

**ECONOMIC GEOLOGY  
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University of the Witwatersrand  
Johannesburg

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**CONTROLS AND STRUCTURAL DEVELOPMENT OF  
EPIGENETIC MESOTHERMAL GOLD MINERALISATION  
IN THE SABIE-PILGRIM'S REST GOLDFIELD,  
EASTERN TRANSVAAL, SOUTH AFRICA**

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by

**M. HARLEY<sup>1,2</sup> and E.G. CHARLESWORTH<sup>2</sup>**

(<sup>1,2</sup>, *Geological Survey of South Africa,  
Private Bag X112, Pretoria.*

<sup>2</sup> *Department of Geology, University of the Witwatersrand,  
P.O. WITS 2050, South Africa)*

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**September, 1993**

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**ABSTRACT**

Bedding-parallel thrust-hosted gold veins are developed in the Sabie-Pilgrim's Rest goldfield, eastern Transvaal, South Africa. The reefs display a complex history characterised by temporally and spatially overlapping events of mineralisation and deformation. Recognition of the episodic reactivation of these low angle (5-10°) thrust faults implicates high fluid pressures (equalling or exceeding lithostatic pressures). Geochemical constraints limit the amount of fluid-rock interaction and the occurrence of transgressive mineralisation within the Archaean granitoid basement suggests that the high pressure fluids originated at depth beneath the Transvaal Basin.

Similarities exist between gold deposits of Sabie-Pilgrim's Rest and Telfer, Western Australia as well as Passagem de Mariana, Minas Gerais, Brazil. All deposits are sub-parallel to the enclosing bedding which is shallowly inclined. Furthermore, they are also hosted by contractional deformational structures and are clearly epigenetic in origin.

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## CONTROLS AND STRUCTURAL DEVELOPMENT OF EPIGENETIC, MESOTHERMAL GOLD MINERALISATION IN THE SABIE-PILGRIM'S REST GOLDFIELD, EASTERN TRANSVAAL, SOUTH AFRICA

### INTRODUCTION

The Sabie-Pilgrim's Rest goldfield is located along the escarpment of the Transvaal Drakensberg range, in the eastern Transvaal. Within the juvenile drainage system, alluvial gold mineralisation was first exploited in 1872, near Pilgrim's Rest. Shortly thereafter, the mineralised veins were located in the hills flanking the river valleys. Approximately 180 mT of gold has been produced since the 1880's. At present, only one producing deposit remains in the goldfield, namely the Elandshoogte Mine; this is an underground operation in the southern part of the goldfield (Fig.1). In addition to this locality, field data have been collected from five, well-exposed, non-operational deposits, spaced throughout the stratigraphy of the goldfield (Fig.2). This paper presents new data regarding structural control to epigenetic gold mineralisation and the structural development of gold deposits in the Sabie-Pilgrim's Rest goldfield. The authors also make comparisons with gold deposits elsewhere, which display similar styles of mineralisation.

### GEOLOGICAL SETTING

The goldfield is underlain by the preserved, shallow westerly-dipping flank of the early Proterozoic Transvaal Basin. The Transvaal Sequence consists of laterally restricted protobasinal assemblages of siliciclastic sedimentary rocks and interlayered volcanic units, the Wolkberg and Godwan Groups (Button, 1986; Myers, 1991). The protobasinal Groups overlie the Archaean Nelspruit granitoid batholith (Robb *et al.*, 1983) and the northwesterly extension of the Jamestown ultramafic schist belt (Visser, 1956). The Black Reef Formation unconformably overlies the protobasinal units, and represents a sheet-like unit which blankets the moderately uneven palaeotopography. This thin (1-50m), but laterally extensive, siliciclastic unit forms the basal portion of the overlying dolomite-dominated Malmani Subgroup. Most of the economic gold mineralisation of the Sabie-Pilgrim's Rest goldfield is hosted within the Malmani Subgroup rocks. The lowermost Oaktree Formation consists of mixed siliciclastic and carbonate rocks, whereas the overlying Monte Christo, Lyttelton and Eccles Formations are dominated by carbonates with subordinate shales and occasionally developed quartzite units. A regional unconformity is located at the base of the Rooihoogte Formation, represented by the Bevet's Conglomerate Member (Fig.2). This unit is overlain by quartzites and shales of the upper Rooihoogte and Timeball Hill Formations of the Pretoria Group (Button, 1973; Eriksson and Clendenin, 1990). The bulk of the Pretoria Group consists of alternating arenaceous and argillaceous formations, with some interlayered volcanic units and in the eastern Transvaal attains a thickness of up to 10505m (S.A.C.S., 1980).

The Bushveld layered mafic complex is intrusive into the upper Pretoria Group. The eastern lobe of this complex trends north-northeast and is located approximately 65km to the west of the Sabie-Pilgrim's Rest goldfield. Pre-Bushveld mafic sills and dykes (Sharpe, 1984) are prominently developed throughout the Sabie-Pilgrim's Rest goldfield. The

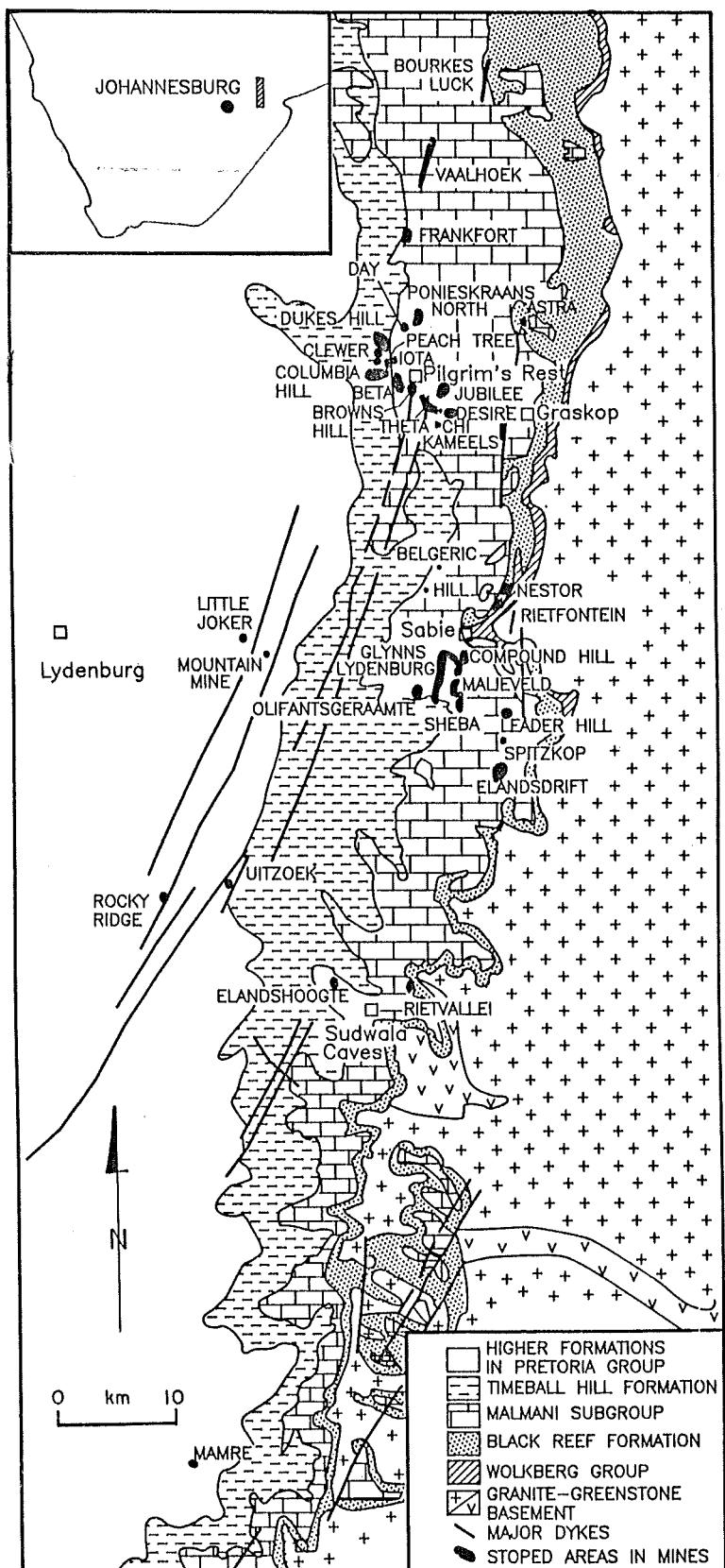
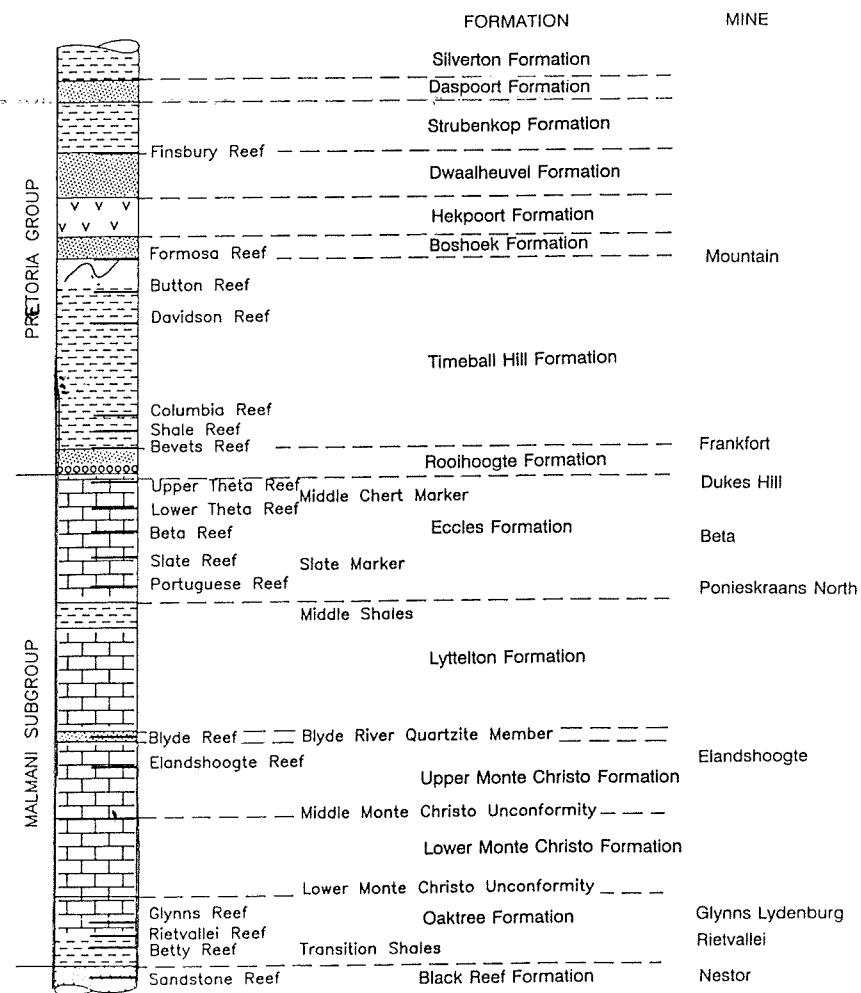


Figure 1: Regional geological map of the Sabie-Pilgrim's Rest goldfield, showing the localities of significant gold mines.



*Figure 2: Stratigraphic column of the lower Transvaal Sequence with the positions of main reefs indicated.*

dominant dyke trend is 010-020°, with a minor trend of 110-120° also represented. It must be stated that the ages of dykes occupying this latter trend are not clearly known; further the dominant trend of 010-020° is displayed by dykes of several ages, ranging from pre-Bushveld to younger. Bushveld-related sills are abundant in the Pretoria Group and may reach up to 500m in thickness. Within the Malmani Subgroup, sills are approximately 10m in thickness. Compositinally, the pre-Bushveld intrusions are mafic, tremolite-actinolite-chlorite rocks (Sharpe, 1984). The less well developed syn-Bushveld noritic and pyroxenitic sills are largely restricted to the Pretoria Group lithologies.

Epigenetic gold mineralisation is also developed within the Archaean granitoid basement, along the eastern flank of the Sabie-Pilgrim's Rest goldfield. Here, steep easterly to vertical dipping gold-quartz-sulphide veins trend subparallel to the north-northeast oriented pre-Bushveld dyke swarm. Bedding-parallel veins of similar composition (termed flat reefs)

are irregularly distributed throughout the lower Transvaal stratigraphy. By far the most gold from the Sabie-Pilgrim's Rest goldfield has been produced from the flat reef deposits. Most of these deposits occur within the Malmani Subgroup, and to a lesser extent within the underlying Black Reef Formation and the overlying lower Timeball Hill Formation (Fig.2). Steeply-dipping, transgressive gold-quartz veins occur as arrays, commonly associated with flat reefs. These so-called leader veins have been exploited on small scales in many localities within the goldfield. Flat reef deposits are typically associated with lithological contact zones, e.g. carbonaceous shale layers within dolomites, shale-quartzite contacts, and dolomite-mafic sill contacts.

### *Flat Reefs*

The reefs investigated in this study occur throughout the Malmani Subgroup and lower Pretoria Group stratigraphy (Fig.2). Literature studies (e.g. Hall, 1910; Wybergh, 1925; Reinecke and Stein, 1929; Swiegers, 1949; Zietsman, 1967; Tyler, N. (1986); Tyler, R., 1989) indicate that these reefs are entirely typical of the documented flat reefs within the goldfield. A typical example of a flat reef was mined at Glynn's Lydenburg, which is the largest mine in the goldfield. The stoped area extends approximately 7000 by 400 m and trends north-northeast. Elandshoogte Mine is a more typical size of deposit and has a stoped dimension of approximately 700 by 300m. An apparent north-northeast trend is present in this case as well. Flat reefs swell and pinch down-dip and along strike. Average reef thickness is of the order of 20-30cm, but ranges between 0.5cm and 2m. The flat reefs consist mainly of quartz, with between 10 and 20% of the reef volume occupied by sulphide minerals. A complex sulphide paragenesis has been recognised (Swiegers, 1949; Meyer *et al.*, 1986; Harley, 1993). The most abundant sulphide mineral is coarse-grained pyrite. Arsenopyrite is locally abundant in some deposits (e.g. at Elandshoogte and Poniekranz North; Swiegers, 1949) and commonly occurs intergrown with the pyrite. Gold occurs as round inclusions (10 $\mu$ m) within pyrite and also in microveins developed in fractured pre-existing sulphides (Swiegers, 1949). Chalcopyrite, complex sulphosalts and rare sulphide minerals (e.g. bismuthinite, galenobismutite) occur, sometimes accompanying gold in the fractures. In general, most of the gold is late and post-dates the majority of the reef minerals.

### *Vertical Reefs*

Vertical Reefs as mentioned previously, are mainly present within the Archaean granitoid basement, but also occur within the overlying sedimentary rocks. The most productive vertical reef was the Rietfontein Reef, situated immediately east of the town of Sabie. The strike length of this reef is approximately 5km and the reef has been traced over a vertical distance of approximately 300m, although the lower limit of mineralisation has not been located. The largest vertical reef is the Bokwa-Stoltz Reef which is situated in the southern and central portions of the goldfield. This quartz vein system has a total strike length of approximately 47km and has been observed cutting stratigraphic units separated by 1000m true thickness (Visser and Verwoerd, 1960). The maximum recorded thickness of this reef is approximately 5m (Visser and Verwoerd, 1960). The small Rocky Ridge Mine (Fig. 1) is the only deposit situated along this major reef system. Unlike the flat reefs, mineralisation within vertical reefs is sporadically developed and is of a consistently lower

grade. The mineralogy of typical vertical reef deposits is similar to that of the flat reefs (Boxall, 1938; Visser and Verwoerd, 1960). Pyrite, chalcopyrite and bismuthinite are commonly developed in both reef styles. Numerous other vertical reef occurrences have been recorded (Visser and Verwoerd, 1960) from throughout the goldfield and have been described from every stratigraphic unit which hosts flat reef mineralisation.

### *Leaders*

Leader veins are commonly seen branching into the hangingwall above or footwall below flat reefs. These veins are almost always subvertical to steeply inclined and may extend for up to 20m from the flat reef and taper closed at their tips (e.g. veins above the Formosa Reef in the Mount Anderson area). In certain cases Leader veins were mined together with the associated Flat Reef, the best example being from Nestor Mine (Fig. 1). At Nestor Mine the "Copper Blow" and the "Pyrite Blow" were mined in conjunction with the Sandstone Reef. These two "blows" consisted of well-mineralised, densely nested leader vein arrays projecting from the Sandstone Reef into the hangingwall. The strike length of these blows was less than 100m and the mined height above the Sandstone Reef was less than 10m. Interestingly, the two blows had different mineralogies, consisting predominantly of pyrite and chalcopyrite  $\pm$  pyrite respectively, with quartz gangue being ubiquitously present. In other cases, leader reef arrays occur without any associated flat reefs being obviously present (e.g. at Leader Hill, north of Sabie). Leader vein arrays may consist of subparallel vein sets, or may contain orthogonal, cross-cutting veins, comprising an open stockwork. Early in the history of the goldfield, leader veins were exploited by small-workers, however, subsequent mining ventures have tended to target flat reef deposits. There is also a paucity of mineralogical data pertinent to Leader veins and very few detailed descriptions of their geology.

## **STRUCTURAL DEVELOPMENT OF FLAT REEFS**

Flat reef deposits hosted within dolomites are commonly located at the contact with narrow (0.5-1m) carbonaceous shale bands interlayered within the carbonates. One of the best exposed examples is the Elandshoogte Reef. Other similar examples include Glynns Reef (e.g. Malieveld Mine), the Theta Reef (e.g. Frankfort Mine), and Rietvallei Reef (e.g. Rietvallei Mine) (Figs. 1 & 2). The Formosa Reef in the Little Joker and Mountain Mines is situated at the contact between the quartzite of the Boshoek Formation and shales of the underlying Timeball Hill Formation. The Bevets Reef (at Frankfort Mine) occurs at the contact between conglomerate and quartzite with the overlying carbonaceous shales of the Rooihooogte Formation. The Finsbury Reef, the highest stratigraphic reef known is located at the contact between the Dwaalheuvel Formation quartzites and the overlying Strubenkop Formation shales. In other cases, an obvious lithological control localising a flat reef is less obvious. For example, the Sandstone Reef (in Nestor Mine) occurs *within* the Black Reef Formation; similarly, the Button and Davidson Reefs are located *within* shales of the Timeball Hill Formation. In some cases authors have described a narrow shale band within the Black Reef Formation, with which mineralisation was associated. This shale band is not ubiquitous and is generally removed during mining activities. In the case of the Button and Davidson Reefs, it appears that the shales in the hangingwall are more siliceous than those in the footwall of the reefs, although no data exist to support this.

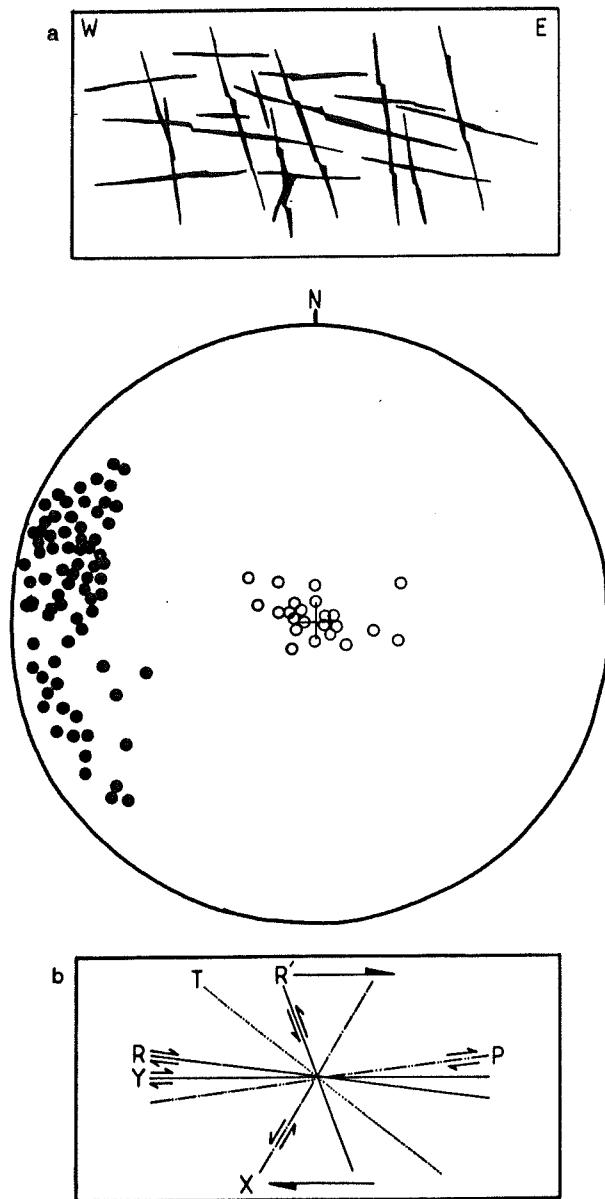
Detailed work at Elandshoogte, Malieveld, Nestor and Frankfort Mines has allowed the development history of a typical flat reef to be described. The earliest recognised deformation results in the formation of subhorizontal cleavages or micro-shear zones in the immediate wall-rocks to the reef. Where shales are present (e.g. Elandshoogte) close-spaced cleavages are well-developed. In the case of the Sandstone Reef, narrow zones (1-2cm) of flattened quartz grains, enveloped in undulose laths of muscovite, occur in the immediate hanging and footwall to the reef. Shales around reef units typically consist predominantly of fine-grained muscovite together with carbonaceous material; this is also true of many shales within the Malmani Subgroup (Meyer and Robb, 1993). Fine-grained euhedral pyrite occurs as laminae, oriented subparallel to the cleavage within the shales. Crystal faces of the pyrites cross-cut the cleavage in the shales. Quartz-fibre-filled pressure shadows are commonly developed around pyrite crystals; the quartz fibres are aligned in the plane of the shale cleavage.

Dolomite-hosted veins commonly display silicification envelopes, between 0.5 to 1m in width, surrounding the reef zone. Within these silicified envelopes the dolomite is totally replaced by microcrystalline quartz. Sedimentary structures such as oolites and stromatolites are obliterated and fine-grained muscovite and pyrite occur as sparse disseminations within the replaced rock. In the case of reefs hosted in shale and quartzite, disseminated muscovite and pyrite may occur for up to 1m from the reef as an alteration envelope. Narrow, steeply-dipping, quartz-carbonate-pyrite veins or quartz-pyrite veins transgress the alteration zones but these veins are themselves cut by the reef. This field evidence suggests that the alteration surrounding the reef zones pre-dates the main phase of reef emplacement.

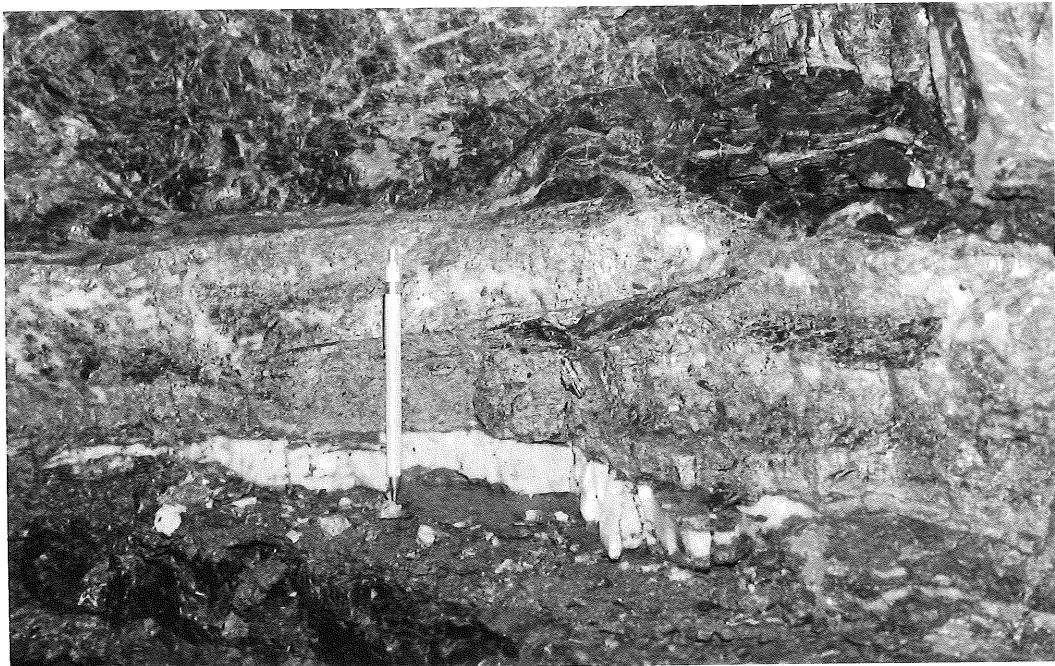
Narrow subhorizontal and steeply dipping vein sets frequently occur in the immediate footwall and hangingwall to the reef. The orientations of these quartz veins in Elandshoogte Mine are presented in Figure 3 and are consistent with emplacement within dilated reidell and reidell conjugate fracture sets within the footwall and hangingwall to the reef zone (Harley, 1993). Asymmetric folds in shales within the reef zone typically have shallowly westward dipping axial planes. The vergence of these structures is broadly to the east-southeast. Narrow (1-5cm) ribboned or laminated quartz veins are commonly developed within shales associated with gold-bearing reefs within the goldfield (Fig. 4). These veins preserve narrow wall-rock septa of carbonaceous shale and may extend for up to 3m. Internally, these veins consist of massive, coarse-grained anhedral quartz, and may have selvages of pyrite along one or both margins. Some veins, however, contain no sulphide minerals at all, and may or may not include carbonate minerals.

## MAIN STAGE OF REEF EMPLACEMENT

Coarse-grained pyrite overgrows and envelopes the fine pyrite lamellae within the shales. Commonly, this pyrite is subhedral to euhedral in form and is frequently associated with coarse-grained, equant arsenopyrite. These two minerals are frequently intergrown and do not show evidence of replacement; rather the textural relationships suggest contemporaneous development. Coarse-grained sulphide aggregates display well-developed cataclastic textures, in the form of fracture networks. The fractures present occur along and across grain-boundaries. Cross-cutting relationships are evident within the fracture arrays, with some fractures displacing others. Micro-veinlets of quartz invade the fractures within



*Figure 3: Lower hemisphere equal area projection showing the orientation of steeply inclined veins (filled circles;  $n = 125$ ) and subhorizontal veins (open circles;  $n = 30$ ) in the footwall and hangingwall of the Elandshoogte Reef. Inset (a) shows an east-west profile depicting the typical forms of the two vein sets as seen underground. Inset (b) shows the profile view illustrating the elements of a brittle shear system (after Bartlett et al., 1981),  $R$  and  $R'$  are the reidell and reidell conjugate respectively. Note the offsets of the veins in inset B constrain the sense of shear, which is consistent with that illustrated in inset B for each of the vein orientations.*



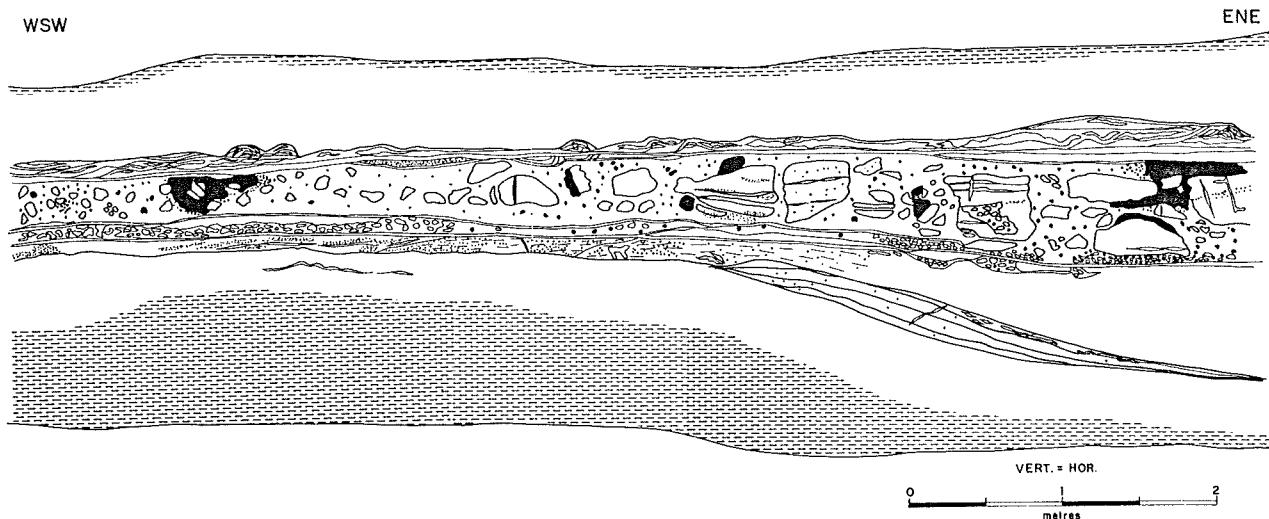
*Figure 4: White unmineralised ribboned veins beneath a well-mineralised section of the Elandshoogte Reef, Elandshoogte Mine.*

the sulphide aggregates; these veinlets are continuous with quartz which now envelopes the sulphides. White, milky quartz makes up the bulk of any particular flat reef. The internal structure of a flat reef is complex and consists of two main components, namely: narrow, laminated, ribbon veins and massive, structureless, quartz-dominated zones. The massive quartz zones truncate the laminated ribbon veins. In many cases, the laminated veins are preserved along the margins of the more massive reef, which can occur as a core zone of the flat reef; the emplacement of the bulk of massive quartz within the reef is generally regarded as the main stage of reef emplacement. The relative proportions of ribboned and massive reef vary widely, both on a mine scale and between individual reef units. For example, the Bevets Reef (in Frankfort Mine) consists predominantly of ribboned vein segments, whereas the Formosa Reef (at Mountain Mine) and the Elandshoogte Reef (at Elandshoogte Mine) contain significant proportions of massive reef.

Breccias are commonly developed within the massive reef component (Fig. 5). Two classes of breccia are distinguished on the basis of their internal structure; these are termed "chaotic" and "mosaic" breccias respectively. The former consist of a densely packed assemblage of small (2-10cm) clasts of shale and silicified dolomite, supported in a milky quartz matrix. Sulphide minerals are commonly present within the quartz. The clasts are commonly equant to subequant and tend to have a similar size distribution. Mosaic breccias consist of highly angular, silicified, dolomite fragments, surrounded by vein quartz and associated sulphides. Clasts, which are composed exclusively of silicified dolomite, have a wide range of sizes between 2-80cm, and vary from plate-like to blocky forms (Fig. 5). The jig-saw nature of the clasts of these breccias clearly indicates an origin through processes of

**TABLE 1: A synoptic summary comparing and contrasting geological features of the Sabie-Pilgrim's Rest goldfield with Passagem de Mariana gold mine, Brazil and Telfer gold mine, Western Australia. Data sources cited in text**

CHARACTERISTICS	SABIE-PILGRIM'S REST E.TRANSAAL REP. OF SOUTH AFRICA	TELFER PATERSON RANGE W.AUSTRALIA	PASSAGEM DE MARIANA MINAS GERAIS: BRAZIL
AGE OF DEPOSIT	Early Proterozoic	Late Proterozoic	Middle to Late Proterozoic
SETTING	Intracratonic basin with quartz veins, concordant and discordant to bedding, modified by bedding-parallel faulting	Intracratonic basin with veins concordant and discordant to bedding, localised within periclinal anticlines ; evidence of bedding planeslip.	Intracratonic basin; concordant and discordant veins to bedding, localised around a major low-angle thrust fault.
SIZE	$\pm 180$ T Au	150 T Au	$\pm 60$ T Au
GRADE	$8 \pm 3$ g Au / T	$\pm 3$ g Au / T	$10 \pm 4$ g Au / T
MINERALISATION STYLE	Stratiform to stratabound quartz reefs + stockworks + transgressive veins.	Stratiform to stratabound, quartz sulphide/oxide reefs; extended over 20 km <sup>2</sup> , also some transgressive veins.	Stratiform to stratabound quartz sulphide tourmaline reef, and minor pyrrhotite-bearing amphibolite schist
HOST LITHOLOGIES	Carbonaceous shales in dolomitic carbonates, zones of competency contrast at lithological contacts and along unconformities.	Calcareous, carbonaceous and argillaceous metasediments.	Quartz-carbonate-biotite schist, sericitic and carbonaceous phyllite, dolomite, sericitic quartzites beneath the contact with overlying itabirite.
METAMORPHIC GRADE	Sub-greenschist to greenschist	Sub - greenschist	Upper greenschist to lower amphibolite
ORE MINERALOGY	Au-pyrite-chalcopyrite-arsenopyrite-bismuthite-fahlore $\pm$ sphalerite $\pm$ galena	Au-pyrite-chalcopyrite $\pm$ bornite $\pm$ chalcocite $\pm$ galena $\pm$ sphalerite	Au-arsenopyrite-pyrrhotite-pyrite $\pm$ chalcopyrite $\pm$ galena $\pm$ berthierite $\pm$ löllingite $\pm$ bismuthinite
GANGUE	Quartz, sericite, carbonate	Quartz, sericite, tourmaline, monazite, xenotime, rutile	Quartz, ankerite, tourmaline (dravite), sericite
ALTERATION	Silicification, Sulphidisation Sericitisation, Carbonation	Silicification, Sericitisation, Sulphidisation, Tourmalinisation Carbonation	Tourmalinisation, Silicification, Sulphidisation, Carbonation, Sericitisation
ORE-METAL ASSOCIATION	Au - Fe - Cu - As - Bi $\pm$ Sb $\pm$ Zn $\pm$ Pb	Au - Fe - Cu - As - Bi - Co $\pm$ Ni $\pm$ Pb $\pm$ Mo	Au - As - Fe - Cu - Bi $\pm$ Pb $\pm$ Sb
FLUID CONDITIONS			
TEMPERATURE ( Th )	200 - 400° C	225 - 440° C	190 - 220° C
GEOTHERMOMETRY	Asp.: 300 to 350° C		
CO <sub>2</sub> CONTENT	Moderate to high Variable up to 30 mole %	Variable up to 10 mole %	Dominance of pure CO <sub>2</sub> over H <sub>2</sub> O solution is reported.
PRESSURE	> 2.5 kb	> 2 kb	1.2 - 1.4 kb
SALINITY	Variable up to 35 equiv. Wt % NaCl.	Variable up to 50 equiv. Wt % NaCl.	Low; 1 to 2 equiv. Wt % NaCl .
SULPHUR ISOTOPIC DATA		$\delta^{34}$ S + 2.45 to 9.30, Av. + 4.92 for Telfer Formation. $\delta^{34}$ S + 1.6 to + 4.60, Av. + 3.29 MVR, Main Dome	
TRANSPORT MECHANISM	Reduced sulphur complexes	Chlorine $\pm$ Reduced sulphur complexes	Reduced sulphur complexes
DEPOSITIONAL MECHANISM	Variable	Fluid mixing + interaction with host. Changes in T and Comp.	Interaction with host $\pm$ cooling ?
FLUID SOURCES	Magmatic	Magmatic $\pm$ basinal	Unknown



*Figure 5: Detailed map section of the Number 7 Gulley, Elandshoogte Mine showing the occurrence of breccias within the reef.*

disaggregation of the reef wall-rocks. Narrow quartz veinlets may be preserved within larger breccia clasts. Relationships between the enclosing quartz and the clast-hosted veins suggest that the latter represent a very early phase of reef development, which is largely overprinted during subsequent events. The apices of the breccia clasts are sharply preserved and there is no evidence of significant dissolution of the clasts. Chaotic breccias tend to occur as laterally restricted, narrow, pod-like bodies, frequently less than 10m long, developed within and occasionally above the reef unit. Mosaic breccias commonly occur within the massive reef. Laterally restricted bodies of mosaic breccia grade into massive quartz-dominated reef. Breccia zones tend to be associated with zones of reef thickening and may reach 3.5 m in total thickness, whereas the massive reef is rarely greater than 0.8m in thickness.

#### LATE-STAGE MINERALISATION

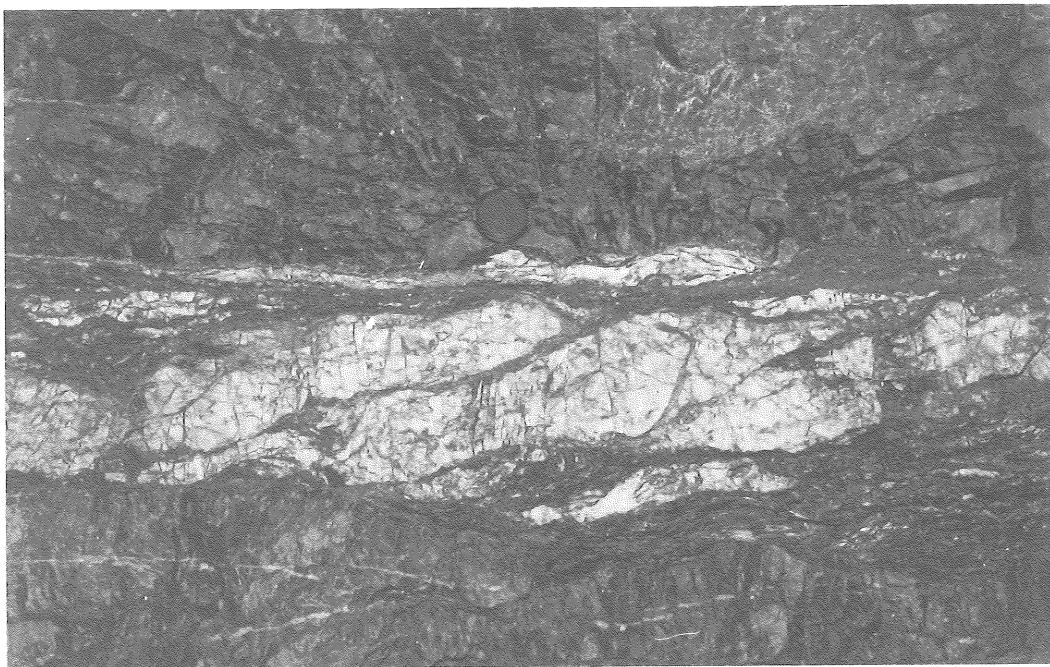
A complex suite of sulphides and native elements is present within the massive reef (Table 1). Frequently, these minerals, which include chalcopyrite, fahlores, bismuthinite, sphalerite, gold and native bismuth are commonly present within quartz micro-veinlets within fractured, pre-existing pyrite and arsenopyrite. Because these quartz microveinlets are

continuous with the massive quartz which characterises the main stage of reef emplacement, it is believed that the late stage mineralisation was synchronous with the deposition of massive quartz within the reef. Chalcopyrite is overwhelmingly dominant in all reefs. Tennantite is the only fahlore mineral present in the Elandshoogte Reef, whereas intermediate tennantite-tetrahedrite species are present in the Theta and Beta Reefs (Boer *et al.*, 1993). Bismuthinite and native bismuth occur in most reefs (Swiegers, 1949; Boer *et al.*, 1993) as small (5-10 $\mu$ m) grains; sphalerite is rare. Complex polymetallic grains may occur. In most cases, chalcopyrite and fahlores are intergrown, or occur in mutual contact. These grains may contain smaller inclusions of gold or bismuth-bearing species. Gold commonly occurs as discrete grains along microfractures. In less common instances, it occurs as inclusions within sulphide minerals or complex sulphide grains. In these latter instances, gold is normally located along the grain boundaries (Harley, 1993). Pyrite is the most important host for the gold. Fracture-related gold commonly replaces pyrite along the fracture margins. In the case of the Elandshoogte Reef, arsenopyrite is not an important host for gold. In other deposits, e.g. Frankfort, Ponieskrantz North and Theta Mine, arsenopyrite as well as tetrahedrite/tennantite species, and in some cases, chalcopyrite can host gold inclusions (Swiegers, 1949) and can also host fracture-related gold grains (Meyer *et al.*, 1988). It must be stressed, nevertheless, that pyrite is the most important host mineral for gold, at the scale of the goldfield.

### **BLIND THRUST DEFORMATION**

Throughout the goldfield there is a similarity in structural style displayed by all observed reef horizons. The last stage of reef development is characterised by the deformation of the reef package in a bedding-parallel, blind thrust system. The sole and roof thrusts which form the upper and lower bounds of the deformation zone are commonly localised within carbonaceous shale units preserved at the reef footwall and hangingwall. This deformation event post-dates the formation of economic mineralisation within the reef unit. The sole and roof thrusts to the blind thrust system are sharp, narrow zones of intense deformation. Where developed in shales, these faults are evident as narrow (< 10cm) bands of highly sheared rock. Narrow anastomosing fractures separate micro-lithons of attenuated shale. These micro-lithons have highly polished surfaces which commonly bear shallowly grooved slickensides. In other instances, the roof or sole thrust may be located at the contact between vein quartz and silicified dolomite. In these cases, the fault is evident as a 10-15cm wide zone displaying a spaced, disjunctive fracture cleavage, parallel to the vein margin.

Narrow fault splays cut upsection from the sole to the roof thrust-forming ramps. These splays transgress the entire reef package (Figs. 6 and 7a) and consist of narrow (< 1cm wide) fault zones, comprising carbonaceous gouge, which always bear deeply grooved slickensides. Splays commonly dip shallowly (15-30°) to the west or northwest. Splays are usually curviplanar in form and may branch. Subparallel, spaced sets of splays constitute duplex arrays, which are commonly developed at a variety of scales, ranging from cm to m (Figs. 7a & 7b) at localities within the goldfield. Less commonly, the splays die out upsection, resulting in the formation of imbricate fan sets (Fig. 7a).



*Figure 6: Shallowly westward-dipping splay faults, bounding horses of quartz reef, Elandshoogte Mine.*

Asymmetric, rootless folds are commonly developed at several scales in shaly units overlying the sole thrust or thrust ramp. These folds are commonly tight and may be overturned or even recumbent in attitude and range from millimetre scale microfolds to folds with metre scale wavelengths. The axial planes of these folds typically dip shallowly westwards. The early, close-spaced cleavage in the shales and cleavage-parallel pyrite lamellae are deformed by these folds. However, no axial planar cleavage is associated with their development. In some cases, narrow quartz veins within the shales are also tightly folded, whereas thicker quartz vein units only display gentle, open fold forms.

Antiformal stacks, consisting of narrow, folded slices of quartz and in some cases, shaly material also occurs within the reef on a variety of scales. Small scale (10cm) stacks, consisting of a quartz core, enveloped in carbonaceous shale are commonly developed along the roof thrust of the blind thrust system (Fig. 7b). Larger stacks, such as that shown in Figure 8, consist predominantly of vertically stacked slices of quartz vein material which are developed within the reef unit itself (e.g. Harley and Charlesworth, 1992). Antiformal stacks can only occur as a result of progressive footwall failure (Schirmer, 1988), because older thrust faults become folded over underlying thrust blocks. This has the effect of inhibiting movement across progressively higher thrust faults and restricting any fault motion to progressively lower thrust faults. Breaching of earlier-formed thrust faults, antiformal stacks and related folds records out-of-sequence deformation (Morley, 1988). A typical example is depicted in Figure 7b. Antiformal stacks are frequently beheaded by shallowly dipping thrust faults which transgress earlier, steeper faults.

Footwall and hangingwall ramps (Butler, 1988) can be identified in many of the duplexes present in the goldfield. The footwall ramps are usually developed along the western margin of any one duplex, whereas the hangingwall ramp is localised at the eastern



Figure 7a. Detailed sidewall profile of the Number 1A gully, Elandshoogte Mine. 7b. Detailed sidewall of the Number 2 Winze, Elandshoogte Mine, showing the development of duplex arrays at various scales within the blind thrust system.

flank of the duplex horse, suggesting eastward-directed thrust movement. This is supported by other evidence, including the westward dip of axial surfaces of asymmetric folds, the westward dip of ramp structures and the eastward-trending slickensides. Locally-developed backthrust structures have been identified within the Elandshoogte Reef (Harley, 1993). Similarly, the large-scale folds developed in the hangingwall of the Bevets Reef (Frankfort Mine) have an apparent westerly vergence. This is suggested to represent a backthrust cover response (Tyler, 1989).

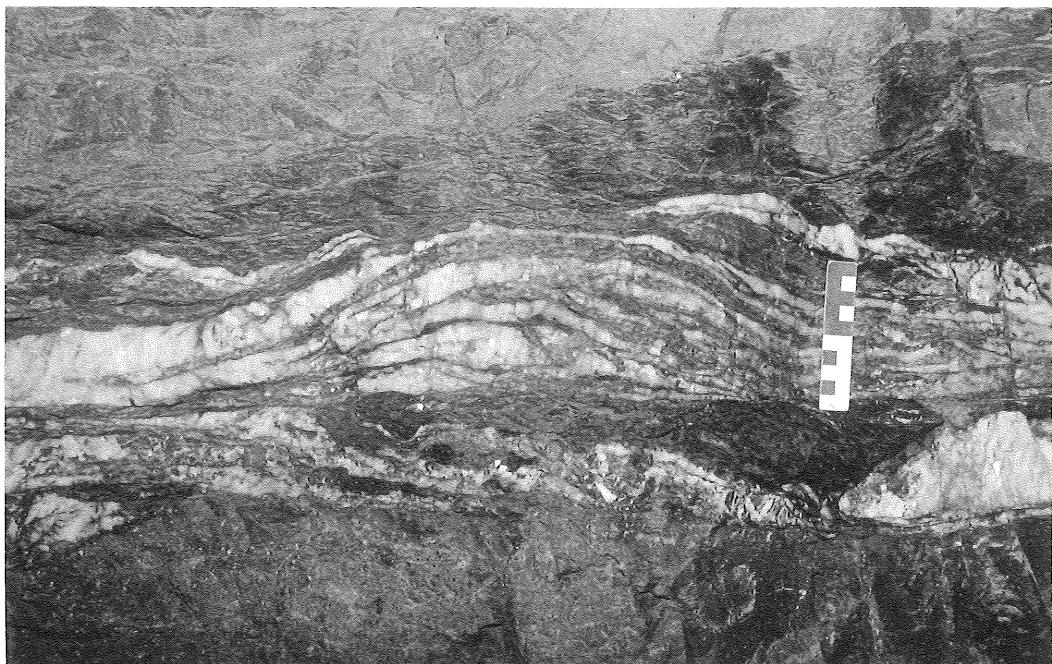


Figure 8: Antiformal stack developed within ribboned quartz reef, Glynns Reef, Malieveld Mine.

#### ROLE OF FLUID IN DEFORMATION

Fluid inclusion evidence from numerous flat reefs implicates a moderate salinity,  $\text{CO}_2$ -bearing, aqueous dominated fluid in the formation of these deposits (Boer *et al.*, 1993; Harley, 1993; Ash and Tyler, 1986; Anderson *et al.*, 1992). Microthermometry indicates that the carbonic species present in the inclusions homogenise to a liquid phase, typically at temperatures between 4 and 20°C. This demonstrates that the carbonic phase densities lie between 0.7 to 0.9  $\text{gcm}^{-3}$ , supportive of high pressures (e.g. Bowers and Helgeson, 1983).

The role of fluid pressure in the formation of bedding-parallel thrust-hosted gold veins has been discussed in detail by Harley (1993) and Harley and Charlesworth (1993). The repeated, episodic nature of the mineralisation and deformation shows that reactivation of the low-angle thrust faults occurred, rather than initiation of higher-angle thrust faults. Consideration of friction theory (Sibson, 1981; 1985; 1989) and its application to the Sabie-Pilgrim's Rest goldfield (Harley and Charlesworth, 1993) shows that high fluid pressures

(approaching or exceeding lithostatic levels) are required to account for the observed, low-angle thrust deformation. A direct consequence of this is that where high-pressure fluids are trapped, the differential stresses required to initiate thrust deformation are greatly reduced, consistent with the observed low levels of preserved strain within the goldfield. The possible source of the fluid must also be able to account for its elevated pressure. Further discussion on this topic is presented later after appropriate data have been introduced.

## DISCUSSION

Pre-Bushveld dykes and sills as well as syn- and post-Bushveld dykes and sills are well developed within the goldfield. The dykes and the vertical reefs display a conspicuous NNE trend, which is perpendicular to the dominant SSE thrust vergence displayed within reefs in the goldfield. The pre-Bushveld and syn-Bushveld dykes appear to bracket the mineralisation. Recent Rb-Sr isotopic data from pre-Bushveld, meta-dolerite sill samples at Olifantsgeraamte Mine (Boer *et al.*, 1993) suggest that alteration zones surrounding mineralised veins post-date the metamorphism associated with the emplacement of the mafic phase. By implication, mineralisation is probably contemporaneous with the felsic phase of Bushveld magmatism (Boer *et al.*, 1993). This leads to an apparent dichotomy: on one hand, vertical reefs are being emplaced, clearly recording a component of ESE directed extension, whilst on the other hand ESE directed thrust faulting appears to be occurring contemporaneously. This point will be addressed in the following sections.

### *Emplacement of the Bushveld Igneous Complex (BIC)*

Emplacement of the eastern lobe of the BIC involved the episodic emplacement (Sharpe and Snyman, 1980) of up to 9km of pyroxenite and gabbro-noritic material, beneath a cap of 1-4km of felsites. The geometry of the eastern lobe is controversial. Two main schools of thought exist; some workers (Molyneux and Klinkert, 1978) suggest that the eastern lobe has a general lopolithic form, which may comprise several overlapping centres of intrusion. Magmatic layering within the complex dips shallowly (10-20°) to the west, beneath the overlying felsites and granites. In contrast, Meyer and De Beer (1981) have suggested a dipping sheet-like morphology for the eastern lobe of the BIC, based on resistivity and gravity data. For the purposes of this discussion, the true form of the eastern lobe of the BIC is not of paramount significance, simply because synclinal warping of the Transvaal Sequence stratigraphy is inherent in both of the end-member models described. Field observations that dips of the Transvaal strata steepen towards the edge of the eastern lobe of the BIC have been made (Sharpe, 1984). The recognition of these features suggests that the original structure of the basin has been further modified by BIC emplacement. The Transvaal Sequence stratigraphy beneath the BIC has been depressed and downwarped, possibly in the form of a large, open syncline. Notably, Tanner (1989) observed that flexural-slip thrust faulting commonly accompanies folding in order to accommodate the space-problems associated with bed shortening in the cores of such folds.

There is a well-recognised, craton-wide thermal event associated with the BIC, which is manifested as a resetting of geochronological isotopic systems, and a prominent 2.10 to 2.05 Ga age anomaly from numerous localities. The influence of such a thermal event on

the lithospheric rheology must be considered. It is well recognised (e.g. Watts, 1982) that hotter lithosphere is thinner than colder lithosphere and is also less rigid. Consequently, it can be suggested that the craton-wide thermal event accompanying Bushveld magmatism would have resulted in "softening" of the lithosphere, such that emplacement of mantle-derived magma will result in sagging of the crust beneath the point of intrusion. De Ritto *et al.*, (1983) recognised a component of rapid elastic subsidence followed by a protracted period of creep subsidence following emplacement of dense mafic intrusions. Rapid elastic subsidence resulting from emplacement of the eastern lobe of the BIC (and occurring on the same time scale as this emplacement) is suggested to account, in part, for the observed steepening of strata adjacent to the intrusion. The subsidence of the BIC and underlying Transvaal Sequence will result in folding of the Transvaal Sequence beneath the intrusion. It is expected that the folds would be pinned beneath the lowest point of the intrusion. Flexural faulting is to be expected along the limb(s) of the large scale fold, arising from the space problem inherent in folding, particularly where mechanically weak layers are encountered or where fluid pressures are enhanced. Gravity surveys of the eastern lobe of the BIC (Smit *et al.*, 1962) indicate three major gravity highs, which occur as a linear array, trending 010-020°. These highs may be interpreted to represent the thickest accumulations of mafic rocks, and describe the axis of the large scale fold structure within the Transvaal Sequence. Significantly, within the Sabie-Pilgrim's Rest goldfield, the vergence of thrusting of the various bedding-parallel gold reefs occurs perpendicular to the axial trend of this fold, which is consistent with the direction to be expected under such conditions. Within the goldfield, the vertical reefs dip vertically to steeply eastwards. As such, they can be interpreted as tensile fractures accompanying flexure of the Transvaal Sequence and the underlying Archaean basement. It is suggested that the interpretation of the vertical reefs as tensile fractures synchronous with the flexure of the Transvaal stratigraphy and portions of the underlying basement can potentially explain the co-existence of both extensional features (tensile veins) and compressional features (thrust-hosted veins) within the goldfield.

Von Dessauer (1912) initially suggested that vertical reefs represent feeders to the flat reefs. Vertical reefs are distributed throughout the goldfield and have similar mineralogies and fluid inclusion characteristics to flat reefs (Anderson *et al.*, 1992, Boer *et al.*, 1993). However, no direct connection between a flat reef and a vertical reef has ever been described. Carbon isotopic evidence from fluid-inclusions trapped within the flat reef environment (Boer *et al.*, 1993) place severe limitations on the amount of interaction of the fluid with the host lithologies. This observation is consistent with the common occurrence of silicification envelopes around most flat reef deposits, which form selvages isolating the reef environment from the surrounding rock. Fluid inclusion chemistries and isotopic signatures (Boer *et al.*, 1993), as well as the occurrence of vertical reefs within the Archaean basement preclude a basinal origin for the fluids and a deep seated magmatic origin is suggested (Boer *et al.*, 1993) for these fluids. At present it is not known how the fluids are transported from a vertical reef environment into a flat reef environment, given the limitations on fluid-rock interaction and recognising the constraint imposed by requirements for high fluid pressure. Harley and Charlesworth (1993) ruled out the possibility of generation of high fluid pressures within the Transvaal Basin and linked high pressure fluids within the reef environment to high pressures in fluids at depth. One cannot cite rapid loading of the underlying stratigraphy by the emplacement of the BIC as a reason for basinal fluid overpressuring for two main reasons. The time delay between deposition of the lower

Transvaal Sequence and emplacement of the BIC is of the order of 400 to 250Ma, furthermore the depth of burial of the lower Transvaal stratigraphy is in excess of 6km at the time of BIC emplacement. It is considered likely that sedimentary rocks between 250 and 400Ma in age and at burial depths below 6km will have undergone permeability collapse such that all contained water will be enclosed in unconnected pore spaces, or bound into minerals such as hydromuscovite. Loading of this stratigraphic pile will result in an increase in pore fluid pressure, but this will be balanced by the increased confining stresses. It is unlikely that highly channelised flow, as is evident in the flat reefs will be produced under any circumstances. A corollary to this suggestion is the requirement of connectivity between the deep seated fluid source and the flat reef environment, such that pressure transmission may occur. Such a requirement is only adequately met by a discrete fluid conduit to the flat reef environment. This in turn, will also satisfy the requirements for minimal fluid-rock interaction as dictated by isotopic studies (Boer *et al.*, 1993).

## SUMMARY

Thrust-hosted gold veins in the Sabie-Pilgrim's Rest goldfield are suggested to be related to downwarping and loading of the Transvaal Sequence lithologies beneath the BIC. Gold deposits were formed, where high pressure fluids ascending from depth diminished the normal stress acting on lithological discontinuities within the sedimentary sequence, allowing low-angle reactivational thrust faulting to occur under conditions of low differential stress.

## COMPARISONS WITH OTHER LOW-ANGLE BEDDING-PARALLEL GOLD VEIN DEPOSITS

A literature survey suggests that while there are numerous occurrences of low-angle, bedding-parallel gold veins worldwide, two main deposits have been identified as being of particular significance. These are the Passagem de Mariana Mine of the Quadrilátero Ferrífero, Minas Gerais, Brazil and the Telfer Mine, Paterson Range, Western Australia. The authors present a brief geological description of each of these deposits and then make comparisons with the deposits of the Sabie-Pilgrim's Rest goldfield in Table 1.

### *Passagem de Mariana*

The Passagem de Mariana Mine is situated in the southeastern corner of the Quadrilátero Ferrífero, approximately 60km southeast of Belo Horizonte, in the State of Minas Gerais, southeast Brazil (Fig. 9). The mineralisation is hosted in early Proterozoic greenschist-to-lower amphibolite grade metasediments of the Minas Supergroup comprising quartzites, iron formations (itabirites), meta-dolomites and meta-pelites. The mineralisation occurs on the mine scale as a stratiform sheet of quartz, pyrite, tourmaline, carbonate, arsenopyrite, bismuthinite and gold (Fig. 10). Locally, the reef displays transgressive relationships with its host lithologies (Figs. 11 and 12). The mineralised interval, which is concordant with the enclosing lithologies occupies a definite stratigraphic position below the Caué Itabirite (Fleischer and Routhier, 1973; Fleischer and Vial, 1991). The mineralised zone has a maximum thickness of 5m and extends for more than 15km. The stoped areas of the mine have dimensions of approximately 2000x1500m (Fleischer and Vial, 1991) and

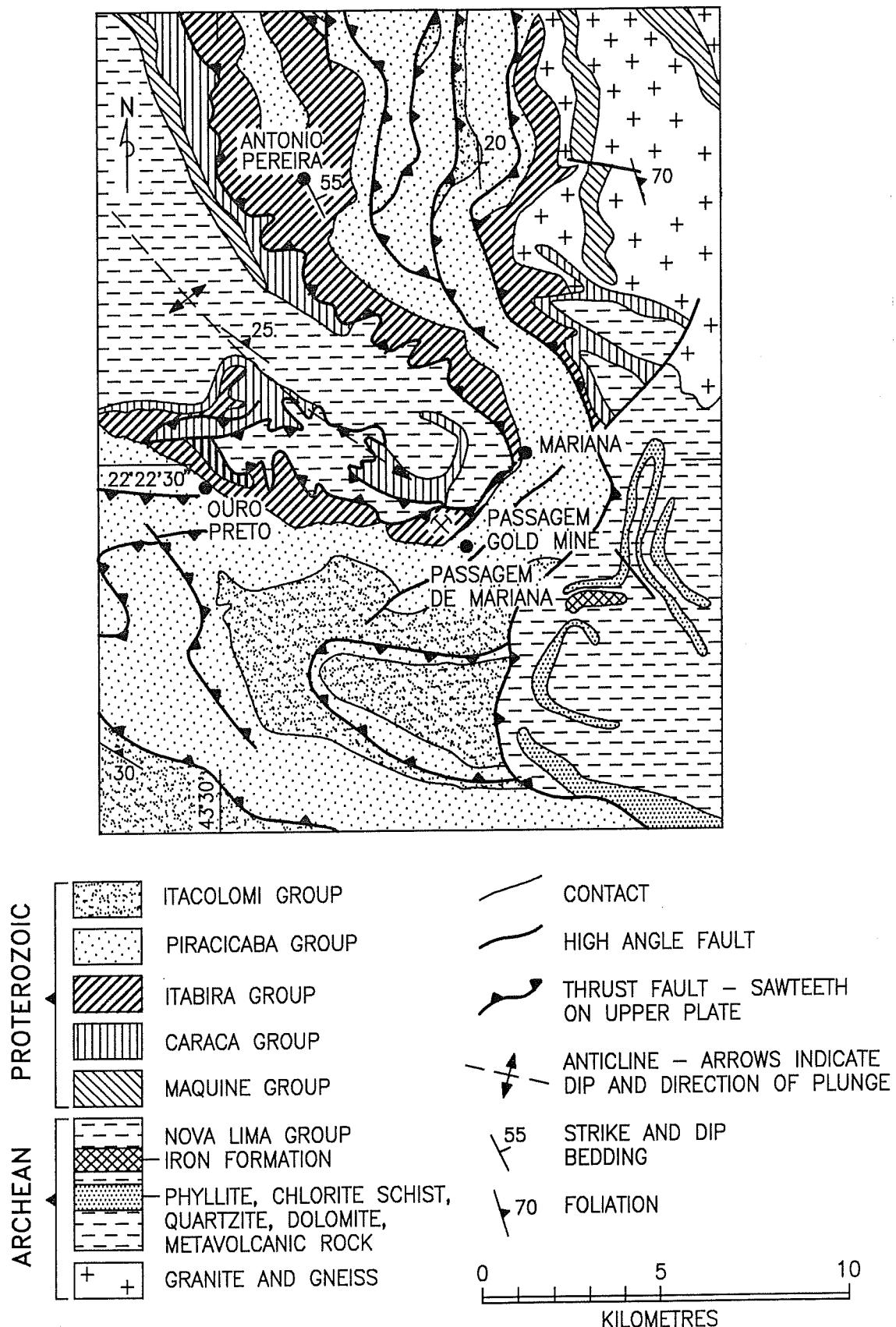


Figure 9: Simplified locality map showing the position of Passagem de Mariana gold mine, within the Quadrilatero Ferrifero, Minas Gerais, Brazil. Modified after Fleischer and Vial (1991) and Vial et al. (1988).

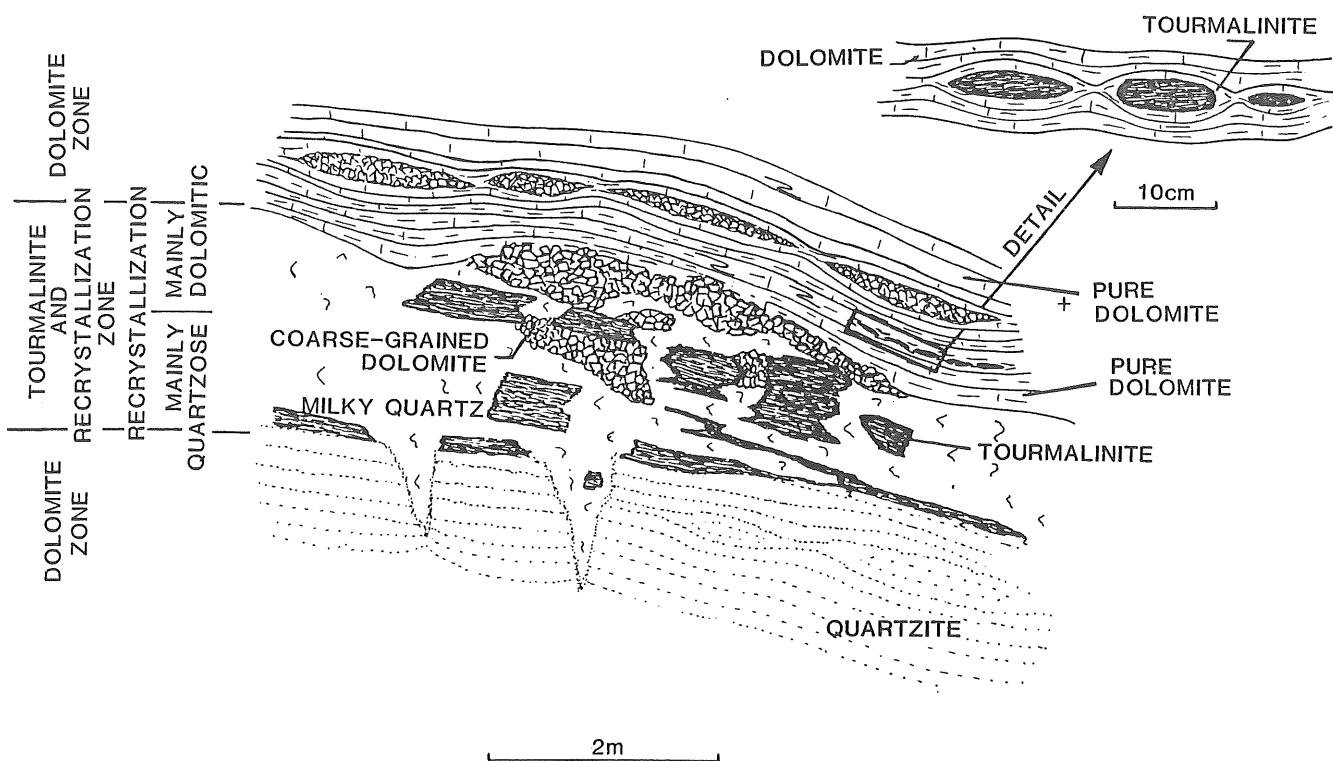


Figure 10: Simplified sketch of the geological features of the orebody within the Passagem de Mariana mine, 175m level, Pia Nova Incline (Fleischer and Routhier, 1973). Reproduced from *Economic Geology*, 1973, Vol. 68, p.17 with permission.



Figure 11: Close up view of part of the Passagem de Mariana reef, Passagem de Mariana mine, Brazil showing the occurrence of wall-rock septa and ribboned selvages within the quartz reef.



*Figure 12: The Passagem de Mariana reef, Passagem de Mariana Mine showing the inclusion of wall rock fragments within the reef. Note also the occurrence of dilatant veins and bedding-parallel quartz stringers above and below the reef.*

display shallowly-plunging, easterly-trending oreshoots (Scarpelli, 1991), developed within the shallowly dipping stratiform orebody. There has been some debate concerning the genesis of the Passagem orebody. Some of the earliest workers suggested that the deposit was a pegmatitic apophysis from a nearby granitic intrusion (Derby, 1911), largely because of the common occurrence of tourmaline in the mineralised zone. An epigenetic origin to gold mineralisation was suggested by workers such as Emmons (1937) and Lindgren (1933). Later workers (Fleischer and Routhier, 1973) suggested that gold mineralisation was syngenetic and related to early-Proterozoic volcanic activity synchronous with sedimentation. Current thinking reaffirms an hydrothermal, epigenetic origin for mineralisation at Passagem de Mariana (Scarpelli, 1991; Thorman and Ladeira, 1991). The source of fluids is not specified; however, mineralisation is confined to a major thrust fault.

### *Telfer*

Telfer is currently the largest gold producing mine in Western Australia. It is situated in the northern part of the Paterson Province (Fig. 13), in siltstones and sandstones of the upper Proterozoic Yeneena Group, which unconformably overlies the Lower and Middle Proterozoic Rudall Metamorphic Complex (Dimo, 1990; Goellnicht *et al.*, 1989; Vearncombe and Hill, 1993). Stratiform mineralisation is developed as sulphide/oxide quartz veins in two en échelon periclinal anticlines, termed the Main Dome and the West Dome. Two main mineralised units are recognised within each of the domes, termed the E reef and the Middle Vale Reef (MVR), the latter reef may be up to 3m thick and covers an area of approximately 10km<sup>2</sup>. These two reefs are hosted within sub-greenschist facies calcareous and argillaceous rocks. Most mineralisation is confined to the bedding-parallel vein assemblages, but some

transgressive stockworks and sheeted vein systems are developed in the footwall and hangingwall of both reefs (Fig. 14). The MVR consists largely of an upper unit of laminated to banded massive sulphide and quartz, with a lower unit of fractured milky white, coarse vein quartz, with interstitial sulphides, namely pyrite, chalcopyrite, bornite, chalcocite with minor galena and sphalerite.

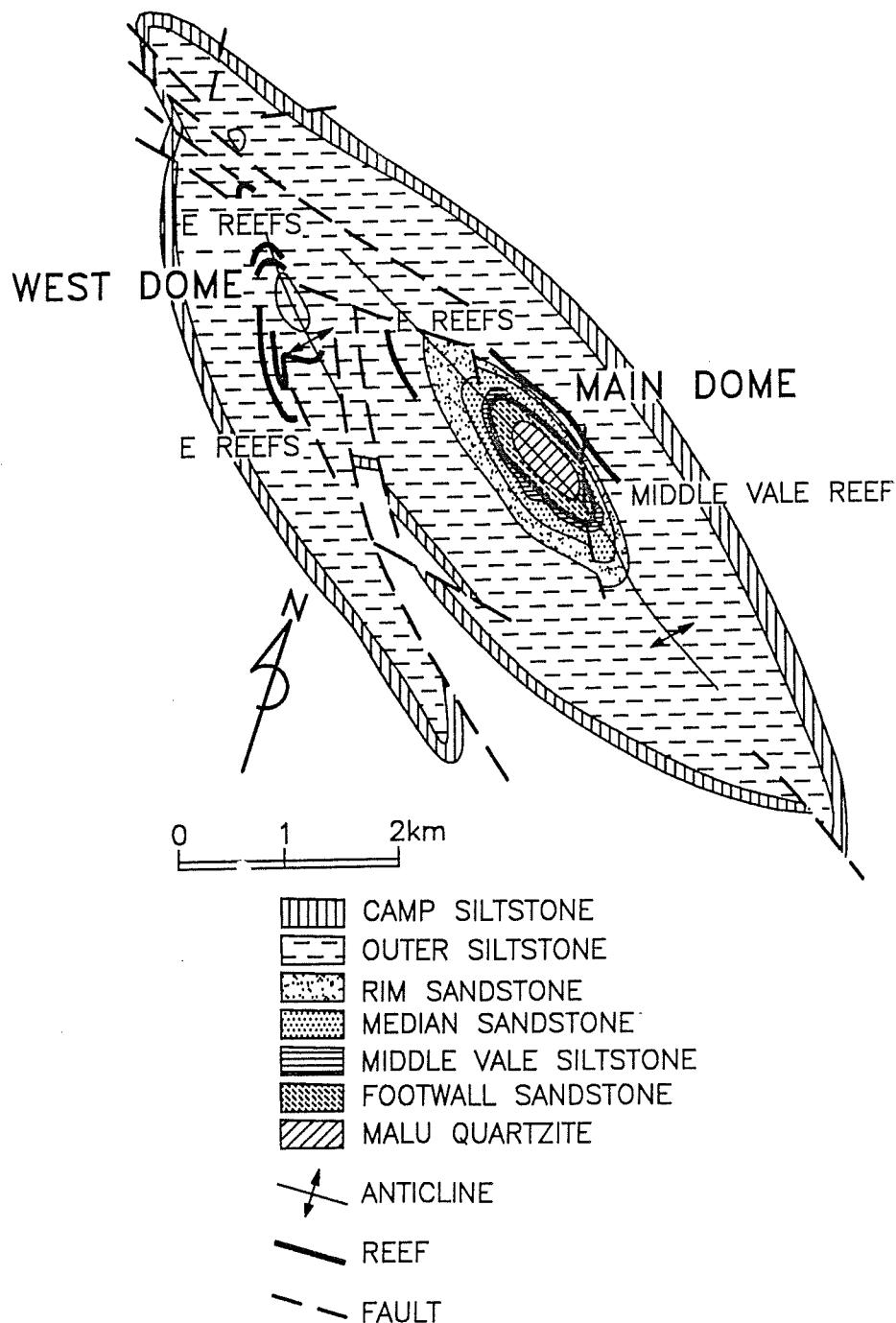
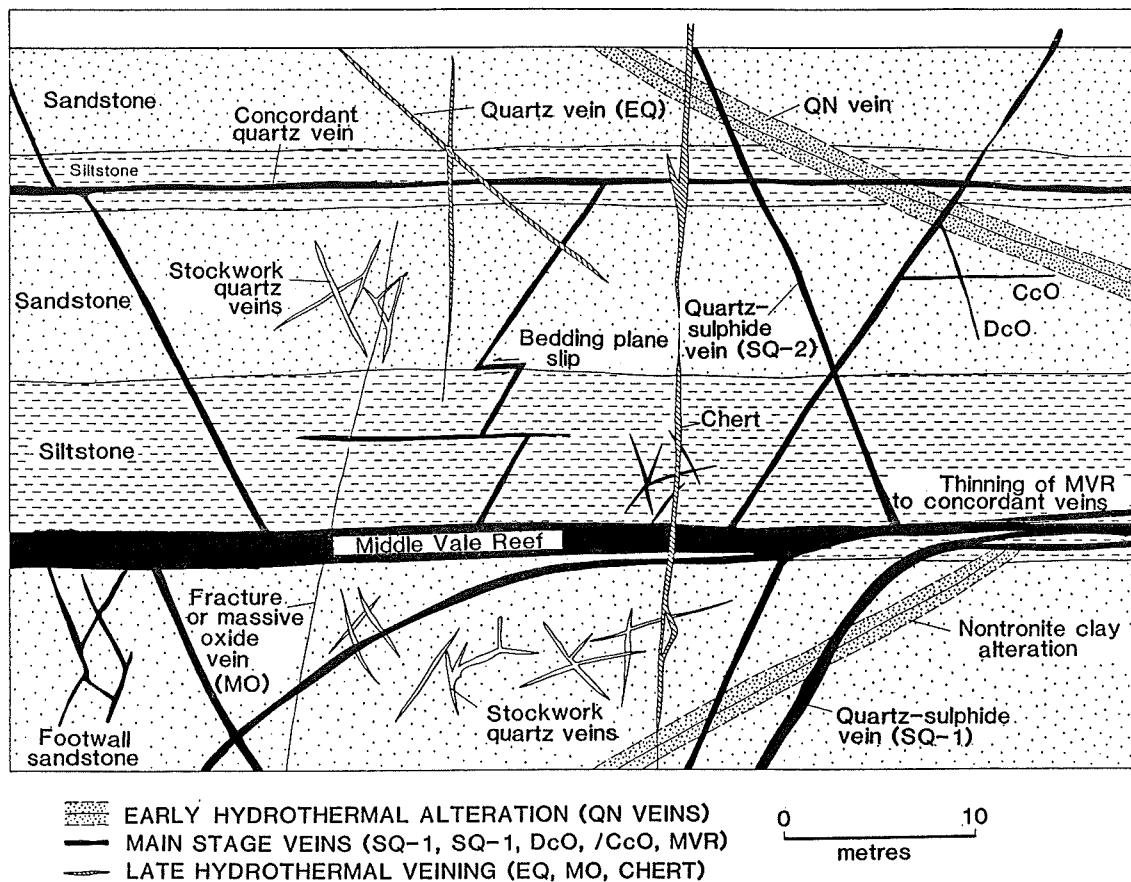


Figure 13: Simplified map of the Telfer Dome, Western Australia, showing the locality of the Telfer gold mine. After Dimo (1990) and Goellnicht et al. (1989).



*Figure 14: A schematic composite cross-section showing the vein relationships evident in the Telfer gold mine. Note the predominant occurrence of bedding-parallel mineralisation (Middle Vale Reef), with the occurrence of transgressive veining and stockworks above and below this main mineralised zone. After Goellnicht et al. (1989), reproduced from *Economic Geology*, 1989, Monograph 7, p.159 with permission.*

Imbricate thrust faults are developed in the axial region of the Main dome, these faults dip to the southwest, are listric, and tend towards parallelism with the bedding at depth (Vearncombe and Hill, 1993). Mineralisation has been shown to be coincident with rocks showing highest preserved strain and reactivation of surfaces such as the MVR are also recognised (Vearncombe and Hill, 1993).

Goellnicht et al. (1988, 1989) have suggested that the gold mineralisation at Telfer is genetically related to the locally developed Mount Crofton granitoid. The ore fluids (and probably the metals) are suggested to have exsolved from the cooling pluton and a similarity with porphyry copper style mineralisation is suggested.

## CONCLUSIONS

The three deposits discussed share several similar features. Firstly, they all occur as low-angle, bedding-parallel, thrust-hosted vein systems. Furthermore, episodic mineralisation and the reactivation of structural features is evident in all three occurrences. Friction theory arguments presented by Hubbert and Rubey, (1959), Sibson (1989), Cox (1991), Harley and Charlesworth (in press) show that low-angle thrust faulting does not occur in the absence of high (lithostatic to supralithostatic) fluid pressures. Dilatancy, at depths of greater than about 4-5km is almost certainly a result of fluid pressure because unsupported dilatancy is not possible below depths of 2km (Fyfe *et al.*, 1978). The consequences of this are that the differential stresses ( $\sigma_1 - \sigma_3$ ) required for fault reactivation are minimised, hence the common recognition of reactivation and episodic mineralisation within these systems. Brecciation of the wall rocks and pre-existing reef material (developed in all three deposits) is also a direct consequence of high fluid pressure and the interaction between fluid pressure and fault reactivation (e.g. Cox, 1991).

The ore-metal associations in all three types of deposit are also very similar, and a common association with Au-Cu-Bi is evident. Telfer and Sabie-Pilgrim's Rest have superficially similar fluid chemistries ( $H_2O$  dominated, high salinity fluids, with variable  $CO_2$  contents) whilst at Passagem de Mariana, the fluid inclusions suggest that the ore fluids were dominated by  $CO_2$ , and that the aqueous component of the ore fluid was of low salinity (Vial, 1988). There are certain problems associated with this reported fluid chemistry, particularly regarding the capability of a  $CO_2$  dominated fluid to transport gold, but further discussion on this topic is beyond the scope of this paper and awaits further data generation. However, the authors would predict, on the basis of arguments presented earlier that the fluid pressure corrections on fluid inclusions in the Passagem de Mariana deposit should yield lithostatic pressures. A magmatic source is suggested for both the Sabie-Pilgrim's Rest deposits and the Telfer deposit ore fluids, but no data have been presented to allow definition of a fluid or metal source for Passagem de Mariana. Notwithstanding the differences in fluid chemistry, the similarities in structural setting and mineralisation/deformation histories of all three deposits are clearly evident.

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