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METAMORPHISM OF SHALES IN THE WITWATERSRAND GOLDFIELDS

G. N. PHILLIPS

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UNIVERSITY OF THE WITWATERSRAND

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by

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ABSTRACT

Pelitic assemblages from all Witwatersrand goldfields record metamorphic conditions of greenschist facies, with minimal, regional-grade changes over at least 200km strike-length. Higher grades are recorded locally, in the vicinity of granitoid domes and of intrusions related to the Bushveld Igneous Complex. Diagnostic, metamorphic assemblages are less common in the volumetrically-dominant quartzites, the actively-exploited, auriferous conglomerates, and some of the regionally-continuous, pelitic horizons. Bulk-rock composition, especially in the pelites, has been a major control on assemblage-development.

Key, pelitic assemblages include pyrophyllite, chloritoid, chlorite, and muscovite in each goldfield, with less-common, metamorphic biotite. Accessory phases are pyrite, tourmaline, rutile, and zircon. Andalusite and kyanite appear related to local areas of higher-temperature metamorphism and are not common in the gold mines. The abundance of chloritoid and pyrophyllite in localized, shaly units, together with their minor, but widespread, distribution in quartzites and conglomerates indicate that metamorphic temperatures reached 350C $\pm$ 50C in all the goldfields. Pressures are less-well constrained, with 1-2kbars being inferred.

The temperatures during peak metamorphism and the abundance of pyrite provided ideal conditions for the (re)mobilization of gold and might explain many of the secondary textural features.

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METAMORPHISM OF SHALES IN THE WITWATERSRAND GOLDFIELDS

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INTRODUCTION

Previous studies have stressed the notion that the Witwatersrand Supergroup represents a virtually-unmetamorphosed, sedimentary pile of late-Archaean-to-early-Proterozoic age (Minter, 1979), or have acknowledged minor metamorphism, without constraining its grade, extent, and influence (e.g. Brock and Pretorius, 1964). From stratigraphic arguments alone, it would appear likely that the Witwatersrand Supergroup has undergone significant metamorphism, as much of it was overlain, at some stage, by parts of the Ventersdorp Supergroup, 2-8km thick (SACS, 1980). Minerals suggestive of greenschist-facies metamorphism have been commonly recorded within the Witwatersrand Basin, e.g. pyrophyllite, chloritoid, but their distribution and geological setting have not been integrated, to constrain regional-metamorphic conditions.

Specific, geologic and logistic problems make the study of the Witwatersrand metamorphism more difficult than it might otherwise be. The dominant lithologies of the Witwatersrand Supergroup, especially in the mined areas, are highly-siliceous meta-sediments, and, as such, diagnostic, metamorphic assemblages are commonly absent. Outcrop of the Witwatersrand Supergroup is limited, and weathering has affected the more-useful, metamorphic assemblages on surface. Sampling must, by necessity, concentrate on underground access (limited to the upper Witwatersrand succession, near to mineralized-reef horizons), and on drill-core.

This paper aims to show that metamorphism has played an important part in generating the present lithologies and their mineral textures and has been of high-enough grade to mobilize gold. Metamorphic studies could eventually be used to constrain tectonic models of the formation of the Witwatersrand and Ventersdorp supergroups.

REGIONAL SETTING

The regional stratigraphy of the Witwatersrand Basin has been summarized by SACS (1980). The Witwatersrand Supergroup overlies granitoid-greenstone terranes of the Kaapvaal Craton, in places, and the Dominion Group. It is overlain by the Ventersdorp Supergroup and Transvaal Sequence (Fig.1). The current age-estimate appears to be best constrained by a 2699 $\pm$ 16Ma age, measured by ion-microprobe on zircon from the Makwassie Quartz Porphyry of the Ventersdorp Supergroup at Klerksdorp (Armstrong et al., 1986) and a preliminary 2750Ma zircon-age from the Klipriviersberg lavas at the base of the Ventersdorp Supergroup (Armstrong, pers. comm., 1986). There is also an U-Pb 2800Ma age for lavas of the Dominion Group (van Niekerk and Burger, 1969), but further ages by this method suggest possible resetting of this isotopic system (Armstrong et al., 1986). Current models would suggest that Ventersdorp volcanism followed Witwatersrand sedimentation with negligible time-break, favouring an age for the Witwatersrand close to 2800Ma. Although there are significant unconformities within the Witwatersrand sedimentary succession, the base of the meta-volcanic rocks of the Ventersdorp Supergroup conformably overlie meta-sediments in several places.

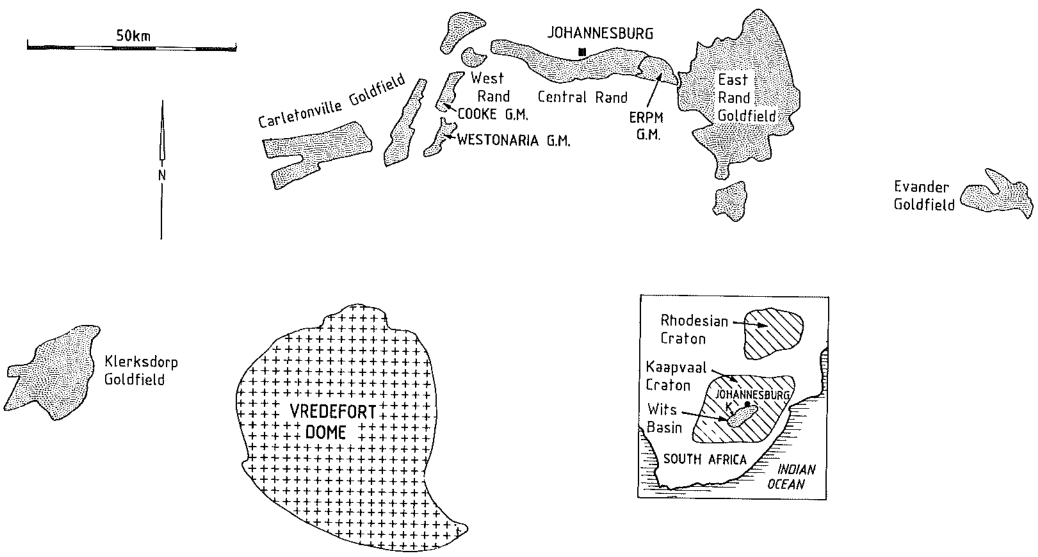


Figure 1: *Map of the Witwatersrand Basin, showing major goldfields (excluding Welkom Goldfield) and some gold mines (G.M.) mentioned in the text. Inset shows positions of Johannesburg and Klerksdorp (K).*

The Witwatersrand sequence has been subdivided historically into an upper and a lower division, now Central Rand and West Rand groups, respectively (SACS, 1980), and comprises mostly-arenaceous meta-sediments, argillaceous meta-sediments, and meta-conglomerates that are extensively mineralized with gold. Mafic extrusive components of the sequence are persistent, and minor dykes of several ages are widespread.

Metamorphic features are apparent in all lithologies, but, in the meta-conglomerates and meta-arenites, they mainly involve induration, polygonization of quartz grains, veining, and pressure-solution phenomena. The last is particularly well displayed in several reef-horizons, where quartz pebbles are dissolved, pyrite and mica are aligned on solution-surfaces, and quartz veinlets are abundant. Diagnostic, metamorphic assemblages are sporadic in these lithologies, but include pyrophyllite and chloritoid. The mafic rocks are generally altered, and their carbonated nature has substantially lessened their usefulness as regional indicators of metamorphic grade.

The use of sulphide-assemblages to define metamorphic conditions has been avoided in this study, for a number of reasons. Using sulphide-assemblages has been rather unsuccessful, when applied to the Witwatersrand in the past (Fuller, 1958), giving a wide range of metamorphic conditions, some of which cannot be supported by other methods. Furthermore, re-adjustment of sulphide-bearing assemblages is much more likely during retrogression, and silicate minerals are more likely to preserve metamorphic compositions. Arguments based on the composition of individual phases, e.g., mercury in gold, (Erasmus et al., 1982) represent unbuffered systems related to low-pressure experiments only and are considered unlikely to prove critical in geothermometric studies.

Pelitic lithologies are found in both the upper and lower Witwatersrand, and units such as the Jeppestown Shale and Booysens Shale are correlated between goldfields over a 300km strike-length (Whiteside et al., 1976). Pelitic rock-types are unevenly distributed, totalling 2000m out of the 4500m-thick lower Witwatersrand (45 percent), but only 200m of the 2500m-thick upper Witwatersrand (less than 10 percent), and it is only the latter that are routinely accessible in mine-workings or exploration-drill-holes. The pelites of the lower Witwatersrand are generally Fe-rich and, in places, grade from Fe-rich shales to iron-formations. Such Fe-rich lithologies are absent from the upper Witwatersrand, and, instead, more-aluminous compositions are common. These compositional differences in the pelitic units control the metamorphic mineralogy and are described in some detail. The chemical signature of some, important, pelitic horizons is also rather distinctive and may offer a means of identifying stratigraphic position, when drilling through otherwise-rather-monotonous, arenaceous sequences.

Sampling was concentrated on the regionally-persistent Parktown Shale and Coronation Shale of the lower Witwatersrand, the regionally-persistent Jeppestown Shale, historically marking the top of the lower Witwatersrand, the Black Bar and Green Bar units, near the Main Reef and Carbon Leader Reef, low in the upper Witwatersrand, the regionally-persistent Booysens Shale, and an impersistent, pelitic horizon within the Kimberley Conglomerate (Fig. 2a and b). Importantly, the regionally-persistent, pelitic horizons are considerably different, in terms of major- and minor-element compositions, from the locally-developed shales of the Green Bar, Black Bar, and Kimberley Conglomerate Formation. Shales from the Black Reef Formation, at the base of the Transvaal sequence, were also analyzed, for comparison.

The metamorphism of certain parts of the Witwatersrand Basin, removed from the major goldfields, has already been documented and is of significantly-higher grade than the areas of this present study. In the Vredefort Dome (Fig. 1), for example, garnet, staurolite, andalusite, and cordierite are common in pelites, and two pyroxenes are recorded in granulites (Schreyer and Abraham, 1978).

PETROGRAPHY

The mineralogy of the various argillaceous units is variable and strongly controlled by host-rock composition. Although pelites comprise approximately 30 percent of the Witwatersrand sequence, this study is biased towards the minor horizons in the auriferous and dominantly-arenaceous, upper Witwatersrand sequence. The stratigraphic terminology is based on SACS (1980), with the exception that the historical terms of "upper" and "lower" Witwatersrand and "Jeppestown Shale" are retained, for clarity and comparison with existing literature. Texturally, the pelites vary from slates to phyllites and rarely-crenulated schists, and sedimentary features are highly modified throughout. It should be stressed that the sampling-density, although adequate for the metamorphic study, gives only an idea of the mineralogical and chemical diversity of certain shale-horizons. Further sampling on different mines has demonstrated greater chemical variations than represented here.

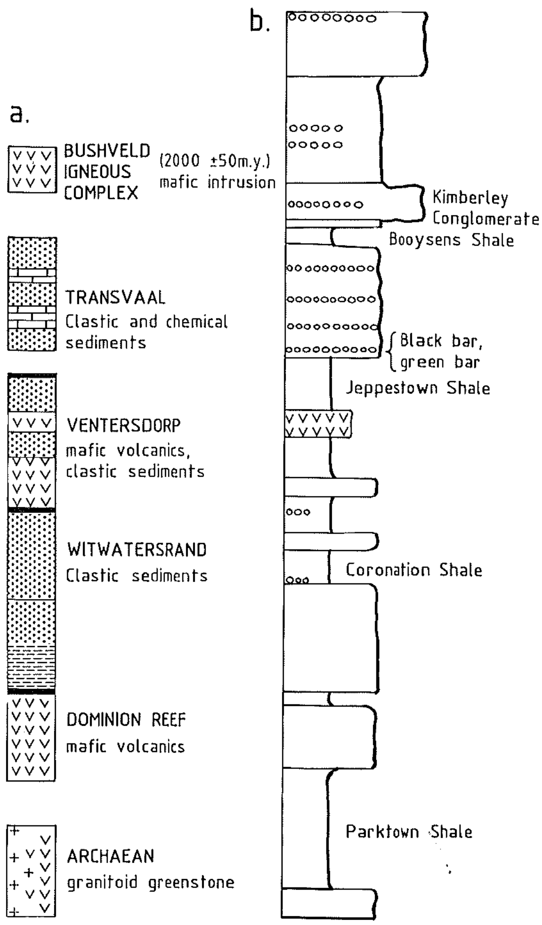


Figure 2: Stratigraphic columns showing (a) the position of Witwatersrand Supergroup in the Archaean and Proterozoic successions of South Africa, and (b) an enlargement of the first column, indicating: the main, clastic, sedimentary lithologies within the upward-coarsening, Witwatersrand Supergroup (wider bars represent coarser lithologies); the positions of auriferous conglomerate-reefs (circles); and the positions of the studied shale-horizons. The total thickness of the Witwatersrand Supergroup is about 7km (based on SACS, 1980).

Shales of the Lower Witwatersrand, West Rand Group

The Parktown Shale forms a 1000m-thick, mostly-argillaceous formation, near the base of the Witwatersrand Supergroup (Fig. 2b). These pelites are red in surface-exposure, magnetic due to variable magnetite, and, locally, either calcareous or Fe-rich, cherty shales or sandy beds. The dominant mineralogy is quartz and chlorite, with white mica, tourmaline, and scattered, fine magnetite (Fig. 3f). Bedding is defined by alternating more-micaceous and more-siliceous layers and is accentuated by weathering. Quartz grains are about 0,02mm in diameter and irregular in shape, with

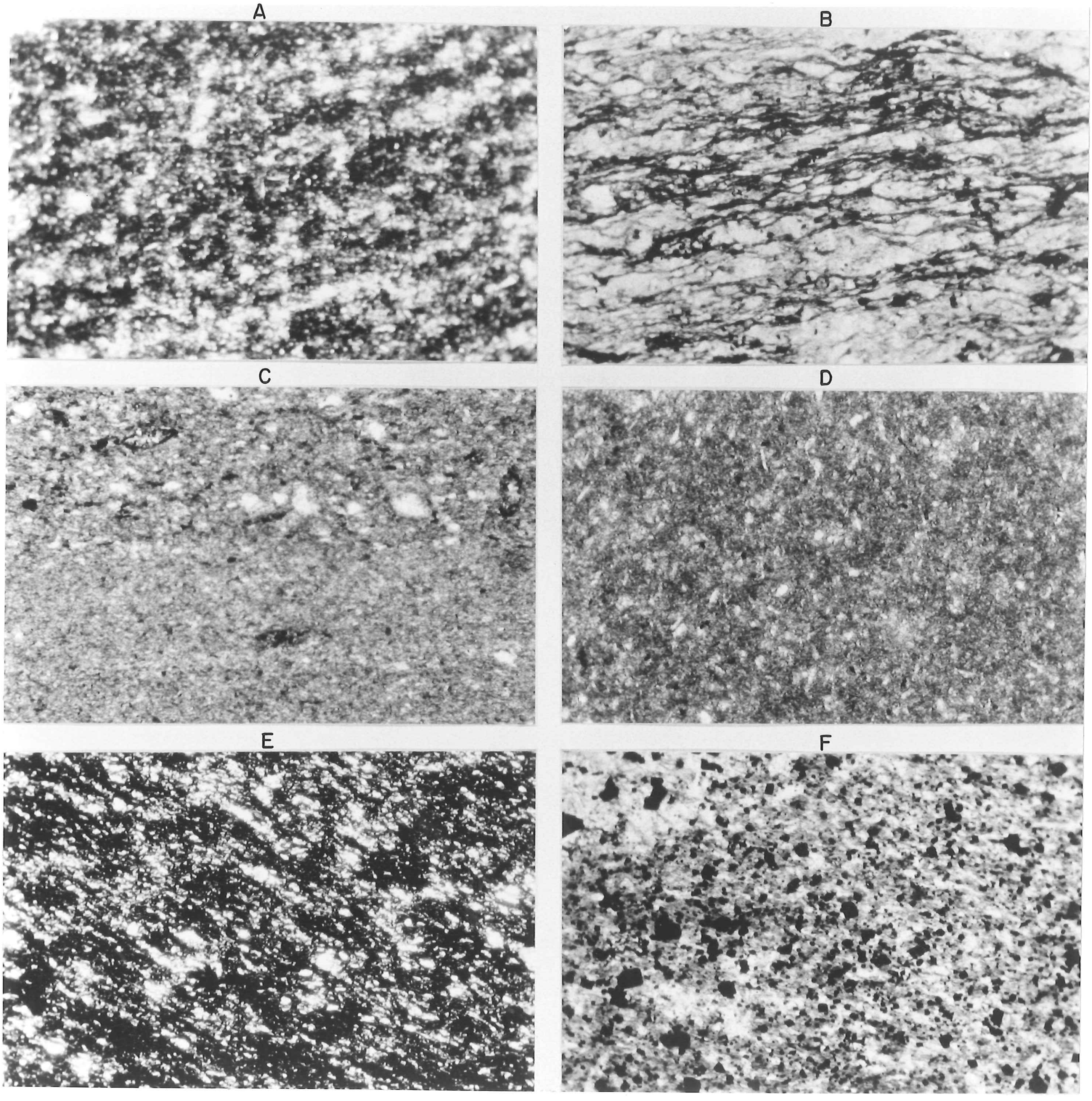


Figure 3: *Photomicrographs of regionally-persistent Witwatersrand shales: (a) Black Reef Shale, near the base of the Transvaal Sequence, with a moderate, lithological layering, defined by alternating light and dark layers, muscovite-chlorite-opaque (?carbon)-quartz; 3874; near Western Areas G.M., West Rand; (b) Black Reef Shale, with well-defined fabric of elongate minerals and anastomosing muscovite and chlorite cleavage; 4097; Consolidated Modderfontein G.M., East Rand; (c) Booysens Shale, with chlorite-muscovite-quartz, overlain by a*

silty layer with modified, detrital, quartz grains; 3982; Evander; (d) Jeppestown Shale, rich in chlorite, with quartz and minor muscovite; 3901; Libanon G.M., Carletonville; (e) Coronation Shale from lower Witwatersrand succession, with chlorite-probable biotite-opaque-quartz and well-defined foliation, MnO = 4 percent; 3899; West Rand; (f) Parktown shale, with abundant magnetite, chlorite, and quartz; 3895; Tarlton, West Rand. Base of each photomicrograph is approximately 1mm.

outlines defined by micas, rather than having clastic shapes (Fig. 3f). Fine, white micas are aligned both parallel and oblique to layering.

The Coronation Shale is a black, magnetic formation, up to 150m thick and surrounded by thick, arenaceous lithologies. The mineralogy is dominated by fine, magnetite grains and diffuse areas rich in opaque minerals. Chlorite and quartz have a grain-size around 0,03-0,1mm, typically demarcate a metamorphic layering of alternating quartz and chlorite, and are elongate, parallel to this layering (Fig. 3e). Elongate quartz and chlorite define a moderate-to-strong foliation, locally. Minor, green,brown biotite forms in small, partly-chloritized patches and as grains evenly disseminated throughout the assemblage. Grain-size is up to 0,05mm.

An assemblage of kyanite-pyrophyllite-hematite-muscovite-quartz has been recorded from the Orange Grove Quartzite, below the Parktown Shale (Fig. 2b) in northern Johannesburg (Schreyer and Bisschoff, 1982), but no attempt was made to document the regional distribution of these minerals. As such, the conclusions drawn may have only local importance, as acknowledged by the authors.

The Jeppestown Shale is an informal term referring to the uppermost pelites of the lower Witwatersrand sequence, within the Roodepoort Formation (SACS, 1980). These pelites are dark green, slaty rocks when fresh, weathering to a red colour on surface, and are relatively well-exposed in underground workings, as they occur a few metres into the footwall of the main Conglomerate on several mines, e.g. E.R.P.M. (Fig. 1). The Jeppestown Shale is up to 150m thick and is a particularly persistent horizon throughout the whole Witwatersrand Basin. The dominant mineral is chlorite, with minor quartz and white mica (muscovite where analyzed by XRD). There are small, silty layers, up to 1mm thick (Fig. 3d). It varies from poorly-foliated to well-foliated, with elongate, quartz grains and strongly-aligned white mica and chlorite that define the fabric (typically near-parallel to bedding). The more-pelitic layers have quartz (0,05mm or less), chlorite, and 5-20 percent white mica and contain quartz grains intergrown with, and wrapped by, anastomosing chlorite. There is a strongly-modified, sedimentary morphology, characterized by pressure-solved margins of quartz. Pyrite, tourmaline, and carbonate are rare components, and a brown pleochroic mineral, resembling biotite or altered chlorite, occurs very rarely. The silty layers have quartz (up to 0,3mm), carbonate, rare, altered, detrital, white mica, and chlorite.

Shales of the Upper Witwatersrand, Central Rand Group

Immediately overlying the Main Conglomerate reefs are distinctive lithologies known as 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, but actual stratigraphic correlations between the two are uncertain. The Green Bar is 1-2m thick, massive-to-phyllitic. It is pale-yellow-green-to-dark-blue-green, with abundant chloritoid and pyrophyllite (Fig. 4a). The chloritoid forms poorly-oriented blades, up to 0,4mm in length, that are surrounded by a matrix of fine (0,1mm), white mica and quartz. Further minerals include muscovite, tourmaline, and rutile, with negligible biotite, chlorite, or opaque phases. The micas define a planar fabric that is overgrown by some of the chloritoid. The Black Bar is predominantly a graded siltstone, with shaly sections, up to 60m thick and locally related to channels. It is dark-green-to-grey-blue in colour, with a moderate-to-strong cleavage, defined by fine muscovite, at an oblique angle to bedding. The mineralogy of the shaly layers is mainly chlorite, quartz, and muscovite, with minor pyrite and biotite, whereas the silty layers are mainly quartz and chlorite, with rare carbonate. Both pyrophyllite and chloritoid are abundant, locally.

Biotite in the Black Bar occurs as discrete, light-brown flakes, making up less than 2 percent, modally. It has been identified optically in a number of thin-sections from E.R.P.M. Mine (Fig. 1) and confirmed by electron-microprobe. The biotite is randomly scattered in a fine-grained muscovite-chlorite-quartz matrix, as grains of 0,05mm in diameter (Fig. 4f). The occurrence of biotite in the shales is closely correlated with pyrite. A metamorphic origin is ascribed to this biotite, based on its microstructural habit, distribution, and relation 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 (of the order of 0,5mm), commonly bent, and strongly chloritized around the edges (Fig. 4e). Detrital biotite is rather rare and would be expected in a coarse,sedimentary fraction, rather than an argillite. The consistent occurrence of biotite only in the slightly-K-enriched pelites with Fe-sulphides, from E.R.P.M. Mine, supports its metamorphic origin as an equilibrium phase, compatible with textural inferences.

The Booysens Shale (originally called Kimberley Shale) forms a regionally-extensive horizon (up to 150m thick) across the whole Witwatersrand Basin and is the only persistent, pelitic horizon in the upper Witwatersrand sequence. It is widely exposed in the mines between the Evander and Carletonville goldfields (Fig. 1), forming an important stratigraphic marker. The Booysens Shale is dominantly a green-grey-to-blue-grey, graded siltstone, with shaly layers. Layering is on a scale of between a few millimetres and several centimetres, and the minerals comprise mainly muscovite, quartz, and lesser chlorite. A moderate foliation is defined by a preferred orientation of muscovite and anastomosing, chlorite grains. The silty layers contain angular, detrital, quartz grains, coarse muscovite, altered, biotite (inferred to be detrital) flakes, and small lenses rich in zircon, an opaque phase (mostly pyrite), and tourmaline, along the base of graded beds. Brown mica, resembling biotite or altered chlorite, is widespread in small amounts. Pyrophyllite is locally abundant, particularly with muscovite, near lithological

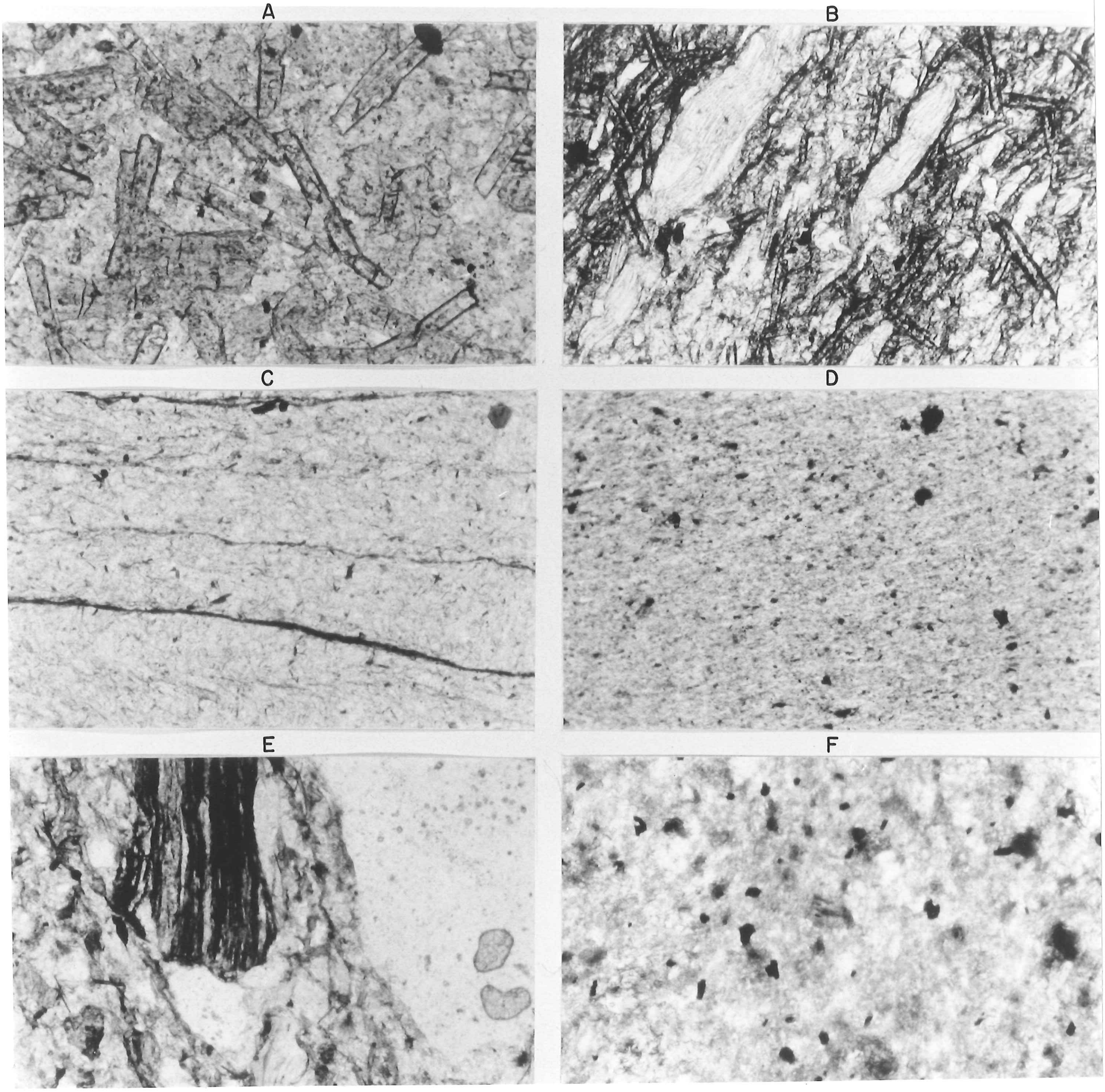


Figure 4: Photomicrographs of shales associated with reef-packages (a) chloritoid-rich schist from Green Bar; 3998B; Libanon G.M., Carletonville; (b) chloritoid-rich schist from Kimberley Conglomerate Shale, with elongate bundles of intergrown pyrophyllite and chlorite; 3860; Western Areas G.M. West Rand; (c) pyrophyllite-rich schist, with minor quartz from Kimberley Conglomerate Shale; domains of pyrophyllite are defined by anastomosing trails of opaque grains; 3857;

Westonaria G.M., West Rand; (d) muscovite-rich schist, with pyrophyllite from margin of Booysens Shale, adjacent to Kimberley Reef; 3912; Crown Mines, Central Rand; (e) detrital biotite in fine-grained, impure quartzite, extensively altered to chlorite, pyrophyllite in matrix; Khaki Shale, President Steyn G.M., Welkom Goldfield (not on Fig.1); 4187; (f) slightly-altered, metamorphic biotite (analyzed by electron microprobe, see Table 3) in Black Bar, with chlorite-muscovite-quartz-pyrite; 3960; E.R.P.M. G.M., Central Rand. There are ten discrete biotite grains in this field of view. Base of each photomicrograph is approximately 1mm.

contacts (Fig. 4d). At Consolidated Modderfontein, for example, muscovite-rich Booysens Shale has numerous pyrophyllite veins, with or without quartz, adjacent to, but not within, overlying Black Reef sediments of the Transvaal Sequence. The Booysens Shale from the Evander area has minor, biotite flakes, in the more-pelitic layers, and diamond-shaped pseudomorphs, in both the pelitic and silty layers, associated with opaque grains. Andalusite and cordierite have both been recorded previously from the Evander area (Tweedie, 1981) and have been attributed to a contact aureole around an unexposed intrusion. The full distribution of metamorphic phases in this goldfield is uncertain.

Shales in the Kimberley Conglomerate Formation of the Central Rand Group

Discontinuous, pelitic horizons, within thick, quartzite and conglomerate units, occur locally in the Kimberley Conglomerate Formation and are considerably different from the shale-units so far described. One exposure of this shale on the Cooke Section of Randfontein Estates has a maximum thicknenss of 50m, is strongly-lensoidal across the mine, and is overlain by small, conglomeratic, gold reefs. Less-deformed parts of this shale-unit vary from siltstone to interlayered, silty and shaly beds, with a weak fabric and well-preserved bedding-features. However, towards the conglomerate, the pelite becomes strongly foliated, with well-developed crenulation cleavage.

Several, distinct lithologies make up this unit, with its characteristic mineralogy and fabric. Weakly-foliated pelites comprise chlorite, muscovite, and quartz. Where silty patches and remnants of bedding are preserved, chloritoid and quartz are abundant, with lesser pyrophyllite, chlorite, and muscovite. These also have 0,8mm bundles of intergrown pyrophyllite and chlorite, in contact with chloritoid. The bundles are elongate, parallel to the slightly-wavy, pyrophyllite cleavage, and chlorite is intergrown along the cleavages (Fig. 4b). The strongly-foliated pelites comprise mainly pyrophyllite, with muscovite, chloritoid, and quartz (Fig. 4c). These have no trace of bedding, but a well-defined, anastomosing cleavage around masses of poorly-oriented mica. Less common are pelites with mainly muscovite and quartz, with minor pyrophyllite and chloritoid, and a moderate fabric, defined by the mica. Tourmaline, pyrite, and rutile are widespread in most lithologies.

Pelitic-Like Horizons Related to Alteration-Zones

Lithological contacts, unconformity-surfaces, and areas around mineralization are commonly the sites of alteration leading to discoloration and/or new mineral-assemblages. In the past, some of these zones have been referred to as paleosols, but recent studies have not supported this conclusion (Palmer et al., 1986).

At Deelkraal Mine, in the Carletonville Goldfield (Fig.1), zones of discoloured, Ventersdorp meta-basalt immediately underlie the Black Reef Formation of the Transvaal Sequence (Palmer et al., 1986). These yellow phyllites are dominantly muscovite, quartz, chlorite, tourmaline, rutile, epidote, and pyrite and are transected by mono-mineralic, pyrophyllite veins. At Evander, zones at the top and bottom of the Bird meta-basalts (lower part of the upper Witwatersrand sequence, i.e. Central Rand Group) are altered to pyrophyllite, chloritoid, chlorite, muscovite, quartz, rutile, tourmaline, epidote, and pyrite. On E.R.P.M. Mine, a 2m-thick zone of pyrophyllite shows no bedding-features and is related to quartz-veining, with some sulphides. The contacts with the surrounding quartzite are very sharp, and this lithology is inferred to be a tectonic zone, rather than an original, argillaceous horizon.

Post-Witwatersrand Shales in the Black Reef Formation

Shales at the base of the Transvaal Sequence are typically black, with a penetrative foliation, defined by elongate quartz and muscovite, and can be almost opaque in thin-section, due to abundant, carbonaceous material (Fig.3a). A marked cleavage is defined, in some samples, by concentrations of this carbonaceous material (Fig. 3b). There is a gradation from shales with very little quartz, to shales with silty lenses, to siltstones with a shaly matrix of carbonaceous material and muscovite. In the former lithologies, the quartz grains show minor modification of their sedimentary shapes, but they are strongly modified in the finer-grained lithologies. The mineralogy is dominantly carbonaceous material (no X-ray diffraction-pattern registered), muscovite, quartz, chlorite, and widespread, equant, tourmaline grains.

CHEMICAL COMPOSITION OF PELITES

Over one hundred samples of pelites have been analyzed, for major and minor elements, by XRF at the Department of Geology, University of Witwatersrand. Samples were mostly collected from underground exposures in the gold mines, rarely from exploration-drill-holes. Sampling was restricted to the northern part of the Witwatersrand Basin and was more extensive in the upper parts of the Witwatersrand Supergroup, due to better access. Identification of the stratigraphic position of samples was well-constrained by the detailed mine-mapping during routine gold-production. Thin-sections of all samples were used to complement the geochemistry and to aid in the separation of more-shaly, from more-silty, types.

The composition of all the pelites is dominated by Si, Al, Fe, Mg, and K (Table 1). Conspicuously, Na and Ca are very low, throughout, precluding the formation of significant Na-bearing phases or Ca-bearing carbonates. Major-element variations, related to stratigraphic position, include a decrease in total (FeO + MgO) up the sequence, parallel to an overall increase in Al_2O_3. K_2O varies from 8 percent in the Transvaal Black Reef shales, to less than one percent, in the Jeppestown Shale. The changes in SiO_2 reflect the silty fraction, i.e. quartz.

	Si	Ti	Al	Fe	Mn	Mg	Ca	Na	K	P	LOI	Total	Rb	Sr	Y	Zr	Nb	Ce	Ba	La	Co	Ni	Cu	Zn	V	Cr
Black Reef	55.00	1.21	21.36	5.91	.07	4.01	.18	.14	6.05	.09	6.56	100.56	165.2	21.5	23.5	182.3	12.4	55.8	331.3	40.5	25.3	121.0	76.4	79.1	193.4	546.9
K8	63.15	1.01	23.69	3.29	.03	1.28	.13	.91	1.83	.06	4.73	100.13	73.9	102.7	34.0	217.9	17.1	102.7	311.2	74.0	23.0	149.0	52.9	32.2	167.5	708.5
Booysens	56.01	.82	20.09	6.33	.08	7.01	.58	.50	2.46	.10	6.22	100.22	103.4	92.1	24.9	155.6	11.5	51.4	638.0	44.5	39.5	400.7	51.7	90.5	167.3	1123.9
Green Bar	50.87	.87	26.21	10.81	.08	1.72	.05	.74	3.35	.05	4.47	99.03	96.2	84.3	29.9	158.2	11.8	109.8	570.7	62.4	64.6	268.2	29.9	54.2	169.1	566.0
Black Bar	59.40	.73	15.09	11.91	.10	5.29	.15	.10	1.84	.10	5.62	100.33	75.3	14.8	24.8	132.1	9.9	48.8	285.1	38.8	47.8	281.6	63.3	90.4	157.9	916.1
Jeppe	53.25	.71	13.98	14.65	.11	7.52	1.30	.30	.85	.13	7.22	100.04	45.5	49.0	24.0	123.0	8.7	38.3	178.8	30.2	63.1	301.8	71.7	87.8	156.3	890.5
Coronation	48.04	.37	9.68	27.12	3.37	4.33	.65	.29	1.57	.09	4.79	100.29	123.8	18.8	14.5	66.9	5.5	40.4	462.9	26.5	93.7	156.0	50.4	43.8	86.2	463.0
Parktown	54.11	1.08	16	16.62	.13	3.73	.09	.21	1.10	.04	7.51	100.61	50.5	22.9	28.0	224.2	18.5	60.4	112.3	41.0	58.8	151.2	46.6	39.4	134.9	518.6
Black Reef	4.97	.13	2.64	.86	.02	2.60	.08	.06	1.25	.04	.91	.36	25.4	11.1	6.3	16.7	.9	17.7	72.0	7.1	6.9	29.0	51.1	31.8	25.3	51.5
K8	5.77	.23	4.09	3.52	.03	1.98	.12	.82	1.46	.05	.98	.55	53.5	88.2	14.7	69.1	3.5	33.5	322.3	21.8	16.1	106.1	53.7	48.5	37.2	166.9
Booysens	3.06	.28	5.20	2.67	.05	3.98	.33	.34	1.65	.04	.98	.35	65.3	76.0	10.0	81.5	5.9	22.4	648.5	15.3	10.3	167.3	17.4	43.3	32.6	317.9
Green Bar	5.97	.14	4.11	5.10	.05	1.24	.04	.41	2.01	.01	1.63	.58	55.3	60.4	9.8	35.5	1.8	46.6	395.7	26.5	94.4	167.5	36.8	58.5	35.0	112.9
Black Bar	4.75	.08	2.00	3.54	.05	1.93	.05	.10	1.07	.03	.98	.48	32.0	12.4	3.3	13.0	1.3	12.8	110.1	11.3	17.0	87.3	17.3	32.7	24.2	78.3
Jeppe	2.03	.10	1.35	3.10	.02	.99	1.53	.21	.71	.03	.76	.63	27.7	62.5	2.9	8.5	1.0	13.8	131.3	10.5	11.0	53.1	28.3	11.7	23.6	125.0
Coronation	2.05	.07	1.39	3.95	1.00	.60	.28	.29	.39	.01	.35	.68	23.6	5.9	2.2	22.0	2.3	4.8	83.4	3.6	14.0	24.1	9.4	6.1	14.8	103.3
Parktown	3.97	1.08	10.75	13.94	.17	1.63	.03	.17	.82	.04	1.28	.54	19.5	33.0	22.8	218.9	23.3	57.8	86.0	28.7	46.3	43.8	30.1	19.2	91.7	132.8

Arithmetic means given above, standard deviations below. K8 is a shale in Kimberley Conglomerate Formation.

TABLE 1

Average Analyses of Important Shale-Units within the Witwatersrand Supergroup

Minor elements in pelites show some systematic trends up the sequence, that include increasing Ti, Zr, Y, Nb, Ce, La, Rb, Sr, and Ba, with stratigraphic height. There is a concomitant decrease in P, Cr, Ni, Co, Zn, and Cu, though Cr, in particular, is conspicuously high for a shale, throughout. These trends do not continue systematically into the Black Reef Shales of the Transvaal Sequence. The ratio of K:Rb is near 130 in the lower Witwatersrand, increases to 200 in the upper Witwatersrand Booysens Shale and Kimberley Conglomerate Shale, and reaches to over 300 in the Black Reef Formation. The Sr:Ca ratio also shows systematic changes, with stratigraphic position, increasing up the sequence. The Coronation Shale is unusual in having high MnO and FeO, with low values of most minor elements. This composition suggests a dominant oxide or carbonate component during deposition, rather than clays.

The generally-limited range of compositions of each of the regionally-persistent, pelitic horizons and the systematic trends in the sequence suggest that one control on their present chemistry is the original composition of the sediment. Post-burial, alteration processes may have accounted for local disturbance of the element-patterns, but not the gross, chemical patterns of the more-immobile elements. The less-persistent pelitic horizons associated with reef packages, e.g. shale within the Kimberley Conglomerate, are exceptional in this regard, as they display much-more variability than other units, that cannot be attributed to sedimentary components alone.

The composition of the regionally-persistent pelitic rocks is best explained in terms of original clay-mineralogy, with some post-burial modification. Variations in SiO_2 represent variable proportions of clastic, silt-sized material, relative to clays. The major- and minor-element chemistry suggests that chlorite-rich clays and Fe-Mn oxides dominated in the lower Witwatersrand pelites and that illite might have been more common in the Black Reef Formation. The uniformly-low Na and Ca suggest negligible vermiculite, montmorillonite, or calcite at the time of deposition.

The high Cr-content of all the Witwatersrand shales is a feature common to most Archaean, pelitic rocks (MacLennan and Taylor, 1984). Interestingly, this high Cr reflects either Cr introduced after deposition or the deposition of Cr-rich clays, as detrital chromite is unlikely in shales and there is no correlation between Cr and an increased, coarser-detrital fraction, e.g. SiO_2).

The element-element plots are useful for separating different, stratigraphic horizons (Fig. 5), and the triangular plots show the main, chemical features that control metamorphic mineralogy (Fig. 6a and b). The lower Witwatersrand shales can be separated on the basis of higher, compatible minor-elements (Cr, Ni, Co) and lower values of the other, minor elements, e.g. Ti, Zr. The upper Witwatersrand shales are separated on the basis of their higher concentration of incompatible elements and the Black Reef Shale by its high potassium and its minor-element patterns. However, element-redistribution after burial has profoundly affected these patterns, in places.

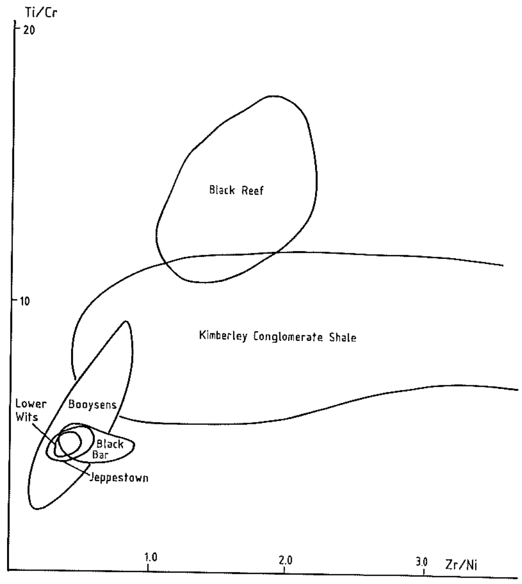


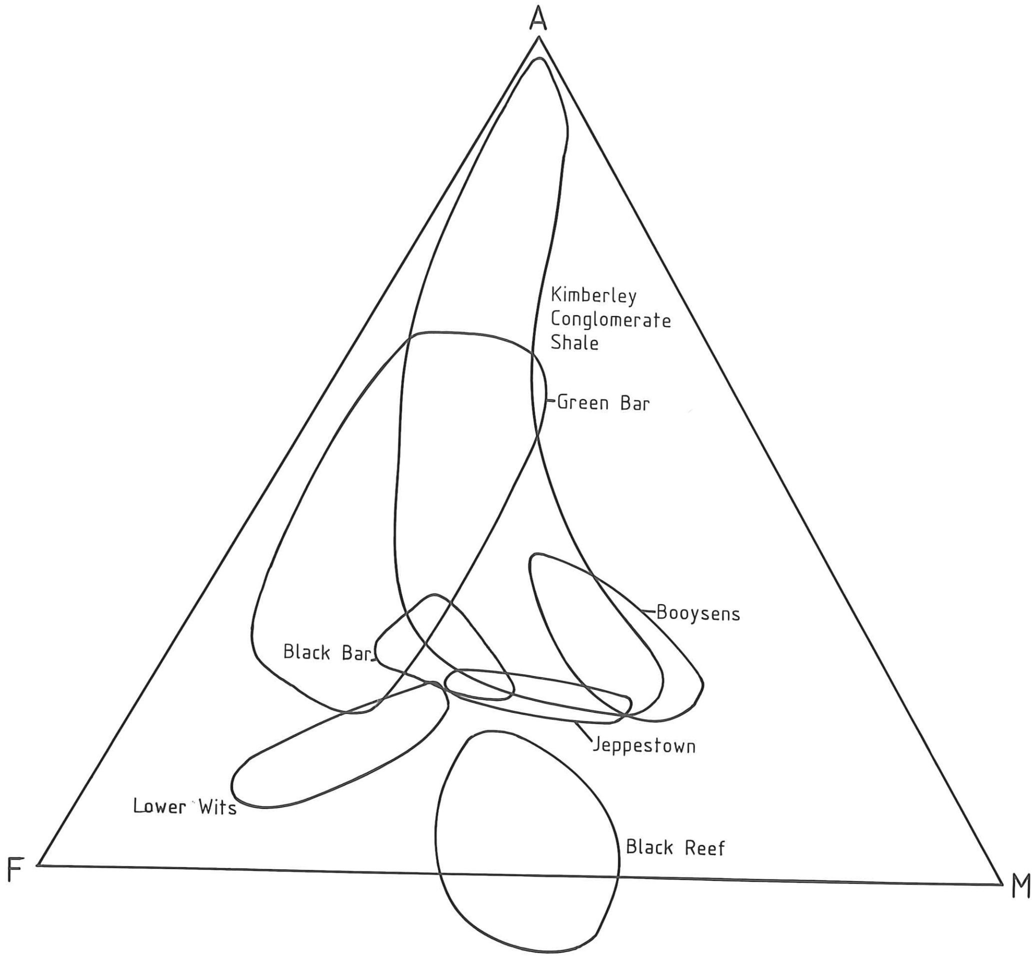
Figure 5 : Plot of element-ratios in different shale-horizons throughout the Witwatersrand Supergroup and overlying Black Reef Shale. This Ti/Cr vs. Zr-Ni plot is one of several methods that can be used to assist in separation of the different, pelite horizons.

METAMORPHIC PETROLOGY

Timing Constraints on Metamorphism

There are major difficulties in placing either absolute or relative age-constraints on events during the evolution of the Witwatersrand Basin. The particularly-siliceous nature of the sequence limits the lithologies suitable for radiometric dating, and the present constraints on absolute age are rather broad (Allsopp and Welke, 1986), suggesting that the Witwatersrand Supergroup is older than the 2,7Ma age attributed to the overlying, Klipriviersberg Group lavas of the Ventersdorp Supergroup. The age-difference between these two sequences need not be great, as lavas overlie conglomerates conformably at a number of locations.

Relative-timing techniques, based on structural overprinting, are virtually unusable in the indurated quartzites that dominate the sequence. The more-shaly units between thick quartzites tend to be the areas of major movement and thus represent zones of intense and heterogeneous strain, marking localized movement over long time-periods, rather than discrete, structural events.



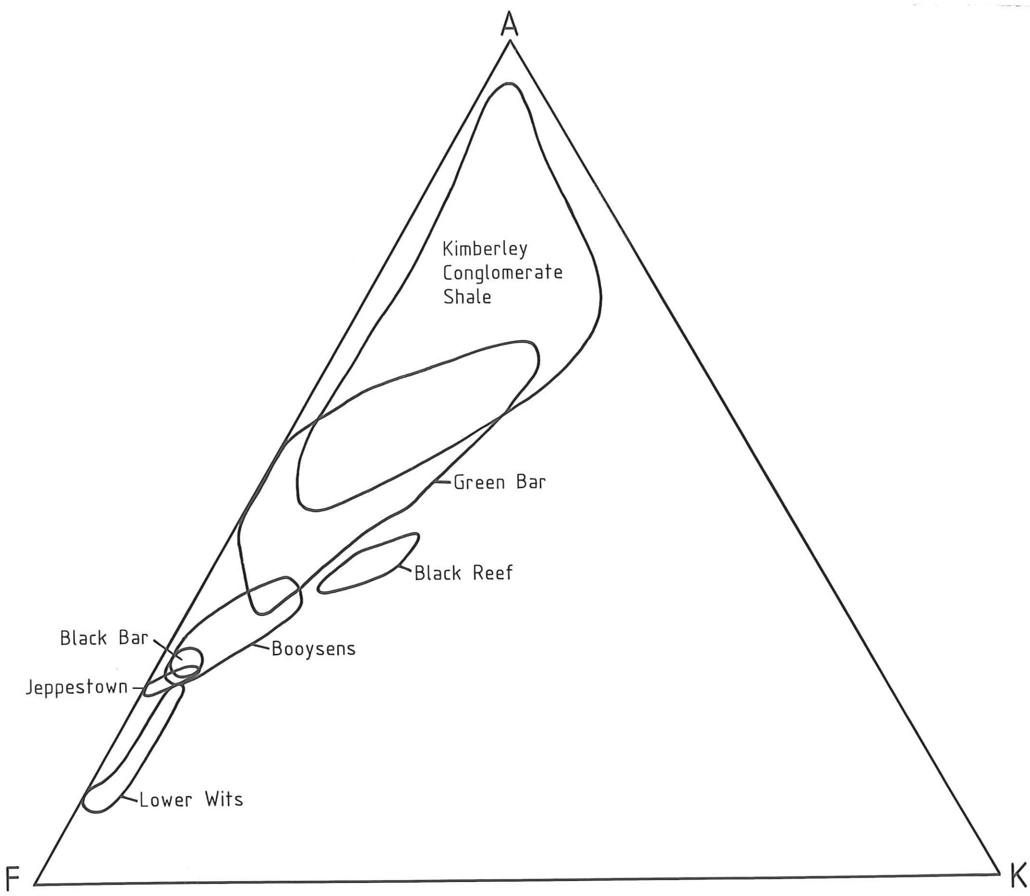


Figure 6 : *AFM and A'KF plots of different shale-groups. The major, regionally-persistent shale-horizons, e.g. Black Reef, Booysens, Jeppestown, lower Witwatersrand shales, are separable, using a combination of geochemical parameters. The minor shales, associated with reef packages, e.g. Kimberley Conglomerate Shale, Black Bar, Green Bar, have a much-wider chemical variation.*

A further difficulty peculiar to Witwatersrand geology is the procedure of dating periods of folding on evidence from gold pay-shoots, e.g. where higher gold-grades follow anticlinal fold-axes, the timing of the folding is inferred to be syn-depositional, the underlying assumption being that the gold-distribution is only a function of sedimentary processes. In different circumstances, the folding would be used to time the gold-mineralization event. The result is that the tectonic history of the Witwatersrand Basin emphasizes this early deformation, synchronous with deposition, and, although growth-faulting is recorded, e.g. Springs monocline (Antrobus and Whiteside, 1964), and thinning is locally noted across anticlinal axes, both are rarely demonstrated where the inferred syn-depositional folding, and its control on gold-grades, are hypothesized.

Dating of the metmorphism of the Witwatersrand Basin relative to deposition of the Transvaal Sequence is not universally established. Locally, chloritoid blades are inferred to overgrow a cleavage that cuts Transvaal meta-sediments (McCarthy et al., 1986), but very few data exist on the metamorphism of the Transvaa Sequence itself. Assemblages in the lowermost Transvaal Sequence (shales of the Black Reef Formation) are chlorite- and muscovite-rich, compatible with Witwatersrand metamorphic assemblages, but rather undiagnostic of specific temperature-ranges. Pegg (1950) has corrected an earlier statement of his that dykes in the Transvaal Sequence are chloritoid-bearing, now claiming that chloritoid is restricted to dykes in the Witwatersrand sequence alone. Given the present whole-rock composition of the Black Reef Shale (Table 1; Fig. 6), they are unlikely to contain chloritoid or pyrophyllite, regardless of their metamorphic history. Cleavages in Witwatersrand shales continue, but are more weakly developed, into adjacent shales of the Transvaal Sequence, as at Consolidated Modderfontein G.M., in the East Rand. Such relations are documented only locally. A number of alteration-zones, rich in pyrophyllite and/or muscovite, occur at the top of the Witwatersrand Supergroup and do not continue into overlying Transvaal rocks; this may signify either a fluid capping by the overlying sequence or an erosional contact, with the former being tentatively favoured, due to the concentration of the alteration zones along this contact, regardless of the lower lithology. Precise dating may clarify this uncertainty.

To overcome the problems of timing, the approach has been to sample widely from different mines in each of the goldfields, emphasizing the occurrence of the more-diagnostic assemblages. The pattern so generated overcomes the possibility of local effects related to hidden intrusions.

Criteria for Equilibrium

Many of the common criteria used to demonstrate equilibrium in high-grade terranes are lacking in the Witwatersrand shales. However, given temperatures of over 300C (see below), the dominance of dehydration-reactions, and the fine-grained nature of the starting material, prograde reactions would be expected to proceed relatively easily. This is supported by the abundance of detrital grains in the coarser meta-sediments, but not in the pelites.

The persistent, mineralogical nature of many of the shale-horizons suggests equilibration in response to broad-scale controls (Table 2). Rapid variations in assemblages that might be attributed to meta-stability

Evander:

WM-chl-carb-py-q
WM-(and?)-py-bi-q
pyro-musc-chtd-tourm-rut-zir-q +/- epid-chl-py:
J. Palmer (1986) (pers. comm.)

East Rand:

musc-chl-carb-q	
pyro-mica-chtd-chl-q	Wiebols (1961)

Central Rand:

pyro?-musc-chtd-tourm-q	
chtd-musc-chl-q-zir-tourm-rut-py	
musc-chl-carb-py-q	
pyro-q	3909
musc-bi-chl-carb-py-q	3959
pyro-mica-chtd-chl-q	Wiebols (1961)

kyanite around Durban Deep GM at west of Central Rand

West Rand and Westonaria:

pyro-musc-chtd-tourm-rut-zir-py-q	3855
pyro-musc-chtd-chl-tourm-rut-py-q	3873
musc-Kfs-chl-carb-py-q	3870

Carletonville:

pyro-musc-chtd-chl-tourm-rut-zir-py-q	4067, 4068

Klerksdorp:

musc-chl-bi?-tourm-py-q	3977
pyro, chtd	

For the purpose of this compilation Cooke section (Randfontein Estates) and Westonaria gold mines are included under the West Rand. Abbreviations: and = andalusite, bi = biotite, carb = carbonate, chl = chlorite, chtd = chloritoid, epid = epidote, Kfs = K feldpsar, musc = muscovite identified by Xray diffraction, mica = undefined mica probably white mica, WM = white mica, py = pyrite, pyro = pyrophyllite identified by Xray diffraction, q = quartz, rut = rutile, tourm = tourmaline, zir = zircon, also local pyrrhotite. Sample numbers of key assemblages given.

TABLE 2

Pelitic Assemblages Recorded in Each of the Major Goldfields from Evander to Klerksdorp are not recorded. Furthermore, there is a very-close relation between bulk-rock composition and mineral assemblages, also supporting general equilibrium. Textures indicative of detrital grains are restricted to the silty and sandy horizons and ae easily distinguished.

Metamorphic Assemblages

Metamorphic assemblages in Witwatersrand shales were recorded from each goldfield between Evander and Klerksdorp (Fig. 1). The uneven distribution of critical assemblages is a function of sampling-density, number of active mines, underground access, and variable pelitic lithologies (Table 2). In the Evander area, for example, mining is confined to the Kimberley Reef, and only the Booysens Shale is readily accessible.

(i) Pyrophyllite, Kyanite, and Andalusite

Pyrophyllite is recorded from all goldfields and occurs in a number of different settings. It forms with chloritoid in massive, continuous horizons, such as the Green Bar, in highly-tectonized pelites between thick, quartzite sequences, on shear-zones within thick quartzites, as the matrix in impure quartzites and conglomerates, as dominantly-mono-mineralic veins, and in quartz veins. Compositionally, pyrophyllite is equivalent to the lower-grade (kaolinite plus quartz) assemblages and to the higher-grade (andalusite/kyanite plus quartz) assemblages. The relevant equilibria place important constraints on the P-T stability-field of pyrophyllite-bearing assemblages. For conditions of water-saturation at 1kbar, (kaolinite plus quartz) is stable to 325C and pyrophyllite breaks down above 400C (Thompson, 1970; Helgeson et al., 1978; Holland and Powell, 1985). For water-undersaturated conditions, these dehydration-reactions move to slightly-lower temperatures. Witwatersrand pyrophyllite shows virtually no departure from pure, end-member composition (Table 3).

Neither kyanite nor andalusite has been found as a regionally-persistent component of any pelitic horizon during this study, yet both are commonly recorded in earlier work. Schreyer and Bisschoff (1982) recorded kyanite from the base of the Witwatersrand Supergroup, adjacent to the southwest corner of the Johannesburg granite dome, and from Krugersdorp in the West Rand. Young (1917) and Frankel (1944) noted kyanite (commonly altered to pyrophyllite) on the Central Rand, associated with quartz veins. These occurrences have chloritoid cutting the main fabric. As they are all along the northern margin of the Witwatersrand Basin, they may not be representative of the whole basin. Andalusite is recorded in the Evander field, where Tweedie (1981) attributed its stability to a buried pluton.

The widespread occurrence of pyrophyllite in the Witwatersrand sequence limits metamorphic temperatures to 300-400C, over most of the basin. Andalusite and/or kyanite are common locally (see below), but kaolinite appears restricted to surface samples (Schreyer and Bisschoff, 1982), where it is inferred to be a product of modern weathering.

	Pyrophyllite		Chloritoid			Musc		Biotite		Chlorite	
	3985	3993	3985	3993	3994	3985	3959	3960.1	3960.2	3960	1703
SiO2	69.49	70.34	28.22	27.01	26.75	49.85	38.22	36.63	35.28	28.35	29.21
TiO2	0	0	0	0	0	0	2.25	1.88	1.43	0	0
Al2O3	29.59	29.55	43.62	44.25	42.85	38.61	17.07	17.63	18.49	23.10	28.07
Cr2O3	0	0	.24	.51	.36	0	0	0	0	0	0
FeO	.29	0	24.79	23.90	25.00	.62	24.08	25.97	27.72	33.57	26.58
MnO	0	0	.52	.54	.60	0	0	0	0	0	0
MgO	0	0	2.54	3.63	1.98	0	8.31	9.23	10.97	13.85	15.93
Na2O	.25	0	0	0	0	1.08	0	0	0	0	0
K2O	.34	.12	0	0	0	9.75	9.92	8.66	6.00	.04	0
Si	3.98	4.01	2.13	2.04	2.08	6.24	5.65	5.44	5.22	2.71	2.65
Ti	0	0	0	0	0	0	.25	.21	.16	0	0
Al	2.00	1.99	3.89	3.94	3.93	5.70	2.97	3.08	3.22	2.61	3.01
Cr	0	0	.01	.03	.02		0	0	0	0	0
Fe	.01	0	1.57	1.51	1.63	.06	2.98	3.22	3.43	2.69	2.02
Mn	0	0	.03	.03	.04	0	0	0	0	0	0
Mg	0	0	.29	.41	.23	0	1.83	2.04	2.42	1.97	2.16
Na	.03	0	0	0	0	.26	0	0	0	0	0
K	.02	.01	0	0	0	1.56	1.87	1.64	1.13	.01	0
Total	6.04	6.01	7.92	7.96	7.93	13.82	15.55	15.63	15.58	9.99	9.84

Biotites 3960.1 and 3960.2 are partially altered to chlorite

3985: chloritoid - pyrophyllite - muscovite - quartz - tourmaline.

3993: chloritoid - pyrophyllite - muscovite? - quartz - tourmaline - rutile, some secondary chlorite.

3994: pyrophyllite - rich, chloritoid - quartz - rutile.

3985, 3993, 3994: from Cooke goldmine.

1703: retrogressed chlorite - rich shale, Evander area.

3959 and 3960: biotite - chlorite - muscovite - carbonate - quartz - pyrite, East Rand Proprietary mine (ERPM)

Analyses by energy dispersive microprobe, and represent averages of several points.

TABLE 3

Composition of Pyrophyllite, Chloritoid, Muscovite, Biotite and Chlorite in Witwatersrand Pelites

(ii) Chloritoid

Chloritoid is found in all parts of the Witwatersrand stratigraphy and in shales from all goldfields. It is also common in the matrices of quartzites and conglomerates and in altered dykes (Rogers, 1933; Pegg, 1950; Wiebols, 1961; Cousins, 1961; de Kock, 1964). In some shale-units, it comprises over 50 percent of the assemblage, the rest being pyrophyllite. However, unlike pyrophyllite, it is not strongly related to highly-tectonized zones, probably, in part, because of its tabular crystal habit. It is far more abundant in the thinner shales associated with reef-packages (e.g. Green Bar) than in the thicker, regionally-persistent Booysens and Jeppestown shales.

Compositionally, Witwatersrand chloritoid has very high Fa/(Fe+ Mg), like other, low-grade chloritoids, and has consistent, minor Cr and Mn (Table 3). The high Cr-content (up to 0,6 wt percent) is a reflection of the chrome-rich nature of the host-rocks (Table 1).

The phase-relations of chloritoid are not well constrained in P-T space, but its incoming during Witwatersrand metamorphism indicates the instability of (chlorite plus pyrophyllite), inferred from the following equations:

$$8Al_2Si_4O_{10}(OH)_2 + 2\ Fe_5Al_2Si_3O_{10}(OH)_8 = 5Fe_2Al_4Si_2O_{10}(OH)_4 + 28SiO_2 + 6\ H_2O$$

pyrophyllite + chlorite = chloritoid + quartz + water

In this reaction, chloritoid is favoured by increased temperature, higher Fe/Mg, and lower water-activity. In general, the dominant assemblage is chloritoid, although (pyrophyllite plus chlorite) is recorded together, commonly with chloritoid. Experimental constraints on this reaction suggest temperatures of 400C (Richardson, 1968; Hoschek, 1969), although natural examples suggest the assemblage (chloritoid plus quartz) may be stable nearer 300C where a (H_2O) is less than 1,0 (Frey, 1978; Paradis et al., 1983). The upper stability of chloritoid and alumino-silicate is over 500C and thus unlikely to have been reached in the major Witwatersrand goldfields.

(iii) Biotite

There are several earlier references to biotite in Witwatersrand lithologies, but none gives the textural and compositional data required to differentiate this mineral from brown chlorite or other phyllosilicates, and thus establish its origin. Metamorphic biotite in Witwatersrand shales has been recorded and confirmed (by probe analysis) from the Black Bar of E.R.P.M. Mine, but searching specifically for this mineral might disclose a wider distribution. On the basis of the dominant, mineral assemblage in the Black Bar, the most-likely biotite-forming reaction is one from muscovite and chlorite, typical of biotite-formation in many other terranes. In the absence of a specific reaction, though, experimental control on the temperature of biotite-formation is unavailable, but Ferry (1984) has demonstrated that initial biotite-formation occurs by a number of different reactions in different lithologies, at approximately the same temperature (just below 400C for an area in Maine,U.S.A.). The presence of biotite in the Witwatersrand shales probably indicates temperatures of 350-400C.

Witwatersrand biotite is typically Fe/Mg rich, with 1-2 percent TiO_2 (Table 3). Many grains, that are partially retrogressed to chlorite, are grossly deficient in K_2O (Table 3). The conversion of biotite to chlorite (Table 3, the four analyses from Samples 3959, 3960) is associated with a loss of SiO_2, TiO_2, and K_2O and with gains of Al_2O_3, FeO, and MgO.

(iv) Muscovite and Chlorite

The dominant phyllosilicates in Witwatersrand shales are muscovite and chlorite. Muscovite is virtually the only K-bearing phase, and its abundance reflects whole-rock K_2O (Table 1). X-ray-diffraction-analysis shows the muscovite to be well-crystallized (J. Palmer, pers. comm., 1985), in keeping with the inferred metamorphic temperatures. Chlorite is relatively Fe-rich, even though it is the most Mg/Fe-rich of all phases (Table 3), and is very widespread, especially in the regionally-persistent Booysens and Jeppestown shales.

Other Metamorphic Terranes

Detailed studies of similar metamorphic terranes are not common, but those that exist provide a useful comparison, when studying the metamorphism of the Witwatersrand.

Temperatures of 350C were inferred, from carbonate pairs, for chloritoid-and-pyrophyllite assemblages in the Lycian Nappe, Turkey, where chlorite was not recorded with pyrophyllite (Ashworth and Evirgen, 1984). The dominance of chloritoid (see above equation) and other mineral phases suggest considerable similarity with the Witwatersrand assemblages. Two studies involving black-shale sequences at low grade, by Frey (1970 and 1978), in the Swiss Alps, and by Paradis et al., (1983), in Brittany, France, invoked temperatures below 300C for the formation of pyrophyllite. These metamorphic progressions contain kaolinite and probably equilibrated under conditions of water-activity less than 1,0, due to the presence of the black shales. Such conditions of water-undersaturation are unlikely to apply in the present study, except, perhaps, within the black shales of the Black Reef Formation.

SUMMARY OF METAMORPHIC CONDITIONS

The combined evidence of shale-assemblages in the Witwatersrand sequence suggests that maximum temperatures were over 300C, regionally, and less than 400C across most of the basin. The agreement from three independent determinations (pyrophyllite, chloritoid, and biotite stability) gives confidence that the shales are generally recording peak-metamorphism of a regional nature. There does not appear to be any detectable grade-variation between the major goldfields. The present estimate is considerably higher than that of Hallbauer and Von Gehlen (1983), based on fluid-inclusion decrepitation, volatiles in carbonaceous material, and Hg in gold, and is incompatible with the assertion of Minter (1979) that parts of the Witwatersrand Basin lack metamorphism. The use of stable silicate-assemblages in the present study is suggested as a more reliable guide to metamorphic conditions.

Higher-grade areas of the Witwatersrand Basin occur around the Vredefort Dome (Schreyer and Abraham, 1978), in the east of the Evander field (Tweedie, 1981), and around the southern margin of the Johannesburg Dome (Schreyer and Bisschoff, 1982). In these areas, andalusite and/or kyanite are common. The inferred metamorphic conditions are those in which garnet and stilpnomelane may occur in rocks of suitable Fe-rich composition; however, any such lithologies are restricted to the lower Witwatersrand and have not been included in this study.

Pressure constraints are limited, but from the progression of pyrophyllite to andalusite or kyanite, depending on area, the ductile nature of major shear-zones, and the cover by Ventersdorp lavas during metamorphism, pressures between 1 and 2kbars are likely. This yields a high,geothermal gradient of 50-100C/km. The Witwatersrand assemblages are not compatible with burial beneath the full 25km-thickness of Ventersdorp Supergroup and Transvaal Sequence (SACS, 1980).

Water-activity is not constrained independently of temperature, but there are good reasons for believing the fluid-phase was dominantly aqueous, viz. the main, metamorphic reactions involve dehydration, and carbonates are rare in the clastic sequence. Carbonaceous material is generally not present in the Witwatersrand shales, where it could lead to methane or CO_2-bearing fluids, and its presence in auriferous, conglomeratic reefs is as mono-mineralic seams, where it would be considerably-more stable with temperature than in multiphase shale-assemblages. Decarbonation of these carbon-seams may be detected in their carbon-isotope signature, but their negligible thickness (few cm only) means they will not influence the overall character of the fluid.

The widespread distribution of pyrophyllite in particular stratigraphic units, e.g. Green Bar, and on shear-zones suggests that major, tectonic activity took place on these zones during metamorphism. The formation of pyrophyllite on these zones would facilitate continued movement and greatly concentrate further strain within these discrete zones.

Based on typical water-contents of unmetamorphosed shales, an estimate of the volume of fluid released during Witwatersrand metamorphism can be made. Compacted mudrocks have around 10 percent H_2O bound in clay-structures, and much of this is released at, or before, reaching the temperatures inferred for Witwatersrand metamorphism.

The total shale-thickness in the Witwatersrand sequence is nearly 2000m, mostly in the lower Witwatersrand West Rand Group (SACS, 1980), and, if it is assumed that only 5 percent H_2O is released during prograde metamorphic reactions, this represents over 250 million tonnes of H_2O per square kilometre. Clearly, major fluid-channelways must have been operative, to facilitate the removal, probably upwards and/or laterally, of such a large volume of fluid, and this may have important implications for the movement of gold (Phillips, 1986), especially given the solubility of gold under these inferred, metamorphic conditions (Phillips and Groves, 1983; Seward, 1984).

CONCLUSIONS

Pelitic assemblages containing pyrophyllite, chloritoid, and/or biotite are widespread in all Witwatersrand goldfields, suggesting mid-greenschist-facies grade. Inferred conditions are 350 ± 50C and 1-2kbars, in equilibrium with an aqueous-rich fluid. Large volumes of fluid are inferred from the dewatering of a total thickness of 2km of shales.

These metamorphic temperatures are considerably higher than some previous estimates and raise the possibility of gold-movement in solution during peak metamorphism. The estimates indicate that metamorphic conditions in the Witwatersrand Basin were no lower than in many, Archaean, greenstone belts (Fig. 7)

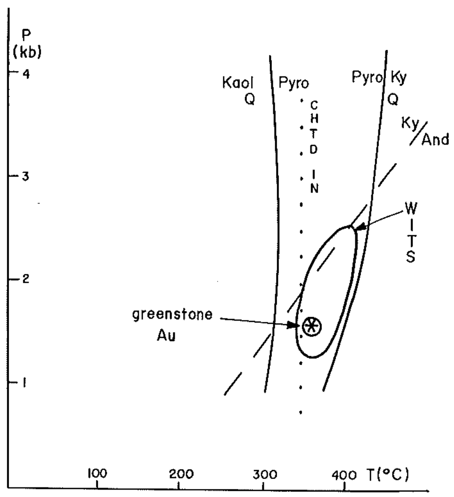


Figure 7 : *Pressure-temperature plot of conditions prevailing during regional metamorphism throughout most of the Witwatersrand goldfields. Slightly-higher-grade conditions than indicated on this figure existed in the east of the Evander field, around the margin of the Johannesburg Dome, and near the Vredefort Dome. However, there is remarkably-little grade-variation over several hundred kilometres, if the basin margins are excluded. Pyrophyllite, chloritoid, and biotite provide three, independent indicators of metamorphic temperature above 300C. The P-T field of Archaean-greenstone gold-formation is indicated (Ho, Groves and Phillips, 1985). Abbreviations: and = andalusite; chtd = chloritoid; kaol = kaolinite; ky = kyanite; pyro = pyrophyllite; q = quartz.*

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