{5c} Refolding	D _{3s} Refolding Eureka syncline with with dextral thrusting on Sheba fault followed by gold mineralisation
Strike-slip and normal faulting; emplacement of alkaline batholiths (~3.1 Ga)		D ₄		D _{4s} Formation of conjugate recumbent crenulation and chevron folds

3.55 Ga and 3.26 Ga (Byerly et al., 1996; Lowe and Byerly, 2007). The overlying Fig Tree Group consists of deep- to shallow-marine turbiditic greywacke, shale and mudstone interbedded with minor chert, banded iron formation (BIF) and felsic volcanic units, deposited in response to erosion of uplifted portions of older greenstone successions (Condie et al., 1970; Hofmann, 2005). Their age is bracketed by volcanics at their base and top dated at 3259 ± 5 Ma and 3225 ± 3 Ma respectively (De Ronde et al., 1991; Kröner et al., 1992). The volcanoclastic unit at the top of the Fig Tree Group is called the Schoongezicht Formation. The Moodies Group consists of shallow marine to fluvial sequences of conglomerate, quartzose to feldspathic sandstone and shale with minor BIF and volcanic units deposited after 3226 ± 1 Ma (Kamo and Davis, 1994). A minimum age

of deposition obtained from detrital zircon from Moodies sediment is ~3.16 Ga (De Ronde and De Wit, 1994).

Structural boundaries divide the BGB into tectonic domains across which the stratigraphy, age, depositional environment and deformation history of especially the Onverwacht and Fig Tree Group rocks change. A major one of these is the Inyoka-Saddleback fault (Figure 1) interpreted as an ~3.23 Ga suture zone (e.g. De Ronde and De Wit, 1994). Onverwacht Group rocks south of the Inyoka fault are 3.46 to 3.26 Ga in age and reach a stratigraphic thickness of perhaps 10 km, whilst mafic to ultramafic sequences north of the Inyoka fault are much thinner (< 1 km) and younger at 3.33 to 3.24 Ga (Lowe and Byerly, 2007). The Inyoka fault similarly divides the Fig Tree sediments into shallow water and alluvial greywacke sandstone of the southern facies, and deep-

water clastic rocks of the northern facies (Hofmann, 2005), whilst Moodies Group rocks tend to be coarser grained south of the Inyoka fault.

De Ronde and De Wit (1994) provide a tectonic summary for the evolution of the BGB and place the locally complex, polyphase deformation history of the belt in a simple deformation scheme with comparisons to modern plate tectonic settings (Table 1). Following the deformation scheme of De Ronde and De Wit (1994), the earliest events, D_0 , (3.49 to 3.45 Ga) represent alteration processes near oceanic volcanic spreading centres (ridges; <3460 Ma) and involved extension. Later (3.45 to 3.42 Ga) thermo-tectonic events, D_1 , involved subduction-like processes with emplacement of proposed ophiolite allochthons in intra-oceanic environments and emplacement of TTG plutons. A second phase of subduction-accretion, D_2 , between 3.26 to 3.23 Ga, likened to an Andean margin, was accompanied by inter-arc deformation and culminated in accretion of unrelated arc systems after ~3.23 Ga with the Saddleback-Inyoka fault system identified as the dominant suture. Convergence and accretion followed by post accretionary, transpressional events grouped as early- D_3 , continued between 3.23 to 3.13 Ga, and resulted in the northeasterly-trending map pattern of the BGB and the formation of strike parallel faults linked to gold mineralisation (De Ronde et al., 1991, Ward, 1999). Gold mineralisation occurred during late D_3 , between 3126 ± 26 Ma and 3084 ± 18 Ma (De Ronde et al., 1992) and marked a shift from transpressional to transtensional tectonics. Regional extensional collapse, termed D_4 (De Ronde and De Wit, 1994), around 3.1 Ga accompanied by the emplacement of potassic granitic batholiths preceded cratonic stabilization (Table 1).

More detailed deformation schemes are available for the southwestern BGB (e.g. Lowe, 1994; Lowe et al., 1999). South of Barberton town (Figure 1), Lowe et al. (1999) describe thrusts that separate tightly folded rocks of the Fig Tree and Onverwacht Groups from more open, but similarly orientated, folds in the Schoongezicht Formation and overlying Moodies Group. Lowe et al. (1999) note that the Fig Tree and Onverwacht rocks were folded before emplacement of the Moodies Group and refer to pre-Moodies Group folding of Fig Tree rocks as D_2 , to tectonic emplacement of Moodies Group rocks on top of Fig Tree as D_3 and to folding of the Moodies (and tightening of D_2 folds in Fig Tree lithologies) as D_4 . Further tightening of all folds with rotation to their current upright northeasterly-trending orientation is referred to as D_5 , and includes upright folding (D_{5a}), emplacement of the Kaap Valley pluton and foliation formation (D_{5b}), and refolding (D_{5c}) (Table 1).

Geological setting of the Sheba-Fairview area

Because of its economic importance as a gold mining district, the Sheba-Fairview area was the focus of detailed geological studies in the 1950 to 70's, with a

comprehensive summary of the geological history published by Anhaeusser (1976). After this study relatively little additional detailed work was done with the exception of mine-based studies at Sheba mine (e.g. Robertson et al., 1994; Schouwstra, 1995), Fairview mine (Wiggett et al., 1986), New Consort mine (Voges, 1986; Harris et al., 1995; Dziggel et al., 2007; Otto et al., 2007) and the production of a new geological map for the BGB and linked review of the metallogeny (Ward, 1999; 2000; 2002). Tectonic summaries of the BGB, such as De Ronde and De Wit (1994), Lowe et al. (1999) and Lowe and Byerly (2007) focus on the southwestern part of the belt and provide only cursory correlations to the geology of the Sheba-Fairview mine area (Table 1).

The area in which the Sheba, Fairview and Consort gold mines are located is situated in a triple junction between the northwesterly-trending Jamestown schist belt and the northeast-trending main body of the greenstone belt (Anhaeusser, 1976; 1984; Ward, 2000) - an area referred to as the Sheba Hills (Figure 1). The structure of the Sheba Hills is dominated by two large reclined, synformal structures called the Ulundi Syncline in the south and the Eureka Syncline in the north, separated by a complex anticlinorium characterised by tight, isoclinal folds (Anhaeusser, 1986; Wagener and Wiegand, 1986; Ward, 1999; 2002; Figure 1). Rocks of the Onverwacht Group are restricted to the cores of tight antiformal structures, and consist of sheared talc-carbonate schist ("grey schist") surrounded by a mantle of quartz-fuchsite-chlorite-talc schist ("green schist") reflecting zoned alteration of an original komatiitic parent rock (Schouwstra and De Villiers, 1988). The top of the Onverwacht Group consists of laminated chert referred to as the "Zwartkoppie Bar" (Visser et al., 1956) that formed in part due to silicification.

Overlying the Onverwacht rocks is a turbiditic sequence of alternating greywacke sandstone and shale beds, containing laterally persistent chert and BIF horizons. Condie et al. (1970) subdivided the Fig Tree rocks into the coarser-grained Sheba Formation composed of greywacke derived from mafic volcanic rocks, overlain by the finer-grained Belvue Road Formation, containing a higher degree of granitic detritus. Unconformably overlying the greywacke units are agglomerate, dacitic tuff and volcanic flow units belonging to the Schoongezicht Formation (3225 ± 3 Ma; Kröner et al., 1992) taken as the stratigraphic top of the Fig Tree Group (Anhaeusser 1976), although Lowe et al. (1999) make note of the fact that, structurally, the unit belongs to the Moodies Group.

Anhaeusser (1976) subdivided the Moodies Group around the Eureka Syncline into three fining-upward cycles with conglomerate at the base, grading into arenaceous sandstone overlain by shale with subordinate jaspilitic ironstone. The three cyclic units are called the Clutha, Joe's Luck and Baviaanskop Formations.

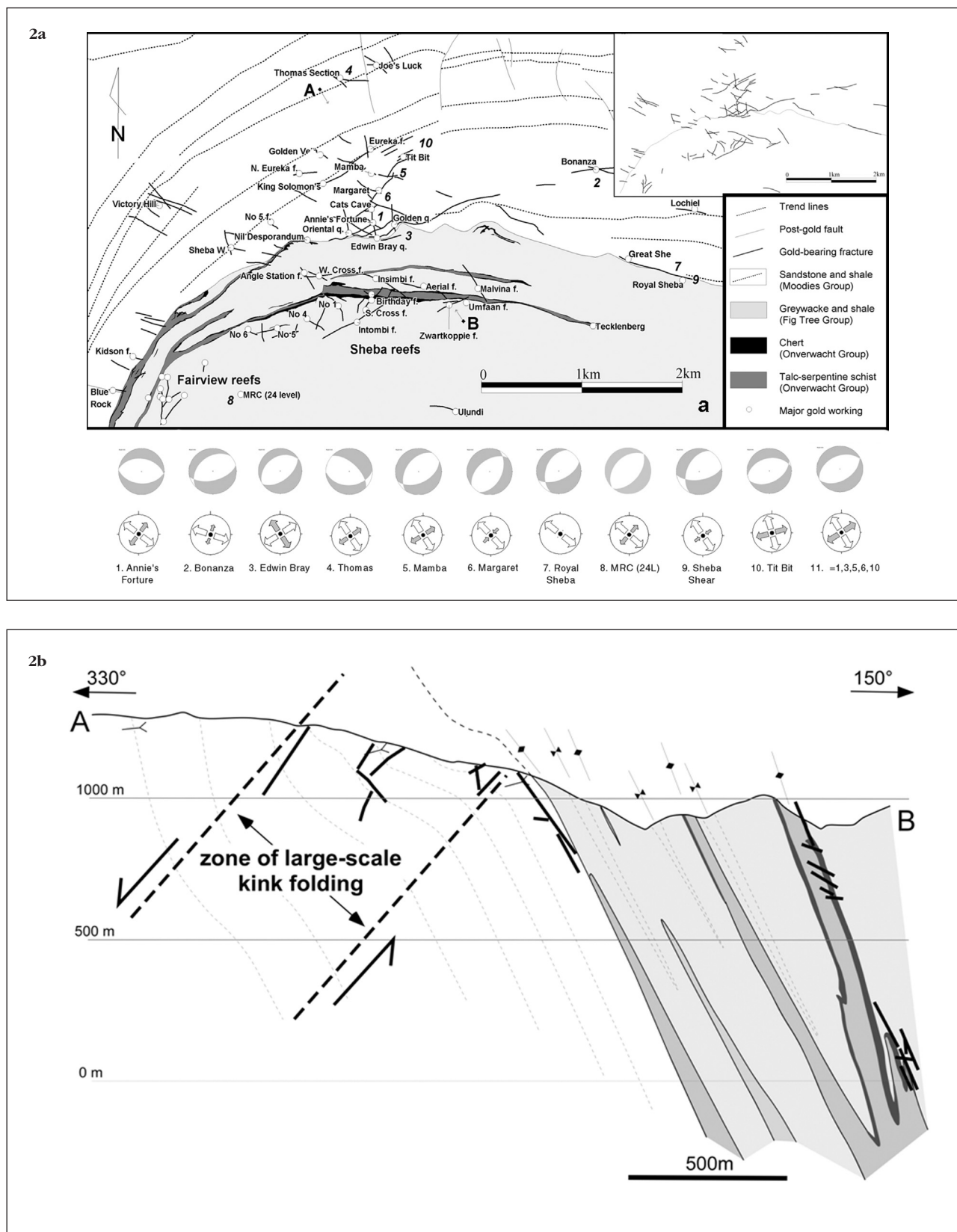


Figure 2. (a) Geological map of the Sheba-Fairview area showing the position and names of major mineralised fracture zones. Fault slip inversions for palaeo-stress are shown as 'beach balls' (grey areas for tension dihedrons), and as stress diagrams ($\sigma_{\min}$ = open arrows; $\sigma_{\max}$ = grey arrows). Detailed results are listed in Tables 2 and 3. (b) Cross section A-B and key as indicated in Figure 2 (a). Sub-surface information is based on mine plans and sections supplied by Sheba Gold Mine (C. Robus, personal communications, cf. Wagener and Wiegand, 1986).

Ramsay (1963) and Anhaeusser (1976) link the earliest deformation in the Sheba Hills area, D_{1s} (the subscript "s" for 'Sheba' is added to this local deformation scheme, to differentiate this event from regional deformation events of De Ronde and De Wit (1994); Table 1) to formation of the Ulundi and Eureka synclines, and the intervening anticlinorium. They suggest that the two synformal structures were juxtaposed across a thrust, the Sheba shear zone, along the base of the Moodies Group, and that a second event D_{2s} resulted in the formation of a regional foliation which cross-cuts the axial planes of D_{1s} folds. The regional foliation was linked to emplacement of the Kaap Valley pluton and not related to large-scale folding.

We like to state categorically that the regional foliation of Ramsay (1963) is in fact axial planar to the tight folds in the anticlinorium between the Ulundi and Eureka Synclines and to the Ulundi Syncline itself. This axial planar foliation and the bedding in folded Onverwacht and Fig Tree rocks are truncated by an unconformity at the base of the Schoongezicht Formation (Ward, 2000). A later, younger foliation, parallel to the one in the Fig Tree shale, developed in sediment of the Moodies Group along the axial plane of the Eureka Syncline. The D_{1s} and D_{2s} events as defined by Ramsay (1963) and Anhaeusser (1976), therefore, combine a range of structures and fabrics, which can be more accurately correlated with the deformation events described as D_2 to D_{5b} by Lowe et al. (1999) for rocks south of Barberton town (Table 1). The next major event to affect the Sheba area as described by Anhaeusser (1976) is D_{3s} refolding of the Eureka Syncline in an open northwesterly-trending, steeply southeasterly-plunging fold, resulting in an arcuate shape. D_{3s} folding has been linked to doming of the Kaap Valley pluton (3227 ± 1 Ma, Kamo and Davis 1994) to the southwest (Figure 1), and simultaneous northwesterly-directed thrusting on major strike-parallel shear zones including the Sheba shear zone, which also controlled concomitant gold mineralization (Anhaeusser, 1976).

Later D_{4s} events affecting the Sheba Hills include normal faulting and the development of conjugate kink bands indicative of extension with σ_1 vertical and σ_3 commonly north to south (Anhaeusser, 1976). This event was tentatively linked to granite emplacement and doming (D_4 of De Ronde and De Wit, 1994), and has been interpreted to post-date gold mineralization (Table 1).

Gold mineralisation in the Sheba-Fairview area

Outside of the Witwatersrand Basin, the BGB is the foremost gold producing area in South Africa. Since 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 Consort (68.5t) mines (Figure 1, C. Robus, personal communication), which continue to produce 2.5 to 3t of gold per year at average grades of ~10 to 12 g/t. Apart from the Sheba-Fairview mines, the Sheba

Hills host other major ore bodies such as the Golden Quarry (historical production of approx. 23.5t), and the area is pock-marked with hundreds of diggings, many still accessible, providing an unique opportunity to study the surface distribution of gold mineralisation in the area (Figure 2a).

In the Sheba Hills gold is hosted by all rock types, with no preferential host lithology (Robertson et al., 1994; Ward, 1999; 2002). Mineralisation 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). Mineralised 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 (Anhaeusser, 1976; Wiggett et al., 1986; Wagener and Wiegand, 1986; Figure 2a). 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 south-southwesterly-trending shear fractures, with competent greywacke horizons of the Fig Tree and chert bars at the top of the Onverwacht forming the locus of mineralisation. Ore fluids penetrated host rocks along dilated cleavage 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 mineralisation (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 (H_2O , CO_2 , 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 mineralisation includes widespread silicification, such as quartz vein stockworks in the hanging wall of the Golden Quarry deposit referred to as the Sheba Bar (Anhaeusser, 1976; Figures 2b; 3a; b). Potassic alteration, carbonitisation, sulphidisation (mostly pyrite, arsenopyrite with minor stibnite) and tourmaline growth have also been noted (Schouwstra and De Villiers, 1988; Schouwstra, 1995). Arsenopyrite, in particular, shows a close correlation with gold values.

Mineralisation in the Sheba-Fairview area has been related to fracture systems that transect earlier D_{1s-2s} structures (Table 1). Robertson et al. (1994) describe mineralised brittle-ductile shear zones of the Main Reef Complex (MRC) in Sheba mine hosted by Fig Tree shale and greywacke as discontinuous overlapping deformation zones up to 240 m in length and 70 cm in

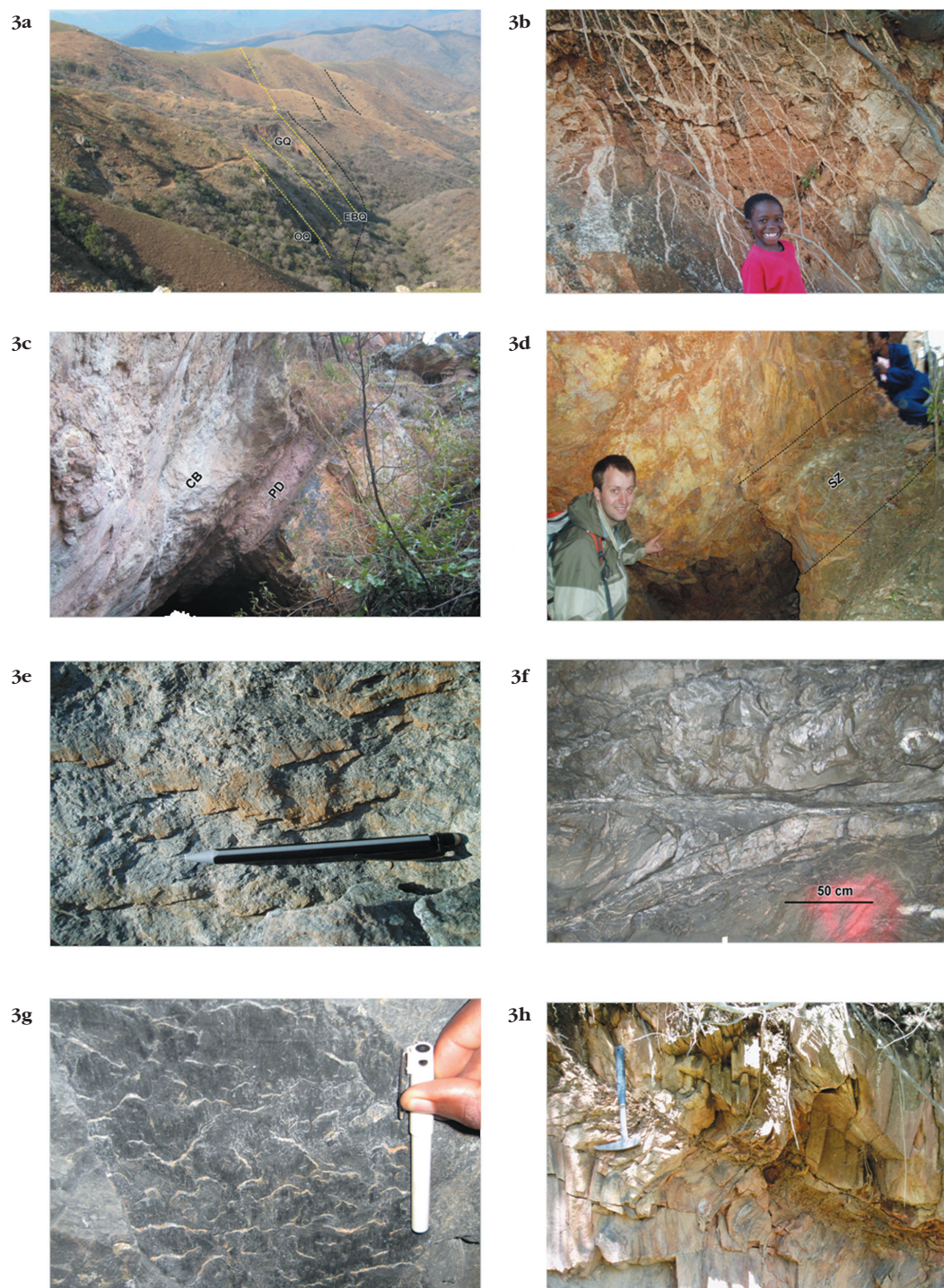


Figure 3. Outcrop photographs of major geological features associated with gold mineralisation in the Sheba Hills. (a) A silicified stockwork called the Sheba Bar (yellow stipple line) merges with the Sheba shear (black stipple line) in a series of en-echelon structures centered on Golden Quarry (GQ), Edwin Bray Quarry (EBQ) and Oriental Quarry (OQ); (b) Close-up of the quartz vein stockwork along the Sheba Bar as exposed in the road outcrop above the Golden Quarry (GR312425-7155480); (c) Feldspar porphyry dyke intruded along the basal contact of the chert bar exposed in the Nil Desperandum deposit (GR311533-7155307); (d) Support pillar in a stope in Tit Bit mine, showing a mineralised shear zone from which kinematic data can be obtained (GR312486-7156114); (e) Typical slickenside with quartz fibre growth indicating a normal displacement on a mineralised shear zone in the Margaret workings (GR312270-7155778); (f) Normal, brittle-ductile shear zone forming the MRC ore body at 24 level in Sheba mine; (g) Slickensided surface in the MRC shear zone showing a normal displacement; (h) Mineralised fracture zone developed along the axial plane of recumbent, kink like folds in stope of the Tit Bit workings.

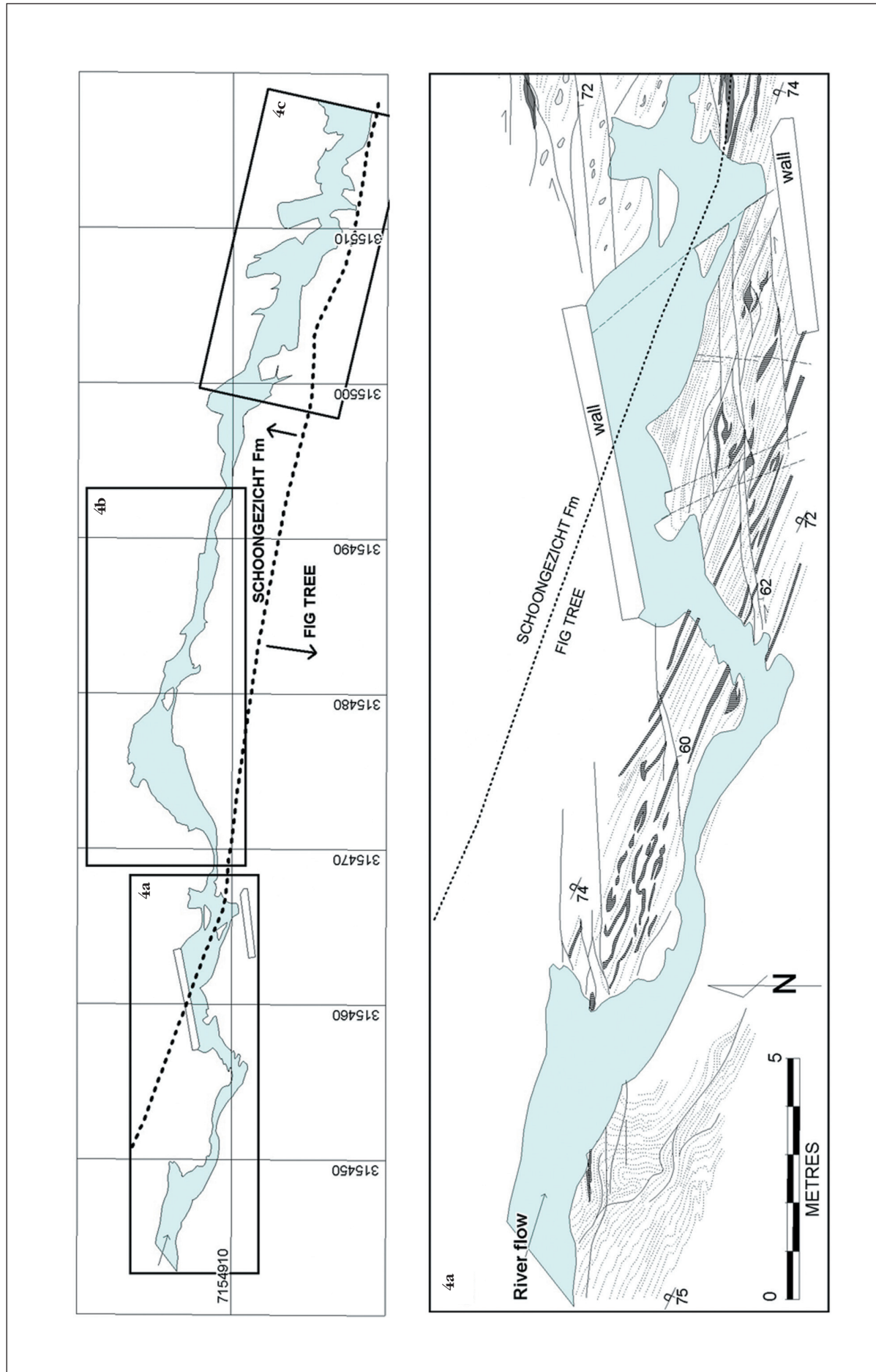


Figure 4. Form surface map of the Sheba shear zone in Sheba Creek (GR315480-7154912) overlying the underground workings of Royal Sheba mine (see text for discussion).

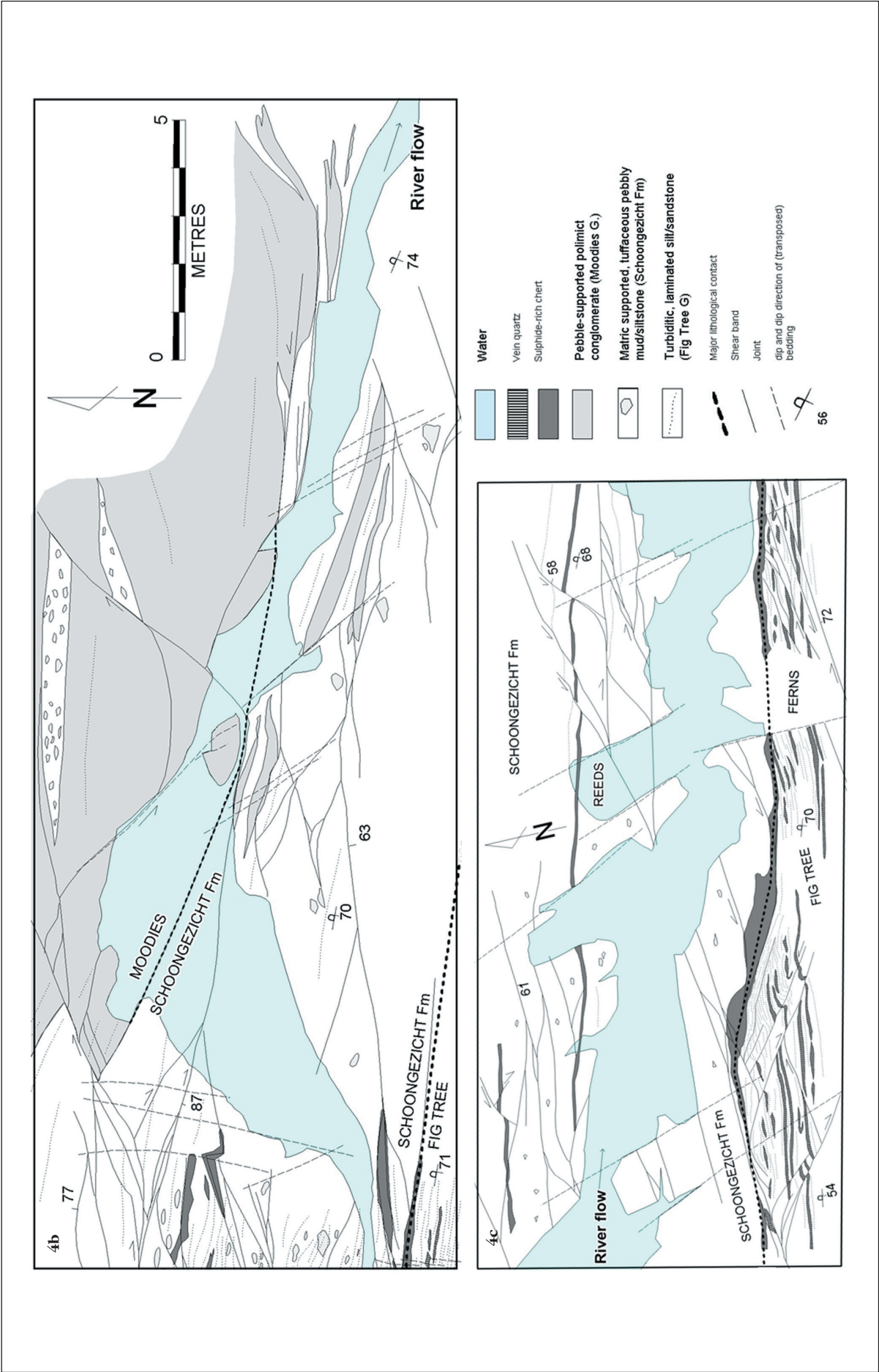


Figure 4. continued

width, dipping 55° to the southeast. The shears are characterised by multiple generations of quartz-carbonate veins, with earlier phases being folded and boudinaged, foliation development (including a crenulation cleavage in surrounding shale), and late-stage brittle fracturing. The main shears are intersected by narrow, steeply south-dipping fractures and shallowly northeasterly-dipping fractures, along shoots that plunge 32° to 50° east to northeast, defining high-grade mineralisation zones surrounded by <5m wide mineralised alteration haloes. Similar descriptions of intersecting arrays of brittle-ductile shear zones with high-grade ore shoots have been provided for the Margaret and Eureka mines (Snow, 1991; Figure 2a) and the Fairview mine (Wiggett et al., 1986). All structural studies interpret the mineralised brittle-ductile shear zones as second-order thrusts related to transpression on the Sheba shear (Table 1). By linking the mineralisation to thrusting, fault-valve models (Sibson, 2001; 2004; Cox et al., 2001) for gold mineralisation along the Sheba shear have been proposed (e.g. Robertson et al., 1994).

In Sheba and Fairview mines and in the Golden Quarry, porphyry dykes have been observed suggesting an igneous link to mineralisation and providing age constraints (Figure 3c). A quartz porphyry from Fairview mine dated at 3126 ± 21 Ma (De Ronde et al., 1991) intruded into the Fig Tree Group. This porphyry is overprinted by hydrothermal rutile dated at 3084 ± 18 Ma (De Ronde et al., 1991), which has been linked to hydrothermal alteration that caused gold mineralisation. The altered porphyry therefore provides a minimum age for gold deposition at Fairview mine (De Ronde et al., 1991). Because fluid compositions in the gold mines are similar, De Ronde et al. (1991; 1992) argue this age to be representative for gold mineralisation across the BGB.

New details on the structure of the Fairview-Sheba gold mine area

Although gold in the Sheba Hills is not preferentially hosted by any lithology, there is a broad spatial association between mineralisation and the lithological contacts of the Fig Tree Group with the underlying Onverwacht and overlying Moodies Groups (Figure 2a). The contact between the Fig Tree and Moodies Groups in particular is locally heavily silicified and deformed (Figure 3a). The nature of this contact, here called the Sheba shear zone (Figure 1), is of importance to our analysis of the structure controlling mineralization, and we will discuss this contact in detail before presenting a comprehensive description and kinematic analysis of mineralised structures in the area.

The contact between the Fig Tree and Moodies Groups and the Sheba shear zone

South and east of the Eureka Syncline, the contact between Fig Tree and Moodies Group rocks changes in character along its strike length (e.g. Ward, 2000). One kilometer east of Royal Sheba mine (Figure 2a) the contact is a low-angle unconformity separating Fig Tree

greywacke from agglomerate and water-laid tuff of the Schoongezicht Formation. Pebbles within the agglomerate include abundant fuchsite-chlorite schist fragments and few shale fragments reflecting a provenance of deformed Onverwacht and Fig Tree schist respectively (Lowe et al., 1999). The unconformity can be traced east around the west-plunging nose of the Eureka Syncline.

West of point 316880-7154920 (all references are given in UTM, WGS84 zone 36S), the Fig Tree contact is marked by a 3 to 5 m wide shear zone, largely located within shale of the Fig Tree Group (Figures 2a; 4). Shear along the contact starts at the point where a thrust responsible for structural duplication of Schoongezicht Formation and basal Moodies Group rocks (Visser, 1956; Ward, 2000), ramps down to follow the base of the Schoongezicht Formation. The exact nature of this thrust (i.e. movement direction and sense) is masked by later reactivation and brittle-ductile overprints (Figure 4).

Between Royal Sheba mine and Oriental quarry (Figure 2a) the contact is a 3 to 5 m wide zone of ductile shear, reactivated as a brittle-ductile fault that transects isoclinally folded Fig Tree rocks. The shear zone is conformable with overlying clastic units of the Schoongezicht Formation and Moodies Group, and basal conglomerate units and agglomerate can be traced as far west as Oriental quarry (Figure 2a). West of Oriental quarry, at the point where the east-northeasterly-trending Sheba Bar joins the sheared contact, the shear zone displays an angular relationship with folded footwall units of the Fig Tree and Onverwacht Groups, and with the overlying Moodies Group as the shear zone gradually cuts up-stratigraphy. In the vicinity of Fairview mine the contact shear zone has cut up-stratigraphy to the extent that it merges with a band of ferruginous magnetite-rich shale and banded jaspilite that Anhaeusser (1976) placed at the top of the first of three fining upward cycles in the Moodies Group. This ferruginous shale is a 30 to 40 m wide ultra mylonite zone intruded by multiple veins of red jasper (Figure 5a); i.e. it is a tectonic ferruginous shale rather than a sedimentary iron formation, which can be traced around the Eureka Syncline (Ward, 2000). As the ultra-mylonitic shale merges with the contact shear zone, the latter becomes a 15 to 20 m wide shear zone characterised by intense intrafolial folding and veining, which can be traced to south of Barberton town (Figure 1).

A detailed investigation of the Sheba shear in relation to gold mineralisation was undertaken in rock platforms exposed in the creek bed immediately north of the Royal Sheba mine (GR315480-7154910, Figure 4). This outcrop represents the eastern end of a mineralised section of the Sheba shear zone (e.g. Snow, 1991) and is underlain by underground workings of the Royal Sheba mine. The Sheba shear zone in this section is about 5 m wide and dips ~70 to 75° towards 190° (Figure 4). It separates thinly bedded greywacke sandstone and shale belonging to the Fig Tree Group, from overturned volcanoclastic units of the Schoongezicht Formation. The volcanoclastic

pebbly mudstone to pebbly siltstone units contain isolated angular to sub-rounded fragments of greenschist, shale, dacite, and feldspar porphyry (all less than 15 cm in diameter) embedded in a highly altered (carbonated and silicified), fine-grained mud to silt matrix with an immature feldspathic to micaceous composition (Figure 5b). The agglomerate is interbedded with several lensoidal bodies of clast-supported, polymict conglomerate. The central part of the outcrop shows a 25 m wide channel filled with pebble-supported, polymict conglomerate at the erosional base of the Moodies Group (Figure 4b). The conglomerate pebbles are well-rounded and occur in a mature quartz-sandstone matrix. Pebbles include chert, granite, gneiss, porphyry, quartz sandstone, and fuchsitic schist (for detailed descriptions of the conglomerate see Anhaeusser, 1976).

Shear fabrics are best developed in a 4.5 to 5 m wide zone almost entirely contained in shale in the immediate hanging wall of the south-dipping contact. This high strain zone is characterised by abundant <5 cm wide, grey-black, coarsely recrystallised quartz veins, many isoclinally folded and subsequently boudinaged, representing a transposition fabric (Figure 5c). Compositional bedding in the shale is planar, occurs on a 1 to 3 cm scale and is paralleled by a well-developed cleavage. Carbonate and silica alteration is intense and concentrated in conspicuous chert bands that parallel the shear foliation and occur along cross-cutting shear bands displaying a characteristic chocolate-brown weathering due to fine-grained sulphide (pyrite, arsenopyrite) mineralisation and associated with gold values. The planar shear fabric is transected by an anastomosing network of thin (<5 mm) shear bands,

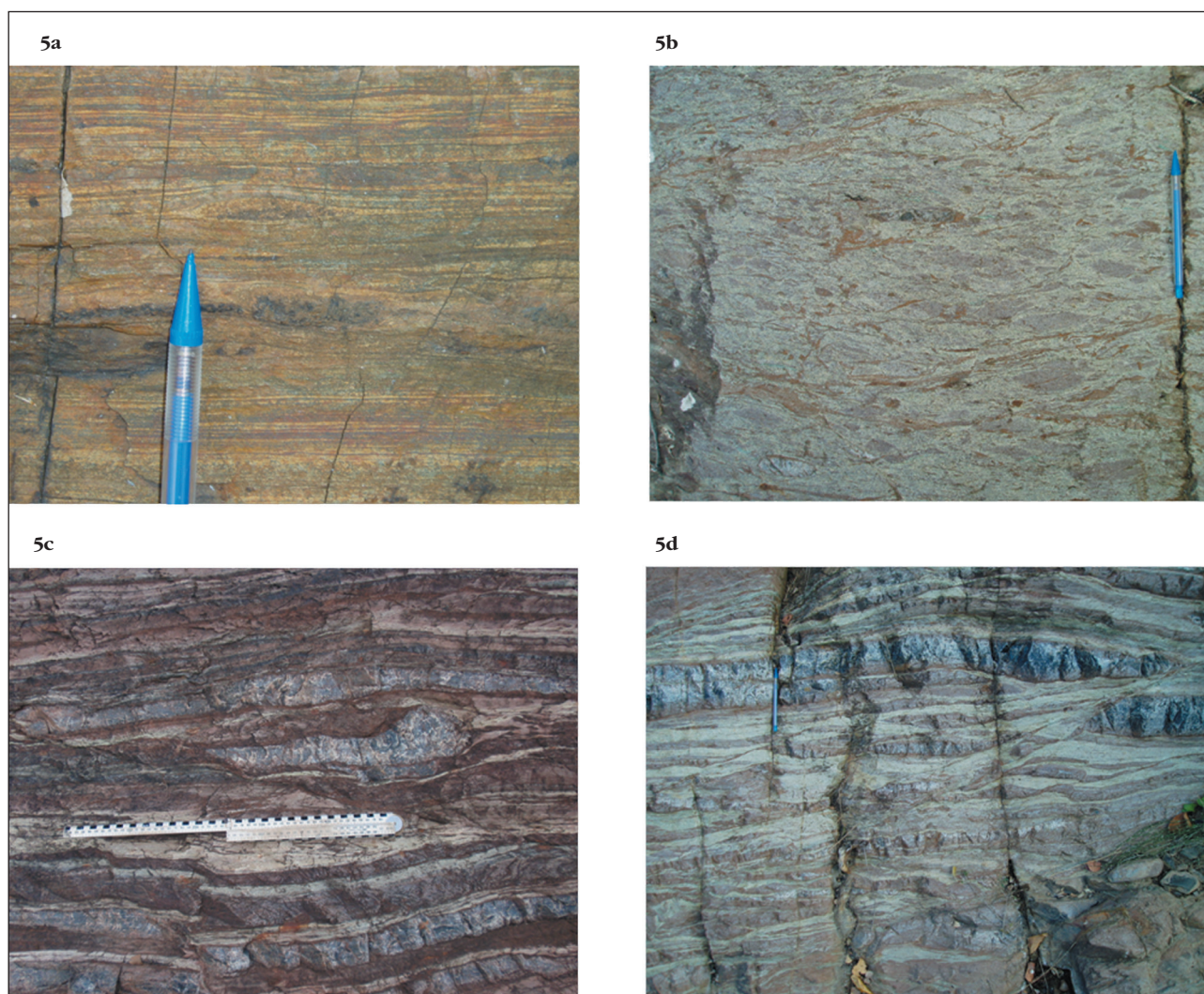


Figure 5. Photographs of the Sheba shear zone and related structures. (a) Ultramylonitic ironstone horizon at the top of the Clutha Formation as exposed underground in the Edwin Bray-Joe's Luck drive; (b) Agglomerate in the footwall of the Sheba shear in the locality shown in Figure 4c; (c) Isoclinally folded and boudinaged quartz veins defining a transposition fabric in strongly altered Fig Tree shale in the core of the Sheba shear zone shown in Figure 4b; (d) Shear bands developed in the core of the Sheba shear zone shown in Figure 4c.

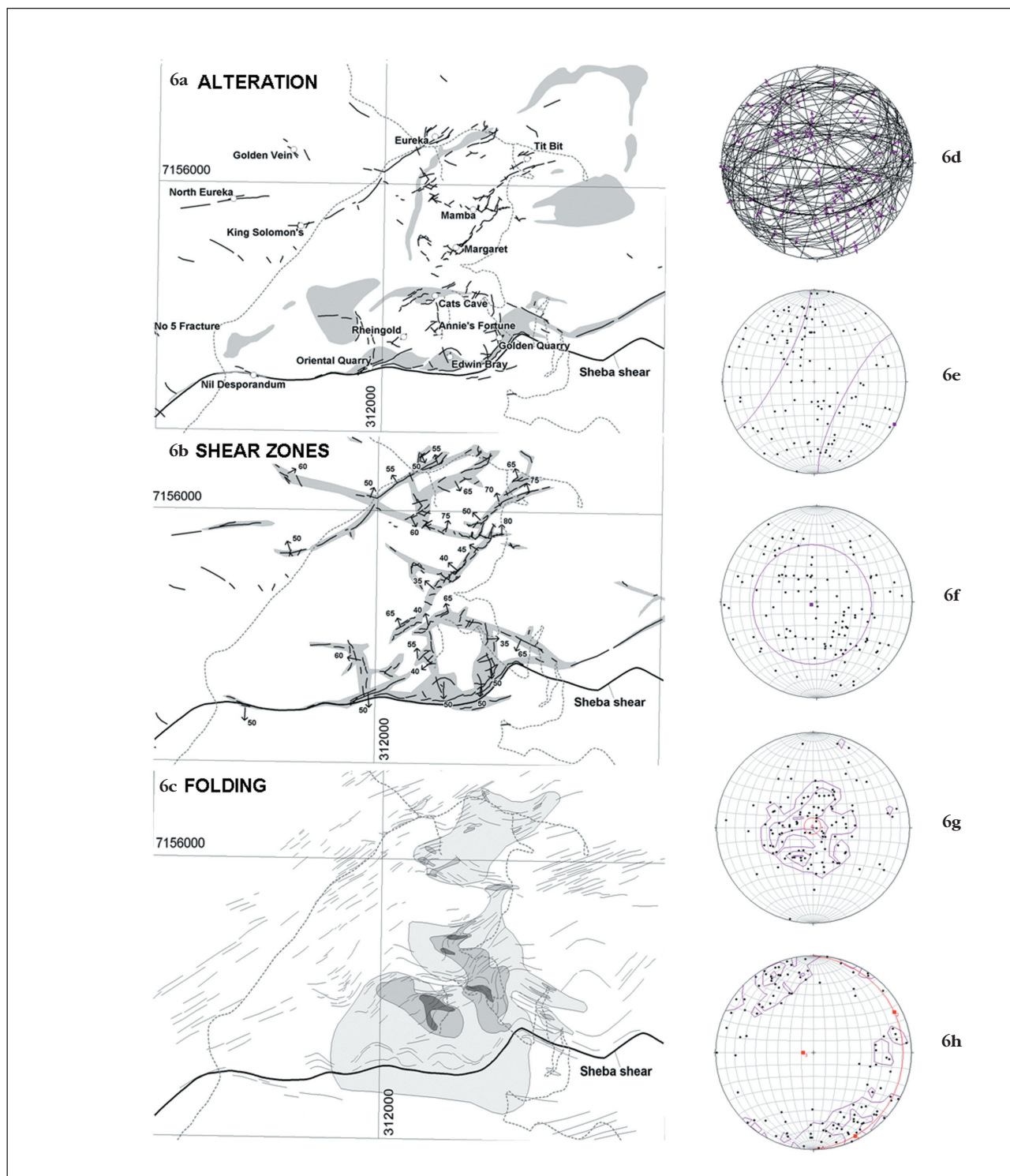


Figure 6. Geological maps of the area between Golden Quarry and Eureka City. **(a)** Position of main gold workings and quartz alteration zones (grey); **(b)** Network of shear envelopes (grey) and orientation of main ore shoots; **(c)** Orientation of bedding planes in the vicinity of shear zones as a result of kink-like folding (dip angle of: 0 to 20° dark grey; 20 to 40° intermediate grey; 40 to 60° light grey). **(d)** Plots of all measured fault planes in the area with slip vectors pointing towards the movement direction of the hanging wall ($n=114$); **(e)** Poles to faults shown in figure 6d. The conical best fit to the data set is shown. The cone axis orientation = $118/01$, the cone half angle = $60 \pm 13.6^\circ$ ($n = 114$); **(f)** Lineation directions for faults shown in figure 6d. The conical best fit to the data set is shown. The cone axis orientation = $242/85$, the cone half angle = $53 \pm 13.3^\circ$ ($n = 114$); **(g)** Plot of P-dihedra axes calculated for the faults shown in figure 6d, using FaultKin (Allmendinger, 2001). The data has been contoured and the mean P vector orientation calculated at $340/88$ consistent with s_1 being vertical ($n = 114$); **(h)** Plot of T-dihedra axes calculated for the faults shown in figure 6d, using FaultKin (Allmendinger, 2001). The data has been contoured and the mean T vector orientation calculated at $154/04$ consistent with σ_3 being horizontal, trending northwesterly ($n = 114$).

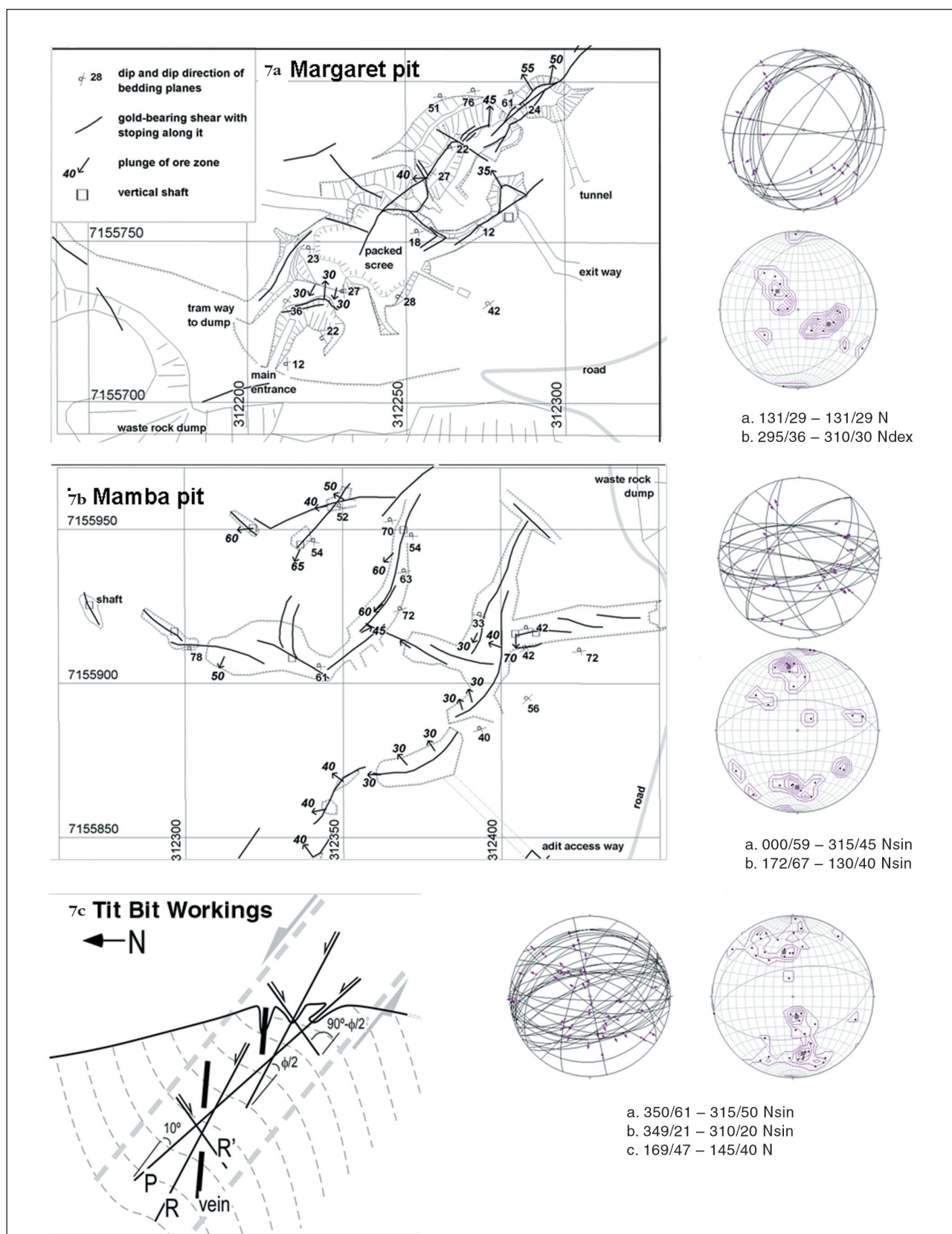


Figure 7. (a) Form surface map and plots for the surface workings of Margaret mine. (b) Form surface map and plots for the surface workings of Mamba mine; (c) Diagram illustrating the spatial arrangement of the dominant faults within a north dipping envelope at Tit Bit mine. Grid blocks on the maps are 50 m. For figures a., b., and c., plots show the orientation of measured fault planes with slip vectors pointing towards the movement direction of the hanging wall (top), together with a contour plot of poles to the faults (base) with the average orientation of the main faults listed below that.

which in plan view show both dextral and sinistral displacements (Figure 5d) and a dominant trend in the direction 260° (Figure 4). The shear bands are associated with chert-sulphide and potassic alteration indicating a coeval relationship between alteration, sulphide mineralisation and shear band formation. The anastomosing network of cross-cutting shear bands preserves mineral lineations on slickensided surfaces dominated by moderately southeast-plunging lineations and a normal-sinistral sense of movement (Figure 4).

South from the core of the shear zone, in overlying turbiditic shale, the intensity of fabric-parallel quartz veining and associated carbonate and silica alteration drops off sharply. At GR315445-7194914 (Figure 4), 1.5 m into the hanging wall of the core of the shear zone, the shear fabric consists of a crenulation cleavage axial planar to centimeter-scale Z-folds that overprint earlier folds and fabrics including duplex-like repetitions of sandstone layers and an early generation of quartz veins along low-angle shears or truncation planes (Figure 4a). These truncation planes are associated with folds developed in their footwall (i.e. north side), which deform the bedding as well as an earlier cleavage, and attest to motion along the shear zone post-dating foliation formation in the Fig Tree shale, but predating the now dominant, sinistral-normal, brittle-ductile event.

The clastic footwall rocks north of the core of the shear zone contain pebbles that are only weakly flattened (Figure 5b), and no shear zone-parallel fabric is apparent. The rocks are, however, strongly altered with extensive chert veining and pervasive silicification, sericitisation and carbonatisation. The anastomosing network of discrete shear bands extends several meters into the footwall rocks, displaying horizontal displacements of <1.5 m (Figure 4). The shear zone is cut by later north-northwesterly-trending vertical joints normal to the dominant shear band trend.

Between Nil Desperandum mine and Golden Quarry the Sheba shear zone slowly turns from an east-southeast to a west-southwest trend and merges with a west-northwest-trending fracture zone referred to as the Sheba Bar, which is characterised by prominent quartz stockwork alteration and associated sulphidisation and gold mineralisation (Figures 3a; b). In the hanging wall of the Oriental, Annie's Fortune and Golden Quarry deposits this stockwork zone reaches a thickness of ~15 m. The hanging wall contact of the Sheba Bar is decorated with a 0.1 to 0.5 m thick, sheared, boudinaged and strongly altered feldspar porphyry dyke, well exposed at Nil Desperandum (GR311543-7155300; Figure 3c). This porphyry is mineralised and known in the mine as the 'clay seam'. Southwest of Nil Desperandum mine, brittle-ductile reactivation of the Sheba shear no longer occurs, but instead the sheared contact is crossed at high angles by fracture networks such as the Kidson and Blue Rock fractures (Figure 2a).

The geometry of gold bearing fracture systems

Mineralised fracture systems are well exposed in the old surface workings that remain between Golden Quarry and Eureka City (Figures 1; 2a; 6). In contrast, surface workings near Sheba and Fairview mines have been largely bulldozed to prevent illegal miners entering underlying workings, and exposure of mineralised shear systems on surface is limited. We concentrate our analyses of the mineralised shear zones in the area north of the Sheba shear zone around Eureka City using surface exposures in pits of the Annie's Fortune, Golden Quarry, Oriental Quarry, Cat's Cave, Margaret, Mamba, Tit Bit and Eureka gold mines (Figure 2a). The fracture systems mapped in this manner have been combined with mine plans provided by Sheba Mine, to produce Figure 6.

Auriferous fracture zones

In workings (i.e. at 10 m scale) mineralisation occurs along complex networks of 20 to 50 m long, brittle-ductile fractures arranged in overlapping, *en-echelon* arrays (Figure 7). Figure 7 shows gold-bearing fractures in the Margaret and Mamba workings hosted by quartzite. The fractures have been mapped along the surface trace of stopes, with actual reefs being exposed in support pillars (Figure 3d).

In the Margaret pit three 50 m-long, northeast-trending and moderately (40 to 50°) northwesterly-dipping fractures overlap in an *en-echelon* array (Figure 7a). These fractures consist of 10 to 20 cm wide brittle-ductile shear zones in which a foliated and folded micaceous ductile fabric is transected by discrete brittle fracture planes that parallel the overall trend of the shear. The fractures preserve slickensided surfaces with fibrous quartz growth defining slickenlines (Figure 3e). The shear zones are associated with several generations of dark-grey, quartz veins and extensive pyrite-arsenopyrite mineralisation occurring in both the quartz veins and as disseminated specks in the shear zone and the immediate hanging and footwall rocks (Figure 3f). Lineations on the shear zones pitch either steeply or shallowly west recording normal or normal-sinistral movements respectively (Figure 7).

The *en-echelon* shears in the Margaret pit (Figure 7a) show an open, S-shape curvature as fault tips in the overlap zones bend towards one another. Complex splays of narrow (<1 cm), slickensided fractures and grey quartz veins characterise the areas where mineralised shears overlap. Such areas have not been mined, because gold grades are low and patchy. A second set of moderately (40 to 50°) southeasterly-dipping shears, was mined sporadically reflecting low-grade mineralisation (Snow, 1991). A third set of near-vertical, northwesterly-trending fractures transect the workings without significant offset. These fractures have not been mined.

In the Mamba pit (Figure 7b), *en-echelon* arrays of 20 to 50 m long mineralised (i.e. mined) fractures occur that overlap in both a right and left lateral fashion.

Individual fractures are identical in appearance to those in the Margaret pit. Stopping occurred along a series of S-shaped, northeasterly- to north-northeasterly-trending, moderately (40 to 50°) northwesterly-dipping, brittle-ductile fractures, arranged in two parallel, north-northeasterly-trending corridors (Figures 6b; 7b). The fractures are intersected by moderately (40 to 50°) southeasterly- to south-southeasterly-dipping fractures. Quartz slickenfibres lineations predominantly plunge either moderately northwestward or moderately southeastward, recording a normal sense of movement (Figure 7).

A separate westerly- to west-northwesterly-trending fracture corridor consisting of an en-echelon array of generally west-northwesterly-trending, mineralised fractures that dip either moderately north or south intersects the northeasterly-trending fracture zones. The west-northwesterly-trending fractures are also associated with quartz slickenfibres lineations that predominantly plunge either moderately northwestward or moderately southeastward, recording a normal-sinistral sense of movement.

Both the Margaret and Mamba workings are situated along a northeasterly-trending corridor of workings, called the "Margaret fracture" that also includes the Rheingold and Cat's Cave workings to the southwest and the Tit Bit workings to the northeast. When all fractures along this corridor are placed together on a map, they form an en-echelon array of three overlapping fracture zones, each approximately 200 m in length, and mined separately (Figure 6). Along its length complex intersections with other fracture zones occur (Figure 6b).

Mine plans for Margaret and Mamba mines show that the envelope of the mineralised zone along the Margaret fracture dips 60 to 70° to the northwest (Snow, 1991; Figure 7); i.e. the envelope to the mineralised fractures dips steeper than most individual fractures. This fracture distribution can be illustrated particularly well in the Tit Bit mine. At Tit Bit mineralised brittle-ductile fractures fall into three groups (Figure 7c): 1. gently north-northwesterly-dipping, normal-sinistral faults (349/21) with a northwesterly-plunging lineation; 2. steeply north-northwest-dipping normal-sinistral faults (350/61) with a northwesterly-plunging lineation and; three moderately south-southeasterly-dipping normal-sinistral faults (169/47) with a southeasterly-plunging lineation. These faults share a common horizontal intersection lineation (080 to 260°). Steep, east-trending, mineralised grey quartz veins also occur. If the fractures are placed in a steeply (70°) north-northwesterly-dipping mineralisation envelope the fracture distribution and the veins define a Riedel array consistent with a normal movement sense with the 350/61 fractures representing Riedel shears, the 169/47 fractures anti-Riedel shears and the 349/21 fractures P-shears. The quartz veins are consistent with tension vein orientations (Figure 7c).

In the Golden Quarry-Eureka area, the Margaret fracture is but one of a number of intersecting fracture zones that are associated with gold workings (Figure 6).

Each of these fracture zones is composed of en-echelon arrays of overlapping brittle-ductile faults as described, with normal faulting being the dominant kinematic mode. Figure 6b shows the trace of the approximate envelope of the various fracture zones, which are dominated by north-northwesterly, northeasterly to east-northeasterly and west-northwesterly trends with ore zones dipping moderately to steeply in a wide variety of orientations (though mainly moderately northwesterly or southeasterly). The Sheba Bar (Figure 3a) is one of the east-northeast-trending fractures. Extensive alteration has occurred where this fracture zone intersects with the Sheba shear zone. Between Oriental Quarry and Golden Quarry there is not one, but three overlapping east-northeasterly-trending fractures that intersect the Sheba shear, one centred on Oriental Quarry, one on Edwin Bray Quarry and one on Golden Quarry (Figures 3a; 6a).

The same complex fracture pattern that controls mineralisation in the Golden Quarry area can be extended to the fracture zones that were mined on surface between Sheba and Fairview mines (Figure 2). Here too, north-northwesterly, northeasterly to east-northeasterly and west-northwesterly-trending fractures dominate, with shear zones of moderate dips displaying a normal sense of movement. As an example, the MRC at 24 level, Sheba mine is composed of an array of southwesterly-trending fractures that dip to the southeast at 50 to 60° (the MRC trend), a set of north-trending 'cross fractures' that dip 50 to 60° east and a set of near-vertical west-southwesterly-trending 'steep fractures' all recording a normal sense of shear (Figures 3f; g). Together these fractures are part of a southwesterly-trending en-echelon array with highest grades occurring along intersections (Robertson et al., 1994).

Kink folding and flattening of bedding

Mineralised fracture zones in many of the old workings occur along the axial planes of recumbent kink folds, with bedding plane orientations changing abruptly across the fractures in a manner consistent with a normal sense of movement. Good examples of this can be seen in the workings of Tit Bit, Bonanza and Annie's Fortune (Figure 3h). The orientation of the kink folds varies with the orientation of the fractures along which they have developed. In places kink folds occur in conjugate sets and their geometry and orientation is consistent with the late-stage conjugate kink zones described by Anhaeusser (1976) as D_{4s} (Table 1).

Folding near shear zones is not restricted to small-scale structures. The orientation of the bedding planes throughout the Golden Quarry-Eureka area is affected with the highest degree of refolding occurring towards the centre of the dense network of mineralised shears. Figure 6c shows a contour plot of the average dip of Moodies Group quartz sandstone in relation to the network of mineralised fracture zones. Away from the fractures, bedding dips are constant at about 70 to 80°S. Near mineralised areas the bedding rotates, locally to near horizontal attitudes. Two centers of rotation can

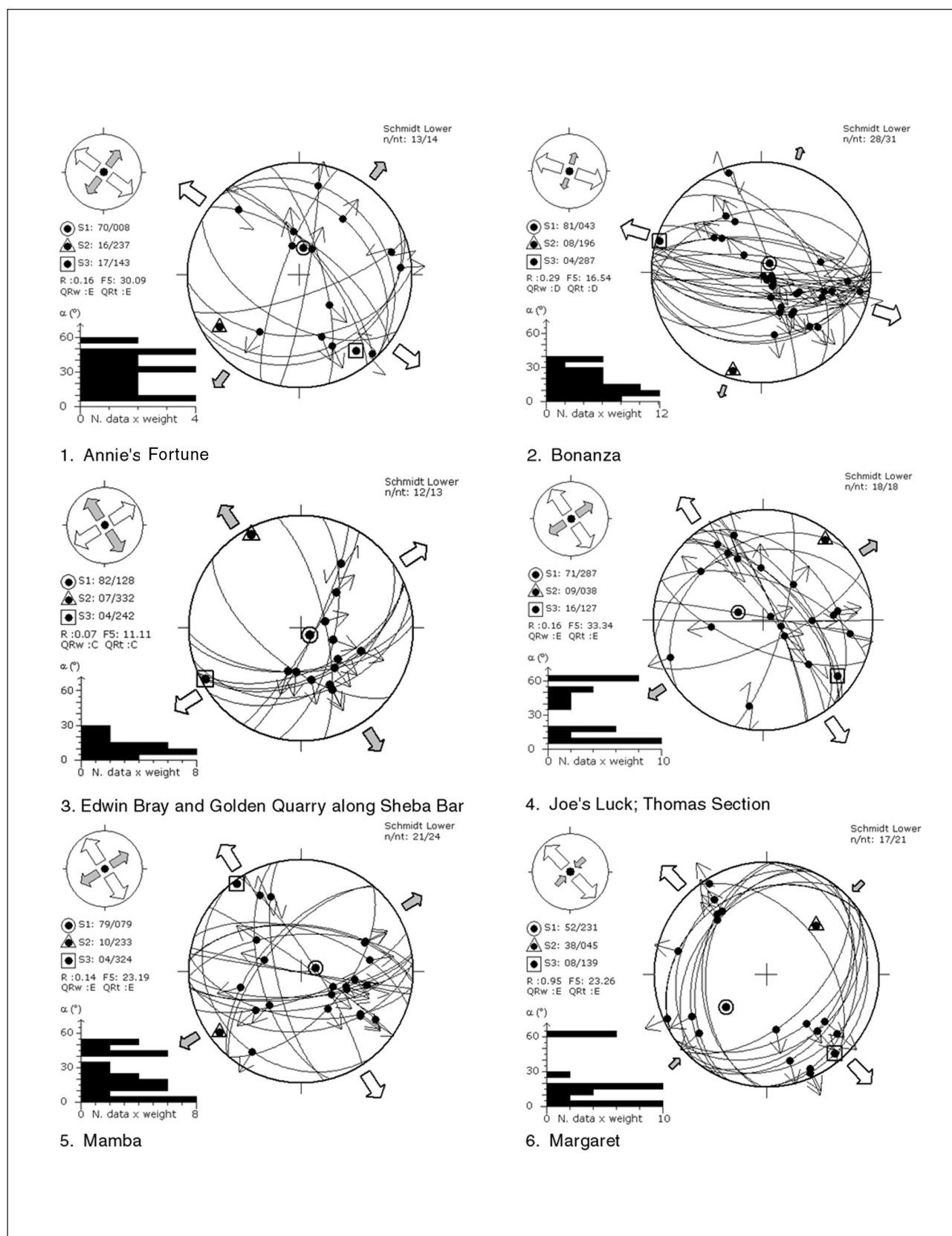


Figure 8. Graphs showing the results of the optimised right dihedral method using TENSOR (Delvaux and Sperner, 2003). For all sites a plot of the fault planes and slip vectors is provided together with the orientation of the principle stress axes (S1-S3), the principle horizontal ($\sigma_{\min}$ = open arrows; $\sigma_{\max}$ = grey 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 provided. Location numbers are shown in Figure 2. Results are summarised in Table 3.

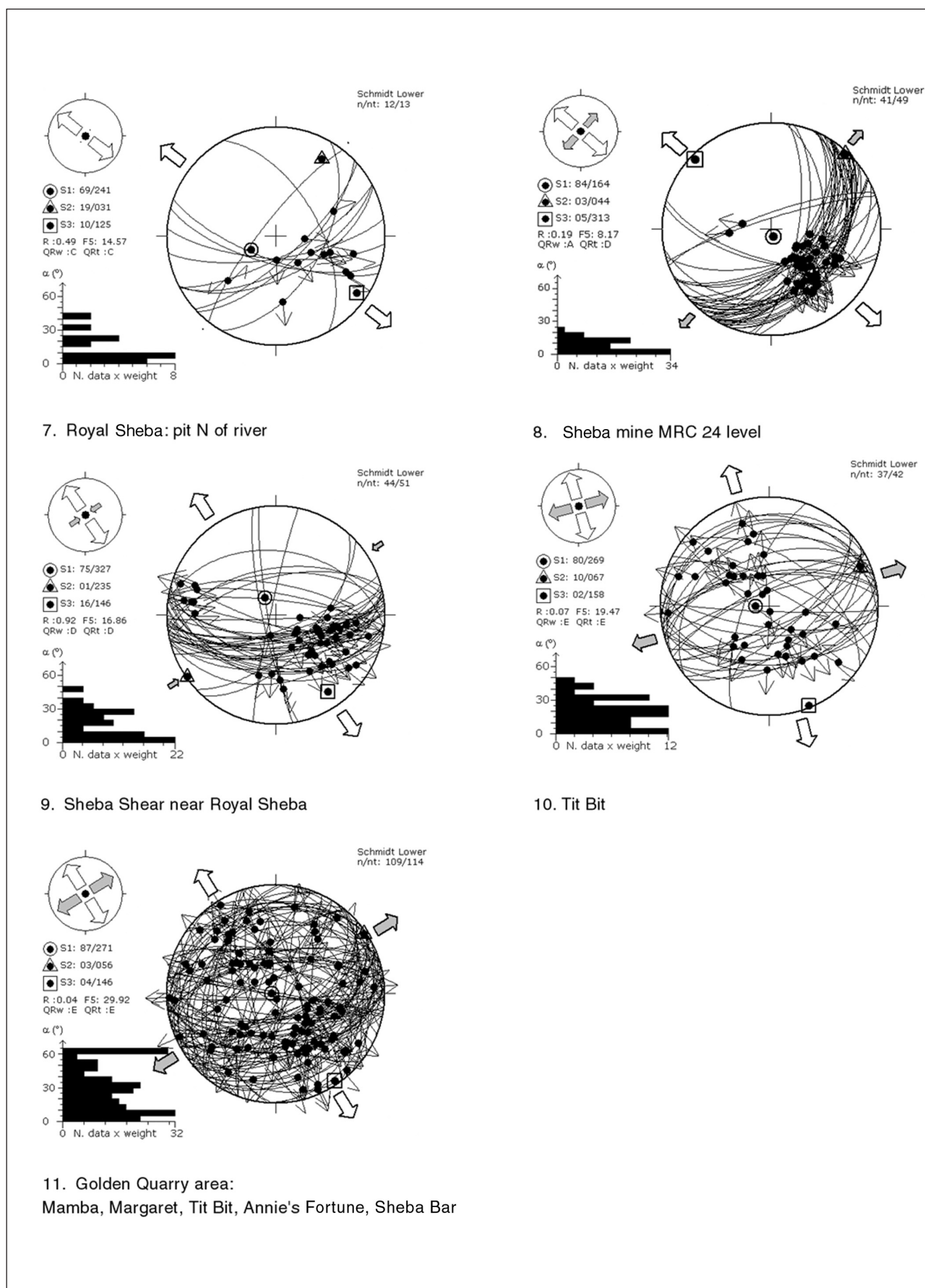


Figure 8. continued

Table 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]). Rev' is an adjusted stress ratio (see text for explanation) to estimate the stress regime.

#	Site ID	X	Y	nt	σ_1	σ_2	σ_3	ev1	ev2	ev3	Rev	Rev'	Stress Regime
1	Annie's Fortune	312180	7155480	14	305/87	095/03	185/02	-0.236	0.009	0.226	0.47	0.47	Pure EXTENSIONAL
2	Bonzanza	314320	7155980	31	027/73	246/13	154/10	-0.266	0.007	0.259	0.48	0.48	Pure EXTENSIONAL
3	Edwin Bray and Golden Quarry along Sheba Bar	312167	7155317	13	309/80	056/03	147/10	-0.384	0.116	0.268	0.23	0.23	Radial EXTENSIONAL
4	Joe's Luck: Thomas Section	311870	7156860	18	270/64	119/23	024/11	-0.290	0.119	0.171	0.11	0.11	Radial EXTENSIONAL
5	Mamba	312400	7155920	24	041/75	231/14	141/03	-0.234	0.008	0.226	0.47	0.47	Pure EXTENSIONAL
6	Margaret	312260	7155770	21	213/76	041/14	311/02	-0.283	0.016	0.267	0.46	0.46	Pure EXTENSIONAL
7	Royal Sheba	315340	7155012	13	026/65	231/23	137/10	-0.288	-0.050	0.338	0.62	0.62	Pure EXTENSIONAL
8	Sheba MRC24level	310740	7153500	49	292/84	042/02	133/06	-0.390	0.076	0.314	0.34	0.34	Pure EXTENSIONAL
9	Sheba shear near Royal Sheba	315505	7154895	51	043/58	241/31	146/08	-0.290	-0.074	0.365	0.67	0.67	Pure EXTENSIONAL
10	Tit Bit	312455	7156070	42	269/82	070/08	161/03	-0.298	0.009	0.288	0.48	0.48	Pure EXTENSIONAL
11 =	Golden Quarry area:												
	1, 3, Mamba, Margaret, Tit Bit,												
	5, 6, Annie's Fortune, Sheba Bar,												
10	combined			114	283/86	062/03	152/03	-0.275	0.035	0.230	0.40	0.40	Pure EXTENSIONAL

Table 3. Summary of results from fault slip inversion for palaeo-stress by using the optimised, 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. The average deviation angles (α), standard deviation and maximum angle are given together with an indication of data quality (QRw), stress ratio (R) and stress regime (R'). See text for full explanation.

#	Site ID	nt	n/nt	σ_1	σ_2	σ_3	σ_{hmax}	σ_{hmin}	α	Std.Dev	max.	QRw	R	R'	Stress Regime
1	Annie's Fortune	14	0.93	70/008	16/237	17/143	37	127	30.09	15.45	58.4	E	0.16	0.16	Radial EXTENSIONAL
2	Bonzanza	31	0.9	81/043	08/196	04/287	18	108	16.54	11.22	39.3	D	0.29	0.29	Pure EXTENSIONAL
3	Edwin Bray Golden Quarry along Sheba Bar	13	0.92	82/128	07/332	04/242	147	57	11.11	7.45	26.2	C	0.07	0.07	Radial EXTENSIONAL
4	Joe's Luck: Thomas Section	18	1	71/287	09/038	16/127	58	148	33.53	24.24	75.9	E	0.15	0.15	Radial EXTENSIONAL
5	Mamba	24	0.88	79/079	10/233	04/324	58	148	23.19	17.34	54	E	0.14	0.14	Radial EXTENSIONAL
6	Margaret	21	0.81	52/231	38/045	08/139	46	136	23.26	27.05	90.5	E	0.95	0.95	Strike-slip EXTENSIONAL
7	Royal Sheba	13	0.92	69/241	19/031	10/125	38	154	14.57	13.14	44	C	0.49	0.49	Pure EXTENSIONAL
8	Sheba MRC 24 level	49	0.84	84/164	03/044	05/313	42	132	8.17	5.43	21.8	A	0.19	0.19	Radial EXTENSIONAL
9	Sheba shear near Royal Sheba	51	0.86	75/327	01/235	16/146	56	154	16.86	12.98	46.1	D	0.92	0.92	Strike-slip EXTENSIONAL
10	Tit Bit	42	0.88	80/269	10/067	02/158	74	164	19.47	12.77	46.1	E	0.07	0.07	Radial EXTENSIONAL
11 =	Golden Quarry area:														
	1, 3, Mamba, Margaret, Tit Bit,														
	5, 6, Annie's Fortune, Sheba Bar,														
10	combined	114	0.96	87/271	03/056	04/146	58	148	29.92	22.58	91.6	E	0.04	0.04	Radial EXTENSIONAL

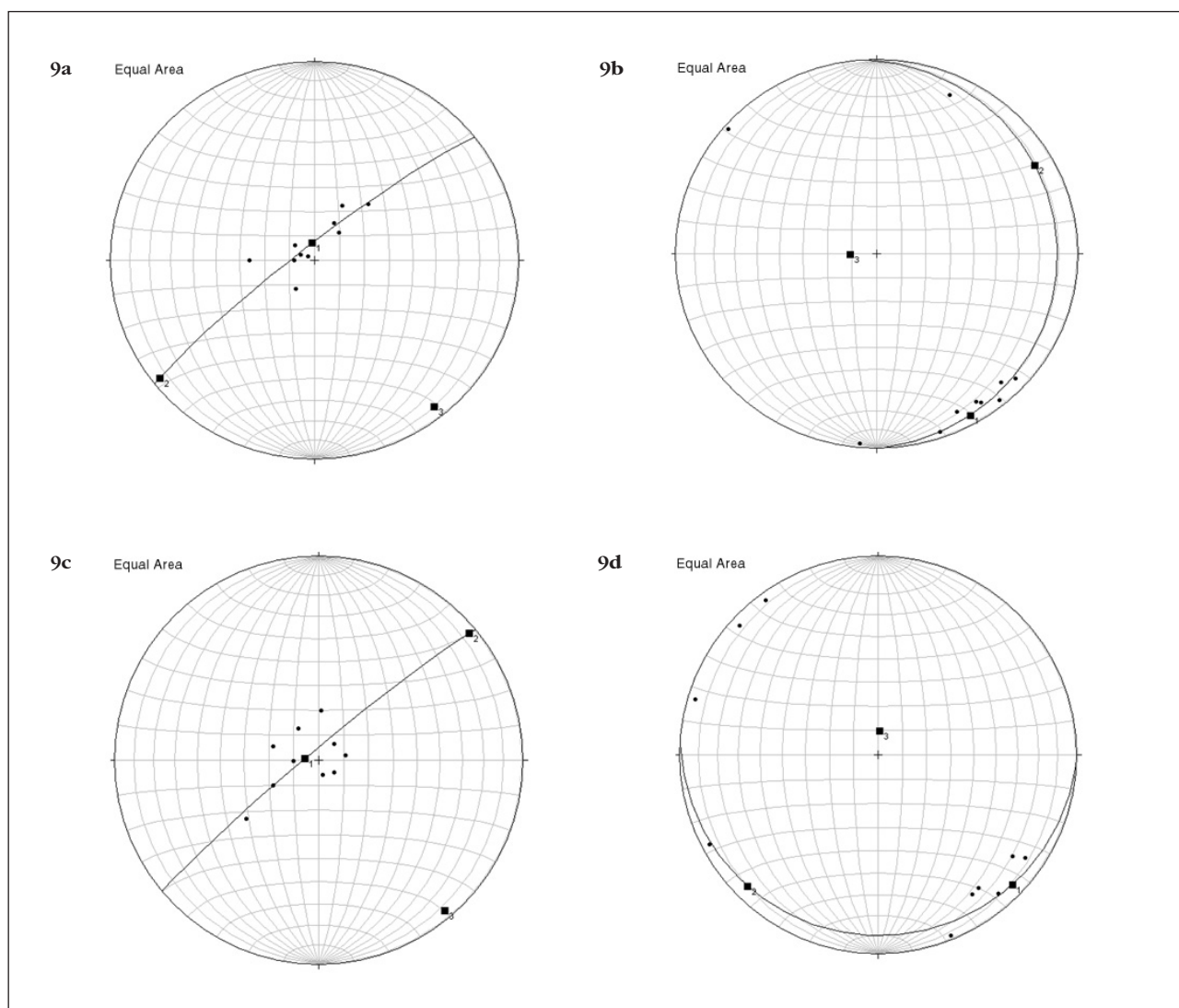


Figure 9. Average σ_1 and σ_3 orientations calculated for the 10 localities shown in Figure 2. (a) σ_1 directions calculated in FaultKin. σ_1 (ave.) = 83/352 (eigenvalue: 0.9211); (b) σ_3 directions calculated in FaultKin. σ_3 (ave.) = 05/151 (eigenvalue: 0.8628); (c) σ_1 directions calculated in TENSOR. σ_1 (ave.) = 85/277 (eigenvalue: 0.9162); (d) σ_3 directions calculated in TENSOR. σ_3 (ave.) = 06/134 (eigenvalue: 0.8381).

be identified: one in the north between the Eureka and Mamba workings, and one centered on the Annie's Fortune workings, where folding is more intense with bedding assuming near-horizontal, overturned attitudes (Figures 2b; 6c). Where the mineralised shears cross-cut the Sheba shear zone, it has been rotated to shallow dips (as low as 40°) similar to the surrounding bedding planes. South of the Sheba shear zone, regional-scale refolding of bedding planes disappears. The large-scale geometry of the kink folds can be envisaged as 300 m-scale bedding rotation (i.e. a 'kink') across steeply northwesterly-dipping fracture zones caused by a normal sense of movement (Figure 2b). Kink-like drag folding also occurs along the main mineralised fractures in Sheba mine (e.g. Robertson et al., 1994) and Royal Sheba mine (Snow, 1991), however the regional extent of bedding re-orientation in these areas has not been investigated.

Silica alteration

On a regional-scale the most conspicuous product of alteration is penetrative silicification most clearly expressed as stockworks of quartz veins along the Sheba Bar (Figures 3a; b), but more commonly resulting is pervasive silicification of sandstone and shale destroying pre-existing bedding and foliation planes to form massive grey boulder- outcrops of chert in which specks of sulphide (mainly pyrite) may be present. In the Golden Quarry-Eureka area, zones of massive silicification occur as oval-shaped haloes centered on the Mamba-Tit Bit workings and Golden Quarry-Annie's Fortune workings (Figure 6a); i.e. the same areas most affected by kink folding (Figure 6c), with the highest intensity of alteration, expressed as multiple stages of hydraulic fracturing and stockwork formation occurring along the Sheba shear zone between Oriental and Golden Quarries. Massive silica alteration is also

prominent around Joe's Luck mine, and occurs in Fig Tree shale overlying ore zones such as the MRC in Sheba and Fairview mines (e.g. at GR 310970-7153870 where the silica alteration cap occurs approximately 800 m vertically above the down-plunge extent of the MRC shoot).

Palaeo-stress inversion from fault-slip data

Kinematic data from faults, which at a minimum should include the orientation of the fault plane, the slip direction visible as slickenlines, striations or gouge marks, and the sense of movement can be used to reconstruct palaeo-stress fields (e.g. Angelier and Mechler, 1977). Stress inversion techniques rely on the assumption that the slip direction coincides with the resolved shear stress on the fault plane, and that the set of faults used in the analysis, formed or were active in response to the same stress field. Fault-slip data can be inverted 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 minimisation 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.

In analysing the fault-slip data from gold workings around Sheba mine we have used the 2009 Windows version of the programme 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 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), subsequently optimised by minimising deviation angles (α) between observed and predicted slip vectors on fault planes, and by maximising the shear stress magnitude (σ_t) 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 nature of the calculated 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 mineralisation in the Sheba area as well. The programme output is a diagram displaying the fault-slip data, a histogram of a 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 (Figure 8).

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 minimisation 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. 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 (Figure 2).

The average orientation of P and T axes of unweighted planes, can also be investigated by contouring or, in the case of clustered vectors by calculating a mean vector orientation and vector length, for which we have used the programme StereoWin (Allmendinger, 2002). Orientation data for other geological planes and lines have been analysed in a similar manner using StereoWin.

We note that, 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 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 TENSOR programme.

Since we will use the same datasets to generate a linked Bingham fault plane solution through FaultKin and an improved right dihedral solution using an iterative approach in TENSOR, we will interpret all results as an indication of the palaeo-stress field. In doing this we are aware of the various pitfalls. 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, inhomogeneities in the rock mass etc. (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 we believe that it does provide valuable new insights in the tectonic controls on gold mineralisation in the BGB as discussed in this paper.

Selection of faults for kinematic analysis

In selecting faults for analyses we have focused on abandoned surface gold workings. The old workings are particularly useful for kinematic analyses, because they are invariably developed on-reef (Figure 7). Support pillars left behind in stopes (e.g. Figure 3d) provide excellent sites to observe the shears associated with the highest grade of mineralisation and ensure that our data set can be linked to mineralisation. Working on the assumption that gold mineralisation 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. The surface data are augmented with data from underground workings in the Golden Quarry and in Sheba mine where measurements were taken along the MRC at 24 level, concentrating on shears that are currently being mined.

Brittle-ductile fault zones related to mineralisation can be traced away from mine workings and are commonly associated with conspicuous silicic and potassic alteration zones including quartz veining (e.g. Figures 5c; d). Although such fault zones have been mapped (Figures 2; 6), they have not been used for kinematic analyses with the exception of the Sheba shear zone overlying the Royal Sheba mine (Snow, 1991), where it is mineralised and decorated by sulphide-gold bearing chert alteration zones (Figure 4).

A common problem encountered in selecting data is that some mineralised fractures contain more than one lineation; usually one steep- and one shallow-pitching

lineation. It is generally not clear whether such overprinting lineations reflect separate events or form as a result of slip partitioning in a continuous 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 TENSOR, data points that obviously do not fit the overall population have been removed in an interactive manner, but we have kept such manual cleaning of the data sets to a minimum considering that much of the pre-selection of the data was already done in the field. In calculating a Bingham tensor solution using FaultKin all data points were included.

Results of kinematic analysis

The results of the kinematic analysis are presented in Figures 2, 8, and 9, and summarised in Tables 2 and 3. Bingham tensor solutions interpreted as principle stresses calculated with FaultKin are presented in Table 2 and Figure 2. Stress inversions using the right dihedral method in TENSOR are presented in Table 3 and Figures 2, and 8, with optimisation of results achieved by minimising deviation angles between observed and calculated slip directions. All localities have been given a reference number which corresponds to the numbers given in Figures 2 and 8 to facilitate cross reference.

Bingham tensor solutions in FaultKin

The Bingham tensor solutions provided in Table 2 are expressed as beach balls (with grey areas representing tension dihedrals) in Figure 2. Results are consistent for all data sets with σ_1 being steep ($>75^\circ$) 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. In the Thomas section of Joes Luck the orientations of σ_2 and σ_3 are reversed from the general trend reflecting a radial extensional setting (equivalent to plane strain). At Annie's Fortune mine the calculated orientation for σ_3 is horizontal, trending north. This deviation could be the result of a biased data set, but at the risk of over interpreting, it is noted that the Annie's Fortune pit occurs at the intersection of several differently orientated fracture zones (Figure 6). The average of all 10 calculated σ_1 and σ_3 orientations is $353/83$ and $151/05$ respectively (Figure 9).

Using the relative size of the normalized eigenvalues (ev) calculated from the Bingham distribution tensor, a ratio, Rev, (with $\text{Rev} = [\text{ev}_2 - \text{ev}_3] / [\text{ev}_1 - \text{ev}_3]$) can be derived that is a function of the stress regime in the same way as described for ratio R in TENSOR (constrictional stress: $\text{Rev}=1$ with $\text{ev}_1=\text{ev}_2$; plane stress: $\text{Rev}=0.5$ with $\text{ev}_2=0$; flattening stress: $\text{Rev}=0$ with $\text{ev}_2=\text{ev}_3$). Considering the orientation of the principle stress axes,

the ratio R_{ev} can be adjusted as a ratio R'_{ev} to provide an indication for the calculated stress regime, again following the method of calculating R' in TENSOR (Delvaux and Sperner, 2003). The results indicate that most datasets are consistent with a pure extensional stress regime. Radial extension dominates at Joe's Luck and the Edwin Bray – Golden Quarry's areas, which are areas where silicic alteration is intense. Results from the Royal Sheba area show higher R values consistent with a more trans-tensional setting (Table 2).

Optimised dihedron method in TENSOR

Results for the optimised dihedron method are consistent for all data sets with σ_1 being steep ($>75^\circ$) and variable around vertical, σ_3 being horizontal and directed along a $140^\circ (\pm 15^\circ)$ trend, and σ_2 being horizontal and directed along a $225^\circ \pm 15^\circ$ trend (Figure 8, Table 3). In the Edwin Bray and Golden Quarry's area the orientations of σ_2 and σ_3 are reversed from the general trend reflecting a radial extensional setting (i.e. equivalent to plane strain). At Bonanza the calculated orientation for σ_3 is horizontal, trending to the east-southeast, i.e. somewhat deviating from the general trend probably because the data set is dominated by faults in one particular orientation (i.e. east-west-trending fault planes; Figure 8). The average of all 10 calculated σ_1 and σ_3 orientations is $277/85$ and $134/06$ respectively (Figure 9).

The nature of the stress regime as expressed in R and R' indicates that most datasets are radial extensional (i.e. σ_2 and σ_3 are close to equal), with the data from Royal Sheba and Bonanza being pure extensional and Margaret and the Sheba shear zone near Royal Sheba being transtensional (Table 3).

The quality ranking scheme provided by TENSOR (e.g. Sperner et al., 2003) suggests that most of datasets are of poor quality (Table 3). The quality rankings can be greatly improved if we homogenize our datasets by removing measurements that do not conform to the dominant result. Optimisation of the final result is a trade off between maximising the amount of input data and minimising the deviation angles, bearing in mind that much of the fault slip data was obtained from complex fracture systems probably involving complex local fault interactions. We note that poor quality rankings occur more commonly in datasets where σ_2 and σ_3 are similar (i.e. when R is of low value, $R < 0.25$) due to large variations in the deviation angle, and that by excluding data the orientation of the principle stress axes does not change significantly, but R is forced to higher values approaching 0.5 (i.e. the determined stress regime changes from flattening stress to pure stress). Separate from this, the removal of data in an iterative manner should only be done if we know from outcrop observation that the data may include mixed sets. In many cases apparent incompatible datasets merge in anastomosing patterns and are linked by a shared gold mineralisation event. We have opted to only remove those datasets that are obviously incompatible,

maximising the number of data points considered in the analysis at the expense of negatively influencing the quality ranking.

When combining measurements from pits in the Golden Quarry-Eureka area (114 faults) a result for the palaeo-stress field is obtained that is similar to the average values for σ_1 , σ_2 and σ_3 obtained for both the Bingham tensor and the optimized dihedron methods (Figure 9). The fault planes, when plotted together, show a high degree of scatter with no preferential strike orientation (Figure 8), but with a generally moderate dip. Lineation data is similarly scattered around a vertical axis, but maxima exist in northwesterly and southeasterly orientations, reflecting the orientation of maximum extension (Figure 8).

The calculated R value for the Golden Quarry area is small (0.04; Table 3) indicating radial extension. The use of the larger data set leads to a better constrained answer without a larger proportion of the data having to be discarded. This means that the data collected along the differently orientated fault zones (Figure 6) are kinematically compatible. When plotting the P and T axes for all 114 data points P axes scatter around vertical whereas T axes are distributed around the horizontal plane reflecting the radial extensional nature of the stress field.

Discussion

Gold mineralisation in granite-greenstone terrains is mostly categorised as mesothermal lode gold (Kerrick and Wyman, 1990; Robert et al., 1991) or orogenic gold (Goldfarb et al., 2001; Groves et al., 2003) and linked to Cordilleran-type accretionary settings. 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 mine, have 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). To provide a mineralisation model for the world-class Sheba and Fairview gold deposits and answer the question whether they can be grouped as orogenic gold deposits, we will discuss three questions:

1. Is the Sheba shear zone a major thrust that has controlled gold mineralisation ?;
2. Are the gold fractures 2nd order structures related to the Sheba shear zone ?; and
3. Did mineralisation occur during thrusting or transpression (i.e. with σ_1 horizontal) ?

The answers to these questions have implications for the way gold mineralisation occurred in the BGB and

perhaps, in Archaean greenstone-hosted, orogenic gold deposits in general, and it also provides constraints and updates on the interpretation of the structure of the BGB in the Sheba Hills area as presented by earlier workers such as Ramsay (1963), Anhaeusser (1976) and Anhaeusser (1984).

Is the Sheba shear zone a major thrust that has controlled gold mineralisation ?

Anhaeusser (1976) interpreted the Sheba shear zone as a thrust that originated when rocks in the Ulundi and Eureka synclines (Figure 1) were juxtaposed. He also interpreted the gold-bearing faults and fractures in the Eureka syncline to have formed during D_{3s} arcuation (Table 1). The interpretations of Anhaeusser (1976) are based on earlier interpretations by Ramsay (1963), and have remained unchallenged by later workers (e.g. Snow, 1991; Robertson et al., 1994). De Ronde and De Wit (1994) categorised the Sheba shear zone as a major, northwesterly-verging thrust that formed during D_3 accretion of the greenstone belt between 3.23 and 3.08 Ga (Table 1).

Detailed mapping of the BGB as long ago as Visser et al. (1956) has shown that the contact zone between the Ulundi and Eureka synclines is complex, that the Moodies Group partly unconformably overlies the Fig Tree Group and that at least part of the base of the Moodies Group and underlying Schoongezicht Formation is tectonically duplicated.

Our observations indicate that the Sheba shear zone is a complex fracture zone that developed along the unconformable contact between folded Fig Tree and Onverwacht Group rocks and overlying Schoongezicht Formation and Moodies Group rocks. Similar to observations made by Lowe et al. (1999) we note that the agglomerate and conglomerate overlying the unconformity contain fuchsite schist, laminated chert and mica schist fragments, and that the unconformable contact transects earlier tight to isoclinal folds (Figures 1; 2a; b), all indicating that the Fig Tree-Onverwacht sequence was folded and metamorphosed before deposition and folding of the Schoongezicht Formation and Moodies Group. We also observe that where the angular unconformity merges with low-angle thrusts and mylonite zones that occur as stratigraphy-parallel shear zones within the Moodies Group (characterised by ferruginous ultramylonitic shale units; Figure 5a), the contact zone becomes a ductile shear that intensifies from northeast to southwest. Our observations are entirely consistent with those made by Lowe et al. (1999) for the Moodies-Fig Tree contact south of Barberton town (Table 1). We therefore suggest that the Sheba shear originally formed as a low-angle basal thrust moving clastics of the Schoongezicht Formation and Moodies Group over folded Onverwacht Group and Fig Tree Group, and duplicating Moodies Group rocks prior to the formation of the Eureka syncline (i.e. similar to D_3 events described by Lowe et al., 1999; Table 1). The Sheba shear represents a folded earlier thrust, one

of many in the sequence, and it is not a major strike-parallel accretionary structure as envisaged by Ramsay (1963) or De Ronde and De Wit (1994).

Between Nil Desperandum mine and Golden Quarry, the sheared contact zone was reactivated along a series of west-southwest-trending, brittle-ductile shear zones that preserve excellent shear sense indicators all indicative of a normal-sinistral sense of movement (Figures 2; 4; 8; 9). These brittle-ductile normal faults are discontinuous structures with strike lengths of several hundred meters that are arranged in an en-echelon fashion (Figure 3a) accommodating displacement in the order of tens of meters; i.e. they are not major structures in terms of offset.

Are the gold fractures second order structures related to the Sheba shear zone ?

Gold fractures in the Golden Quarry – Eureka area (Figure 6a, b) consist of 10 m-scale fractures that anastomose and are arranged in *en-echelon* fashion within envelopes that define 100 m-scale fracture zones such as the Margaret, Mamba and Eureka fractures, which trend predominantly northeasterly to east-northeasterly, west-northwesterly and north-northwesterly with variable, moderate dips (Figures 6; 7). The 10 m-scale fractures define a regular pattern of Riedel, anti-Riedel and P-Shear arrays within the 100 m-scale fracture envelopes, consistent with a normal sense of movement on the fault zones. The fracture zones form a regular pattern that can be extended across the Sheba-Fairview area, and are related to kink folding and silica alteration (Figure 6).

We note that the fracture zones truncate all earlier, large-scale ductile geometries including the D_{3s} arcuation of the Eureka syncline. The fractures do not occur along the axial planar direction of this arcuation nor do they occur as compressive fractures along the inner arc of the refolded Eureka Syncline as suggested by Anhaeusser (1976). For example, the west-northwesterly-trending gold fracture zone passing through Oriental Quarry and Nil Desperandum mine can be traced through the No.5 workings to the Victory Hill workings 1500 m west as a continuous shear fracture with a normal sense of movement (Figure 2a). Likewise, the north-northwesterly-trending gold fracture zone passing through Annie's Fortune quarry and the Eureka workings can be traced to Joe's Luck, and the north-northeast-trending Sheba Bar can be traced to Bonanza mine (Figure 2). In other words there exists a regular pattern, of straight, fracture zones, that are gold-bearing and that overprint all regional ductile folding and shearing events. These fractures are extensional in nature. The alteration and kink folding associated with the mineralised fractures overprint earlier fabrics. In the Golden Quarry and Royal Sheba areas the Sheba shear zone is overprinted by the fractures and locally refolded to relatively flat orientations together with rocks in especially the Moodies Group.

Did mineralisation occur during thrusting or transpression?

In determining whether gold mineralisation is related to compressional or extensional structures it is absolutely paramount that kinematic data is obtained from the shear zones that are mineralised, and that movement on these shear zones is unambiguous. In conducting our kinematic analysis we investigated stopes in surface workings where the exact shear zones mined can be measured. Over 95% of the several hundred shear zones measured have a normal movement sense. Complications do occur, for example many slickensided surfaces contain more than one lineation. Such lineation variations are generally consistent with the final result (e.g. Figure 8) reflecting progressive slip partitioning on a transtensional fault with sequential dip-slip and strike-slip steps. We note that in some workings reefs are truncated and offset by later reverse faults (e.g. Margaret mine; Snow, 1991). Apart from this, scale-dependent strain partitioning, and complex fault interactions may result in localised thrusting.

The calculated palaeo-stress fields determined from fault-slip inversions are similar across all workings, both underground and on surface, irrespective of what method was used, with σ_1 being vertical, σ_2 being horizontal, trending towards 235° and σ_3 being horizontal, trending towards 145° (Figures 2; 8; Tables 3; 4). The different methods show slight differences in the calculated stress regime with TENSOR more strongly indicating radial extension and FaultKin tending towards pure extension, however the regional orientation of the maximum compression and the extension directions is clear.

We note that the kinematic analyses conducted can be improved if fault-slip data is supplemented with a full characterisation of the analysed fault planes, which includes estimates for gouge thickness, displacement and trace lengths (e.g. Marrett and Allmendinger, 1990). Because many gold workings are difficult to access, exposure of mineralised faults is discontinuous and variable at best, and because exposure of mineralised faults outside the workings is generally zero, we have chosen to analyse all faults as if they are of equal importance and size. Considering the highly discontinuous nature of the mineralised faults (e.g. Figures 6, 7) this assumption is reasonable.

Implications

The short answer to the three questions posed above is that gold mineralisation occurs along fractures that formed independent from the Sheba shear zone, and that the Sheba shear is not a major, strike-parallel thrust formed during terrane accretion, but rather a sheared and folded unconformity, re-folded by the mineralised fractures during a later extensional event. These observations contradict earlier workers in the area who linked mineralisation to thrusting or transpression. De Ronde and De Wit (1994) and De Ronde et al. (1991) comment on the fact that gold mineralisation occurred at

the onset of a sudden shift from transpressional to transtensional tectonics between 3.13 to 3.08 Ga, but they note that mineralisation formed in close spatial association with large D_3 thrusts (Table 1), and, most importantly, that normal faulting observed in Fairview mine displaces and, therefore, post-dates gold mineralisation. Anhaeusser (1976), following Ramsay (1963) assumed that the Sheba shear was a thrust reactivated during refolding of the Eureka syncline. Robertson et al. (1994) provide detailed descriptions of the mineralised shears, but again assume that the faults are thrusts or thrust-related. Mine exploration reports make mention of normal displacements across reefs, but interpret this to be the result of a later unrelated normal faulting phase, following De Ronde and De Wit (1994). All previous studies critically lack kinematic data and a systematic analysis of the regional network of mineralised shear zones, and all heavily rely on models that link gold mineralisation to thrusts, formed during late tectonic compressional or transpressional movement (e.g. Sibson, 2001, 2004; Cox, et al., 2001; Kerrich and Wyman, 1990; Groves et al., 2003).

Gold mineralisation in the Sheba-Fairview area occurs along a network of complexly interconnected fracture zones that cross-cut all earlier ductile structures including the constrictional fold structures that have been linked to doming of the Kaap Valley pluton and Nelspruit batholith (Anhaeusser, 1976; Harris et al., 1995). Gold mineralisation is, therefore, late and probably post-dates the main stage of potassic plutonism involving emplacement of the Nelspruit batholith at 3105 ± 3 Ma (Kamo and Davis, 1994). The Sheba shear zone was not a controlling structure, but instead was crosscut and folded during the mineralisation event. The network of mineralising shear zones formed in an extensional environment in which σ_1 was vertical and σ_3 orientated in a horizontal northwest-southeast direction. The stress regime was predominantly radial extensional, with maximum extension occurring at right angles to the greenstone belt, suggesting the entire system was in extensional collapse as mineralising fluids entered from depth. On 10 m to 100 m scales the mineralised fractures are arranged in overlapping Riedel, P-shear and anti-Riedel arrays. In the Margaret and Mamba workings the R-shears contain the highest grade mineralisation (Figure 7), whereas in the MRC, mineralisation is best along fracture intersections (Robertson et al., 1994). In the Golden Quarry-Eureka area, Riedel arrays can be observed in individual mines on a 10 m scale and between different mines on a 100 m scale. This raises the important question whether such scaling can be stepped up a dimension or two, and whether the Sheba mine can be linked to, for example, the Clutha and Consorts mines to the northwest, by applying a similar, but larger-scale en-echelon arrangement of regularly spaced mineralised fracture systems.

Gold mineralisation was accompanied by kink folding and extensive silicification. The kink folds

resemble those described by Anhaeusser (1976) as part of his (post-mineralisation) D_{4s} event. Silicification shows a clear spatial association with the mineralised zones and appears to occur as a halo around mineralised areas (Figure 6a), thus providing useful information for exploration targeting. Mineralisation can also be linked to the emplacement of porphyry dykes. In the Golden Quarry area, feldspar porphyry dykes intrude along the footwall of the quartz vein stock work of the Sheba Bar (Figure 3c), and therefore post-date a major phase of silicification. The same porphyry is altered, sheared and mineralised. These relationships suggest that emplacement of porphyry dykes coincides with mineralisation. De Ronde et al. (1991) dated an altered, mineralised quartz porphyry (different in appearance to the coarse-grained feldspar porphyry at Golden Quarry) in Fairview mine at 3126 ± 18 Ma, with mineralisation linked to alteration dated at 3084 ± 18 Ma. A similar link between mineralisation and pegmatite emplacement was made by Harris et al. (1995) for sheared pegmatite veins in Consort mine. The pegmatite veins have been linked geochemically to the nearby ~ 3.11 Ga Nelspruit batholith and were dated at 3081 ± 54 Ma (Rb-Sr errorchron). Thus, mineralisation 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 3.11 Ga.

This brings us back to the question whether the gold deposits at Sheba and Fairview mines should be classified as orogenic gold or not. The distribution of mineralised fractures indicates that the mineralising structures are not related to major strike-parallel shear zones linked to terrane accretion (e.g. De Ronde and De Wit, 1994), and that they could be significantly younger. The thrusts probably demarcate areas of higher permeability and they are, therefore, excellent fluid traps, however that does not mean that the thrusts are generically related to mineralisation. Mineralisation occurred well after accretion of the greenstone belt and can be linked to extension of the craton, which at the time had probably already acquired the thick lithospheric root characteristic for Archaean granite-greenstone terrains and distinct from modern day accretionary margins (e.g. Bleeker, 2002). Such timing broadly overlaps with the onset of deposition of rift and platform sequences on top of the stabilised Kaapvaal Craton, commencing with the infill of graben systems by sediments and volcanics of the Dominion Group dated at 3074 ± 6 Ma (Armstrong et al., 1991), which subsequently led to the opening of the Witwatersrand and Pongola basins. Our evidence indicates that mineralisation is not orogenic, but must be linked to an extensional event affecting the Kaapvaal Craton.

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