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METAMORPHIC PETROLOGY OF THE WITWATERSRAND SUPERGROUP

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ABSTRACT

Silicate mineral assemblages suggest near-uniform peak metamorphic conditions of greenschist facies (equivalent to chlorite zone) in all the major Witwatersrand gold fields. The maximum assemblage pyrophyllite-chloritoid-muscovite-chlorite-quartz-tourmaline-rutile-pyrite is found in several areas, whereas coexisting pyrophyllite-chloritoid is present in most of the gold mines. Kaolinite, paragonite, biotite, pyrrhotite and arsenopyrite have more local distribution. Meta-pelites ("shales"), quartzites, meta-conglomerates, meta-basalts and some dykes all record the same metamorphic assemblages, albeit in different mineral proportions, and pyrophyllite and chloritoid are known from many gold-producing reefs.

Andalusite-, kyanite-, garnet- and/or cordierite-bearing assemblages indicate higher metamorphic grades along the NW margin of the Witwatersrand structural basin, to the NE of the Evander Goldfield, and around the collar of the Vredefort Dome. Concentric metamorphic facies around this Dome culminate in granulite facies assemblages near the centre.

Metamorphic conditions of 350 $\pm$ 50°C and 1-3 kb are inferred for the gold fields, with temperatures increasing to around 700°C in granulites of the Vredefort Dome. Other geothermometric methods, including illite crystallinity, fluid inclusions, carbon elemental ratios and vitrinite reflectance, are compatible with the above estimates but are each associated with considerable temperature uncertainties. Fluids in equilibrium with pyrophyllite-muscovite-quartz-pyrite $\pm$ paragonite are inferred during metamorphism, suggesting slightly acid conditions and elevated sulphur activities.

Peak metamorphism was accompanied by regional deformation, large fluxes of aqueous fluid and considerable element mobility. The low-intermediate pressure nature of this metamorphic terrane and the lack of large-scale tectonic thickening favours underplating by mafic magmas as the likely cause of the metamorphic pattern.

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INTRODUCTION

The age of the Witwatersrand Supergroup (ca. 2800 Ma, Armstrong *et al.*, 1990), combined with its thickness (ca. 7 km, SACS, 1980) and the thicknesses of the overlying Ventersdorp Supergroup and Transvaal Sequence (ca. 5 km) indicates elevated temperatures and pressures would have existed after burial, possibly accentuated by superimposed thermal perturbations during a regional metamorphic event. Reports of minerals suggestive of significant metamorphic grade, such as chloritoid (Young, 1917; Wiebols, 1961) and pyrophyllite (Liebenberg, 1955; Fuller, 1958a), are common in the literature, but the first systematic basin-wide study of the distribution of metamorphic minerals was only reported after 100 years of mining on the Witwatersrand.

Potential difficulties confronting metamorphic studies of the Witwatersrand are the dominance of psammitic and ruditic rocks, especially in the Central Rand Group, the poor outcrop of pelitic horizons, difficulty in separating low-grade metamorphism from weathering effects in surface samples, concentration of underground access to mined intervals of the Central Rand Group, and the non-diagnostic nature of the mineral assemblages in many Witwatersrand meta-pelites. To overcome these problems, sampling was concentrated on underground samples outside the influence of weathering, and supplemented by drill core.

The first systematic approach to the metamorphic petrology of the basin was a pilot study to identify those minerals providing the most useful constraints on metamorphic grade, and the horizons hosting these minerals (Phillips, 1986). In general, chloritoid and pyrophyllite distribution was deemed to be critical in the formulation of a regional metamorphic synthesis, and the fullest coexisting mineral assemblages were compiled for each gold field, supplemented by electron microprobe analysis of selected samples. A philosophical basis of most modern metamorphic studies is that silicate assemblages are more likely to reflect peak metamorphic conditions than sulphides and ore minerals that commonly reset during cooling even in the short time span of laboratory experiments (Barton and Skinner, 1979). Finer-grained sediments are considered more likely to approach equilibrium during metamorphism on two accounts: their fine grain size increases reaction rates through the greater area of grain contact, and the breakdown of clays and micas evolves a fluid phase that greatly promotes reaction progress. Sensible metamorphic patterns in other greenschist facies terranes (that also contain pyrophyllite or chloritoid), and relatively rapid approach to equilibrium in laboratory experiments at similar temperatures do not suggest major departures from equilibrium on a regional scale given the time available during regional metamorphism. The systematic distribution of mineral species and compositions, and mica textures, provide further support for an approach to equilibrium within the Witwatersrand mineral assemblages.

Note: in the following text, "Witwatersrand Basin" refers to the presently-preserved structural basin as defined by Winter (1989).

REGIONAL METAMORPHISM

Regionally persistent meta-pelites

A number of pelitic horizons are persistent across much of the Witwatersrand Basin and sufficiently distinctive to form valuable stratigraphic markers (SACS, 1980). In the West Rand Group, such horizons include the Water Tower Slate Member, the Parktown Shale Formation, the Coronation Shale Formation and the Roodepoort Shale Formation (formerly the Jeppestown Shale). The Booysens Shale is the only persistent meta-pelite in the Central Rand Group, and a shale in the Black Reef is widespread near the base of the Transvaal Sequence (Figure 1).

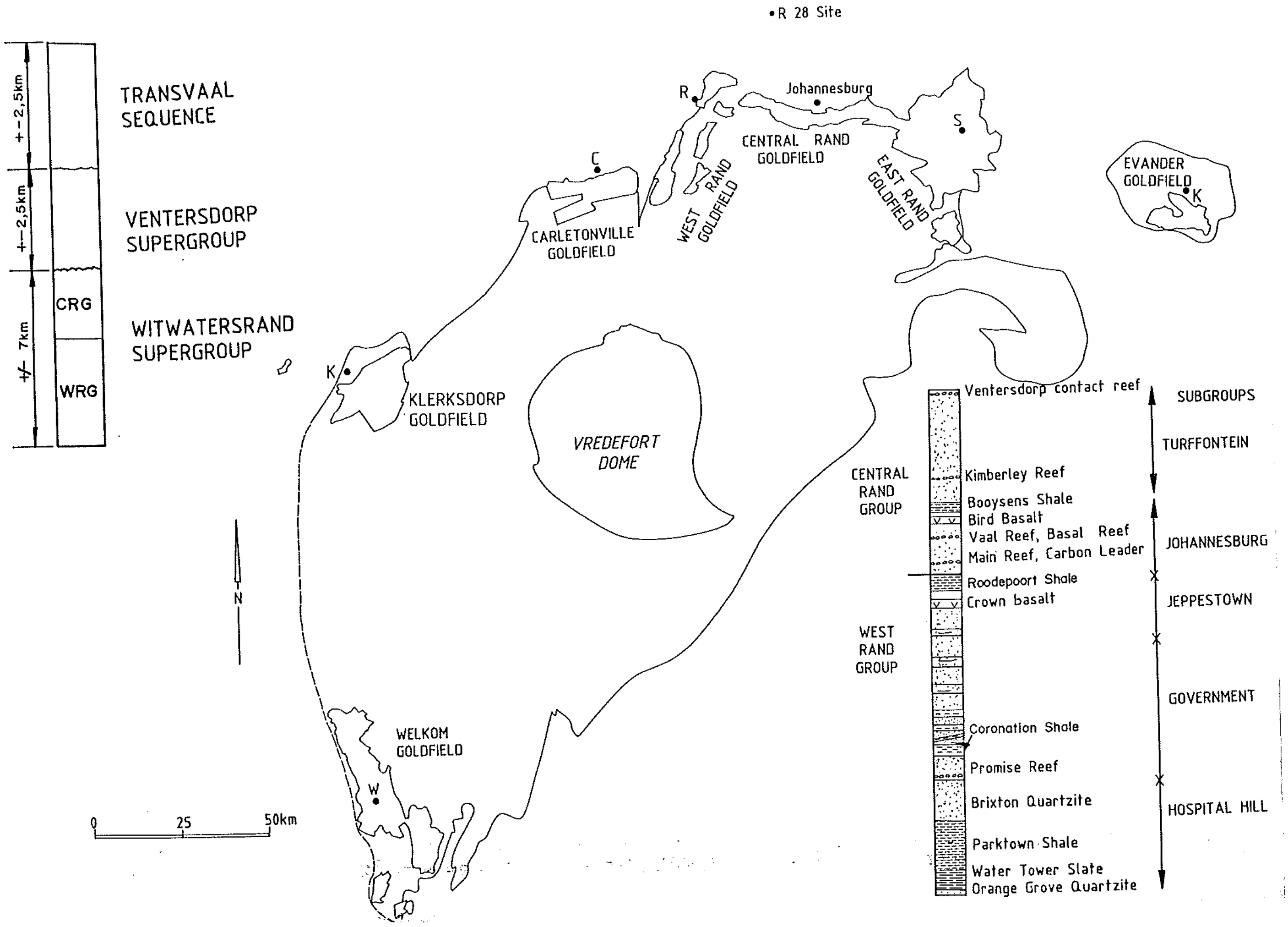

Figure 1: Map showing the approximate outline of the Witwatersrand Basin, the major gold fields, the Vredefort Dome, Johannesburg, and other important towns (Welkom, W; Klerksdorp K; Carletonville, C; Randfontein, R; Springs, S; and Kinross, K in the Evander Goldfield). A generalized stratigraphic column shows the relationship of the Witwatersrand, Ventersdorp and Transvaal sequences, and a more detailed column shows subdivisions of the Witwatersrand Supergroup (± 7km) thick) that are referred to in the text.

Water Tower Slate (the basal member of the Parktown Shale Formation): Fresh exposure of this meta-pelite is limited, as most surface occurrences are weathered and drilling and underground development rarely intersect the horizon. An area on the R28 motorway near Krugersdorp provides near-fresh Water Tower Slate extending several hundred metres along strike, immediately overlying the Orange Grove Quartzite (Figure 2). Here the meta-pelite is massive, dark and with visible chloritoid blades and a slaty cleavage. The Water Tower Slate Member appears more slaty in weathered outcrops in central-north and east Johannesburg.

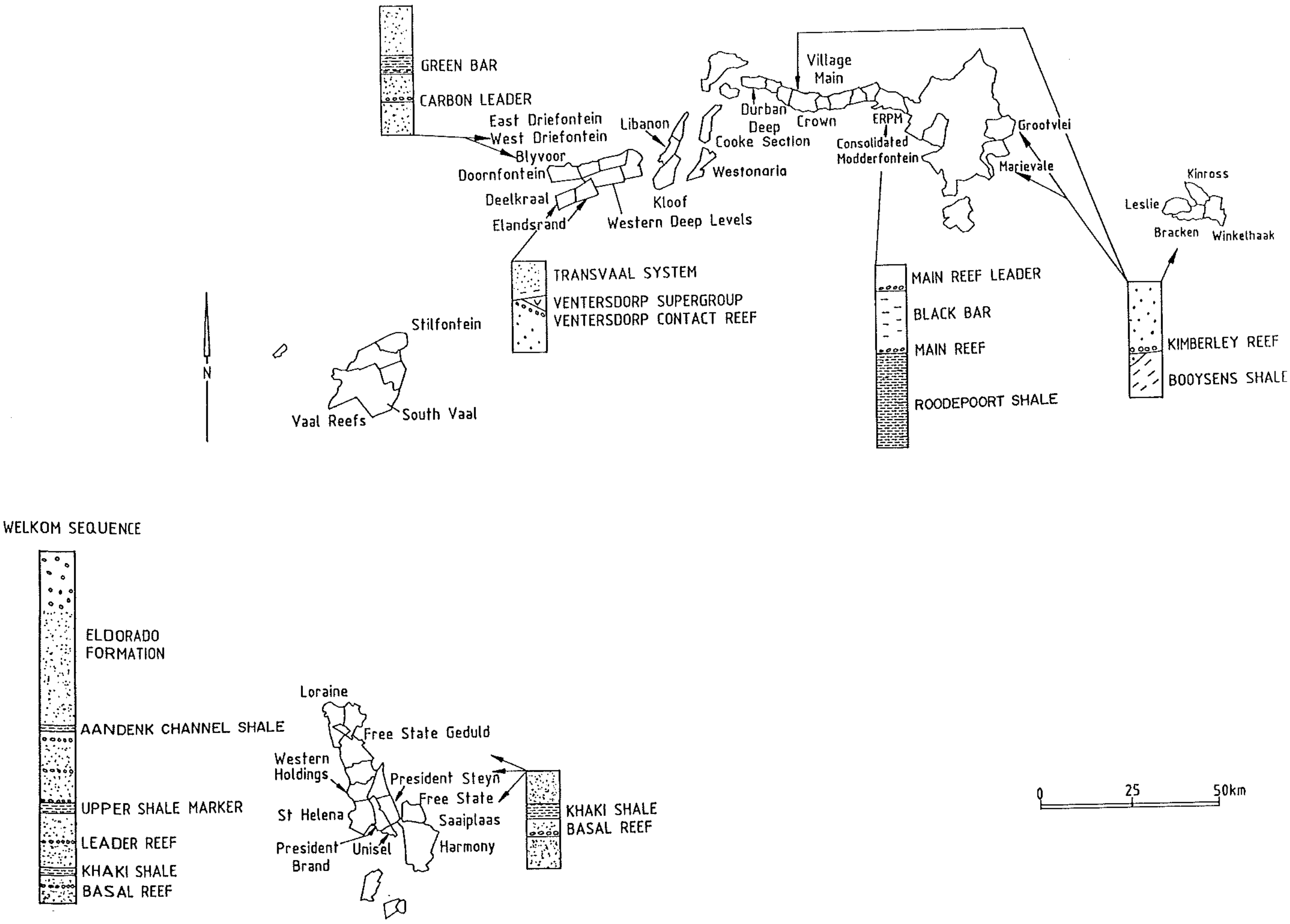

Figure 2: Map of all gold mines mentioned in the text, and a generalized stratigraphic column for the Welkom area. Also shown are diagrammatic columns (on the scale of a stope, i.e. a few metres) for the rock horizons mentioned in more detail in the text.

Parktown Shale Formation: The greatest thickness of pelitic rocks in the Witwatersrand Basin is in the Parktown Shale Formation. This formation comprises a 1000m thick, mostly argillaceous, sequence of banded rocks with common Fe-rich cherty meta-pelites in the Central Rand area. The dominant mineralogy is quartz and chlorite with white mica, tourmaline, minor biotite and disseminated fine magnetite. The meta-pelites are moderately to strongly magnetic.

Coronation Shale Formation: The Coronation meta-pelites are Fe-rich like those in the Parktown Shale Formation, but differ from all other Witwatersrand meta-pelites in terms of their high MnO content, typically above 1 wt percent, and up to 3 wt percent, in the Fe-rich parts.

Roodepoort Shale Formation: The Roodepoort Shale Formation (informally known as the Jeppestown shale) is a very prominent horizon near the West Rand Group - Central Rand Group boundary. It is persistent for much of the Basin and reaches 450 m in thickness (e.g. Whiteside *et al.*, 1976). The Roodepoort Shale Formation typically comprises dark green meta-pelites, with a well-developed slaty cleavage defined by chlorite and lesser quartz and white mica (muscovite where analysed by XRD). Small silty layers are up to 1mm thick. Pyrite and tourmaline are rare components, and carbonate, although still minor, is more abundant in the Roodepoort meta-pelites than in other Witwatersrand shales. A brown pleochroic mineral resembling biotite or altered chlorite occurs very rarely. Pyrophyllite and chloritoid are only abundant locally, particularly with muscovite near lithological contacts and shear zones (Figures 3 and 4).

The Master Bedding Plane Fault is approximately parallel to bedding and known across much of the Carletonville Goldfield: this fault lies consistently within the Roodepoort Shale Formation and is associated with local alteration of the meta-pelite to pyrophyllite-rich lithologies. Similar examples of preferential strain in the pelitic horizons can be found in all other meta-pelites and in all gold fields.

Booysens Shale: The Booysens Shale (formerly the Kimberley shale, and correlated with the Upper Shale Marker at Welkom, Figure 2) is the only regionally persistent meta-pelite in the upper Witwatersrand succession and is generally ca. 75 m thick (Figure 2). It is similar in many localities to the Roodepoort meta-pelites although not as dark green, but rather more grey to blue-grey in places. Chlorite is the dominant mineral, with quartz, white mica (mostly muscovite), tourmaline, pyrite and rutile.

Some of the more important variants of the Booysens Shale are the chloritoid and/or pyrophyllite-bearing slates and schists below unconformities where this unit is more strained. Such situations are found in the Central and East Rand gold fields where the Kimberley Reef unconformably overlies the Booysens Shale, and the upper 1-2 m of the latter are schistose and/or quartz veined. Such features are well exposed on the No. 14 decline at Crown Mines where the Booysens Shale underlying the Kimberley Reef is pyrophyllite-rich, and also in similar situations on Grootvlei and Marievale Mines of the East Rand Goldfield where chloritoid is common. In the Evander Goldfield, the truncated upper contact of the Booysens Shale is markedly discoloured to khaki, light-olive green or black in several locations below the Kimberley Reef on Bracken and Kinross Mines (Palmer, 1986; Law *et al.*, 1988a; 1991).

These chloritoid and pyrophyllite-rich variants cannot always be traced into normal chlorite-rich Booysens Shale due to insufficient access underground, but the widespread occurrence of these features at the top of truncated Booysens Shale and their dissimilarity

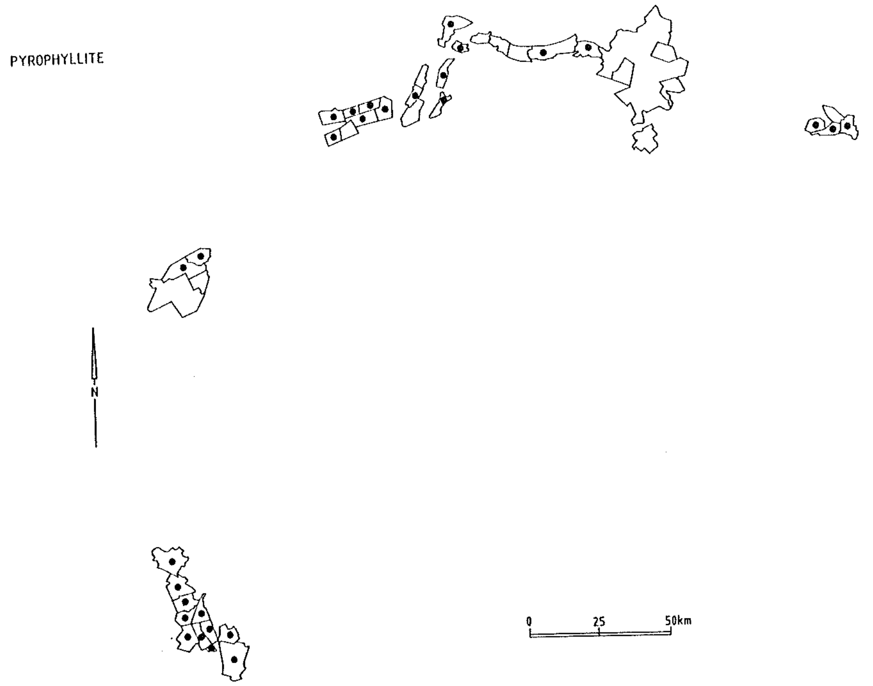

Figure 3: Pyrophyllite distribution in gold mines of the Witwatersrand Basin. The pyrophyllite symbol is only included where the pyrophyllite has been confirmed by X-ray diffraction. Pyrophyllite is also suspected at Vaal Reefs, Buffelsfontein, Hartebeestfontein (see also De Waal, 1982), Elandsrand, Kloof (see Ingle, 1986), Ventersport (see also De Waal, 1982)., Durban Deep, Consolidated Main Reef and Rand Leases based on underground and hand specimen study (but no XRD confirmation).

Footnote: The absence of confirmed pyrophyllite at a mine does not imply that the mineral is absent. Although all operating mines were visited during this reseearch, in several areas the lithologies sampled were of inappropriate composition for pyrophyllite growth. The authors have hand specimen identification (not XRD) of pyrophyllite at Vaal Reef Mine (P. Borrego, pers. comm.), as well as the Marievale, Grootvlei and Kinross mines.

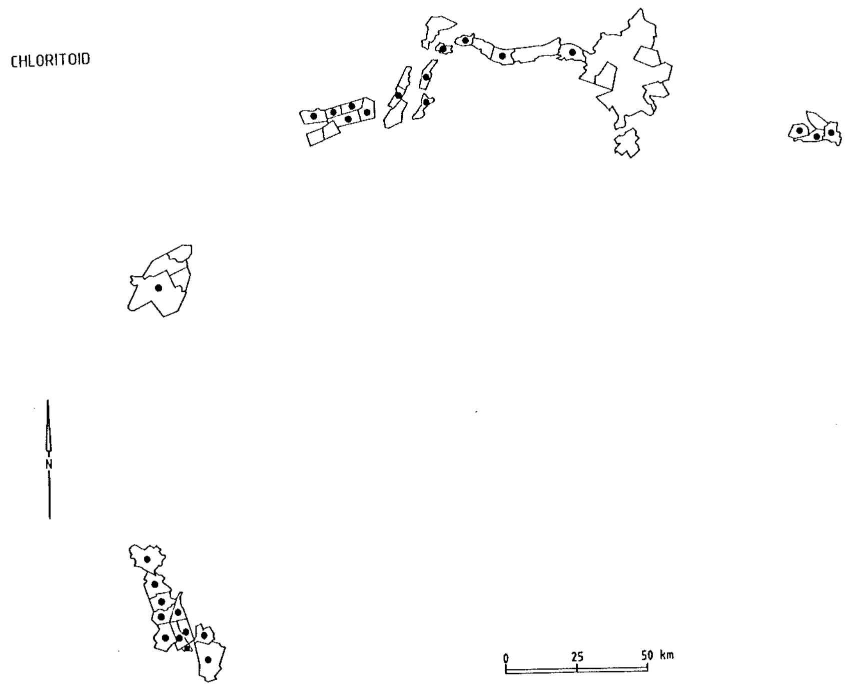

Figure 4: Chloritoid distribution in gold mines of the Witwatersrand Basin. The chloritoid symbol is based on samples in which chloritoid is confirmed by thin section petrography.

Footnote: The absence of confirmed chloritoid at a mine does not imply that the mineral is absent. Although all operating mines were visited during this research, in several areas the lithologies sampled were of inappropriate composition for chloritoid growth. Hand specimen identification of chloritoid (not thin section) includes Marievale, Grootvlei and Kinross mines.

with palaeosols (Palmer *et al.*, 1987; 1989) implies they originate after burial, and do not represent an anomalous horizon within the Booysens Shale: this is confirmed by inspection of Tweedie's (1969) sections through the Booysens Shale, none of which show a pyrophyllite - cloritoid stratigraphic interval. The association with quartz veining and ductile tectonic fabrics suggests that alteration has been important near this contact during metamorphism and deformation.

The Upper Shale Marker is present across much of the Welkom Goldfield and is thought to be equivalent to the regionally persistent Booysens Shale (SACS, 1980). Quartz - pyrophyllite - muscovite - chloritoid - chlorite - rutile assemblages are recorded (Borrego and Phillips, 1987).

Reef package meta-pelites

Immediately overlying many of the major conglomeratic reefs are distinctive pelitic lithologies. Examples include the Black Bar on the Central Rand (below the Main Reef Leader), and the Green Bar around Carletonville (a few metres above the Carbon Leader Reef). They form the top of the ca. 2 m-thick reef packages of carbon seam - conglomerate - quartz arenite - wacke/meta-pelite that lie on unconformities and host much of the Witwatersrand gold. These meta-pelites are generally 1-2 m thick across whole gold mines, and are quite different in lithology and environmental significance from the 50-100 m deep erosion channels found at a similar level of the stratigraphy on Doornfontein, East Driefontein, Village Deep and ERPM gold mines. The latter possibly include debris flows with diamictites (Stanistreet *et al.*, 1988) rather than thicker variants of otherwise uniformly thin meta-pelites.

The Green Bar is a massive to schistose, pale yellow-green to dark blue-green meta-pelite with abundant chloritoid and pyrophyllite (Figure 5). The chloritoid forms poorly oriented blades up to 0.4 mm in length that overgrow the mica fabric and are surrounded by a matrix of fine (0.1 mm) white mica and quartz. Further minerals include chlorite, muscovite, tourmaline and rutile, with negligible biotite and/or opaque phases. The distribution of pyrophyllite, chloritoid and chlorite is patchy, with chlorite being more common towards the top of the unit.

The Black Bar is predominantly a graded siltstone with some shaly sections of mainly chlorite, quartz, muscovite with minor pyrite and biotite. Both pyrophyllite and chloritoid are abundant locally. Biotite in the Black Bar occurs as discrete light-brown flakes comprising less than 2 modal percent of the assemblage. It has been identified optically in a number of thin sections from ERPM Mine (Figure 1), and confirmed by electron microprobe analysis. The biotite is randomly scattered in a fine-grained muscovite - chlorite - quartz matrix, as grains of 0.05 mm diameter. A metamorphic origin is ascribed to this biotite based on its microstructural habit, distribution, and relationship to bulk rock chemistry. It is quite different in shape and size from the inferred detrital mica grains (mostly muscovite) in silty layers which are coarser grained (~ 0.5 mm), commonly bent and strongly chloritized around the edges (see Phillips, 1987, Figures 4 e and f).

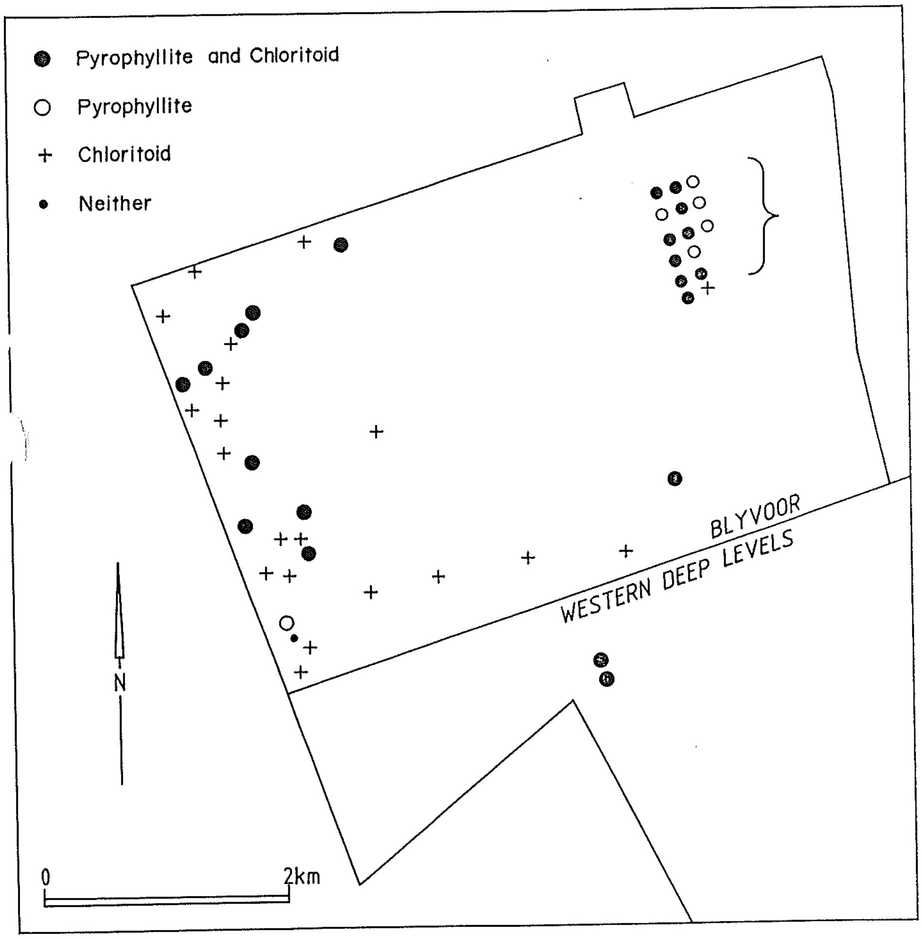

Figure 5: Pyrophyllite and chloritoid distribution within the Green Bar shale on Blyvooruitzicht and Western Deep Levels Mines, Carletonville Goldfield.

Meta-pelites in the Kimberley Conglomerate Formation (K8 shales) have a similar mineralogy to the Green Bar and Black Bar but are within a stratigraphically higher, and only modestly mineralized, succession. Weakly foliated meta-pelites comprise chlorite, muscovite and quartz, in which remnants of bedding are associated with chloritoid and subordinate pyrophyllite (Figure 6). These also have 0.8 mm bundles of intergrown pyrophyllite and chlorite that are elongate parallel to the slightly wavy cleavage. The strongly foliated meta-pelites comprise mainly pyrophyllite with muscovite, chloritoid and quartz. Less common are meta-pelites with mainly muscovite and quartz, with minor pyrophyllite and chloritoid. Tourmaline, pyrite and rutile are widespread in most lithologies.

Khaki Shale: The Khaki "shale" is known from much of the Welkom Goldfield but terminates to the SE in the area of Harmony Mine. It occupies a position in the stratigraphy immediately above the Basal Reef and an overlying clean, well-sorted quartzite (a sequence analogous to those of the Green Bar and Black Bar), and continues across the boundary between the Steyn "placer" - Basal "placer" boundary in the Basal Reef (Minter *et al.*, 1986). The Khaki shale is deformed in many exposures, where it has a strong slaty, phyllitic or even schistose fabric and common quartz-vein stringers. It thickens to several metres against some faults and is eliminated elsewhere.

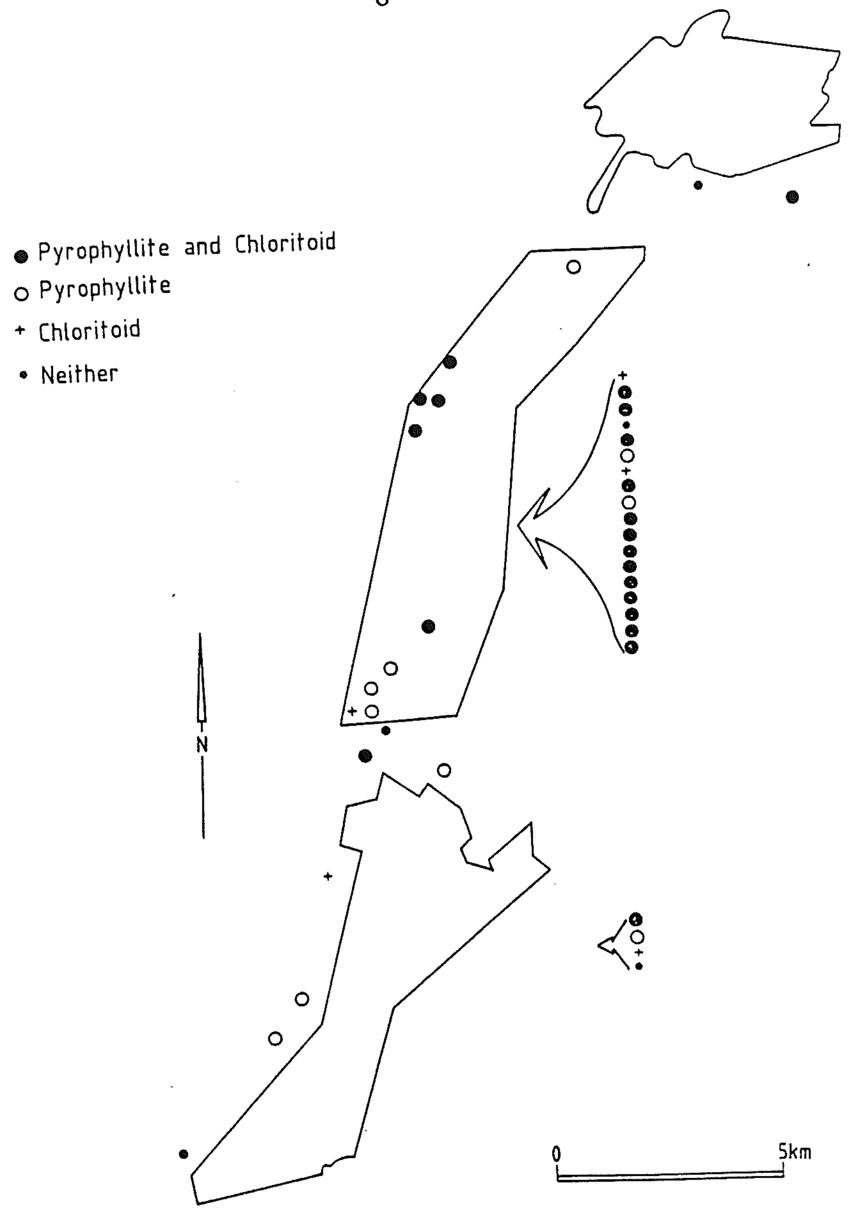

Figure 6: Pyrophyllite and chloritoid distribution within the K8 shale on Western Areas, Cooke Section and Doornkop Mines, West Rand Goldfield. Closely-spaced samples from underground are linked by brackets and placed east of the mines. The chloritoid, and particularly the pyrophyllite-rich samples, are inferred to have formed from alteration of chlorite-rich shales with substantial loss of silica and high inferred fluid-rock ratios (Phillips, 1988).

Aandenk Channel shale: Access to the Aandenk Channel "shale" during mining operations is limited, but samples from President Steyn, President Brand and Western Holdings areas suggest that the qualitative mineralogy is not significantly different from that of the Khaki shale (Borrego and Phillips, 1987; Figure 7).

Quartzites

The only detailed studies of the mineralogy of the quartzites unrelated to reef packages are those of Fuller (1958a), covering the West Rand Group, and a single hole through the Central Rand Group on the East Rand, of Law (1991), covering the Central Rand Group in the Welkom Goldfield. Sutton *et al.* (1990) covered the Central Rand and the

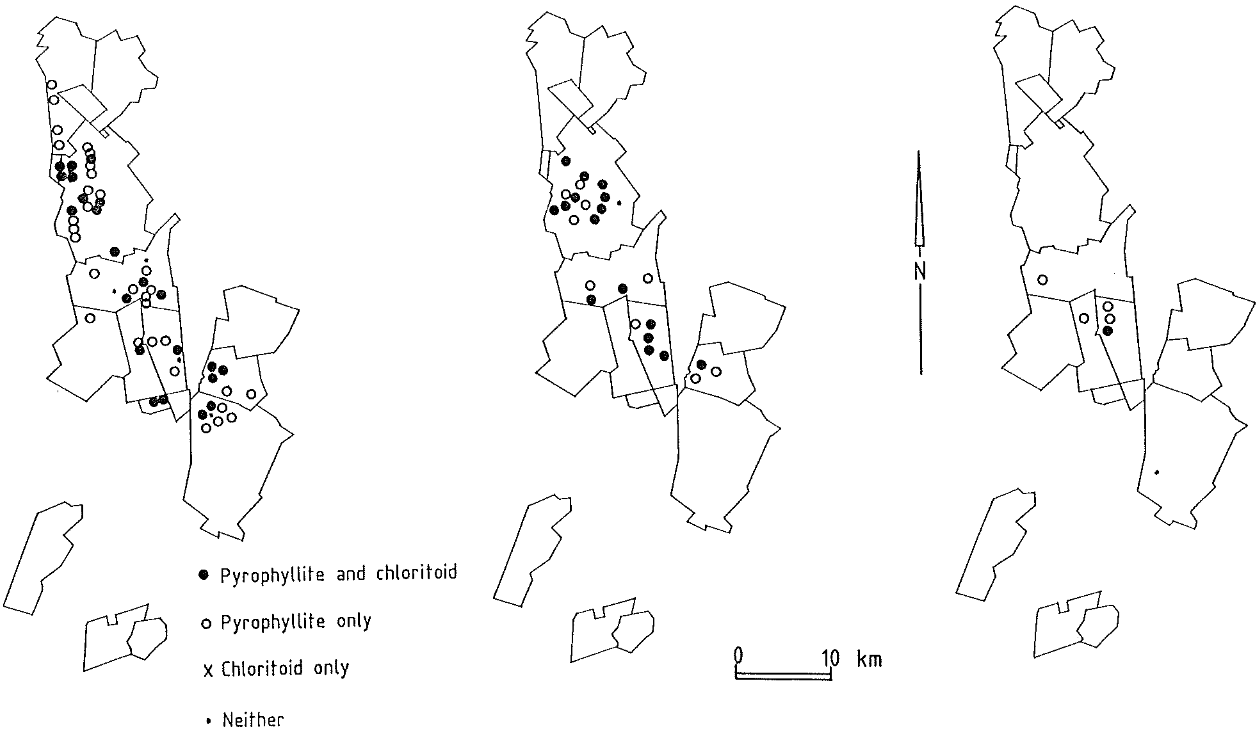

Figure 7: Pyrophyllite and chloritoid distribution within the Khaki shale (a), the Upper Shale marker (b) and Aandenk shale (c) of the Welkom Goldfield (sources of data: Borrego and Phillips (1987); Ramos (1987); and unpubl. data).

upper West Rand Groups in the Klerksdorp area. The following is a general summary of petrological aspects of these studies, but much is still to be learned about the variations across the Witwatersrand Basin, within this, the dominant rock type.

The Orange Grove Quartzite is composed of dominantly polygonal quartz with rare muscovite aggregates after detrital feldspar. The Brixton quartzites are also quartz-rich with minor green mica (inferred to be Cr-bearing fuchsite), detrital chromite, and common stylolite surfaces. The arenaceous members of both these formations are correctly referred to as "orthoquartzites" (Fuller, 1958a).

The quartzites within the Government and Jeppestown Subgroups are mostly poorly sorted sub-greywackes, with quartz, up to 30% pristine to slightly altered feldspar, rock fragments, biotite, chlorite, calcite, muscovite, epidote, pyrite, leucoxene, tourmaline, apatite and zircon. Both plagioclase and microcline have been recorded, especially in the Jeppestown and Government Subgroups (Fuller, 1958a).

Post-depositional processes within Central Rand Group quartzites have made the identification of sedimentary precursors difficult. The reconstructive approach to quartzite classification proposed by Law *et al.* (1990) has therefore been applied in the following discussion. Quartzites in the Central Rand Group are mainly massive to cross-bedded sub-labile (i.e. lithic and feldspathic grains no longer distinguishable) to labile arenites and quartz arenites comprising detrital quartz grains in a secondary assemblage of 5-30% muscovite, pyrophyllite, chlorite, chloritoid, chert, rutile, tourmaline and pyrite. Rock fragments which may rarely be unequivocally identified as primary rock fragments become indistinguishable from the enclosing matrix during diagenetic and/or metamorphic alteration. A negative correlation between chlorite versus secondary silica and pyrophyllite was noted in quartzites from the East Rand (Fuller, 1958a). These quartzites of the Central Rand Group have been referred to as "hydrothermally altered feldspathic quartzites or arkoses", although no timing of the alteration has been suggested excepting that it was post-burial (Fuller, 1958a).

In a detailed study of quartzites from the St. Helena area of the Welkom Goldfield, representative samples of the Central Rand Group were collected, and unusually pyritic and deformed samples excluded (Law *et al.*, 1988b; Law, 1991). Quartzites range in colour from grey/white through various shades of drab grey/green, to almost black for some samples from the Eldorado Formation. Cross-bedding is common, and units commonly fine upwards. Three broad quartzite groups may be distinguished on the basis of their appearance in hand specimen and in thin section: (1) true quartz arenites with over 95% quartz, (2) quartz-wackes (massive argillaceous quartzites containing poorly sorted quartz grains in a fine-grained matrix of muscovite -pyrophyllite - chlorite $\pm$ kaolinite), and (3) sub-labile to labile arenites (well-sorted cross-bedded arenites comprising a homogeneous assemblage of detrital quartz and indistinguishable labile framework grains). The general appearance, grain size, sorting, and roundness characteristics are fairly consistent within the three groups, but vary significantly between groups (Law *et al.*, 1990).

Colour changes within quartzites are generally subtle and gradational except where bedding surfaces are crossed. The changes are related to:

1) a change in the type, rather than the abundance, of matrix minerals (particularly chlorite near foresets, stylolites, dykes, sills, fractures and breccias);
2) detrital variations reflected in a change in the type and/or abundance of matrix minerals; and
3) reduction in grain size and the associated increase in the abundance of matrix minerals (Law *et al.*, 1988b).

Pyrophyllite is the dominant phyllosilicate and was identified by X-Ray diffraction in 47 out of 52 samples analysed (Law, 1991). Quartz and muscovite are widespread, but chlorite was limited to 0 to 14% modal except in chloritized shear zones, breccias and samples from the Fe-rich chloritic Eldorado Formation. Pyrophyllite and kaolinite co-exist in some samples from one borehole but kaolinite appears absent from virtually all samples with chlorite. Fuller (1958a) has documented pyrophyllite and chlorite as being mutually exclusive in the East Rand. These minerals, however, commonly co-exist in the Welkom Goldfield. There appears to be no consistent quantitative relationship between the silicate mineralogy of the quartzites and their Au contents (Law, 1991).

Pyrophyllite, chlorite and chloritoid are all widely distributed both vertically within the stratigraphic sucession and laterally within stratigraphic units of the Central Rand Group in the Welkom Goldfield (Figures 3, 4, 8 and 9). The modal abundances of the minerals vary over small distances, but the same suite of minerals persists throughout. The maximum

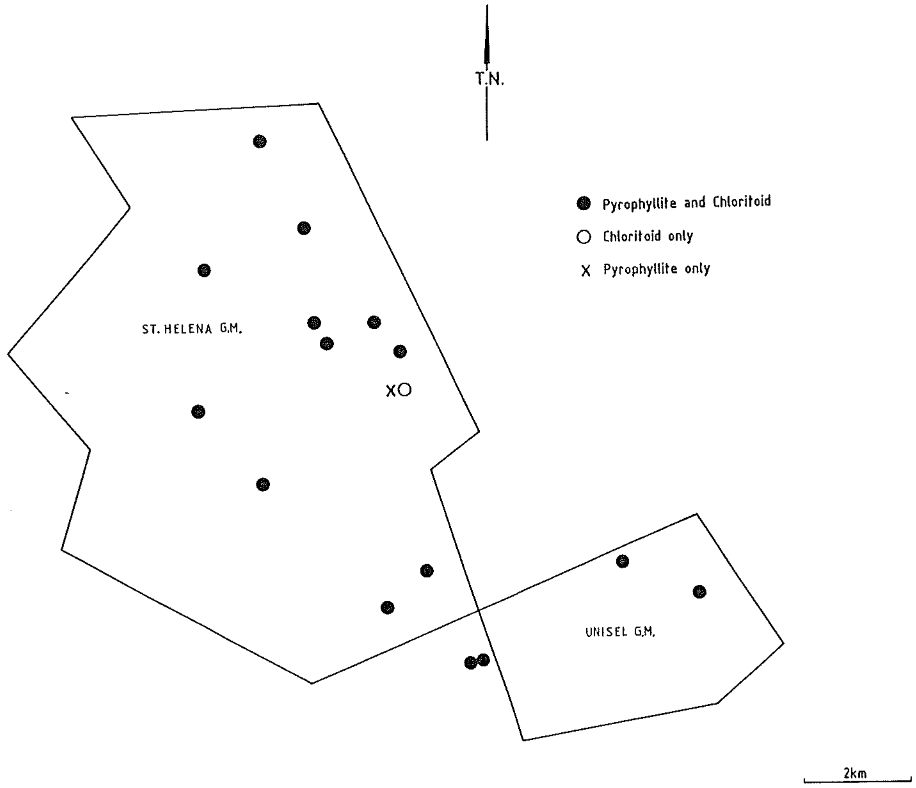

Figure 8: Pyrophyllite and chloritoid distribution within quartzites of the Central Rand Group on St. Helena and Unisel Mines, Welkom Goldfield.

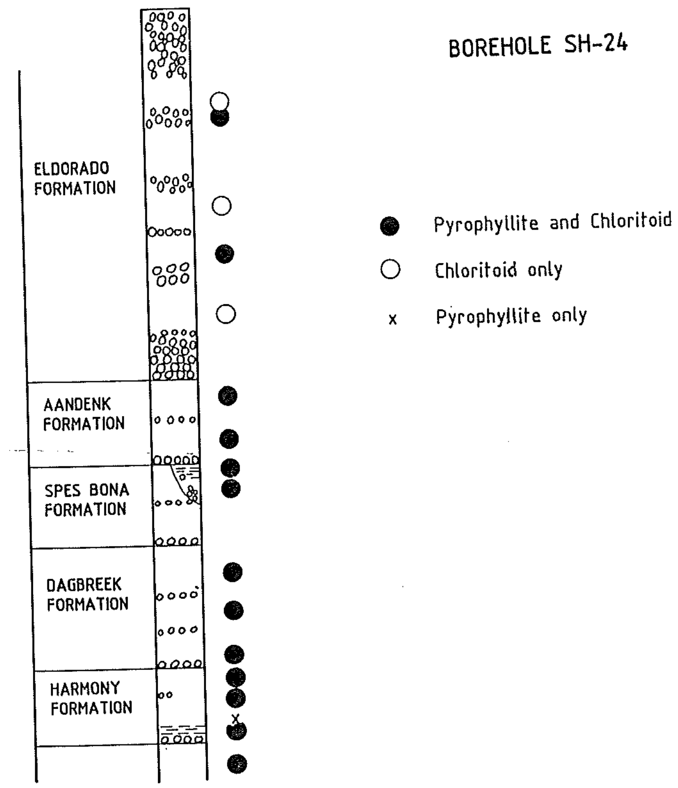

Figure 9: Stratigraphic column of the Central Rand Group at St. Helena Mine showing the distribution of pyrophyllite and chloritoid in quartzites throughout the succession.

mineral assemblage documented is pyrophyllite - muscovite - chlorite - chloritoid - tourmaline - quartz - pyrite - rutile - chromite - zircon - leucoxene. Feldspar was not detected in thin-section or by XRD analysis. Chloritoid occurs as discrete, randomly orientated clusters and is erratically distributed. Chlorite is spatially related to pyrite particularly along foresets, stylolites and bedding surfaces and is rarely pervasively distributed throughout the rock except in quartzites from the dark green parts of the Eldorado Formation. Mica growth occurs at the expense of pre-existing minerals and detrital quartz grains are partially consumed during reaction. At least three modes of mica occurrence can be identified: 1) large mica porphyroblasts (up to 3 mm), many of which are deformed and grow at the partial expense of detrital quartz grains, 2) fine-grained mica - quartz intergrowths (with a similar size distribution to modified detrital grains) occur as scattered yellow/orange specks in hand specimen, and 3) fine-grained mica intergrowths forming a homogeneous matrix to, and commonly reacting with, detrital quartz grains.

The bulk rock compositions of the various quartzites has been systematically studied only in the Welkom area, where the compositions are not easily related to the lithological groupings. As a whole, the quartzites of the Central Rand Group at Welkom are characterized by low alkalis, and only small variations in ratios between Ti and Al, and mobile elements, including K/Rb, Na/K and Au/U (Law, 1991).

To summarize, Witwatersrand quartzites from the Central Rand Group are unusual in that they generally lack feldspar, contain disseminated pyrite and have a simple and regionally persistent mineralogy. Feldspar has been described in rare instances (e.g. from the Maraisburg Quartzite; Winter, 1957). Pyrophyllite - muscovite - chlorite - chloritoid - quartz - pyrite assemblages are widespread irrespective of the rock texture and sedimentary characteristics. The assemblage is inferred to be the product of alteration and metamorphism of the original detrital assemblage (Fuller, 1958a; Law *et al.*, 1990; Law, 1991). Sedimentary textures are recognizable in all lithologies studied, but evidence of silica movement (pressure solution, grain overgrowths, stylolites) and secondary minerals (especially chloritoid, chlorite, pyrophyllite, muscovite and rutile) is widespread.

Conglomerates

Although numerous studies have recorded the mineralogy of Central Rand Group conglomeratic reefs in considerable detail (Young, 1917; Feather and Koen, 1975; Hallbauer, 1986), less attention has been paid to the metamorphic significance of assemblages, particularly those involving silicate phases. Studies of the detailed mineralogy of the non-auriferous conglomerates are less common.

Chloritoid, pyrophyllite, chlorite, muscovite, rutile, quartz, tourmaline and pyrite appear to be widespread in conglomeratic reefs in all gold fields, and coexist at least locally. Chlorite abundance and minor pyrrhotite may have a negative relationship to white mica, pyrite and gold grade in some reefs (Mullins and Martin, 1986), and elsewhere, pyrite and chlorite appear related (Viljoen, 1963; Tucker, 1980; De Waal, 1982); however, no single phyllosilicate has been related to gold grades in a consistent and quantitative fashion.

Garnet, diamond, monazite, cassiterite, chromite, zircon and apatite are recorded from some conglomerates, but their paragenesis is unclear. As some of these minerals (e.g. diamond) have obviously not re-equilibrated to conditions within the basin, the significance of these resistate minerals as guides to metamorphism is dubious.

A detailed study of the mineralogy of the Promise Reef in the West Rand Group suggests a similar mineralogy to the reefs of the Central Rand Group (Meyer and Tainton, 1986; 1990). Pyrophyllite, chloritoid, muscovite, chlorite, kaolinite, quartz and rutile are common, along with feldspar and calcite. Veins contain siderite, pyrite and chalcopyrite.

Geothermometers based on sulphide assemblages within auriferous conglomerates suggest temperatures up to 600°C during metamorphism. Sphalerite assemblages indicated temperatures in excess of 500°C (Fuller, 1958b); whereas studies on the cobaltite - gersdorffite - arsenopyrite system (Feather, 1981) yielded temperatures of < 300 to 600°C for both "detrital" cobaltites and secondary gersdorffites. The high temperature estimates have been attributed to non-equilibrium assemblages (see Discussion after Feather's paper) and to contact metamorphism related to intrusives.

Meyer *et al.* (1988; 1990) have used trace element geochemical data for various pyrite morphologies to demonstrate that post-depositional equilibration between different morphological types of pyrite has occurred. In contrast, Hallbauer (1986) has inferred that pyrite compositions have remained essentially unchanged since their deposition or formation (i.e. to have remained unchanged during regional metamorphism). The sulphide minerals do not appear to constrain the metamorphism as well as the silicate minerals, and careful sampling would be needed to eliminate the effects of resetting during retrograde cooling.

Mafic rocks

The Crown meta-basalt below the Roodepoort Shale Formation, and the Bird metabasalt below the Booysens Shale, are the only horizons of stratabound mafic rocks in the Witwatersrand Supergroup. Access to the Crown meta-basalt is restricted and limited study suggests it is carbonate - chlorite rich locally.

The Bird meta-basalt is exposed in mines and bore holes of the Evander and East Rand gold fields where alteration to a yellow, khaki or green colour is common along top and bottom contacts. The less altered meta-basalt is predominantly chlorite-rich, with epidote, albite, muscovite and quartz; whereas the khaki phyllite is muscovite-rich with quartz, carbonate, tourmaline and rutile, but without feldspar, epidote or chlorite (Palmer, 1986). Pyrophyllite and chloritoid coexist, and thin pyrophyllite partings are widespread. A number of important mineral assemblages have been documented in altered Bird meta-basalt from Evander (Table 1).

Dykes and sills in the Witwatersrand Supergroup may have altered margins containing chloritoid (Pegg, 1950), pyrite and white micas (as in the Welkom Goldfield) and other mineral assemblages that lead to marked discolouration. Primary magmatic assemblages in virtually all syn- and pre-Bushveld intrusives are hydrated and the primary silicate minerals are variably altered to tremolite, chlorite, saussurite, leucoxene, amphibole, serpentine, pyrite, quartz, albite, clinozoisite, chloritoid, pyrophyllite assemblages. Accessory minerals

Table 1: Mineral assemblages found in each Witwatersrand gold field

Welkom (Upper Shale Marker):
pyro - musc - chtd - chl - q - rut - tourm - py - zir (4162.2 President Steyn)

Welkom (Khaki shale):
pyro - musc - chtd - chl - q - rut (Borrego and Phillips, 1987; 4148 President Brand, 4130 President Steyn, 4161 Free State Geduld mine, 4187 President Steyn, 4186 President Steyn, 4169 also has kaolinite, Free State Geduld)

Welkom (quartzites):
pyro - musc - chtd - chl - q - rut - tourm - py - zir (plus chromite and leucoxene; Law et al., 1991)
pyro - kaolinite - musc - q - rut

Klerksdorp:
no systematic study
pyrophyllite widely reported in shales near reef
chloritoid reported from conglomerates

Carletonville (Green Bar):
pyro - musc - chtd - chl - tourm - rut - zir - py - q (4067, 4068 Blyvooruitzicht)
pyrophyllite and chloritoid common at most mines

Carletonville (minerals recorded in altered Ventersdorp Supergroup lavas, Palmer, 1986):
musc - py - rut - q - amphibole
pyrophyllite
musc - chl - q - rut - py - epid - feld (least altered)

West Rand and Western Areas:
pyro - musc - chtd - tourm - rut - zir - py - q (3855)
pyro - musc - chtd - chl - tourm - rut - py - q (3873)

Central Rand:
pyro? - musc - chtd - tourm - q
musc - chtd - chl - rut - zir - tourm - py - q
musc - chl - carb - py - q
pyro - q (3909)
musc - bi - chl - carb - py - q (3959)
pyro - mica - chtd - chl - q
kyanite in the west, including: kyanite - pyro - q (Schreyer and Bisschoff, 1982)

Table 1 (continued)

East Rand:
musc - chl - carb - q
pyro - mica - chtd - chl - q
chloritoid-rich shales common
pyrophyllite common in shales below Kimberley Reef unconformity (no XRD confirmation)
pyrophyllite widespread in arenites, especially in Johannesburg Subgroup

Evander:
bi - chl - musc - q - py (187, 188; Palmer, 1986)
kaolinite in local alteration patches
pyrophyllite common in shear zones
andalusite, cordierite, anthophyllite and biotite noted in shales by Tweedie (1981; 1986)
musc - chl - q - rut (Booysens Shale, Law et al., 1988a)

Evander (minerals recorded in Bird metabasalt; Palmer, 1986):
actin - epid - q - chl - calcite (133, 134, 135)
actin - epid - q - chl - calcite - pyrite (136)
feld - q - chl - actin - sider - rut - calcite (143 no cc, 144)
musc - chl - q - clinozo - rut (158)
musc - chl - q - epid - rut (159, 160, 161, 117, 118, 119)
musc - chl - q - epid - rut - calcite (162)
chl - calcite - q - oxide - clinoz - rut (166, 167, 168)
leucox - musc - rut - q - chl (107, 108, 110, 112, 113, 114)
leucox - musc - rut - q - chl - epid (111, 109 no leuco)
leucox - musc - rut - q - chl - py - epid (115, 116)
pyro - musc - chl - rut - q - clinoz - feld (145)
pyro - musc - oxide - chl - q (142)
pyro - musc - chl - rut - q - epid - py (155, 156)
pyro - musc - epid - rut (164, 165)
pyro - musc - oxide - rut (138, 139, 140, 141)
pyro - musc - chtd - chl - rut - q - epid (149, 150)
pyro - musc - chtd - rut - q - epid - py (151 no py, 152)
pyro - musc - chtd - epid - rut - feld (163)

Note: pyrophyllite has been confirmed by X-ray diffraction, except where stated.

Abbreviations: actin=actinolite; bi=biotite; carb=carbonate; chl=chlorite; chtd=chloritoid; clinozo=clinozoisite; epid=epidote; feld=feldspar; leucox=leucoxene; musc=muscovite; plag=plagioclase; py=pyrite; pyro=pyrophyllite; q=quartz; rut=rutile; sider=siderite; tourm=tourmaline; zir=zircon.

include sphene, apatite, ilmenite and magnetite. McCarthy *et al.* (1990) noted that Ventersdorp age diabase intrusives are typically more altered than subsequent intrusives on the East Rand. This observation appears to be true in all of the gold fields. Primary magmatic assemblages in all Klipriviersberg Group lavas are hydrated and the primary minerals are variably altered to assemblages comprising chlorite, actinolite, Na-feldspar ± epidote, zoisite, sphene, pyrite and quartz (Myers *et al.*, 1990). In spite of the metamorphism, original magmatic textures are generally well preserved.

Kerogen

Kerogen (colloquially referred to as carbon) is concentrated in the Central Rand Group as seams close to major unconformities, and as "fly-speck" nodules mostly within conglomerates. Quartz pebbles in some conglomerates are coated with a fine film of kerogen. Minor reduced carbon is recorded from the Booysens Shale at Evander (Law *et al.*, 1988a; 1991).

Although the origin of carbon in Witwatersrand seams is uncertain, vitrinite reflectance techniques have been applied with some caution. Kerogen seams from the Carbon Leader at Doornfontein and the Basal Reef from Western Holdings give vitrinite reflectance values near 3.3 (Rv max). These values are in the anthracite range and equate with temperatures of 200 - 400°C in younger rocks (e.g. Rowsell and De Swardt, 1976 and references therein; Karoo Sequence).

The coal rank of the kerogen seams varies from semi-anthracite to anthracite (De Kock, 1964); and atomic ratios of H/C and O/C are around 0.50 to 0.61 and 0.03 to 0.08, respectively, based on material from the Carbon Leader, Vaal Reef and Basal Reef (Hallbauer, 1986). Preliminary chemical analyses and Raman spectroscopy of a representative suite of kerogen samples from a number of Witwatersrand mines by Landais *et al.*(1990) indicates that Witwatersrand kerogens are mature (catagenic zone) and highly aromatic. H/C and O/C atomic ratios vary between 0.423 and 0.550, and 0.030 and 0.074, respectively.

Significant problems with metamorphic estimates based on kerogen seams arise from the lack of understanding of the corrections required to allow for the age of the succession, and the significance of vitrinite techniques. Generally, the methods using carbon are very sensitive at temperatures below 200°C (Tissot *et al.*, 1974; Bostock, 1979; Teichmuller, 1987), but less understood above 300°C. In addition, it has been demonstrated by several authors (e.g. Robb *et al.*, 1991; Law *et al.*, 1991) that carbon has been mobilized in post-depositional fluids and that at least some of the carbon has been introduced long after the deposition of the enclosing sediments. The relationship between metamorphism and carbon is therefore uncertain.

Metamorphic assemblages around the Vredefort Dome and Evander

The metamorphic grade of the Witwatersrand meta-sediments within 20 to 25 km of the centre of the Vredefort Dome is higher than that described above for the gold fields (Bisschoff, 1982; 1988; Figure 10). Steep dips of the meta-sedimentary sequences around

Figure 10: Map of the Witwatersrand Basin showing areas of pyrophyllite-chloritoid, andalusite ± kyanite, amphibolite and granulite grade metamorphism. Temperatures appear to have been remarkably uniform for hundreds of kilometres along the arc of the gold mines, but higher towards the Vredefort Dome and some structural margins of the Basin. The strike of major fold axes (post-Transvaal age; data from Johannesburg Dome area are excluded) are concentric to the Vredefort Dome, based on available information (McCarthy et al., 1986).

the Dome have resulted in metamorphic isograds being approximately parallel to lithology, and thus the metamorphism around the Dome is reconstructed here on the basis of all assemblages rather than just those found in the Witwatersrand Supergroup. A major deformation event of regional extent is recorded in the Transvaal and older sequences, and involves schistosities and fold axes that are concentric to the Vredefort Dome: on this basis the deformation has been interpreted as being synchronous with the Dome-forming event (McCarthy *et al.*, 1986) as inferred by Du Toit (1954).

Metamorphic assemblages around the Vredefort Dome provide convincing evidence of metamorphic grades of greenschist, amphibolite and granulite facies (Table 2), with mappable isograds of the incoming of staurolite, kyanite, sillimanite, hornblende plus zoisite, hornblende plus andesine and two pyroxenes (Bisschoff, 1982; 1988).

Metamorphic textures around the Vredefort Dome are dominantly hornfelsic, rather than schistose or gneissic, suggesting either that metamorphism was not accompanied by deformation, or that strain was localized to particular thin intervals rather than being pervasive and evenly distributed. Some retrogression of prograde assemblages has occurred.

Table 2: Assemblages recorded around the Vredefort Dome (Bischoff, 1982)

Pelitic
andalusite - almandine - cordierite - muscovite - biotite - quartz
andalusite - kyanite - chloritoid - muscovite - quartz
andalusite - cummingtonite - almandine - quartz
andalusite - cordierite - almandine - chlorite - biotite - quartz
almandine - cordierite - magnetite - biotite - quartz
chlorite - cordierite - almandine - biotite - quartz
chlorite - almandine - magnetite - biotite - quartz
chlorite - almandine - muscovite - biotite - quartz
chlorite - cordierite - muscovite - biotite - quartz
staurolite - andalusite - sillimanite - cordierite - chlorite
- muscovite - biotite - quartz
staurolite - andalusite - sillimanite - muscovite - biotite - quartz
staurolite - andalusite - kyanite - muscovite - biotite - quartz
staurolite - chlorite - muscovite - biotite - quartz
staurolite - almandine - chlorite - magnetite - biotite - quartz
staurolite - chlorite - cummingtonite - almandine - quartz
staurolite - andalusite - almandine - muscovite - biotite - quartz
cordierite - cummingtonite - biotite - quartz
cordierite - cummingtonite - almandine - quartz

Calc-Silicate
fosterite - diopside - calcite - dolomite
tremolite - diopside - calcite - dolomite

Mafic
anthophyllite - cummingtonite - quartz
cummingtonite - magnetite - quartz
hornblende - almandine - anthophyllite - quartz
hornblende - almandine - chlorite - biotite - quartz
hornblende- zoisite - sphene - magnetite - plagioclase
hornblende- zoisite - sphene - plagioclase - quartz
cummingtonite - almandine - chlorite - quartz
hornblende - cummingtonite - almandine - magnetite - quartz
cummingtonite - almandine - magnetite - plagioclase - quartz
actinolite -chlorite -epidote - calcite - magnetite - plagioclase
hypersthene - almandine - magnetite - quartz

Retrograde chlorite has not been specifically mentioned in the original source of the assemblages. The host rocks for the above assemblages include the Witwatersrand Supergroup, but, closer to the Vredefort Dome, extend to underlying successions.

Coesite and stishovite have been described from the NW collar of the Vredefort Dome (Martini, 1979) and further evidence for "shock" metamorphism has been described by Lilly (1978; 1981). Several generations of pseudotachylite have been described by Nel (1927).

The northeastern part of the Evander Goldfield is also characterized by higher metamorphic grade minerals in the Booysens Shale, including biotite (now commonly chloritized), andalusite, anthophyllite and cordierite (Tweedie, 1981; 1986), which he attributed to thermal metamorphic effects from the Kalabasfontein pluton interpreted to be a discrete intrusive body related to the intrusion of the Bushveld Complex.

Metamorphic assemblages around fault planes and intrusives

Although many important metamorphic assemblages are found on fault surfaces throughout the Witwatersrand gold fields, four representative examples are documented here.

A 1-2 m thick zone of green pyrophyllite-rich schist was noted in drill core in a thick sequence of Central Rand Group quartzites from ERPM Mine (Palmer, 1986). This highly sheared zone lacks sedimentary features and has sharp contacts with the enclosing quartzites.

The Master Bedding Plane Fault described previously roughly follows the Central Rand - West Rand Group boundary at the top of the Roodepoort Shale Formation. Pyrophyllite is found on the surface of foliated quartzites where the fault is within quartzites of the Jeppestown Subgroup (Phillips, 1988). Elsewhere the quartzites appear to lack pyrophyllite over large areas.

Numerous low-angle reverse faults cause repetition of conglomeratic reefs, and one of these faults adjacent to the Booysens Shale on Leslie Mine, Evander, is spatially associated with a 1.5 m thick discoloured meta-pelite zone adjacent to an overlying conglomerate (Palmer *et al.*, 1989). A 10 cm thick, khaki phyllite, rich in muscovite, contrasts with its precursor, the dark-green, chlorite-rich Booysens Shale.

Thrust slices along the north-western margin of the Witwatersrand Basin follow bedding planes and illustrate a positive correlation between pyrophyllite abundance and degree of deformation (Roering and Smit, 1987; Coetzee *et al.*, 1988). Mineral assemblages associated with thrusting are syn- or post-tectonic and include:

1) pyrophyllite-quartz-sericite-kaolinite-chlorite (with pyrophyllite abundance increasing with increasing deformation),
2) kyanite-quartz-pyrophyllite-sericite;and
3) quartz-chlorite-sericite (Coetzee *et al.*, 1988). It is not indicated what the nature of "sericite" is, nor whether the kaolinite is from weathering effects in these surface samples.

Dykes and sills are invariably associated with wallrock alteration of varying type dependant on the thickness and composition (and hence age) of the intrusive. The enclosing meta-sediments are commonly chloritic, dark green in colour, with moderate euhedral pyrite. Quartz $\pm$ carbonate $\pm$ sulphide veins may be associated with the intrusives.

Metamorphism of the Ventersdorp Supergroup and Transvaal Sequence

Meta-basalts from the base of the Ventersdorp Supergroup unconformably overlie the Ventersdorp Contact Reef and Witwatersrand quartzites at several localities including Deelkraal Mine. Here, the less-altered meta-basalt is dominantly chlorite, epidote, muscovite after feldspar, quartz, rutile and pyrite. More intense alteration associated with the unconformity coincides with a strong foliation in a yellow phyllite that has formed by meta-basalt alteration. The phyllite is dominantly muscovite, quartz, amphibole, rutile and pyrite (Palmer, 1986), with monomineralic pyrophyllite veins, and quartzitic veins with tourmaline, pyrite, zircon and sphene, in the phyllite.

Shales from the base of the Transvaal Sequence contrast with those from the Witwatersrand Supergroup in that they contain significant amounts of reduced carbon and are less aluminous. Bedding is defined by thin silty layers richer in quartz, whereas a weak to moderate foliation defined by muscovite and trains of carbon is common. Individual quartz grain shapes suggest considerable modification after burial, with boundaries controlled by adjacent mica and chlorite grains. Muscovite, chlorite, quartz, carbonate and tourmaline are widespread, with lesser albite. However, chloritoid, pyrophyllite and rutile have not been recorded to date. Higher grade assemblages are recorded in shales and intrusives NE of the Evander Goldfield.

Constraints on regional metamorphic conditions

Muscovite (illite) crystallinity

The degree of ordering in sheet silicates increases with metamorphism, and can be used as a qualitative guide to metamorphic grade. The technique has been applied widely in the European Alps as the primary means of subdividing this terrane into different metamorphic zones (see Frey, 1987, for examples). The half-height peak width of the first muscovite (illite) X-ray diffraction peak is measured (Frey, 1987, p. 16) and is expressed in degrees 2 theta. A preliminary analysis of illite crystallinity data suggests that the Kubler index (see Frey, 1987 for examples) is near 0.20 to 0.25 in most Witwatersrand meta-pelite samples, and any variation between gold fields is small (Table 3). Discoloured alteration zones in meta-pelites below the Kimberley Reef at Evander also have Kubler indices of 0.3 to 0.35. Kubler indices presented here for Witwatersrand lithologies are not directly comparable with those reported from the Cape Supergroup and Karoo Sequence at similar depths (i.e. up to 4600 m) by Rowsell and De Swardt (1976) as half height peaks in their study were measured in mm (rather than in degrees 2 theta).

Kubler indices for muscovite (illite) in quartzites of the Welkom Goldfield range from 0.3 to 0.6 with a mean of 0.42 for 29 samples, and remain relatively constant irrespective of textural variations between samples. The muscovite content of the quartzites is low ($<15\%$ modal) and so Kubler indices have only been calculated for those samples in which the height to width ratio of the (001) basal reflections exceeds 2. In contrast, in meta-pelites from the same areas at Welkom where the only mica present is muscovite, Kubler indices are lower and more consistent ($<$ 0.35).

Fluid inclusions

Fluid inclusions from quartz veins within the Witwatersrand meta-sediments include aqueous-rich and CO_2-rich types. Trapping temperatures for inclusions from a vein adjacent to C Reef in Southvaal Gold Mine range from 130-180°C suggesting that pressure-corrected, filling temperatures would be considerably higher (Phillips *et al.*, 1988).

Fluid inclusions from quartz veins at Marievale Mine homogenize at 340 to 360°C (Hallbauer, 1983) close to the maximum metamorphic temperature indicated by the mineral assemblages in this area: their significance is uncertain.

Fluid inclusions from granitoids adjacent to the northern outcrops of the Witwatersrand Basin include some with similar compositions and homogenization characteristics to those found in quartz veins from within the Basin (Klemd, 1987; Phillips *et al.*, 1988).

Fluid inclusions in presumed syntectonic quartz veins associated with thrusting in the northwest of the Witwatersrand outcrop margin have temperatures of homogenization ranging from 100 to 400°C with most inclusions in the range 150° to 200°C. Isochores suggest pressures ranging from 2.5 to 4 kb (Coetzee *et al.*, 1988).

Critical minerals and assemblages

The assemblage pyrophyllite - chloritoid - muscovite - chlorite - quartz - tourmaline - rutile - pyrite is found at several horizons of the Central Rand Group, and in many of the gold mines (Table 1). The subset assemblage pyrophyllite - chloritoid provides important constraints on metamorphic conditions and has been applied widely to all gold fields (Fig. 11). Similar constraints on metamorphic conditions have been derived independently by Wallmach and Meyer (1990).

Pyrophyllite is common in sheared pelitic units, but also recorded from many other lithological settings (see Phillips, 1988; Table 1). It is recognized by its "soapy" feel in hand specimen but confirmed by X-ray diffraction analysis.

Chloritoid is also widespread in many lithologies, but most common in quartzites, meta-pelites and some conglomerates. It is usually recognizable in hand specimen when in proportions of several percent, does not report in X-ray diffraction analysis of the clay fraction, but is easily confirmed in thin section even when in minute amounts. The texture of chloritoid blades varies from being near-random aggregates when in abundance, to individual tabular grains at a high angle to the dominant fabric (commonly the post-Transvaal cleavage; McCarthy *et al.*, 1986). A number of independent lines of evidence suggest that this chloritoid has grown at a high angle to the fabric during deformation (see Bell *et al.*, 1986) rather than grown after deformation as its cross-cutting nature may at first appear to imply. Syn-deformational chloritoid growth is favoured by the mineral chemical data indicating the chloritoid is in equilibrium with the other minerals including the muscovite and chlorite that define the dominant cleavage, the systematic relationship between bulk rock composition and chloritoid abundance suggesting it is part of the full assemblage rather

Table 3: Muscovite crystallinity expressed as Kubler indices for various Witwatersrand shales. Samples tested for kaolinite are also noted

Number	Location	Kubler	Kaolinite
4371	Evander		Present
4369	Evander	< 0.3	Present
4370	Evander		Present
4371	Evander	< 0.3	Present
4367	Evander	.24	Present
4095	Consolidated Modderfontein	.21	
4097	Consolidated Modderfontein	< 0.24	Absent
4098	Consolidated Modderfontein	.32	
3978	ERPM		Absent
3979	ERPM	.21	Absent
3980	ERPM		Absent
3909	Crown mines	< 0.2	
3912	Crown mines	< 0.3	Absent
4283	Krugersdorp surface	.19	Present *
4284	Krugersdorp surface	.21	Present *
4281	Krugersdorp surface	.22	Present *
3992	Cooke section		Absent
3985	Cooke section	< 0.35	Absent
3985	Cooke section		Absent
3864	Cooke section	< 0.4	
3869	Cooke section	.21	Absent
3873	Cooke section	.21	Absent
3998	Libanon	.31	
3999	Libanon	.24	
3999	Libanon	.26	
4327	Blyvooruitzicht	.22	Absent
4065	Blyvooruitzicht	.28	
4066	Blyvooruitzicht	< 0.3	
4067	Blyvooruitzicht	< 0.3	Absent
4068	Blyvooruitzicht	< 0.3	
4069	Blyvooruitzicht	.30	
4070	Blyvooruitzicht	.25	
4071	Blyvooruitzicht	.25	Absent
4072	Blyvooruitzicht	< 0.28	
4074	Blyvooruitzicht	< 0.28	Absent
4075	Blyvooruitzicht	.20	Absent
4076	Blyvooruitzicht	< 0.3	
4079	Blyvooruitzicht	.22	Absent
4081	Blyvooruitzicht	.40	Absent
4082	Blyvooruitzicht	< 0.3	
4085	Blyvooruitzicht	< 0.25	
4086	Blyvooruitzicht	.32	Absent
4087	Blyvooruitzicht	.28	Absent

Table 3 (continued)

4088 Blyvooruitzicht		Absent
4089 Blyvooruitzicht		Absent
4090 Blyvooruitzicht	< 0.3	Absent
4091 Blyvooruitzicht	.32	Absent
4093 Blyvooruitzicht	.22	Absent
4094 Blyvooruitzicht	.27	Absent
4103 Blyvooruitzicht	.22	Absent
4105 Blyvooruitzicht	.22	
4106 Blyvooruitzicht	< 0.3	Absent
4259 Western Deep levels	.21	
4256 Western Deep levels	.22	
4254 Western Deep levels	.32	Absent
4258 Western Deep levels	< 0.3	
4260 Western Deep levels	.25	? Present
4253 Western Deep levels	.22	Absent
4003 Western Deep levels	.24	
4004 Western Deep levels	.25	
4385 Stilfontein	.30	Absent
4384 Stilfontein	.35	Absent
4376 Stilfontein	.22	Absent
4378 Stilfontein		Absent
4379 Stilfontein	.18	
4383 Stilfontein	.21	Absent
4382 Stilfontein	.19	Absent
4381 Stilfontein		Absent
3977 Klerksdorp	.36	Absent
4365 Unisel	.18	Absent

* kaolinite at Krugersdorp is attributed to surface weathering. Other kaolinite bearing samples are from underground.

than being a retrograde addition, and quartz pressure shadows around chloritoid grains. In detail, the textures around the chloritoid grain terminations are similar to those described by Bell *et al.* (1986) for syn-deformational growth.

The determination of mica species apart from pyrophyllite has usually involved a combination of X-ray diffraction and microprobe analysis. Biotite is difficult to distinguish from brown altered chlorite but easily confirmed by microprobe analysis particularly of K_2O. Paragonite is commonly intergrown with muscovite, and confirmed by high whole rock Na_2O coupled with probe analysis of white micas for K_2O and Na_2O. Limited investigations of muscovite (illite) crystallinity have suggested that the 2M1 form predominates in meta-basalt and phyllite from the Ventersdorp Supergroup at Deelkraal and the Bird meta-basalt at Evander (Palmer, 1986), the Vaal reef at Stilfontein, the Basal reef at Unisel, the Green Bar at Blyvooruitzicht, the Upper Shale Marker at St. Helena, and in the quartzites of the Central and West Rand Groups at Welkom.

Some chemical analyses of metamorphic minerals are available for meta-pelites (see Phillips, 1987, Table 3) and from quartzites from the Welkom Goldfield (Law, 1991). Meyer (1991) has used chlorite compositions in the Ventersdorp Contact (VCR) and Carbon Leader Reefs (CLR) of the West Wits Line (near Carletonville) to constrain the temperature of formation of hydrothermal chlorites. The data are relatively consistent within each reef; however, there is a decrease from $\pm$ 340°C in the CLR to $\pm$ 305°C in the overlying VCR (a vertical stratigraphic distance of $\pm$ 1500 m). These data suggest a geothermal gradient of about 27°C/km. Spatial relationships suggest that the hydrothermal event occurred in post-Transvaal times.

Tourmaline is widespread in pelitic rocks and conglomerates in small amounts. Its habit is similar to chloritoid, and where it cross-cuts the post-Transvaal cleavage, it too is inferred to be syn-deformational.

Kaolinite has been identified from a number of pelitic samples from various gold fields. Electron microprobe identification has confirmed the presence of kaolinite in the Khaki shale and quartzites from Welkom, and altered samples from the Evander gold field. X-ray diffraction identification of kaolinite was complicated by the overlap of a chlorite peak with the first kaolinite peak near 7.2 Å and these were confidently separable in some samples only. The second kaolinite peak (3.6 Å) provided a better separation from a nearby chlorite peak (Frey, 1987). X-ray diffraction analysis suggested that kaolinite is common in the Water Tower Slate at Krugersdorp (Table 3) but it is almost certainly supergene, as inferred by Schreyer and Bisschoff (1982).

Rutile is extremely widespread in pelitic rocks as the dominant Ti-bearing phase; and its modal proportion is closely correlated with whole rock TiO_2 content. Pyrite is widespread in small amounts in meta-pelites, and appears to dominate over other opaque phases such as magnetite, hematite, ilmenite, pyrrhotite and arsenopyrite, except in the West Rand Group and particularly the Parktown Shale Formation. The rutile and pyrite distribution is better understood in the Central Rand Group conglomeratic reefs where these minerals are very widespread, and pyrite, chlorite and chloritoid are the main hosts of Fe to the virtual exclusion of oxide phases.

Pyrrhotite is absent from many reefs but is common locally, in particular in the Ventersdorp Contact Reef immediately below the meta-basalts and ultramafic lavas of the Ventersdorp Supergroup (Ingle, 1986). In some cases, the proportions of pyrite to pyrrhotite may decrease towards the overlying lavas, whereas in other cases, the proportion increases. The presence of pyrrhotite in the Ventersdorp Contact Reef has not been fully explained, although thermal and/or chemical effects of the lavas are both possible.

Kyanite distribution is not well constrained but it appears relatively common in shear zones and quartz veins near the northwest outcrop margin of the Witwatersrand from the vicinity of Durban Deep Mine to the Krugersdorp area (Schreyer and Bisschoff, 1982), and in some quartz veins in the Central and East Rand mines. However, it is rare or absent in many gold mines.

Summary of metamorphic conditions

Although a large number of independent methods of estimating metamorphic conditions are available in the Witwatersrand gold fields, not all are of equal value. Mineral assemblages have the advantages that they are readily duplicated in laboratory experiments under known and controlled P-T conditions, and resetting or retrogression is usually recorded in the petrographic microstructures. Sulphide assemblages can also be generated in experiments, but are more prone to resetting in the temperature interval of interest (below 400°C). The difficulty of detecting small concentrations of weathering products can be avoided by utilizing only underground and core samples.

Calibration of vitrinite reflectance, muscovite crystallinity, the Kubler index, coal rank and carbon elemental analyses are not easily related to absolute temperature scales, as none rely directly on thermodynamic relations (cf. mineral assemblages). The effect of time and retrograde processes on these methods is not well understood (Frey, 1987), but they still provide a qualitative guide to metamorphic grade and a useful comparative method against other metamorphic terranes. A further limitation of these methods is the lack of existing constraints on the degree to which carbon phases have migrated after burial. In contrast to the metamorphic studies of the Alps where illite crystallinity (Kubler index) has been used as the primary control on grade because significant methane is suspected in the fluid phase (Frey, 1987), mineral assemblages have been used as the primary temperature control in the Witwatersrand. Except for the mineral assemblage method, the combined influence of geothermal gradient, time and cooling rate on these techniques is mostly unknown. Fluid inclusions provide a temperature minimum only, in the absence of evidence for boiling or accurate pressure corrections. U-Pb isotopic studies (Allsopp *et al.*, 1986) suggest that the kerogen may be as young as ca 2320 Ma.

The pelitic assemblages provide relatively tight constraints on temperature in all the gold fields. The stability of pyrophyllite and chloritoid, in particular, demonstrates no major variations in temperature between Welkom and Evander around the gold fields (a distance of 350 km). More subtle temperature differences between gold fields are indicated by changes in chloritoid composition from the four phase assemblage of chloritoid - chlorite - pyrophyllite - quartz (unpubl. data). The mineral assemblage data suggest temperatures reached 350 +/- 50°C in all the gold fields. The stability of kaolinite in underground samples from Evander and Welkom (Table 1) suggests temperatures may have been at the lower end of this limit for these areas.

The vitrinite reflectance, carbon elemental analyses, coal rank, muscovite crystallinity, chlorite crystallinity, Kubler indices and fluid inclusions all indicate temperatures above 200°C, and are compatible with the lower end of the temperature range suggested by the mineral assemblages (Table 4). Temperature variations between Welkom and Carletonville may be reflected in kaolinite at the former and differing chloritoid compositions, but these trends are superimposed on an otherwise remarkably uniform metamorphic grade in all gold fields.

Textural changes in shales during low-grade metamorphism are very broadly correlatable with metamorphic grade. The Witwatersrand meta-sediments do not generally preserve clear cut boundaries between quartz grains and clay matrix, and instead phyllosilicates are preferentially oriented, siltstones show extensive pressure solution and meta-pelites include slates and phyllites. These textures are typical of prehnite - pumpelleyite facies and above, rather than zeolite facies and below (Kisch, 1983).

Muscovite (illite) crystallinity values (Kubler index) of 0.40 are commonly taken as representative of the lower boundary of the anchimetamorphic zone, and 0.25 as the upper limit (Frey, 1987); several values would be necessary for a reliable grade indication. Sixty muscovite crystallinity indices for Witwatersrand meta-pelites are mostly below 0.25, with minor variation between gold fields; i.e. representative values are: Evander, 0.23; Consolidated Modderfontein, 0.25; ERPM, 0.21; Crown, 0.2; Krugersdorp surface, 0.20; Cooke Section, 0.21; Libanon, 0.27; Blyvooruitzicht, 0.24; Western Deeps, 0.24; Stilfontein, 0.24. These data suggest the Witwatersrand gold fields represent conditions above the anchimetamorphic zone, and thus probably signifying temperatures of 300°C or above (Frey, 1987). Large temperature variations between gold fields are not indicated by the present data, but more analyses from the Witwatersrand area would be needed to test if the Central and West Rand represent statistically higher temperature conditions than other gold fields. Higher and more erratic Kubler indices from quartzites from Welkom (0.30) contrast with the pelitic populations and are tentatively attributed to the low modal abundances of muscovite, and associated high pyrophyllite to muscovite ratios causing peak definition problems.

The dominance of the 2M1 muscovite polytype is typical of meta-sediments in which the original 1Md polytype has been converted by temperatures above 200°C; however, without knowledge that the main detrital K-bearing phase was 1Md illite this method is not used as a diagnostic constraint on metamorphic grade. 2M muscovite is also the dominant form of muscovite in quartzites from the Central Rand and Welkom (Fuller, 1958a; Law, 1991), Booysens Shale, Chloritoid shale, Bird meta-basalt and altered Ventersdorp lavas (Palmer, 1986).

Fluid inclusion homogenization temperatures provide a minimum temperature estimate for the temperature of filling, in the absence of an accurate knowledge of the necessary pressure corrections. The fluid inclusion data do not particularly constrain the metamorphic temperatures, but are compatible with the more definitive results from phase assemblages

Table 4: Comparison of temperatures in the Witwatersrand gold fields indicated by different geothermometric techniques

Method	Distribution of data	Confidence	Temperature
pyrophyllite	widespread	***	300 to 400°C
chloritoid	widespread	**	over $\approx$ 300°
2M1 muscovite plus chlorite IIb	widespread	**	over 200°C
biotite	local only	**	over 350°C
paragonite plus quartz	local	**	below 550°C?
illite crystallinity	widespread	**	over 300°C
fluid inclusions	local	*	over 180°C
carbon O/H, C/H	local	*	over 140°C
vitrinite reflectance	local	*	over 200°C
coal rank	widespread	**	over 200°C
muscovite polytype	local	*	over 200°C
chlorite polytype	local	*	over 200°C
texture of shales	widespread	*	over 200°C

(i.e. 300 to 400°C; Figure 11).

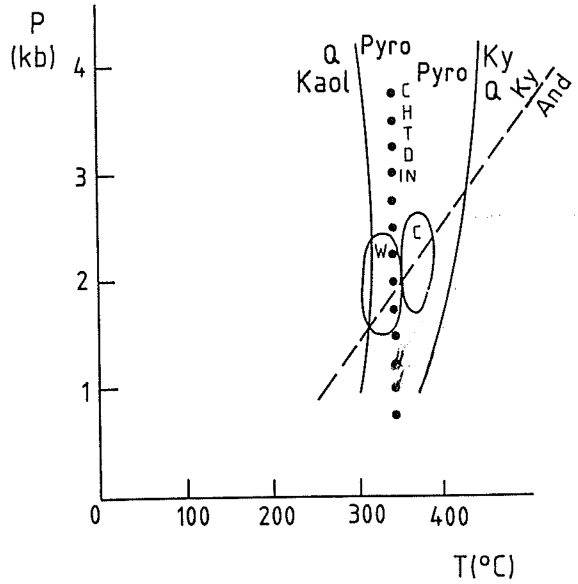

Figure 11: Pressure-temperature diagram for peak metamorphic conditions inferred for the Witwatersrand gold mines based on the widespread distribution of pyrophyllite and chloritoid in most gold fields. Temperatures at Welkom (W) may have been slightly lower than those at Carletonville (C), based on kaolinite at the former, and differences in the pyrophyllite-chloritoid-chlorite three-phase compositional relations. Kyanite around the Johannesburg Dome area indicates higher temperatures that probably extend to Durban Deep and neighbouring gold mines (Central Rand Goldfield).

The very low H/C and O/C atomic ratios are compatible with low-grade metamorphism, and temperatures substantially higher than the "oil window" of around 140°C. The vitrinite reflectance measurements and anthracite rank confirm metamorphic temperatures significantly in excess of 200°C but do not provide exact estimates.

Pressure is not as well constrained as temperature, and much depends on the interpretation of the metamorphism at Vredefort and its relationship to the gold fields. Utilizing the transition from chloritoid rocks to amphibolite facies to granulite facies around Vredefort to imply a low-intermediate pressure (andalusite - sillimanite type, +/- kyanite) terrane suggests pressures in the gold fields may be only 1.5-3 kb (Phillips, 1987). Pressures much lower than 1.5 kb appear unlikely given the brittle-ductile to ductile deformational regime synchronous with metamorphism (Roering and Smit, 1987). Fluid inclusions from the NW outcrop margin of the Witwatersrand also indicate relatively low pressures (Coetzee *et al.*, 1988).

The pressure-temperature conditions inferred around the Vredefort Dome range from 400°C and 2 kb, to over 700°C and 5 kb (Bisschoff, 1982; Schreyer and Abraham, 1978), suggesting a high geothermal gradient of 50°C/km. A similar, high geothermal gradient is inferred for the Witwatersrand gold fields (possible above 50°C/km; Phillips, 1987).

Peak metamorphism appears to have involved an active fluid phase in equilibrium with pyrite, muscovite, pyrophyllite, paragonite (locally), reduced sulphur and oxidized carbon. Permeation of these fluids was uneven through the Central Rand Group, and zones of lower metamorphic fluid permeability may preserve diagenetic characteristics.

Processes during metamorphism

Relationship between deformation and metamorphic assemblages

Although the distribution of both strain and critical metamorphic assemblages is heterogeneous in the Central Rand Group, the two features are closely related both spatially and genetically.

Strain in the Witwatersrand Supergroup is substantially higher in the heterogeneous reef packages of 1 to 2 m thickness, compared to the surrounding quartzite-rich intervals of tens of metres thickness. The reef packages are characterized by numerous fractures and shear zones that are typically near-parallel to bedding, and considerable pressure solution of conglomerate pebbles against mica selvedges. In many reefs, thin quartz veining is widespread in the reef package interval, but terminates or diminishes within a few metres into the surrounding thick arenites (e.g. Carbon Leader on West Driefontein Mine, Kimberley Reef on Bracken Mine and Crown Mines, Ventersdorp Contact Reef on Kloof Mine, Zandfontein Reef on Kinross and Bracken Mines). In the latter situation, the Zandfontein Reef has quartz veins that become less common in the overlying quartzite and terminate abruptly in the underlying Booysens Shale because of ductility contrasts. Using the preservation of bedding in pelitic rocks as one guide to the degree of strain, chlorite-rich meta-pelites have well-preserved bedding and sedimentary features, whereas pyrophyllite-rich meta-pelites are dominated by tectonic fabrics, and chloritoid-rich meta-pelites are intermediate in character between the chlorite-rich and pyrophyllite-rich types. The extent of quartz veining mirrors the preservation of bedding and appears strongest in pyrophyllite-rich meta-pelites.

The distribution of pyrophyllite and chloritoid in the pelitic rocks is compatible with their origin as products of alteration, rather than original sedimentary variations (see Borrego and Phillips, 1987; Phillips, 1988). The thick meta-pelites (e.g. Booysens Shale) are chlorite-rich except near contacts and where they underlie unconformity surfaces (commonly foliated, e.g. below the Kimberley Reef unconformity on the East Rand). The reef package meta-pelites have highly variable (Figures 5, 6 and 7) modal mineralogy that is not easily explained by sedimentary processes, but does correlate with zones of different strain (veining, foliation, lack of bedding). Wallmach and Meyer (1990), however, while recognising the importance of a compositional control on the growth of pyrophyllite and chloritoid, argue for isochemical diagenesis and metamorphism to generate the observed assemblages.

A similar relationship may extend to coarser-grained lithologies where examples exist of pyrophyllite-rich shear zones within quartzite packages suggesting substantial alteration (removal of silica and other elements) to stabilize pyrophyllite in the higher strain zones (e.g.

Master Bedding Fault in Jeppestown quartzites on East Driefontein Mine, and numerous small-scale examples from the Welkom Goldfield). Certain "argillaceous quartzites" appear to represent foliated and altered quartz arenites and labile arenites rather than clay-rich precursors.

There is thus a spatial coincidence between thin lithologically-heterogeneous intervals, deformed rocks, intervals of veining, pyrophyllite-rich rather than chlorite-rich meta-pelites, small-scale bedding parallel discontinuities and unconformity surfaces. The data support an intimate association between the processes of deformation, metamorphism, fluid activity and alteration. The heterogeneous distribution of strain and fluid flux appear responsible for the heterogeneous metamorphic assemblages.

Timing of regional metamorphism

The regional metamorphism recorded in the Witwatersrand Supergroup has also overprinted the overlying Ventersdorp Supergroup, based on the stability of pyrophyllite in alteration zones within the latter (Palmer *et al.*, 1987) and the similarity of mineral assemblages in equivalent bulk rock compositions (e.g. 2M muscovite - chlorite). The metamorphism has also postdated the intrusion of some dykes in the Witwatersrand Supergroup as these have altered margins containing chloritoid (Pegg, 1950).

The age of the regional metamorphism relative to the Transvaal Sequence is less definitive in the absence of critical metamorphic minerals in the latter. However, the concentration of alteration zones, including pyrophyllite in various rock types immediately below the Transvaal unconformity (suggesting the Transvaal acted as a less-permeable cap to fluid flow during the alteration), the relationship of the metamorphic zonal scheme to the post-Transvaal cleavage, and fold axis orientations strongly favour regional metamorphism being after deposition of the oldest Transvaal members.

The relationship of the higher-grade assemblages adjacent to the Evander Goldfield (Tweedie, 1981; 1986) to those in the Evander mines is uncertain, but need not be an event separate from that recorded throughout most of the Witwatersrand Basin (based on existing data). The role of the kyanite assemblages in veins and shear zones NW of Johannesburg is difficult to constrain, or relate to other areas of the Basin.

The age of the Ventersdorp Supergroup is constrained by a zircon age of 2699 $\pm$ 16 Ma (Armstrong *et al.*, 1990) placing an upper age limit on Witwatersrand metamorphism: Bushveld-related dykes may be late-to post-metamorphism and thus place a lower age limit of 2050 Ma. The multitude of reset ages in the interval of 2500 to 2100 Ma (Rb-Sr, U-Pb and Pb-Pb methods; Ventersdorp Supergroup, Ventersdorp felsic meta-volcanics, Carbon Leader Reef, pyrite from Witwatersrand reefs, and alteration in surrounding granitoids; data summarized in Phillips *et al.*, 1989) indicate a large-scale alteration event during this period (Armstrong *et al.*, 1990), which has been inferred to coincide with peak metamorphism (Phillips, 1988).

Role of the Vredefort Dome event

The Vredefort Dome appears to play a major role in the distribution of both structural and metamorphic features throughout the whole Witwatersrand Basin. Cleavages and fold axes relating to a regional post-early Transvaal deformation are concentric to the Dome, and recorded for over 200 km along the basin margin from the East Rand to Klerksdorp (McCarthy *et al.*, 1986). Over an even greater distance, chloritoid-pyrophyllite-grade conditions are recorded from Evander to Welkom around the basin margin and also as a peripheral zone around the Vredefort Dome. Isograds representing higher metamorphic grade zones ring the Vredefort Dome. The thermal aureole in the vicinity of the Vredefort Dome is commonly perceived to be concentric to the structural outline of the dome i.e. sub-parallel to the lithological boundaries in the collar rocks. In fact, the aureole is elongated towards the NW where the boundary lies close to the Central Rand Group/ Klipriviersberg Group contact. In the E and SW portions of the dome, the boundary lies close to the basal West Rand Group contact. Such a pattern could be generated by a single metamorphic event affecting the whole basin and culminating in the Dome, or a Vredefort Dome metamorphic event superimposed on regional greenschist facies metamorphism across the Witwatersrand Basin.

Bisschoff (1982; 1988) inferred four metamorphic periods, of which his last two were tentatively attributed to a similar time of formation as the Vredefort Dome-forming event. His first two metamorphic periods (amphibolite to granulite facies metamorphism of the core granite - greenstone rocks; and greenschist facies burial metamorphism of the younger Dominion, Witwatersrand, Ventersdorp and Transvaal sequences) are not temporally distinct on the basis of his published data.

It appears that the thermal metamorphism of lithologies in and around the Vredefort Dome (Bischoff's third metamorphic event) is not simply "contact metamorphism" (in the sense of the heat energy for metamorphism being introduced by the plutons), as the plutons appear minuscule compared to the scale of the metamorphic zones, particularly given the felsic nature of some intrusives. The higher metamorphic grade zones wrapping some small plutons might be better interpreted as the products of the same heat event as that producing the plutons, rather than the plutons introducing the heat for metamorphism, *per se*. Furthermore, the gradational transition from thermal metamorphic assemblages around the Dome to regional greenschist assemblages in the gold fields may imply temporal overlap between regional and thermal metamorphism. Thermal metamorphism has resulted in the development of retrograde assemblages in the basement lithologies (pyroxene hornfels) and evidence for two discrete thermal events is present in some samples (Bisschoff, 1982; 1988).

The fourth metamorphic event of Bischoff involves the formation of several generations of pseudotachylite in all lithologies of syn- and pre-Bushveld age and was tentatively ascribed to shock metamorphism. Recent observations by the authors suggest that at least one generation of pseudotachylite has been thermally metamorphosed and contains the same mineral assemblages as the surrounding host rocks. Pseudotachylite generation therefore appears to have spanned a considerable period of time.

Additional constraints on the relative ages of metamorphism that have affected the Vredefort Dome are provided by the large variety of igneous rocks whose ages span the entire history of the Dome. Six generations of intrusive and extrusive rocks are described by Bischoff (1982; 1988):

(1) hydrated epidiorites comprising the Dominion, Witwatersrand and Ventersdorp lavas and associated intrusives;
(2) hydrated tholeiites comprising sills and dykes of Bushveld age and the Losberg Complex (these rocks (1 and 2) were emplaced before overturning;
(3) hydrated dioritic and alkaline rocks which pre-date the basic granophyre;
(4) basic granophyre which is associated with the final stages of Bushveld magmatism and represent the oldest rocks without pseudotachylite or shattercones;
(5) dolerites of post-Waterberg age; and
(6) dolerites of Karoo age.

Regional hydration is less intense in the Bushveld age basic rocks than in the pre-Bushveld intrusives (Bischoff, 1982; 1988). On the basis of petrographic observations and field data, Bischoff concluded that the thermal metamorphism was Bushveld in age. In addition, it appears that deformation, metamorphism and the intrusion of the Bushveld Complex are intimately and possibly genetically related.

Geophysical modelling by Corner *et al.* (1986) has identified a major magnetic anomaly (the Colesburg trend) which sub-parallels the present day south-western margin of the Witwatersrand Basin at a distance of approximately 100 km. It has been suggested that this anomaly may represent a major mid-crustal discontinuity (Corner *et al.*, 1986; Hart and Andreoli, 1986; Corner and Wilsher, 1987) similar to one described from the Vredefort area where the exposed basement is inferred to represent a near vertical, 15 km profile through the crust (Bischoff, 1972; Slawson, 1976; Stepto, 1979, Hart *et al.*, 1981). Both the Vredefort and Colesburg discontinuities have been interpreted to occur at similar vertical distances beneath the Witwatersrand sediments (± 8km). However, the crustal profiles differ with respect to granite type, relationships to Witwatersrand strata and possibly metamorphism (Drennan *et al.*, 1990). Deformation and overturning of sediments along the western margin of the Welkom Goldfield is, at least in part, syn-depositional (Callow and Myers, 1986; Bailey *et al.*, 1988), whereas the Vredefort structure is post Transvaal in age and was inactive during Witwatersrand sedimentation (palaeocurrents are unaffected by the Dome; Holland *et al.*, 1988).

Mineral assemblages to the east of the Colesburg trend are not indicative of large-scale metamorphism. However, assemblages related to deuteric- and vein-related alteration (Drennan *et al.*, 1990) are compatible with those described by Phillips (1987) from pelitic lithologies within the Witwatersrand Basin. In contrast, the gneissic to migmatitic rocks west of the Colesburg trend are characterized by a penetrative fabric, compositional banding and high-grade mineral assemblages (Drennan *et al.*, 1990). Preliminary results based on Fe-Mg partitioning in co-existing garnet and biotite and on the structural distribution of Al in tschermakite yielded temperatures of 577 and 566°C and 9 and 9.7 kb (Drennan *et al.*, 1990). These values are probably associated with large (unspecified) errors, but would correspond to depths of 26 km and a geothermal gradient of 20°C/km: as such, they represent a lower crustal level than rocks exposed in the centre of the Vredefort Dome.

Given that the scale of the metamorphism around the Vredefort Dome is indicative of regional rather than contact (pluton derived) metamorphism, and that no break or temporal discontinuity occurs at the upper grade limit of the chloritoid assemblages around the Dome, and that the structural elements are concentric to the Dome, the existing data appear more compatible with a single metamorphic event culminating in the core of the Vredefort Dome, rather than separate metamorphic events.

Overall, the data are compatible with, and strongly suggestive of, an important spatial and temporal association between post-Transvaal deformation, the regional metamorphism recorded in the gold fields and basin centre, and emplacement of the Vredefort Dome. The data imply contemporaneity between metamorphism recorded in the gold fields and that recorded around the Dome, and a post-Transvaal age for Witwatersrand regional metamorphism synchronous with Vredefort Dome emplacement. The alternative model of unrelated metamorphism, deformation, and Vredefort Dome emplacement has considerable difficulty explaining the coincidental concentric deformation and metamorphic patterns around the Dome, and the required multiple events of mid-greenschist facies metamorphism in different parts of the Basin. The authors have not found it possible to temporally separate the regional metamorphism of the Witwatersrand and Vredefort Dome from Bushveld activity on the basis of field relationships, structural relationships or petrological constraints. The main reason for placing the Bushveld as a separate event from Vredefort and Witwatersrand metamorphism appears to rely on geochronological evidence: such evidence is regarded with suspicion by the authors until independent corroborative evidence is found. The possible association of Witwatersrand metamorphism, the Vredefort Dome event and the Bushveld magmatism should not be dismissed lightly.

Summary of metamorphic processes

The inferred synchroneity of alteration, metamorphism and deformation suggests that post-burial fluid activity was intense across all the Witwatersrand gold fields. The large-scale migration of certain elements from many different lithologies, and the abundance of veining, indicate that present mineral compositions are, at least in part, a result of metamorphic processes, rather than being inherited from sedimentation or a source terrane. This is most easily demonstrated by the presence of pyrophyllite- and chloritoid-bearing assemblages in all rock types and the unlikelihood that two such different minerals would be deposited together, especially in sediments of all grain sizes: the mineral textures readily confirm an epigenetic origin for the pyrophyllite and chloritoid. Inferred fluid conditions during metamorphism are summarized in Table 5.

The inferred high geothermal gradient places important constraints on the ultimate cause of metamorphic heating. Tectonic thickening and thrusting, as has been inferred for the Alps, yields generally low geothermal gradients, whereas the emplacement of a large mafic body near the base of the crust would yield high geothermal gradients (England and Richardson, 1977). Preliminary data favour the latter scenario for the Witwatersrand regional metamorphism, although evidence of the mafic body has not been specifically sought. Maree (1944) inferred from gravity anomalies that the core of the Vredefort Dome

Table 5: Summary of inferred fluid conditions during regional burial metamorphism of the Witwatersrand gold fields

Temperature	300 to 400°C
Pressure	1.5 to 3kb (150 to 300 Megapascals).
Fluid volumes	dependent on structural/stratigraphic horizon, locally very high fluid/rock ratios, some units essentially impermeable during metamorphism.
Fluid composition	dominantly H_2O, some CO_2 (undetermined) probably slightly acid K/H buffered by pyrophyllite-muscovite Na/H near pyrophyllite-paragonite silica saturated throughout 200 ppm in solution or greater.
Redox state	sulphur in reduced field (H_2S) some carbon is oxidized state (CO_2, CO_3=) some reduced carbon in some reefs and shales perhaps local methane.
Age	probably post-Black Reef (Transvaal) syn-deformational isotopic resetting ca 2350 Ma.

is underlain by a body of mafic rocks. If the latter model applies, the Witwatersrand metamorphism may have followed an anticlockwise P-T path ending in near-isobaric cooling, rather than a clockwise path ending in isothermal uplift.

At higher metamorphic temperatures than those recorded in the gold fields, Witwatersrand metamorphism might have involved partial melting or dehydration (depending on pressure). Whether syn-metamorphic processes of melting, granitoid emplacement and some overturning of the sequence are represented within the Vredefort Dome depends very much on the interpretation of suggested meteorite and/or shock textures in rocks at the centre of the Witwatersrand Basin. Our alternative model, applicable for lower pressure progressions, would be one in which higher grade parts of the Basin underwent almost complete dehydration of pelitic assemblages (muscovite breakdown) before melting boundaries were reached. In this case, large amounts of fluid would be expelled during metamorphism, and melting would be negligible.

Overview

Given the need to sort out and allow for post-depositional modifications before any complete interpretation of the sedimentary environment, sedimentary sorting processes, or source terrane, the relatively late commencement of systematic metamorphic studies of the

Witwatersrand Basin and its gold fields has handicapped any realistic synthesis of the Basin history.

Current studies suggest that peak temperatures exceeded 300°C regionally and increased towards the Vredefort Dome, the Johannesburg Dome, and to the NE of the Evander Goldfield. There is strong evidence of extensive fluid activity and widespread alteration during metamorphism, and suggestions of a high geothermal gradient.

The Witwatersrand succession offers an unrivalled workshop to test and compare less-commonly used geothermometric techniques such as mica crystallinity, fluid inclusions and the nature of carbon, against the more conventional mineral assemblage and thermodynamic/experimental approach.

Outstanding problems in a synthesis of Witwatersrand metamorphism include a fuller understanding of the fluid flux at various points across the Witwatersrand Basin, including gold mines; the relationship of the metamorphism in the gold mines to that around the Vredefort Dome; the nature of the metamorphic fluid, including its composition and source(s); reliable age dates in the Basin, including the depositional age of the Transvaal Sequence; changes in mineral assemblages and phase compositions between gold fields and vertically in the stratigraphy; the relationship of peak metamorphic mineral growth to various deformational events; the relationship of the alteration recorded in marginal granitoids to that recorded in the Witwatersrand meta-sediments; and the potential of the metamorphic fluid to (re)mobilize gold and related mineralization.

It is difficult to "see through" the metamorphic overprint and decipher various diagenetic stages that might be expected to have occurred after burial. These diagenetic processes and the regional metamorphism provide important complications in constraining several aspects of the syn-sedimentary stage. The quartzites may be providing an opportunity to infer diagenetic processes not afforded by the pelitic rocks.

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