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PROCEEDINGS OF THE SYMPOSIUM ON THE ECONOMIC SIGNIFICANCE OF METAMORPHISM AND FLUID MOVEMENT WITHIN THE WITWATERSRAND BASIN

COMPILED BY W.U. REIMOLD

INFORMATION CIRCULAR No. 296

UNIVERSITY OF THE WITWATERSRAND
JOHANNESBURG

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INTRODUCTION

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Nearly a decade after Geocongress '86, when metamorphism and hydrothermal alteration of Witwatersrand strata and granitoids in the hinterland to the Witwatersrand Basin featured prominently, and after a workshop on Metamorphism in the Witwatersrand Basin organized later in the same year by Neil Phillips, the Witwatersrand Interest Group (WING) of the Mineralogical Association of South Africa, the Geological Society of South Africa (GSSA), and the Western Transvaal Branch of the GSSA jointly organized a one-day symposium on *The Economic Significance of Metamorphism and Fluid Movement Within the Witwatersrand Basin*. This Symposium was held on 26 October 1995 at the Western Deep Levels Village Club near Carletonville.

The organizers aimed with this venture at reviewing, between academic and industry geologists, the current state of affairs, namely the existing data base as well as genetic interpretations with regard to hydrothermal processes that affected the gold and uranium mineralization in the Basin and that were possibly involved in ore formation. Judging from recent debates and publications, the controversy regarding the origin of Witwatersrand ore by either pure placer development, pure hydrothermal action, or a combination of both processes is still far from being resolved. The continuing interest in this controversy and the fact that some companies have embarked in recent years on strong fluid focussed research programmes resulted in no less than 100 geologists, mostly from the industry, having participated in this Symposium.

In the mid-Eighties, the work by Phillips and co-workers established that metamorphism and hydrothermal alteration indeed affected major parts of the Witwatersrand Basin and the associated ore. The main outcome of the 1995 Symposium is that, since then, study of these aspects of the basin has become more quantitative, due to the application of modern mineralogical-petrological and chemical techniques. Wits researchers (led by a strong contingent from the University of the Witwatersrand) have come a long way towards an understanding of the nature of the metamorphism, constraining the timing of major geological events resulting in fluid movement and activity, and of at least one major event that left its mark on the whole Basin and its resources - the Vredefort impact event. The fact that it has been possible to tighten the constraints on the age of the Vredefort event provides a prerequisite for further investigation of possible metamorphic effects of Bushveld magmatism on the wider Witwatersrand Basin.

However, it was also obvious from a number of the Symposium presentations that the database at hand in 1995 is still far from satisfactory and that it is mandatory to continue with these efforts to arrive finally at an integrated model for the formation and evolution of the Witwatersrand ores. The majority of Symposium attendees clearly favoured the modified placer hypothesis for the genesis of Witwatersrand gold, and controversy with regard to Basin and ore evolution was only rife where the multi-stage post-formational history of the ore was discussed. For example, how reliable are the chronological constraints on a 2.5 Ga event that some workers favour for fixation of hydrocarbons in the Basin? And despite very detailed metamorphic accounts of the relatively high grade of metamorphism encountered in core and collar of the Vredefort Dome, much debate ensued concerning the rapid drop from an amphibolite facies metamorphic environment to greenschist metamorphism in the remaining parts of the Basin.

It is hoped that the coming years will see a further intensification of detailed and multidisciplinary studies of Witwatersrand strata, including metamorphic petrological, fluid inclusion petrographical and analytical, alteration, ore petrographical, rock deformation, and chronological studies. While exploration for gold-enriched Witwatersrand horizons has, in recent years, been to a large extent abandoned or transferred to outlying areas perhaps constituting subsidiary basins, the importance of the Witwatersrand Basin for the country's economy and employment security in the mining industry cannot be underestimated and must be protected and carried into the future. In the interest of achieving maximum benefit from the accessible reef deposits and of potentially increasing the extent of mineable and profitable areas, such studies have to continue.

Recent discoveries in the area of the Vredefort Dome have raised the need to reconsider structure and deformation in those parts of the Witwatersrand basin in the environs of the Dome. And the fact that it has now been established that the Vredefort Structure represents one of the world's largest known impact structures does not necessarily entail that there is detailed knowledge about the geological situation to be expected in the deeply eroded parts of such a structure. There is a major need for detailed modelling of thermal and hydrothermal effects related to the formation of a massive central uplift structure in the central part of such an impact basin, and of the corresponding effects of an overlying, several kilometres thick impact melt layer (comparable perhaps to the 'Sudbury Igneous Complex', which is now widely regarded as a major part of the impact melt volume produced in the 1.85 Ga Sudbury impact event).

Besides these remaining individual problematics, the next step in Witwatersrand analysis has to be an attempt at synthesis of sedimentological, structural, petrographical, geochemical, and chronological data.

Finally, it must be emphasized that without the initiative and hard work of a few dedicated WING and Western Transvaal Branch members, above all Hannes and Christie Wagener, this Symposium would not have been held so successfully. We are further indebted to Carl Anhaeusser who shared our belief that the abstracts to the contributions to this symposium might be of use to a wider community and, thus, agreed to publish them in the form of this EGRU Information Circular. On behalf of WING, I would also like to thank the GSSA and the Western Transvaal Branch for their co-sponsorship of this meeting.

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CONDITIONS OF GOLD REMOBILIZATION IN THE VENTERSDORP CONTACT REEF, WITWATERSRAND BASIN

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Detailed analysis of the fluids preserved in the auriferous and uraniferous Precambrian oligomictic conglomerates of the Ventersdorp Contact Reef (VCR) provide a unique insight into the conditions under which the ores formed. This investigation deals with fluid inclusions occurring within footwall and hanging-wall quartzites, hydrothermal quartz and quartz-carbonate veins, the matrix of VCR conglomerate, and pseudotachylite samples from the VCR fault zone on Vaal Reefs and Elandsrand Mines in the Klerksdorp and West Wits Line gold fields. Age constraints on the formation of pseudotachylite and associated hydrothermal alteration in the fault zone are obtained from ^{40}Ar-^{39}Ar stepheating dating of pseudotachylite, which resulted in consistent 2 Ga ages (Trieloff *et al.*, 1994). ^{40}Ar-^{39}Ar thermochronology furthermore indicates that less intense thermal events occurred in the time interval 1300 - 1600 Ma and at around 400 Ma ago. No attempt was made to characterize the numerous fluid inclusion populations within the quartz pebbles.

PREVIOUS FLUID INCLUSION STUDIES ON THE WITS

Shepherd (1977) distinguished five principal types of "predepositional" fluid inclusions in the pebbles of the Witwatersrand conglomerates. These types differed in the amount of CO_2 and collectively indicated a moderate to high pressure, high temperature environment of presumed original vein-quartz formation. Systematic variation in the relative abundance of these inclusion assemblages for different sections of the ore field demonstrated the presence of several different, well-defined provenance areas or multiple entry points into the basin. A marked sympathetic relationship between uraniferous banket ores and the presence of vein quartz containing inclusions rich in liquid CO_2, together with a corresponding antipathetic relationship with Au, strongly suggested separate sources for the two metals. Post-depositional inclusions are subordinate and offer no support for the alternative epigenetic model, showing only later interaction of relatively cool circulating ground waters.

A series of papers by Hallbauer (1982a,b;1983) and Hallbauer and Kable (1979; 1982) indicated that data from fluid inclusions in quartz pebbles have permitted the recognition of another distinct class of "blue opalescent quartz pebbles". Using SEM, these authors have identified numerous solid phases in inclusions in both quartz and pyrite, including orthoclase, muscovite, calcite, apatite, iron-rich phyllosilicate, barium feldspar,

chlorite, rutile, corundum, anhydrite, cassiterite, and various mixed chlorides, including $CaCl_2$. Although called "daughter crystals", some of the crystals in their photomicrographs actually look more like solid inclusions. Whatever they are, these crystals could provide valuable insight into the original environments of formation of the quartz pebbles.
Killick *et al.* (1988) focused on pseudotachylite associated with the bedding-parallel fault zone between the Ventersdorp and Witwatersrand Supergroups in Western Areas gold mine. Weak brines with up to 6 wt% eNaCl were identified in pseudotachylite-associated discordant quartz veins. Clathrate melting temperatures of 6°C to 13°C were indicative of CO_2. The authors suggested that pseudotachylites may have formed at similar depths to the associated mylonites, as the result of intermittent reactivation of the fault zone. They, furthermore, suggested a genetic link between the pseudotachylites in the Vredefort area and those on the fault zone. Frimmel *et al.* (1993) and Frimmel (1994) described five different fluid inclusion populations, two of which are only found in detrital quartz grains, from the Basal Reef in the Welkom goldfield. These two generations of fluids compare favourably with the fluid inclusions from hydrothermally altered Archaean granites around the Witwatersrand basin described by Klemd *et al.* (1989). The remaining three types of fluids consist of: (1) moderately saline (7 - 17 wt% eNaCl), $CaCl_2$-rich, aqueous brines with homogenization temperatures around 130° to 140°C; (2) low-salinity (<4 wt% eNaCl), KCl-containing aqueous inclusions, with homogenization temperatures around 130° to 140°C, and (3) rare CO_2-rich inclusions. Using textural relationships and mineral parageneses, fluid entrapment temperatures of 240° to 300°C were inferred at a pressure between 2 and 3 kbars.

Meyer *et al.* (1991) investigated the conditions of Au-U mineralization in several Witwatersrand Reefs. They found textural evidence for allogenic and authigenic minerals. Furthermore, two types of late metamorphic/hydrothermal fluids were identified, namely a salt-rich and a CO_2-rich fluid. Microthermometric data indicated temperatures between 250°C and 400°C. Fluid and mineralogical constraints suggested that uraninite has limited solubility under the prevailing conditions, while gold could have been re-distributed via the $AuCl_2^-$ complex at temperatures above 350°C. The uraninite-kerogen association is explained by the fixation of hydrocarbon residues around allogenic uraninite accumulation.

FLUID INCLUSION PETROGRAPHY AND MICROTHERMOMETRY

For this study, fluid inclusion data were obtained by microthermometric heating and freezing, using the standard technique described by Roedder (1984). Temperatures of phase changes were obtained with a FLUID INC. adapted U.S.G.S. heating freezing system, which operated by passing cooled N_2 gas or heated air directly above or beneath the sample. The thermocouple was calibrated against synthetic fluid inclusions (Sterner and Bodnar, 1984). Reproducibility of measurements during calibrations was within 0.2°C below 0°C, and better than 2°C on heating the sample. Salinities were standardized and are expressed as weight percent NaCl equivalent (wt% eNaCl) using the conversion factors of Bodnar (1993).

In general, three types of secondary fluid inclusions have been recognized: (1) The earliest type of fluid inclusions (Type I) is characterized by small, moderately saline (10 wt% eNaCl) inclusions, forming a wispy texture, with homogenization temperatures around 210°C; (2) Type II is a slightly less saline (9 wt% eNaCl), late-stage fluid, with homogenization temperatures between 115° and 190°C, and (3) Type III consists of a carbonic-rich fluid with variable CO_2/H_2O ratios. Salinities centre around 4 wt% eNaCl and homogenization temperatures are around 130°C. Fluids from the VCR quartzites, both footwall quartzite and reef quartzite, show similar microthermometric behaviour. Secondary inclusions in pseudotachylite clasts from Vaal Reefs have a significantly higher CO_2 content than those from Elandsrand Mine. However, suppression of the CO_2 eutectic melting point suggests a larger CH_4 content in the Elandsrand samples, compared to the samples from Vaal Reefs. Assuming 2.5 kbar (Wallmach and Meyer, 1990) as a minimum pressure for the upper Witwatersrand at about 2 Ga, the average entrapment temperatures for the fluids analyzed in this study are calculated between 220° and 370°C.

QUADROPOLE MASS SPECTROMETER RESULTS

Analyses of gases in fluid inclusions were made with a VG SXP 600 quadrupole mass spectrometer. For most samples, 16 masses were monitored, allowing simultaneous real time analysis for a number of components including H_2O, CO_2, CH_4, C_2H_6, N_2, Ar, H_2S and SO_2 (Jones and Kesler, 1992).

In almost all analyses of the VCR associated samples, H_2O, CO_2 and CH_4 make up more than 99 mole% of the gas composition, with H_2O being the dominant species. On a CO_2-CH_4-C_2H_6 ternary diagram the Elandsrand and Vaal Reefs samples plot in distinctly separate fields, with CO_2 not exceeding 0.60 mole% in the Elandsrand samples and CH_4 not surpassing 0.59 mole% in the Vaal Reefs samples. On a CO_2 - H_2O binary diagram the Vaal Reefs samples show a good correlation, whereas the Elandsrand samples scatter. The opposite is true for a binary H_2O - CH_4 plot of the data. Higher alkanes (C_2H_6) show enhanced concentrations, up to 0.14 mole%, but do not correlate consistently with other gaseous compounds. Argon was detected in amounts of up to 0.01 mole%. Average total sulphur gas contents ($3S_{Total} = H_2S + SO_2$) for Elandsrand and Vaal Reefs are 0.02 and 0.01 mole%, respectively. VCR samples show significantly enriched HCl values.

Quadrupole mass spectrometer (QMS) analyses of the type III inclusions are consistent with the increasingly well-documented association of dilute CO_2-rich inclusions with Au mineralization. For the VCR samples analyzed, a good correlation between gold content and elevated volatile gas content (mainly CH_4) was recognized. Such a relationship has been quantitatively demonstrated for auriferous veins of the Dolgellau gold belt, North Wales, where CH_4 was found to be directly correlated with gold grade (Shepherd *et al.*,1991). The CH_4/CO_2, as well as SO_2/H_2S ratios, are different for Vaal Reefs and Elandsrand samples, respectively. Recently Naden and Shepherd (1989) suggested that the reaction of a fluid with graphite-containing rocks, leading to the production of CH_4 ($C + 2H_2O = CH_4 + O_2$), promotes the onset of unmixing of the gaseous phase, during which H_2S is preferentially partitioned into the volatile phase - promoting gold precipitation by destabilization of the gold-transporting bisulphide ligands. The data presented above are in keeping with the generation of methane, although no direct petrographic evidence of such unmixing has yet been observed. The presence of evolved hydrocarbon species is confirmed by the relative high C_2H_6 concentrations measured, as well as vibrations in the 2900 cm^{-1} wavenumber part of the Raman spectrum. Relatively low N_2, and high Ar concentrations suggest a connate character for these fluids and do not favour interaction with meteoric waters or exposure to atmosphere.

THERMODYNAMIC MODELLING

From the QMS data obtained the following parameters pertaining to the nature of the ore-transporting fluid and environmental conditions at the time of deposition can be obtained. Mineralization took place at a temperature of approximately 350°C (ranging from 220° - 370°C) for a minimum pressure of 2.5 kbar (Wallmach and Meyer, 1990). Mean X_{CO2} and X_{CH4} concentrations in the Elandsrand fluids were 0.27 and 1.03, corresponding to activities of aCO_2 = 0.34 and aCH_4 = 0.46, respectively. Mean concentrations for Vaal Reefs samples were X_{CO2} = 1.95 and X_{CH4} = 0.33, corresponding to aCO_2 = 2.44 and aCH_4 = 0.15. Fluid salinities were moderate around 2.6 molar with a mean Na:K ratio of 4. In terms of the reaction $CO_{2(aq)} + H_2O = HCO + H^+$ (log K = -7.658; calculated using SUPCRT92, Johnson *et al.*, 1992; log a_K = -1.11; ionic strength = 2.46) an acidic pH of approximately 3 (neutral pH at 350°C is 5.1) was calculated for the VCR fluids ((CO_2 - 2.26 [calculated from Patterson *et al.*, 1981]). QMS gas data were utilized to determine redox conditions: fO_2 was calculated using the reactions $CH_4 + 2H_2O = 4H_2 + CO_2$ and $H_2O = H_2 + 2O_2$, which yielded values of $10^{-29.02}$ and $10^{-26.05}$ for Elandsrand and Vaal Reefs samples, respectively. QMS data yielded sulphur fugacities for Elandsrand and Vaal Reefs of fH_2S_g = 1.099 & 0.598, assuming $\Sigma S_{Total} = X_{H2S} + X_{SO2}$, which corresponds to aH_2S_{aq} of $10^{-1.5}$ to $10^{-2.6}$, respectively.

Using these fluid characteristics, inferences on the gold speciation and precipitation mechanism are possible. Solubility calculations indicate that VCR gold in the Elandsrand area was an order of magnitude more soluble as a chloride complex than as a bisulphide complex. In the Vaal Reefs area, gold was equally soluble as a chloride complex or as a bisulphide complex. The precipitation mechanisms that account for gold deposition within the VCR are not well understood. It is possible that gold was precipitated as a result of adsorption/reduction reactions (e.g. Schoonen *et al.,* 1992), as locally suggested by the relationship between gold content and arsenic zonation in pyrite (Meyer, 1992). A number of precipitating mechanisms may have been active simultaneously within any one reef unit.

DISCUSSION

Based on our chronological information, it appears that the low-temperature secondary fluids are either associated with Bushveld hydrothermal/thermal overprint, or with regional fluidization caused by the Vredefort event in the centre of the Witwatersrand Basin. The chemical characteristics of this fluid suggest that it may have limited capability of mobilizing gold.

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CHARACTERISTICS OF POST-DEPOSITIONAL FLUIDS IN THE WITWATERSRAND BASIN, WITH EMPHASIS ON HYDROCARBON-BEARING FLUIDS

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INTRODUCTION

The characteristics of post-depositional fluids affecting the Witwatersrand Basin are important when considering the nature and origin of the gold and uranium mineralisation, because the nature of fluids determines their metal-carrying capacity, which, in turn, determines the role played by these fluids in remobilising and reprecipitating the mineralisation. An analysis of the post-depositional fluids (trapped in late-stage quartz veins) affecting the Witwatersrand sediments (Drennan, in prep.; Meyer et al., 1991) facilitates the evaluation of syngenetic as opposed to epigenetic models for the origin of the Witwatersrand mineralisation and the occurrence of authigenic and allogenic mineral phases.

CHARACTERISTICS OF POST-DEPOSITIONAL WITWATERSRAND FLUIDS

Post-depositional fluids associated with late circulation of metamorphic/hydrothermal fluids are recorded as secondary inclusions within healed microfractures in conglomerate clasts, in quartz overgrowths and in cross-cutting quartz veins. To distinguish between pre- and post-depositional inclusions in clasts and overgrowths was not possible because of the complexity of the numerous, intersecting and/or cross-cutting inclusion trail relationships. Where it was possible to clearly identify post-depositional fluids, the numerous generations of inclusion trails in any one sample made it difficult, and sometimes impossible, to suggest a chronological order for the trapping events with any certainty. These problems were compounded in fine-grained quartzite samples and quartz overgrowths where inclusions are generally very small (less than 1 micron), making accurate microthermometric observations impossible. In coarse, crystalline, late-stage quartz veins, however, these problems were largely overcome. For these reasons, a detailed microthermometric investigation was carried out concentrating on late-stage quartz veins sampled throughout the basin.

At least three types of quartz veining were identified: veining associated with intrusives, veining associated with faulting (bedding plane- and normal faults), and seemingly non-structurally related veining. After an initial petrographic study of sample material from these vein types it was realised that the Witwatersrand Basin had been affected by numerous post-depositional fluid events and that a variety of inclusion populations and fluid types existed. Petrographic observations combined with microthermometry suggest that at least four fluid types exist (Table 1) in at least six generations of inclusions. Complex cross-cutting relationships between pseudo-secondary and secondary inclusion trails suggest that multiple fluid trapping events have taken place within the Witwatersrand sediments.

Table 1: Fluid types within late-stage quartz veins, Witwatersrand Basin

FLUID SYSTEM	INCLUSION SIZE (micron)	OCCURRENCE	Tfm (°C)	Th (°C)	wt % eNaCl
H_2O-rich (+ salts)	4 - 50	isolated, clusters, trails,	-10	170	2 to 15
	5 - 20	X-cutting trails	-9 to -4	120	5 to 10
H_2O-CO_2-rich (+ salts)	4 - 40	trails	+2 to +8	230	5 to 30
CO_2-CH_4-N_2-rich	<20	trails	-5 to 0	230 to 280	8 to 10
	<30	trails	-70 to -40	-80	
CH_4-N_2-rich vapours	5 - 30	trails		-40	

The earliest generation of fluid is characterised by inclusions <1 micron across, forming a whispy texture in the quartz. The second generation comprises aqueous fluids of varying salinity (2 - 20 wt% eNaCl), sometimes saturated with respect to salts as evidenced by the presence of daughter crystals. These inclusions are typically very small (<5 microns) to small (5 - 20 microns) and are present in all studied samples. A third CO_2-rich fluid, with variable CO_2/H_2O ratios, is present in a number of samples as large inclusions (20 - 50 microns) that coexist with large aqueous inclusions (Fig. 2, Table 2). Daughter crystals were identified in both CO_2-rich and aqueous population three inclusions. A fourth vapour-rich, CO_2-rich fluid generation with variable amounts of CH_4, C_2H_6, H_2S, N_2 and H_2 (Fig. 3, Table 2) cross-cuts trails comprising the three earlier fluid generations. Aqueous inclusions coexist with these inclusions in the same fluid inclusion trails. A common feature of these aqueous inclusions is the presence of abundant carbon nodules (Fig. 4) as well as sulphide daughter crystals. These inclusions also have a lining of hydrocarbon-rich material, identifiable only by Raman spectroscopy. A number of these inclusions underwent some form of electro-chemical reaction when exposed to the power of the Raman laser, causing the previously invisible hydrocarbons to nucleate and precipitate a carbon nodule within the inclusions. These precipitated nodules exhibited similar characteristics to existing carbon nodules in other inclusions. A fifth generation of CH_4-N_2 vapour-rich inclusions (Fig. 5, Table 2) was also identified by Raman spectroscopy. The fourth and fifth generation inclusions are generally 10 to 30 microns in size and occur predominantly in fault-related samples. A late sixth generation aqueous fluid occurs in all samples.

Table 2: Composition data for volatile-rich inclusions from late-stage quartz veins, Witwatersrand Basin

Sample	Th (°C)	Density	XH_2O	XCO_2	XCH_4	XC_2H_6	XN_2	XH_2S	XH_2	wt % eNaCl
2729/4	-99,3	0,046	0	0	0,897	0,011	0,053	0,011	0,023	-
2729/9	-73,6	-	0	0	0.891	0,014	0,036	0,009	0,05	-
VRS1/1	178	0,81	0,815	0,171	0	0	0	0	0	5,5
VRS1/3	151	1,001	0,929	0,052	0	0	0	0	0	6,3
VRS1/3/1	145	1,006	0,904	0,042	0	0	0	0	0	29,4
VRS1/3/2	154	1,006	0,904	0,041	0	0	0	0	0	16,5
FSG6/2	151	0,837	0,9	0,001	0,003	0,003	0	0	0	4,6
FSG6/1	-44,8	-	0	0	0,769	0,059	0,159	0,014	0	-
PS3/1/4	-57,6	0,162	0	0,071	0,856	0	0,072	0,001		
PS3/2/5	-73,1	-	0	0,094	0,794	0	0,107	0,006	0	-
PS3/2/1	-65,7	-	0	0,068	0,826	0	0,1	0,006	0	-

Generation four and five hydrocarbon-rich fluids are predominantly associated with fault-related veining but these inclusions were also recognised in some intrusive-related veining. Microthermometry suggests entrapment temperatures of between 300 and 400°C for the more complex, hydrocarbon-bearing fluids. These temperatures are related to localised high P-T conditions experienced during post-depositional faulting.

HYDROCARBONS AND THE WITWATERSRAND FLUIDS

Diagenetic maturation of primitive algal material released hydrocarbons that were able to migrate through the sediments. The migrated hydrocarbons underwent polymerisation and condensation due to the effect of ionizing radiation in the proximity of detrital uraninite. Isotopically heavy hydrocarbons precipitated out as "bitumen/kerogen seams" where uraninite concentrations were high or as "fly-speck" bitumen/kerogen around isolated uraninite grains, giving rise to **sediment-hosted** bitumen types. Lighter hydrocarbons liberated during catagenic radiolysis were incorporated into circulating basinal brines. During late-catagenic/early-metagenic processes, hydrocarbon-bearing fluids along aquifers (faults, bedding planes and unconformities) precipitated insoluble carbonaceous matter or **migrated** bitumen under prevailing physico-chemical conditions.

Light (migrated) hydrocarbons precipitated as cross-cutting bitumen veins, where veins intersected uraniferous seam bitumen/kerogen, as well as carbon/bitumen nodules within late-stage quartz veins and as carbonaceous wall-coatings to fluid inclusions.

ASSOCIATION BETWEEN POST-DEPOSITIONAL FLUIDS AND MINERALISATION

Progressive maturation of primitive algal material from diagenesis to metagenesis would have produced kerogen and released CO_2, H_2O, CH_4 and oil. Decomposition of organic material rich in sulphur and nitrogen would also have released H_2S and N_2 (Tissot and Welte, 1978; Bottrell et al., 1988). Methane and petroleum have been shown to scavange a variety of metals from solution (Saxby, 1976; Hennet et al., 1979; Parnell and Eakin, 1987; Eakin and Gize, 1992) before migrating through sediments towards basin margins. Hydrocarbon-bearing fluids within the Witwatersrand Basin share this same potential for generating components which would enhance the formation of organo- and thio-metallic complexes and facilitate the transportation and subsequent concentration of elements such as Au, U, Cu, Pb, etc.

Migrated carbon/bitumen nodules from fault-related quartz veins are characterized by enriched Au, U, Fe, Cu, As, Pb and Ni concentrations as well as other trace elements (Table 3). Uranium is pervasively distributed throughout the nodules whereas gold occurs pervasively distributed (but in lower concentrations) throughout the nodules as well as in localised high concentrations (Fig. 1). Iron, Pb, Ni, Cu and As also occur in particular form (associated with sulphides) and pervasively distributed throughout the nodules. These nodules also exhibit a close association with recrystallised sulphides (Fig. 6) and gold (Fig. 7) sampled from the same fault-related quartz veins. This suggests that U, Au and other metals were transported in the same solutions as light hydrocarbons and probably formed organo-urano-gold complexes as well as thio-gold complexes and/or organo-urano-gold-sulphide complexes.

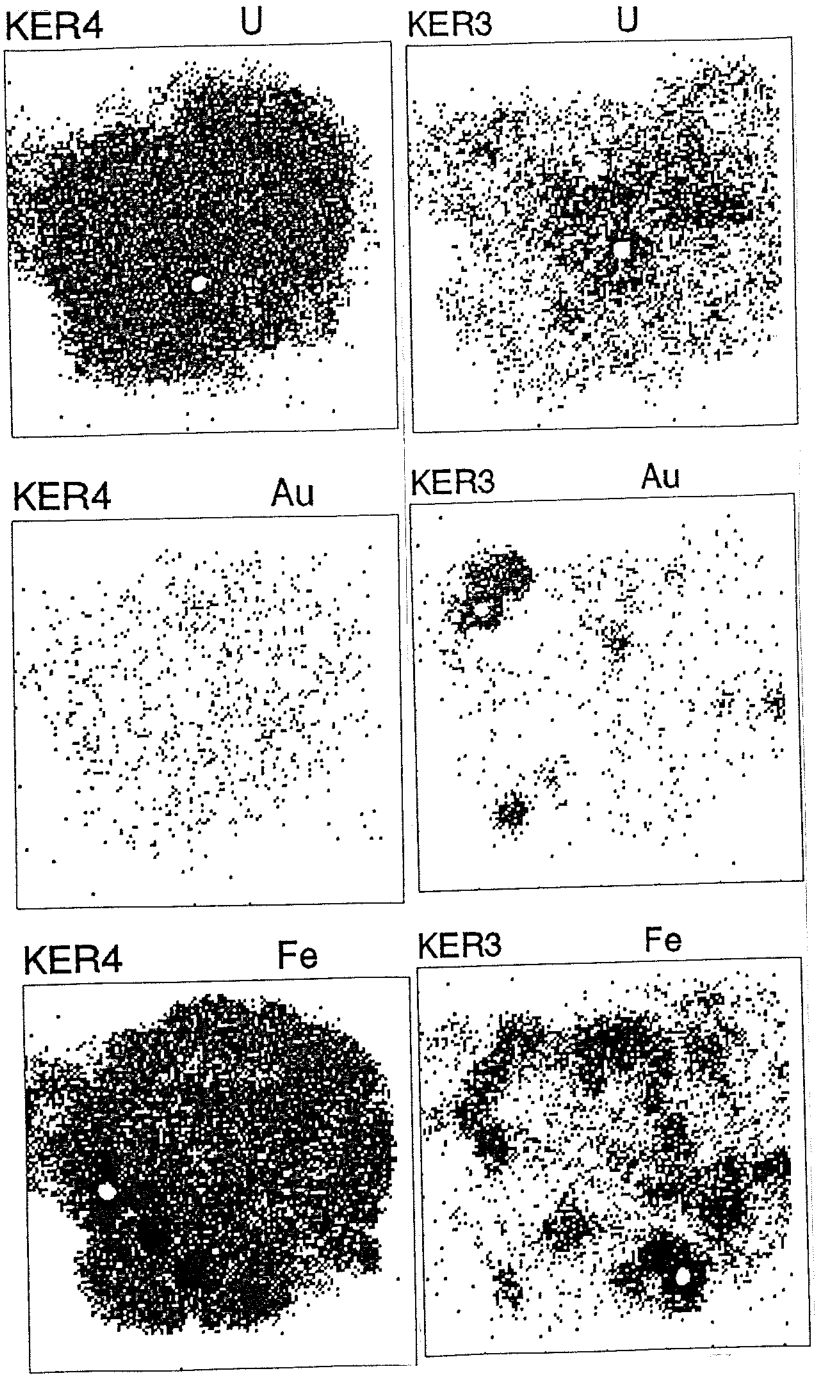

Figure 1: PIXE maps showing the distribution of uranium (U), gold (Au) and iron (Fe) in migrated carbon/kerogen nodules from late-stage quartz veins in the Witwatersrand Basin. Full scan size (FS) is 0,4 x 0,4mm. Spot (SS) positions are illustrated by white dots within areas of high elemental concentrations.

Table 3: Trace element analyses (in ppm) of migrated kerogen nodules from late-stage quartz veins, Witwatersrand Basin

	Ker 3 FS	SS-HIGH U	SS-HIGH Au	SS-HIGH As	SS-HIGH Fe	Ker 4 SS-HIGH-U	SS-HIGH As	SS-HIGH Fe
K	5756							
Ca	2950	6690	4256		29548			
Ti			13504	8944				
Fe	1360	2054	1088		55987	6261	6928	26784
Co	450	7770	814	4225	1968		5458	
Ni	330	1420	3533	16544	2496	759	1164	359
	1130	84	571	4050	60094	4915	5656	9982
Zn	127	422	154	200	425			
As	1670	12057	8520	220	6716		8361	451
Br	5450	5218	8338	30650	9106			
Sr	60			6402	214	83		
Y	620	4056	95		253	11391	4789	3394
Zr		354	33	763	577	3461		638
Ag		40	3755	103				
Ba		292					4311	2929
Ce	1250	810			4116	1309	300	185
Pr		442		878		1097		
Nd	860	1238	66	78	2173	2638	1196	683
Sm		360	104	584		1631		
Eu		83	102		704			
Gd		715	82		1912	2287		295
Tb		327				1191		
Dy		757				4079		
Ho		316						
Au	1860	97	29167	308	408	143	46	
Hg		66		152				
Pb		1675			2120	16102	6791	4016
Ac	820			121				4016
Th	2390	8646	615	3852	1355	42776	37458	21351
U	9530	78999	1751	20468	5568	156612	80185	41020

CONCLUSION

The data presented account for the intimate textural relationship between carbon/kerogen, gold and uranium within the Witwatersrand sediments. The paragenetic sequence comprises early detrital uraninite followed by heavy hydrocarbon fixation and uraninite replacement, with subsequent gold (and other metals and elements) remobilisation and reprecipitation around (inter-alia) the sediment-hosted kerogen. Liberated light hydrocarbons incorporated into circulating basinal brines formed organo-urano-gold-, thio-gold- and/or organo-urano-gold-sulphide complexes. Under suitable physico-chemical conditions these fluids underwent reduction and dehydrogenation, resulting in the reprecipitation of remobilised gold, sulphides and REE enriched uraniferous carbon/kerogen nodules, providing an explanation for the apparent hydrothermal component of the Witwatersrand mineralisation. The modified placer theory is, therefore, considered to best reflect the nature and origin of Witwatersrand mineralisation.

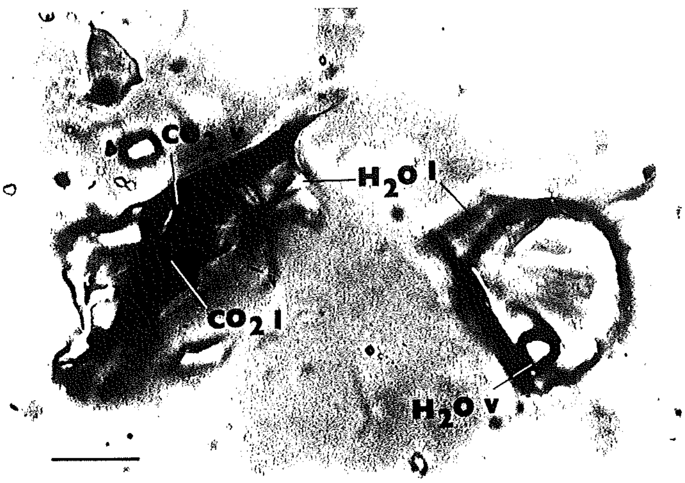

Figure 2: CO_2-H_2O inclusions coexisting with aqueous inclusions (scale bar = 10 microns).

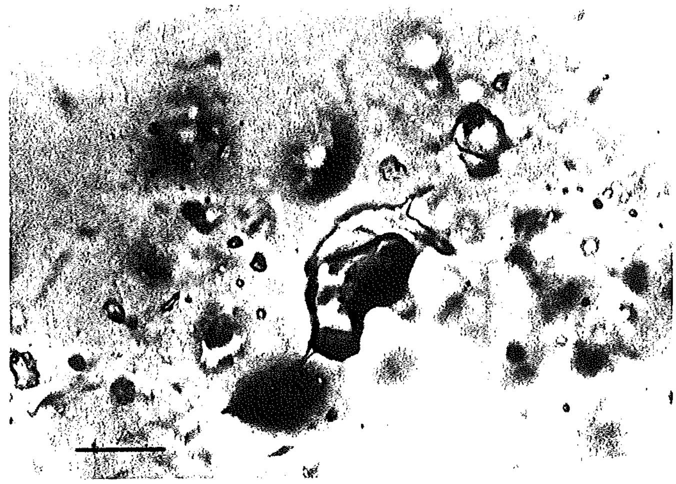

Figure 3: CO_2-CH_4-N_2-rich inclusions (scale bar = 10 microns).

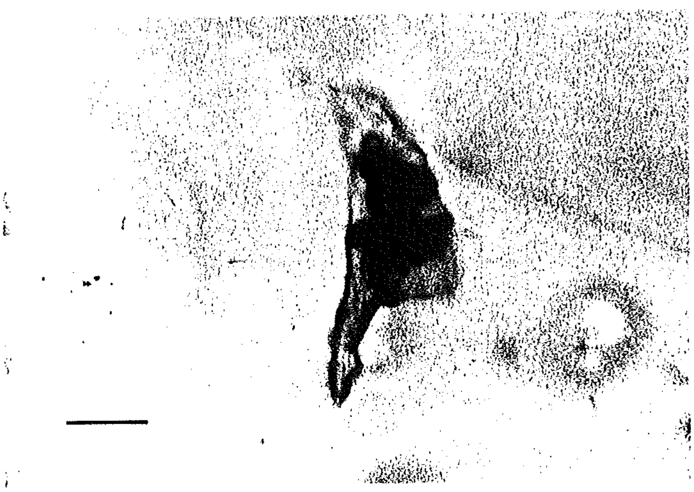

Figure 4: Bulbous carbon nodules in H_2O-rich inclusions (scale bar = 5 microns).

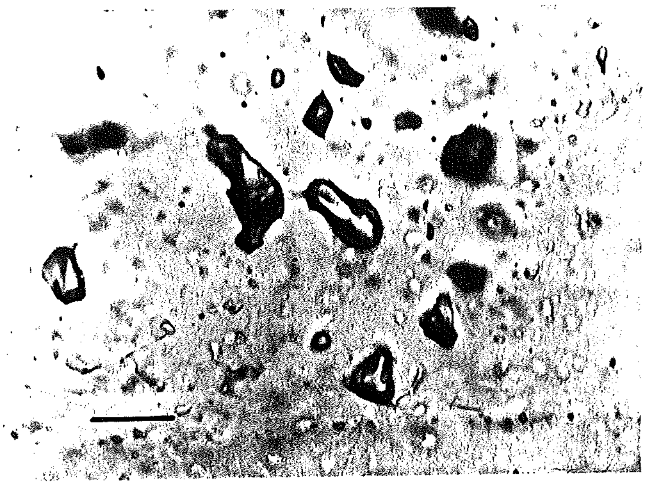

Figure 5: CH_4-N_2-rich inclusions (scale bar = 20 microns).

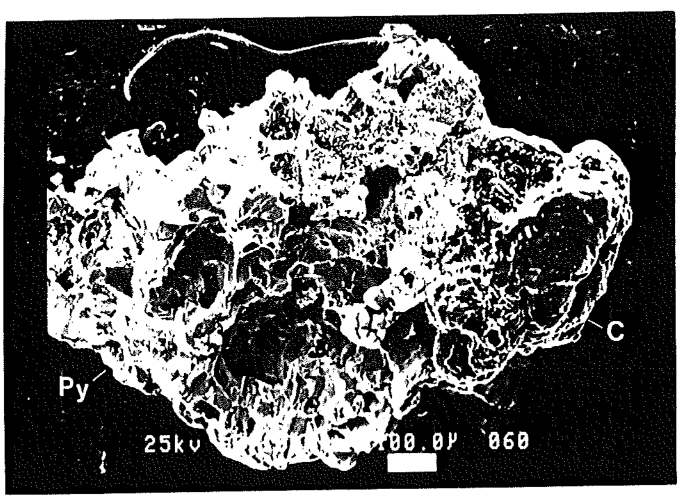

Figure 6: Migrated carbon (C) associated with recrystallized pyrite (Py) from a late-stage quartz vein cross-cutting the Witwatersrand sediments.

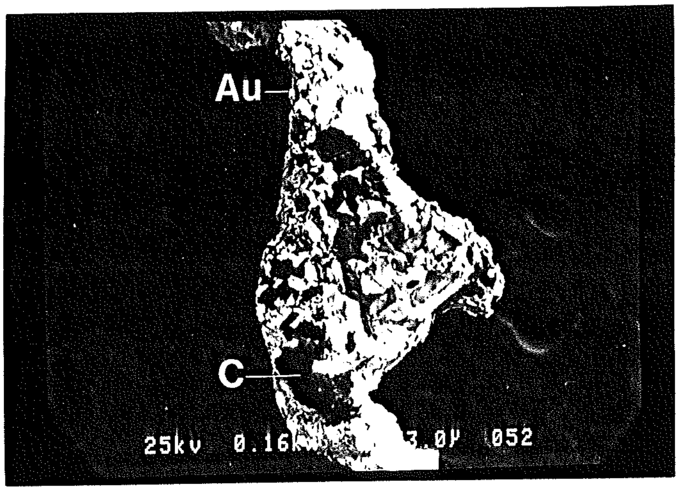

Figure 7: Migrated carbon (C) associated with recrystallized gold (Au) from a late-stage quartz vein cross-cutting the Witwatersrand sediments.

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FACTORS CONTROLLING THE COMPOSITION OF THE WITWATERSRAND FLUIDS

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INTRODUCTION

During its ca. 3 Ga long history the Witwatersrand Basin must have been repeatedly infiltrated and percolated by various fluids. The economic importance of the Witwatersrand Basin places an enormous significance on the composition of these fluids, in particular on the question of which fluid(s) were capable of transporting the amounts of metals required to produce the different types of ore deposit found within the basin. The relevance of this question is highlighted by the on-going debate concerning the genesis of the Witwatersrand gold, i.e. whether it is of detrital (e.g. Minter 1978) or of hydrothermal/metamorphic origin (e.g. Phillips and Myers 1989). Any future exploration in the Witwatersrand Basin should take cognisance of the chemical and physical parameters that controlled the composition and the flow pattern of the various fluids that have migrated through the Witwatersrand Basin. Only the integration of hydrothermal geochemical methods with fluid dynamics can lead towards a successful assessment of the economic potential of a certain fluid generation. Therefore, the aims of this contribution are (i) to present evidence of economically significant responses of the Witwatersrand rocks to fluid infiltration, (ii) to constrain the important factors controlling the fluid composition using petrological (mineral parageneses), geochemical (minerals and fluid inclusions), and textural (high resolution cathodoluminescenc imaging, CLI) information, and (iii) to place different generations of fluid into a regional geological context based on recently acquired age data.

MOBILITY OF DETRITAL COMPONENTS

The active role played by fluids in the mineralogical evolution of the Witwatersrand Basin is evidenced by the partial to total recrystallisation of the sedimentary and igneous protoliths. Peak metamorphic temperature-pressure conditions of 300 - 350 °C and 2 - 3 kbar have been constrained for most of the Witwatersrand rocks, except for those which form the collar of the Vredefort Dome (Frimmel 1994; Phillips and Law 1994). In most areas no strong fabric developed during metamorphism, suggesting that the recrystallisation can be explained as a response to burial. A volumetrically important reaction at this stage was

$$\text{kaolinite} + 2\ \text{quartz} = \text{pyrophyllite} + H_2O. \qquad (1)$$

CLI confirms the widespread consumption, rather than recrystallisation, of quartz during metamorphism of the clay matrix. Resorption of the predominantly detrital quartz clasts and pebbles implies that an increase in the palaeo-porosity enabled the advective upward escape of aqueous fluid produced during reaction (1).

The palaeo-porosity was further enhanced during subsequent fracturing events. Most of these fractures are infilled with secondary quartz, resulting in micro- to macro-scale quartz veins. Wallmach and Meyer (1990) have already noted textural evidence for the sericitization of some of the pyrophyllite produced in reaction (1), and sericite pseudomorphs after andalusite and shear-zone related kyanite have also been described (McCarthy et al. 1986; Frimmel 1994). The formation of these Al-silicates can be explained by acidic fluids leaching the alkalies out of the rocks. Later sericitization reactions, such as:

$$2\ K^+ + 3\ \text{pyrophyllite} = 2\ \text{muscovite} + 2\ H^+ + 6\ \text{quartz} \qquad (2)$$

released major amounts of SiO_2, resulting in the formation of quartz veins.

A complex growth history is not only evidenced for quartz, using CLI, but also for both pyrite and gold. Some reefs may be characterized by the predominance of well-rounded pyrite grains, others by that of perfectly euhedral pyrite, and others by any combination of both extremes. By analogy, a case study on the shape of the gold grains in the Basal Reef (Minter et al. 1993) revealed that both rounded to oblate shaped, evidently detrital, gold micro-nuggets and irregularly shaped, secondary gold can occur together in a given reef. The latter variety dominates in many reefs, making the origin of the gold ambiguous. Recent ion microprobe analyses of S isotopic ratios in different morphological pyrite types, occurring within a single reef, revealed considerable differences in $\delta_{34}S$ both between and within the grains (Eldrige et al. 1993; Armstrong et al. 1995). These results lend strong support for the detrital nature of the rounded pyrite grains. In summary, it appears that not only the quartz clasts and pebbles, but also the detrital pyrite and the gold nuggets were subjected to dissolution and subsequent, usually in situ, precipitation. The extent to which these processes varied from one locality to the next can only be explained by variations in the amount and/or composition of the local fluid(s).

CONSTRAINTS ON THE FLUID COMPOSITION

Assuming similar P-T conditions during the time span over which the most intense post-depositional alteration occurred, changes in the composition and/or amount of fluid, that equilibrated with a given volume of rock, are considered the driving force behind mineral mobilisation in the Witwatersrand Basin. For instance, changes in the pH or the ambient sulphur fugacity would be very efficient means for mobilising the gold, assuming it was transported as $HAu(HS)0_2$ complex (Frimmel 1994).

Acidic conditions must have prevailed during diagensis and burial metamorphism because the pH was buffered over wide areas by the assemblage pyrophyllite + muscovite. This is the reason for the ubiquitous absence of detrital feldspars. However in a few stratigraphic horizons, mainly in the marine deposits of the West Rand Group, feldspars were stable during metamorphism, thereby suggesting higher pH values in those horizons and a stratigraphic control on pH.

The amount of CO_2 in the metamorphic fluid was variable and dependant on the local availability of carbon. The Ca^{++} content was generally low due to the dominance of essentially carbonate-free siliciclastic strata. It is only in the immediate vicinity of Ca-bearing rocks, such as mafic bodies or Ca-bearing banded iron formation, that the influence of Ca-rich fluids is indicated by the presence of calcite veins. Such veins do not usually persist across stratigraphic boundaries but grade into quartz veins, which may contain, in places, hydrothermal bitumen. This again highlights a stratigraphic control not only on the amount of Ca^{++}, but also on pH. In other areas, however, evidence for Ca^{++}- and SiO_2-infiltration exists (Frimmel et al. 1993).

The oxygen and sulphur fugacities can be estimated from the stability of Fe-oxides, Fe-sulphides, and Ti-oxides, and from the composition of co-existing Fe-Mg silicates such as chlorite. The widespread ocurrence of pyrite and rutile in the siliciclastic rocks implies relatively high $f(S_2)$. Only locally, such as in the Ventersdorp Contact Reef, where pyrrhotite may be the predominant Fe-sulphide, is there evidence for a lower $f(S_2)$. Whereas Fe-sulphides are typical of the coarser-grained, fluvial metasedimentary rocks, which form the bulk of the Central Rand Group, magnetite is characteristic of the transgressive pelitic horizons in the West Rand Group, which were deposited in a shallow marine environment (Frimmel, in press). This demonstrates major differences in the ambient $f(O_2)$ and $f(S_2)$ between stratigraphic horizons. Even on the scale of a thin-section, however, variation in the X_{Fe}-fraction of chlorite (sensu stricto) reflects local inhomogeneity with respect to $f(O_2)$ and $f(S_2)$.

Two important conclusions are that in most areas of the Witwatersrand Basin the fluid composition appears to have been controlled mainly by the local bulk composition of the infiltrated rock and that gold mobility is directly linked to that of pyrite. An acidic aqueous fluid reacting with pyrite would cause the increase in $f(S_2)$ required for the mobilisation of the gold. The gold mobility, thus, becomes directly proportional to the amount of sulphide (pyrite) present, but it is inversely related to the extent to which the local sulphuric pore fluid was diluted by externally derived aqueous fluid, i.e. the fluid:rock ratio. This relationship explains the very limited distance over which the gold was transported, as documented for the Basal Reef (Frimmel et al. 1993).

GEOLOGICAL SETTING OF INFILTRATION EVENTS

Gold mobilisation in the Basal Reef, Welkom goldfield, is associated with secondary quartz veins that also contain calcite, and is, therefore, not related to burial metamorphism, but to a Ca^{++}- and CO_2-infiltration event. This conclusion is also supported by the chemistry of co-genetic fluid inclusions (Frimmel et al. 1993). Secondary zircon within the auriferous secondary quartz has been dated at 2.58 Ga (Armstrong et al. 1995). A similar age has been reported by Robb et al. (1990) for authigenic rutile from the West Rand Group. This age overlaps with the timing of carbonate deposition in the Transvaal Supergroup. Extension tectonics at that time probably provided both the conduits and the increased heat flow that drove hydrothermal convection cells to bring meteoric/formation waters from the near-surface platform carbonates to the deeper levels of the Witwatersrand Supergroup.

Another major phase of infiltration, often masking previous events, can be ascribed to the Bushveld and Vredefort events at ca. 2.06 and 2.03 Ga, respectively. Widespread K^+-metasomatism in the Witwatersrand Supergroup may be related to the emplacement of the Bushveld Complex. The deformation associated with the Vredefort Dome is evident in the form of shattered quartz clasts in the Witwatersrand rocks. Microfractures within these clasts are infilled with quartz containing carbonic-rich aqueous fluid inclusions.

Based on their chemical characteristics, the fluids involved in these processes might also have been capable of mobilizing both the pyrite and the gold.

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REGIONAL METAMORPHISM IN THE WITWATERSRAND BASIN: THE BUSHVELD-VREDEFORT CONNECTION

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INTRODUCTION

Metamorphic studies in the Witwatersrand Basin have assumed added importance in the last few years with the recognition that the mineralization in the goldfields has been affected by postdepositional hydrothermal fluid movement. Since the work of Phillips (1987) which established that the reefs throughout the Witwatersrand goldfields experienced remarkably uniform, lower greenschist facies, grades of metamorphism, research interest has concentrated on the reef packages themselves, focussing mainly on the identification of the metamorphic parageneses and on the nature of the hydrothermal fluids responsible for gold mobilization. The causes and nature of the thermal event responsible for the metamorphism and hydrothermal fluids are, however, less well understood. This is due largely to the low-grade nature of the metamorphic assemblages in the goldfields, which precludes elucidation of the P-T path followed by the rocks during the metamorphism.

This contribution examines the metamorphic history of the Witwatersrand Basin from a broader perspective than has been possible in the detailed studies that have, thus far, been concentrated in the goldfields. Based on results from higher-grade assemblages found in other parts of the Witwatersrand Basin, it proposes that the basin experienced a series of thermal-hydrothermal events concomitant with the intrusion of the Bushveld Complex and the formation of the Vredefort Dome, at ca. 2.0 Ga, that may explain a significant part of the metamorphic history observed in the goldfields.

METAMORPHISM IN THE WITWATERSRAND GOLDFIELDS

Phillips (1987) noted the existence of similar metamorphic parageneses, involving chloritoid and pyrophyllite, in goldfields throughout the Witwatersrand Basin and concluded that the metamorphism was of regional extent. Independent studies have corroborated his estimates of 350 ± 50 °C, 2-3 kbar for the peak metamorphic conditions in most areas in the goldfields (see review in Phillips & Law, 1994). Various hypotheses have been proposed to explain this peak event, including elevated heat flow associated with extension during the early stages of Transvaal Basin formation at 2.5-2.6 Ga (Frimmel, 1994); a thermal event related to the formation of the Vredefort Dome (by unspecified processes; Phillips & Myers, 1989); a thermal event of unspecified origin at ca. 2.3 Ga (Phillips et al., 1989); and one or both of the Bushveld Complex and Vredefort Events (Layer et al., 1988). While it is unlikely that the rocks of the Witwatersrand Basin experienced only a single thermal event during their postdepositional history, the significance of the peak metamorphic assemblages lies in the fact that they indicate the existence of an upper crustal thermal gradient of some 35-40 °C/km in the region of the Witwatersrand Basin at some point in its postdepositional history. Gradients of such magnitude are highly unusual in cratonic environments, which are typically characterized by geothermal gradients of ~ 15-20 °C/km. They indicate a significant deviation from the steady-state geotherm and, thus, by definition, reflect a thermal event of transient nature. The most commonly-invoked mechanism for the development of such abnormal gradients is the advective transfer of heat to mid- to upper crustal levels by voluminous intrusions (De Yoreo et al., 1991). An important consequence of the elevated thermal gradient is that rocks in relatively close proximity to the goldfields should show grades of metamorphism significantly higher than the lower greenschist facies. Several such areas of higher-grade rocks exist in the region (see review in Phillips & Law, 1994). This study concerns the results of an investigation into the higher-grade rocks exposed in the central parts of the Witwatersrand Basin, in the Vredefort Dome.

METAMORPHISM IN THE VREDEFORT DOME

Rocks of the Witwatersrand Supergroup are exposed in the central parts of the Witwatersrand Basin in the steeply-dipping collar of the Vredefort Dome. The origin of the dome has been a matter of controversy for several decades (e.g. Reimold, 1993). Recently, however, several studies have provided additional evidence that suggests an origin for the dome as a result of a large meteorite impact. These include (a) confirmation of the shock origin of planar microdeformation features in quartz (Leroux et al., 1994); (b) evidence of similar shock features in zircons (Kamo et al., 1995); and (c) evidence of an extraterrestrial Re-Os component in the Vredefort Granophyre, which is interpreted as an impact-melt (Koeberl et al., 1996). Kamo et al. (1995) interpreted an age of 2025 $\pm$ 4 Ma for pseudotachylite in the dome as the age of the impact event. Recent radiometric studies have confirmed that most of the pseudotachylite in the Witwatersrand Basin formed concomitant with the Vredefort Event (Trieloff et al., 1994; Spray et al., 1995). Modelling of the impact event by Therriault et al. (1993) suggests that the impact structure encompasses the known limits of the Witwatersrand Basin and that the Vredefort Dome represents the central uplift of this structure.

The rocks of the Witwatersrand Supergroup exposed in the dome display higher grades of metamorphism than their counterparts in the goldfields (mid-greenschist facies in the Central Rand Group, upper greenschist to mid-amphibolite facies in the West Rand Group). This metamorphism has generally been perceived as a product of a localised igneous heat source that is centred on the dome and that is somehow linked to the formation of the dome (e.g. Bisschoff, 1982). This contact-metamorphic scenario has led to most workers discounting a possible link between the Vredefort metamorphism and the metamorphism in the goldfields (e.g. Phillips & Law, 1994). Gibson & Wallmach (1995), however, have established a P-T path for the mid-amphibolite facies rocks (Fig. 1) which (a) shows that the metamorphic peak pre-dated the formation of the dome, and was, therefore, unrelated to the doming event; and (b) indicates that the metamorphism occurred concomitantly with crustal thickening no more than a few tens of millions of years before the doming event. Peak metamorphic temperatures of ~ 570-600 °C were attained at depths of 14-16 km during this event, indicating a peak thermal gradient in excess of 40 °C/km. A second, lower-grade, event (T ~ 500-530 °C, P < 3.5 kbar) affected these rocks after a widespread pseudotachylite-forming event which accompanied the formation of the dome.

A similar two-stage P-T path geometry has also been established for the metapelitic granulites in the Archaean basement core of the dome (Stevens et al., 1995). Peak metamorphic conditions reached > 900 °C, ~ 5.5 kbar (corresponding to a peak thermal gradient of > 45 °C/km), whereas during the later, post-pseudotachylite event, temperatures exceeded 700 °C at pressures of ~ 2.5 kbar.

ORIGIN OF THE METAMORPHISM IN THE WITWATERSRAND BASIN

The P-T path geometries for the rocks in the Vredefort Dome are fully consistent with a syn-Bushveld timing for the peak metamorphic event. The Complex, which reaches thicknesses in excess of 3-4 km immediately to the north of the Witwatersrand Basin, and which originally overlay the Witwatersrand Basin at least as far south as the Losberg Complex, has been dated at 2065-2054 Ma (Walraven et al., 1990; Walraven & Hattingh, 1993), i.e. only 30-40 Ma older than the Vredefort Event. The presence of the Bushveld Granites and the felsites of the Rooiberg Group in the Bushveld Complex indicates that significant amounts of deep crustal melting occurred on a regional scale during this event, corroborating the evidence of very high-temperature metamorphism found in the rocks in the core of the dome. The P-T paths also suggest that the rocks in the Vredefort Dome were exhumed prior to complete cooling of the crust. The post-shock thermal event may have involved prograde heating depending on (a) the amount of thermal energy released from the crater basement following the passage of the impact shock wave; and (b) heating effects beneath the envisaged impact-melt sheet (the parent body to the Vredefort Granophyre) that would have formed in the impact crater.

Extrapolation of the P-T_{max} data array from the medium- and high-grade rocks in the Vredefort Dome to lower grades produces results that are fully consistent with the P-T_{max} estimates obtained from the goldfields. The increase in dT/dP of this array towards higher grades is a feature typically observed in contact metamorphic aureoles. In this case, the scale of the metamorphism indicates that it is better described as regional-contact metamorphism (e.g. De Yoreo et al., 1991).

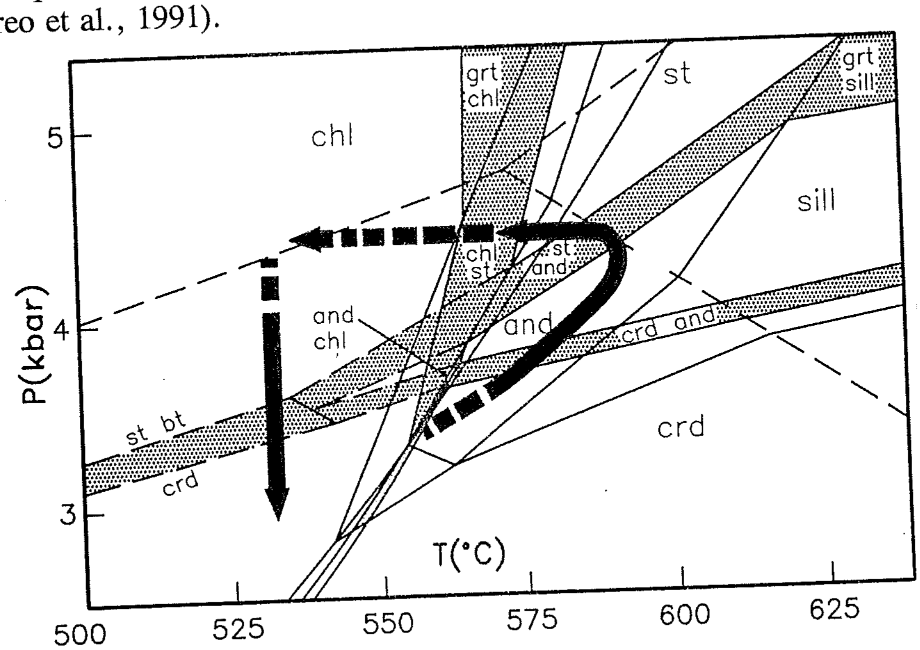

Figure 1: *P-T path for West Rand Group metapelites in the collar of the Vredefort Dome, inferred from reaction textures (see explanation in Gibson & Wallmach, 1995).*

THERMAL MODELLING OF THE METAMORPHISM

The peak metamorphic P-T array for the rocks in the Witwatersrand Basin has been modelled using the computer program CONTACT of S.M. Peacock (1990) for sills of varying thicknesses intruded at different crustal levels into rocks of varying temperature, assuming a magma composition similar to that found in the Main Zone of the Bushveld Complex. A reasonable correlation between the observed array and the model predictions was obtained for a 3 km thick, conductively cooling mafic sill intruded at a depth of 19 km. Modelling of the contact effects beneath the Bushveld Complex suggests that it may also have had a limited effect on the rocks in the goldfields.

The post-doming metamorphic event is less well-constrained due to the uncertainties surrounding the contributions to the post-doming thermal budget of the Witwatersrand Basin by the thermal energy released from the crater basement following the passage of the impact shock wave and by an impact melt body. The P-T path data suggest, however, that the pre-impact crustal geotherm may have been as high as 25-30 °C/km. As a result, differential exhumation and uplift of rocks in the crater basement would have juxtaposed relatively hot mid-crustal rocks in the Vredefort Dome against somewhat cooler upper crustal rocks in the surrounding Witwatersrand Basin. This lateral thermal gradient would have led to renewed heating in the Witwatersrand Basin in a scenario analogous to emplacement of a vertical cylindrical intrusion into the centre of the Basin. First approximation thermal modelling of this process suggests that cooling to a normal geothermal gradient may have extended for several tens of millions of years after the Vredefort Event.

IMPLICATIONS OF THE MODEL FOR THE WITWATERSRAND GOLDFIELDS

The proposed model for the metamorphism in the Witwatersrand goldfields envisages two thermal events at ca. 2.0 Ga. The former is attributed to a regional event produced by intraplating of mafic magmas into the middle and lower crust during the Bushveld Event at ca. 2.05-2.06 Ga. It is likely to have been accompanied by a major fluid pulse generated by (a) prograde dehydration reactions in the metasediments, by crystallization of (b) the mafic mantle-derived magmas, and (c) the crustally-derived anatectic melts at deeper levels. Fluid generation is likely to have been episodic and to have continued while elevated geothermal gradients persisted, up until the Vredefort Event at 2.02 Ga, and may, thus, be registered as a series of apparently discrete fluid infiltration events in the rocks of the goldfields. The retrograde event following the formation of the Vredefort Dome, although lower-temperature, may have involved a more voluminous fluid fluxing event due to the catastrophic nature of the deformation and thermal processes accompanying the formation of the dome. This may be the source of the K-metasomatism documented by *inter alia*, Frimmel (1994), which has been established as having postdated the pseudotachylite development in the goldfields, and the absolute timing of which has been corroborated by geochronological studies (e.g. Trieloff et al., 1994; Zhao et al., 1995).

The evidence in support of a syn-Bushveld regional metamorphic event does not preclude the existence of earlier, lower-temperature, thermal-hydrothermal events which may have affected the Witwatersrand Basin, nor does it necessarily imply that the observed gold mobilization was related solely to this event and/or the post-Vredefort retrograde event.

Recent studies of the Ventersdorp Contact Reef do, however, suggest that these events had a major influence on the gold mineralization (e.g. Boer et al., 1995).

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AN OVERVIEW OF METAMORPHISM AND METASOMATISM IN THE WITWATERSRAND BASIN: RECENT TRENDS AND OPPORTUNITIES

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INTRODUCTION

The first systematic study of the metamorphic petrology of shales in the Witwatersrand goldfields was published by Phillips (1986), 100 years after the initiation of mining on the Central Rand. Lower greenschist facies assemblages were described from nearly every mine in each goldfield and were inferred to result from regional, lower greenschist facies, burial metamorphism and associated alteration. Prior to 1986, research was guided by the general belief that the Witwatersrand goldfields had either escaped metamorphism or had undergone only minor, isochemical, lower greenschist facies burial metamorphism. Even advocates of hydrothermal ore genesis (Graton, 1930; Davidson, 1953, 1955), who noted the similarity of the ore assemblage to many epigenetic deposits, failed to address the nature and extent of alteration. As the understanding of the role of metamorphic fluids and their potential to mobilise metals has progressed, so the potential importance of metamorphism in the Witwatersrand has been recognised. Recent debate has focused on the nature of the metamorphism (isochemical versus allochemical) rather than on the existence and grade of the metamorphic assemblages. In addition, studies of the tectonics of the basin have shown that the basin has undergone an active syn- and post-depositional tectonic history (Roering, 1984; McCarthy et al.,1986) and the link between metamorphism and tectonism is receiving increasing attention. Further controversy surrounds the origin of the Vredefort Dome and its relationship to metamorphism within the basin.

METAMORPHISM AND METASOMATISM WITHIN THE GOLDFIELDS

The drilling and mining in the Witwatersrand provides unrivalled access to study metamorphic processes in a sedimentary basin. Initial systematic metamorphic studies undertaken by Phillips (1986) in the mid-1980's focused on meta-pelites within the goldfields. This work demonstrated the widespread distribution of chloritoid and pyrophyllite and recognised systematic stratigraphic and geographic variations in bulk-rock compositions. These variations were interpreted in terms of metasomatic reactions involving large fluid fluxes focused within specific lithological and structural features (Phillips, 1988). In general, West Rand Group shales are chlorite-rich, whereas Central Rand Group shales are more aluminous containing abundant muscovite, chloritoid and pyrophyllite. Within the Central Rand Group, thin laterally impersistent shale horizons in the vicinity of mineralised conglomerates (e.g. Khaki shale, K8 shale) are compositionally distinct from thick regionally persistent shales (e.g. Booysens shale, Jeppestown shale) except in highly strained areas particularly near lithological contacts and mineralised conglomerates. These studies have identified very high fluid rock ratios ($>>100$) and the resultant alteration has generated volume changes of up to 45% (defined relative to immobile element concentrations). Mobile elements typically include Si, K, Na, Fe, Mg, Ca, Rb, Sr, Ba, Co, Ni, Zn, Au, U and C, whereas Ti, AI, P, V, Cr, Nb and Ga are generally immobile (Palmer et al., 1989; Phillips, 1988; Law, 1991). Other authors have argued that isochemical metamorphism is compatible with the observed compositional and mineralogical variations (e.g. Wallmach and Meyer, 1990). Nevertheless, the unusual aluminous composition of the sediments required to stabilise pyrophyllite and chloritoid is widely recognised and it has been suggested that intense weathering (either in-situ or at source) is responsible for the observed compositions.

Similar compositional and mineralogical variations have been reported from meta-quartzites and meta-conglomerates (Fuller, 1958; Sutton *et al.*, 1990; Law, 1991) which dominate the Central Rand Group stratigraphy. They contain more complex assemblages than the interbedded meta-pelites and preserve detrital, diagenetic, and metamorphic minerals. The distribution of diagenetic assemblages in the Central Rand Group is virtually unconstrained, as they have been widely overprinted by hydrothermal and metamorphic, processes. In the absence of direct evidence, the diagenetic assemblages have been inferred by analogy with younger basins and from relatively unaltered lithologies mainly in the West Rand Group. Law *et al.* (1990) have argued for syn-metamorphic alteration of the pre-existing diagenetic assemblages, whereas Sutton *et al.* (1990) have supported weathering as the dominant control on bulk rock compositions. Each of these studies indicate that there are systematic compositional variations, with the most aluminous lithologies being spatially related to mineralised conglomerates overlying angular unconformities. In addition, areas of high fluid flux are inferred along bedding sub-parallel structural features, with shear fabrics defined by the peak metamorphic assemblage.

There is now general agreement that peak metamorphic conditions in the goldfields are constrained between 300 and 400°C and 1.5-3kbar (pressure is relatively poorly constrained due to steep reaction slopes in P-T space) by the co-existence of pyrophyllite and chloritoid, and the widespread distribution of the assemblage pyrophyllite-chloritoid-muscovite-chlorite-quartz-tourmaline-rutile-pyrite. These estimates are further supported by illite crystallinity, vitrinite reflectance, chlorite geothermometry, and fluid inclusion studies (Phillips and Law, 1994). Pelites, quartzites, conglomerates, basalts, and some dykes record these metamorphic assemblages, albeit in different mineral proportions. Mineral assemblages and limited fluid inclusion data have been used to infer the composition of the aqueous phase co-existing with the observed mineral assemblages during metamorphism (Phillips and Law, 1994). The inferred presence of a sulphur-rich metamorphic fluid in the goldfields has prompted numerous studies aimed at constraining the solubility and, hence, mobility of gold in solution. Most studies conclude that there is potential to mobilise gold, but the absolute gold concentrations inferred vary by several orders of magnitude.

HIGHER GRADE ASSEMBLAGES AND THE VREDEFORT DOME

Andalusite, kyanite, garnet, and/or cordierite-bearing assemblages indicate higher metamorphic grades in three discrete areas:

* along shear zones near the NW margin of the Witwatersrand Basin;
* in the Bushveld thermal aureole to the NE of the Evander Goldfield;
* around the collar of the Vredefort Dome.

Concentric metamorphic facies around the Vredefort Dome culminate in granulite facies assemblages near the centre. Two discrete metamorphic events have been recognised by Gibson and Wallmach (1995):

* mid-amphibolite facies coeval with a period of crustal thickening;
* a younger, lower grade event coeval with the formation of the Vredefort Dome.

There has been a tendency to relate the metamorphism of the Vredefort Dome and the surrounding goldfields to a single post-Transvaal event, overlapping in time with the development of the Vredefort structure. This interpretation is compatible with the available data, but is not uniquely constrained. High temperature decompression textures in the amphibolites and granulites of the dome suggest that metamorphism of the dome and collar rocks may be coeval (Gibson and Wallmach, 1995). The high geothermal gradient, anticlockwise P-T path, lack of large scale tectonic thickening and absence of widespread intrusive rocks strongly supports mafic underplating as the likely cause of the metamorphic pattern.

RESEARCH TRENDS AND OPPORTUNITIES

The following research opportunities have yet to be fully exploited:

* the ages (absolute and relative) of metamorphism in the goldfields and within and around the Vredefort Dome are poorly constrained.

* the regional and stratigraphic distribution of mineral assemblages (especially away from the goldfields).

* the spatial and possible genetic relationships between alteration, metamorphism, structure, and mineralisation. These studies require the compilation of data sets that have yet to be systematically collected in the Witwatersrand, but are essential for a realistic evaluation of the importance of hydrothermal processes.

* studies of fluid volumes, composition, and metal transport.

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A CHRONOLOGICAL FRAMEWORK FOR THE WITWATERSRAND BASIN - WITH EMPHASIS ON METAMORPHIC/HYDROTHERMAL EVENTS

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INTRODUCTION

This contribution presents a summary of chronological results obtained for rocks from the Witwatersrand Basin and its environs, in order to provide a discussion basis for the Symposium on 'Economic Significance of the Metamorphism and Fluid Movement within the Witwatersrand basin'. The current chronological knowledge regarding the ages of crystalline basement in and around the basin, as well as the known constraints on sediment deposition and on magmatic, tectonic, and thermal metamorphic episodes in the evolution of the basin are reviewed. A summary of the thermochronological data, mainly obtained on minerals and fault rocks from the central part of the basin including the Vredefort Dome, is presented, which contains a number of new, previously unpublished, ^{40}Ar-^{39}Ar stepheating results.

SUMMARY OF KNOWN EVENTS PRIOR TO AND DURING THE EVOLUTION OF THE WITWATERSRAND BASIN

Several detailed summaries of the chronological knowledge regarding the basement to, and the evolution of, the Witwatersrand Basin have been presented in the recent past (e.g., Walraven et al., 1990; Reimold et al., 1993; Robb and Meyer, 1995). Particularly the latter authors discuss the results of individual studies in detail and present a full bibliography of relevant publications. Therefore, only a summary table of pertinent, geochronologically defined, events is provided (Table 1).

Several isotopic studies (mainly Rb-Sr and Pb-Pb whole rock and mineral analyses) have indicated that resetting events occurred within the region of the Witwatersrand basin around 2500 Ma ago (e.g., Barton et al., 1986; Giusti et al., 1986; Giusti, 1988; Robb et al., 1990), 2300 Ma (Van Niekerk and Burger, 1964; Allsopp et al., 1986; Barton et al., 1986; Giusti et al., 1986; Giusti, 1988; Walraven et al., 1990; Robb et al., 1994), and 2000-1900 Ma (Rundle and Snelling, 1977; Layer et al., 1988; Zhao et al., 1995 - this volume). Robb et al. (1994) interpreted their U-Pb isotopic data of Witwatersrand kerogen samples as indicating kerogen/bitumen (?; Robb et al., this volume) formation in both reefs and granites from the environs of the basin around 2300 to 2380 Ma ago.

The Vredefort 'event', which has long been of controversial origin by either a catastrophic impact event or endogenic processes, has recently been confirmed to be of unequivocal *impact origin* (Leroux et al., 1994 - confirmation of shock metamorphic planar microdeformation in the form of basal Brazil twins in quartz; Kamo et al., 1995 - shock-diagnostic planar deformation features in zircon; Koeberl et al., 1995 - Re-Os isotopic data confirming the presence of a small meteoritic component in the Vredefort Granophyre). Kamo et al. (1995) also provided a precise U-Pb zircon age for pseudotachylite from the

Table 1. Chronologically well-defined events in the history of the Witwatersrand Basin

Event	*Age [Ma]*	*Constraints*
Formation of basement granitoids	>3086	U-Pb zircon
Dominion Group Emplacement	3086-3074	U-Pb zircon
Witwatersrand Supergroup Depos.	<3074-2714	U-Pb zircon
Crown Lava	2914 ± 8	U-Pb zircon
Ventersdorp Contact Reef	2714<t<2780	U-Pb zircon
Ventersdorp Supergroup	<2714	U-Pb zircon
Late Basement Granitoids	3031-2687	U-Pb zircon
Transvaal Supergroup	ca. 2560-2250	Pb-Pb WR
Schmidtsdrif Fm (Chuniespoort Gr.)	2557 ± 49	Pb-Pb WR
Ongeluk Lava (Pretoria Gr.)	2239 ± 90	Pb-Pb WR
Hekpoort Andesite	2224 ± 21	Rb-Sr WR
Rooiberg Felsite	2061 ± 2	Zircon Evap.
Bushveld Granite	2054 ± 2	Zircon Evap.
Vredefort Impact Event	2025 ± 4	U-Pb zircon
Various Magmatic Events	1250-1000	Rb-Sr WR/Min.
Karoo Magmatism	180 Ma	^{40}Ar-^{39}Ar step.

Vredefort Dome, which accurately dates the impact event at 2025±4 Ma (cf. also Trieloff et al., 1994 and Spray et al., 1995), some 30 Ma later than the Bushveld magmatism at 2054-2061 Ma (e.g., Walraven and Hattingh, 1993).

A number of workers have established in the last years that widespread magmatic activity occurred along the southern edge of and throughout the Kaapvaal Craton at about 1000-1250 Ma ago (e.g., Pybus et al., 1994 and Reimold et al., 1995a, as well as papers cited therein).

THERMOCHRONOLOGICAL (^{40}Ar-^{39}Ar STEPHEATING) DATING OF FAULT ROCKS AND OF MINERALS FROM "WITWATERSRAND" ROCKS

In the past 5 years, our group has undertaken thermochronological analysis of fault rocks (pseudotachylite, cataclasite, mylonite) and of metamorphic and hydrothermally grown authigenic minerals from the central part of the Witwatersrand Basin. The purpose of these studies was to date the Vredefort event through analysis of pseudotachylites, to test the hypothesis that several generations of fault rocks occurred in the Vredefort Dome and surrounding parts of the Witwatersrand basin, to date the metamorphic events that affected the Vredefort Dome and wider Witwatersrand Basin, and to examine the possible effects of the Bushveld Complex within the region of the Basin. The previous results on fault rocks and metamorphic minerals from the Vredefort Dome and the Witwatersrand Basin were discussed by Trieloff et al. (1994) and Reimold et al. (1995a,b). Spray et al. (1995) presented laser Argon probe dating results on pseudotachylites and confirmed that *most* pseudotachylites from the Vredefort Dome were formed at about 2018±14 Ma. Trieloff et al. (1994) showed that Witwatersrand pseudotachylites are related to this event as well.

The latest series of samples dated with the ^{40}Ar-^{39}Ar stepheating method comprises several fault rock samples from Joel Gold Mine in the Welkom gold field and the western collar of the Vredefort Dome, as well as a suite of metamorphic minerals from both the core and the collar of the Dome. A cataclasite from Joel Gold Mine yielded a complex age spectrum with ages fluctuating between 1900 and 2090 Ma. The integrated age for this sample is 2050±7 Ma, but post-2 Ga disturbances are significant. A mylonite specimen, also from Joel G.M., yielded an excellent plateau spectrum with about 80% of the released gas corresponding to an age plateau at 2038±5 Ma. The third sample from Joel G.M., an ultracataclasite, yielded ages for individual degassing steps between 1200 and 1750 Ma, resulting in an integrated age of 1478±23 Ma. Clearly late overprinting at (or more recent than) about 1200 Ma caused this disturbed spectrum.

Four whole rock samples, two pseudotachylite specimens and two samples of sericite-rich quartzite (courtesy Anglo American Prospecting Services), from a drillcore into Central Rand Group strata from the western collar of the Vredefort Dome, were also analysed. Pseudotachylite QE901p provided a disturbed age spectrum with a badly defined 'plateau' feature around 2050 Ma and a drop-off to younger ages (1100 Ma/550 Ma) for the low-temperature fractions. The other pseudotachylite sample (QE903p) yielded an equally disturbed age pattern, but here the partial plateau and integrated ages calculated are 2025±5 and 2023±6 Ma, respectively - indistinguishable from the U-Pb single zircon age for the Vredefort impact event obtained by Kamo et al. (1995). The two sericitic quartzite samples (QE902q, QE903q) were analysed to test how the Argon isotopic characteristics of muscovite in selected Vredefort rocks (muscovite is a mineral which is more Ar retentive than biotite, which was analysed already in earlier studies; the sericite component is the only important K-bearing phase in these samples) would compare against those of biotite and pseudotachylite. Both quartzite samples yielded excellent age plateaus corresponding to ages of 2029±7 and 2029±5 Ma. The age spectrum of QE903q shows minor post-2 Ga Argon loss in the low temperature part.

Other analysed mineral separates of rocks from the collar of the Dome include an amphibole separate from a BIF unit in the Hospital Hill Subgroup (I4), as well as two biotite separates from Government Reef metapelites (S6, S11). The complex I4 age spectrum consists of two partial 'plateau features', one, at high temperature steps, corresponding to a mean age of 3100±10 Ma, and the other, at intermediate temperature steps, including 2840 to 2485 Ma ages. At lowest temperatures further Ar loss at or below 1500 Ma ago is indicated. We attribute the >2840 Ma ages, which are unrealistic in the light of the probable age of the Hospital Hill Subgroup between 3074 and 2914 Ma ago (e.g., Robb and Meyer, 1995), to partial alteration of the amphibole to chlorite, as well as to possible recoil effects. Analysis of the S6 biotite resulted in a rather good age plateau, with a slight 'buckle' at the lower end, corresponding to an average age of 2034±4 Ma. The elevated ages of about 2150 Ma may be the result of excess Argon. For biotite S11 a relatively good age plateau corresponding to an average age of 2032±4 Ma was obtained. The results for this sample also indicate minor Argon loss at, or since, 1700 Ma ago.

Four mineral separates (biotite, amphibole, plagioclase, a pyroxene/amphibole mixed separate) from a charnockitic gneiss (VH13b) from the high-grade Steynskraal Metamorphic Zone (Stepto, 1990) were analysed. For the plagioclase sample, a typical saddle age spectrum was obtained with a saddle age of 1987±4 Ma and ages for low and high temperature steps in excess of 2600 Ma. The biotite separate yielded a well-defined plateau averaging at 2026±4 Ma, with a two-step hump of 2080/2164 Ma ages. This hump is interpreted as indicating that the plateau age likely represents a resetting age. At lowest temperature fractions, ages decrease dramatically to 1000 and 660 Ma. For the pyroxene/amphibole separate unreliable age information (some steps with 2200-2900 Ma ages) was obtained, whereas the amphibole seperate yielded a very flat plateau pattern, unfortunately marred by two age drops at the high and low ends. The plateau fractions yielded ages corresponding to a mean age of 2817±5 Ma; steps in the drop-offs correspond to 2.3-2.5 Ga ages.

CONCLUSIONS

Figure 1 summarizes all currently available thermochronological information on Witwatersrand and Vredefort rocks and minerals and compares it against other relevant chronological data. U-Pb single zircon and amphibole Argon data suggest that the basement to the Vredefort Dome is older than 3.1 Ga and underwent a first phase of metamorphism at 3.08 Ga ago. Other amphibole stepheating results could be interpreted as either the result

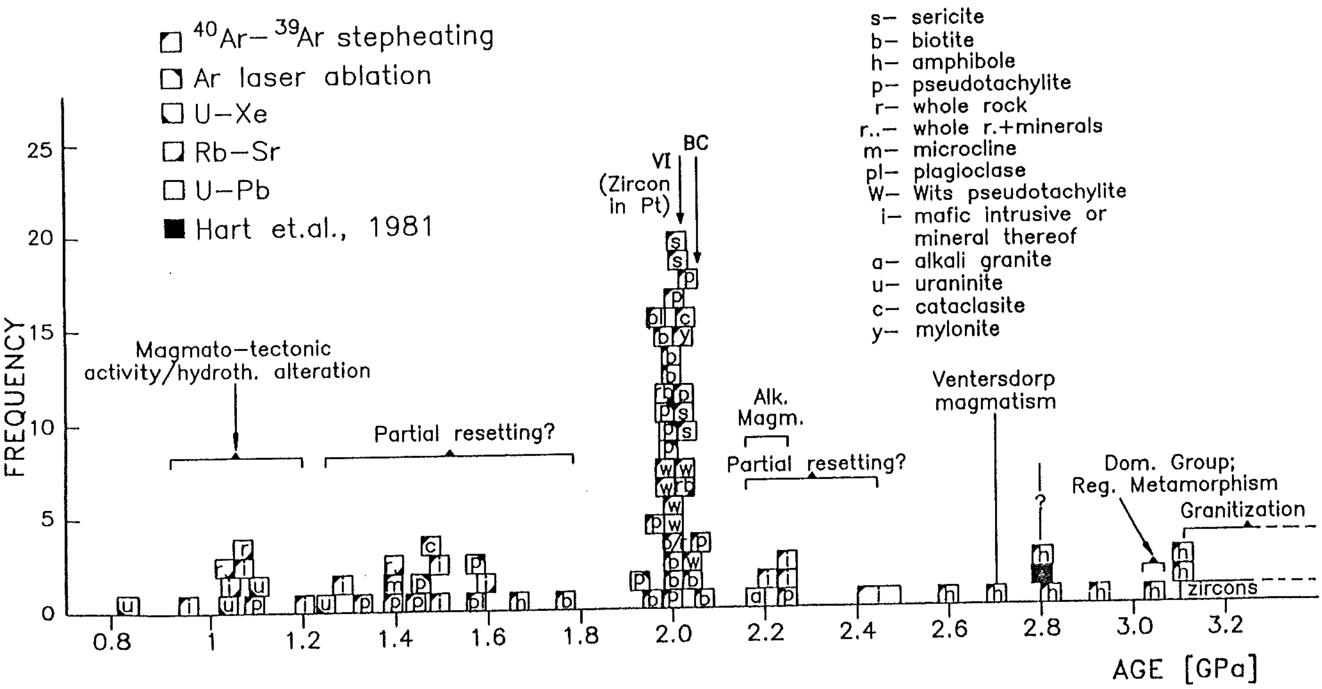

Figure 1. *Summary of thermochronological and related chronological information.*

of resetting (to 2.9-2.6 Ga ages) or, possibly, as being partly related to a 2.8 Ga event already postulated by Hart et al. (1981). No evidence for a significant 2.5 Ga event is found in this data base. However, at ca. 2.15-2.2 Ga ago alkali granitic intrusions occurred in the collar of the Vredefort Dome (Walraven and Elsenbroek, 1991), and this period is emphasized in the diagram of Figure 1 as well.

Only a small number of data concur with the 2.05-2.06 Ga Bushveld age, whereas the bulk of the thermochronological results fall into a narrow bracket between 2.02 and 2.03 Ga, coinciding with the Vredefort impact event dated by U-Pb analysis of single zircon grains at 2.025 Ga (Kamo et al., 1995). It is significant that hardly any data fall into the period between 1.8 and 2.0 Ga, thereby strictly defining a narrow time window for Vredefort-related metamorphism and/or hydrothermal activity (compare Trieloff et al., 1994). This latter result is clearly in contrast to the findings by Zhao et al. (this volume), who favour an extended periof of post Bushveld/Vredefort metamorphic/hydrothermal activity. A broad range of ages between 1.3 and 1.8 Ga has to be related to secondary overprint and partial resetting due to strong thermal activity around 1-1.25 Ga ago. Effects of this period of tectonic, magmatic, and hydrothermal activity have been observed by a number of workers (e.g., Pybus et al., 1994; Reimold et al., 1995c; Spray et al., 1995). It is believed that this event, effects of which cannot be separated by the U-Ar technique which only yields integrated ages, is responsible for the partial lowering of K-Ar ages towards 1830 Ma observed by Zhao et al. (this volume).

It can be concluded that the strong 2.025 Ga Vredefort event, which was shown by Trieloff et al. (1994) to be directly related to alteration and gold remobilization in the VCR fault zone, was too strong to allow detection of any earlier thermochronological events (such as the postulated 2.2 and 2.5 Ga events) by the ^{40}Ar-^{39}Ar stepheating technique. However, these efforts have resulted in secular separation of the Bushveld and Vredefort events and demonstrated the strong effect that the Vredefort event and the $\pm$ 1.1 Ga event had on the region of the Witwatersrand Basin.

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PETROGRAPHIC, CHEMICAL AND SPECTROSCOPIC STUDIES OF CARBONACEOUS MATTER AND THEIR BEARING ON THE METAMORPHIC EVOLUTION OF THE WITWATERSRAND BASIN

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INTRODUCTION

The presence of carbonaceous matter in the gold- and uranium-bearing conglomerates of the Witwatersrand Basin is one of the more intriguing and controversial aspects of the genesis of these deposits. Its occurence and evolution is particularly relevant to an understanding of the metamorphic evolution of the basin since the composition and structural characteristics of hydrocarbons are particularly sensitive to even low pressure/temperature changes in the post-depositional history of a sedimentary sequence.

Unfortunately, widely differing opinions exist in the literature as to the origin of the carbonaceous material in the Witwatersrand Basin and arguments still persist as to whether it represents the *in situ* fossilized remnants of algal/fungal organisms, or the solidified remains of a hydrocarbon bearing post-depositional fluid. Early stable isotope analyses of carbonaceous matter indicated depleted $\delta^{13}C$ values typical of sedimentary organic carbon, suggesting that the material had a biogenic origin. Support for the presence of primitive life-forms in the Witwatersrand Basin first came from observations by Manfred Schidlowski of circular and annular micro-structures of bacterial or algal morphology preserved, ironically not in carbonaceous matter, but in detrital pyrite grains. Schidlowski has, however, persistently rejected the *in situ* biogenic hypotheses and regarded the Witwatersrand carbonaceous matter as the solidified product of mobile hydrocarbons that had undergone radiolytic polymerization in the vicinity of detrital uraninite lags. He argued that *in situ* preservation of delicate fossil life-forms in compacted and metamorphosed sediments was unlikely and also pointed to the biological problems of having relatively advanced life-forms in existence in rocks as old as 2.7-2.9 Ga.

TERMINOLOGY

The terminology applied to carbonaceous matter is dependent to a large extent on its origin. Recent review has simplified usage to two terms: ***kerogen*** refers to a solid, polymer-like organic substance which has remained *in situ* since deposition, while ***bitumen*** is a macromolecular organic compound which was once mobile as a viscous fluid but has since solidified. Kerogen is normally the most abundant organic substance in a sedimentary sequence and represents the residue after a normal cycle of organic maturation. Bitumens are the products of such maturation which have been solidified, at sites sometimes well removed from their source, by processes such as thermal stress or radiation induced polymerization.

METAMORPHIC EVOLUTION AND ORGANIC MATURATION

No study of organic matter in a sedimentary setting can be undertaken without some appreciation of the thermal and burial history of the deposit. Several studies have reiterated the view that a regional P-T climax of $350\pm50°C$ and 1,5-3 kbars applied throughout much of the Witwatersrand Basin. Although the timing of metamorphism is difficult to constrain, review of isotopic age determinations in and around the basin suggest that metamorphism may have been episodic, occurring mainly in response to increments of progressive burial at ca. 2500 and 2300 Ma, and then to a final thermo-tectonic perturbation at ca. 2000 Ma related to intrusion of the Bushveld Complex and/or Vredefort catastrophism.

Organic maturation in the Witwatersrand Basin will have been controlled by the successive increments of post-depositional burial and thermal evolution of the host rocks. The basin was subjected to slow burial and it is likely that the "oil window" in the upper parts of the sequence was attained long after the termination of sedimentation. U-Pb isotopic analyses of carbonaceos matter from the conglomerates yielded an upper intercept concordia age of ca. 2330 Ma, which is similiar, statistically, to an apparent age of 2380 Ma for bituminous nodules from granitoids surrounding the basin. It is suggested that this may reflect an extended event of oil generation and migration in the basin, followed by solidification of bitumens and re-setting of the U-Pb isotope systems within the carbonaceous matter. This age span also approximately coincides with the onset of upper Transvaal Supergroup deposition (i.e the Pretoria Group), an event which may have stimulated oil production and migration in the Witwatersrand Basin.

PETROGRAPHIC CHARACTERISTICS

There appear to be at least four modes of occurrence of carbonaceous matter in an around the Witwatersrand Basin:

Carbonaceous seams

Carbon seams commonly occur at the base of a conglomeratic unit and may be underlain by shale, but they are also seen to anastomose through the conglomerate, bifurcate around pebbles and gradually disaggregate. Well-developed seams, particularly at the base of a conglomerate, may exhibit a fibrous aspect which has either been attributed to algal/fungal symbionts preserved as micro-fossils or as "fibre-vein" growths formed by precipitation of solid hydrocarbons in an extensional fracture environment. Carbon seams incorporate most of the primary mineral constituents of the conglomerate, including uraninite, pyrite, quartz, chromite, zircon, uraninite and gold. Uraninite is, however, undoubtedly the most common constituent associated with the seams, although its abundance varies from $\pm$ 20% of the volume of the seam to a virtually undetectable presence.

Carbonaceous nodules

The existence of discrete nodules of carbonaceous matter, often unrelated to seams, is difficult to reconcile with an *in situ* biogenic origin. The suggestion that nodules are the fragmented and abraded remnants of algal mats does not account for the globular outlines of the nodules and would also require a high degree of compaction prior to degradation. Nodules are very often distributed in the matrix of the same conglomeratic units that contain extensive developments of seam carbon, but may also occur well removed from seams, as well as in hangingwall and footwall quartzitic sequences.

Quartz vein- and fluid inclusion-hosted carbonaceous matter

A recent, detailed study of post-depositional fluids in the Witwatersrand Basin has revealed the presence of, *inter alia*, a hydrocarbon bearing fluid population comprising CO_2 and variable proportions of CH_4, C_2H_6, H_2 and N_2. Inclusions bearing these fluids are occasionally coated by a thin film of solid hydrocarbon, or actually contain bituminous hydrocarbon nodules up to 10 microns in diameter. In addition, small bituminous nodules are occasionally observed along the sites of annealed micro-fractures within quartz pebbles in the conglomerates and have also recently been discovered in association with pyrite and gold from quartz veins that cut the conglomerates and are associated with late stage faulting in the basin. Quartz vein hosted bitumen nodules either occur as discrete warty aggregates of hydrocarbon, or intimately intergrown with pyrite and occasionally gold. The presence of these bitumens clearly demonstrates that hydrocarbon circulation in the basin was not restricted to the conglomeratic horizons, but also involved aquo-carbonic solutions migrating along other conduits such as faults and shears.

Granitoid hosted carbonaceous nodules

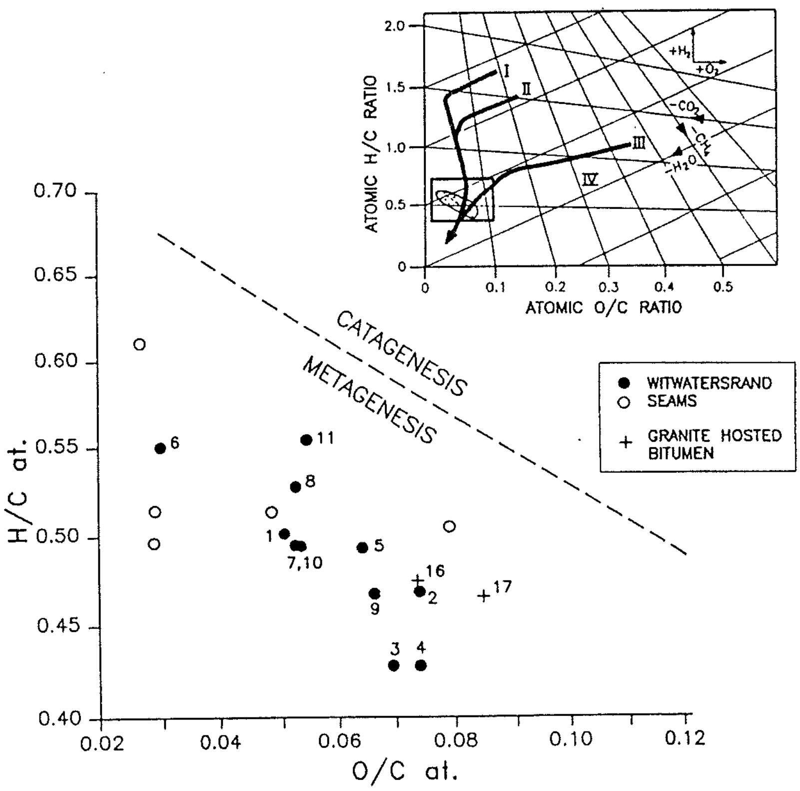
Several workers have now recorded the presence of bituminous nodules in granitoids surrounding the Witwatersrand Basin. These nodules or nodular stringers commonly occur in peraluminous granitoids that contain primary uranium-thorium bearing accessory minerals. The nodules are paragenetically late in terms of the sequence of alteration of the granitoids and exhibit progressive increments of replacement of either uraninite or uranothorite.

CHEMICAL CHARACTERISTICS

Carbonaceous matter in the Witwatersrand Basin generally has a bulk composition ($0,4 < H/C < 0,6$) consistent with that of a semi-anthracite (i.e between bituminous coal and true anthracite). Carbonaceous matter is more reduced, and has a restricted range and lower O/C ratios ($0,03 < O/C < 0,08$), than other uraniferous bitumens from, for example, epigenetic, unconformity-related deposits such as Cluff Lake, Cigar Lake, and Oklo. Pyrolysis-gas chromatographic-mass spectroscopy (Py-GC-MS) of carbonaceous matter from the Vaal Reef has identified numerous organic compounds, summarized as alkyl-substituted aromatic hydrocarbons, low molecular weight aliphatic hydrocarbons, and lesser aromatic sulphur and aliphatic oxygen compounds. The absence of graphite in the Witwatersrand carbonaceous matter has been confirmed in numerous petrographic and XRD studies.

A Van Krevelen-type plot of atomic H/C versus atomic O/C shows that Witwatersrand carbonaceous matter is highly mature with compositions coinciding with the field of metagenic maturation (Fig.1). This is consistent with other features such as reflectance (in oil) which ranges between 1,5-4%, relatively high T_{max} values (444-490 °C), and low hydrocarbon potential. Atomic ratios are fairly restricted in terms of the total range exhibited by natural kerogens (Fig. 1, inset) and generally have lower O/C, or higher H/C, ratios than is to be expected for catagenic Type I (algal-derived) kerogens. The variability exhibited in terms of H/C ratios appears to be the result of devolatilization, probably involving removal of methane (Fig. 1, inset) with the consequent loss of four atoms for each carbon atom lost.

Figure 1:



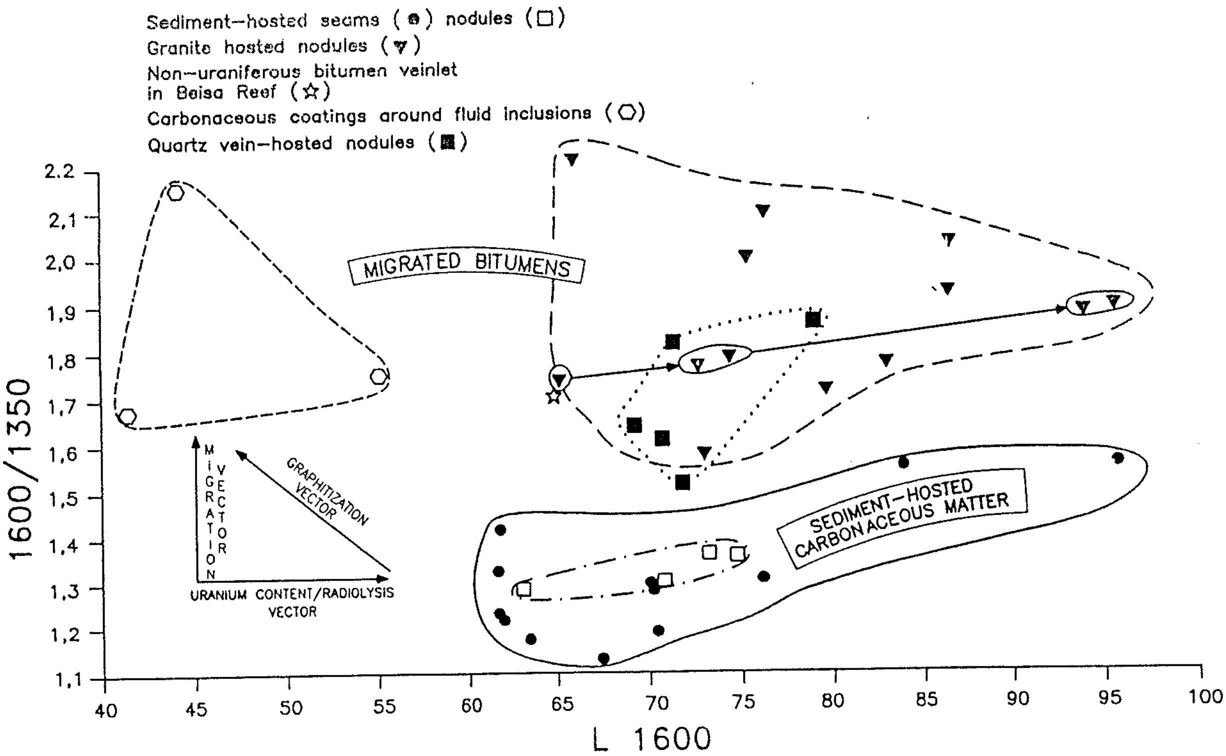
This process may be at least partly due to radiation, as is evidenced by the positive correlation between H/C and uranium content. Variation in the O/C ratios reflect a mild oxidation trend caused either by radiation, or interaction of carbonaceous matter with oxygenated fluids.

SPECTRAL CHARACTERISTICS

Raman spectral characteristics are summarized in a plot of peak intensity ratio 1600/1350 versus half-height peak width L1600 in Figure 2. It is clear here that migrated bitumen nodules (i.e. granitoid-, quartz vein- amd fluid inclusion-hosted) show higher peak intensity ratios than both seams and nodules from the Witwatersrand reefs, but that half height widths are similiar with the exception of the carbonaceous linings in fluid inclusions.The higher peak intensity ratios in the migrated bitumens could be related to enhanced thermal maturation or a graphitization trend as this is normally indicated by increasing I1600/I1350 ratios (due to the elimination of the 1350 cm^{-1} peak) accompanied by *decreasing* L1600 . The peak intensity shifts might also reflect a migration factor related to the tendency for lighter hydrocarbon compositions to be more labile and migrate further in the rock medium (Fig. 2).

Interesting structural and compositional changes are also evident in FTIR spectra of seam related organic material as a function of proximity to individual uraninite particles within the seams. Spectra obtained within the high reflectance pleochroic halos which often surround uraninite grains in seams are characterized by a loss in both aliphatic and aromatic CH and an increase in the concentration of C=C and C=O functions. The diameter of the halo surrounding the uraninite grain approximately coincides with the travel distance of an α particle emitted from the edge of the uraninite grain and appears to provide evidence for the fact that severe compositional and structural changes result from α-radiation.

Figure 2:



DISCUSSION

Organic maturation

As in modern environments, the production of liquid and gaseous hydrocarbons in the Witwatersrand Basin must have been related to progressive sediment compaction and kerogen maturation, with maxima occurring during and subsequent to the "oil-window", which is typically at around 150°C and 1-1.5 kbars/3-6 km. The duration of hydrocarbon production and the period of time subsequent to sediment deposition, when the oil window is attained are highly variable and depend largely on subsidence rates. Oil production can be ongoing for anything between 5 to 100 Ma, while the elapsed time between sedimentation and petroleum generation may vary from a few million years to more than 300 Ma.

In the Witwatersrand Basin any *in situ* prokaryotic micro-organisms present would have undergone normal biodegradation and diagenesis to form Type I kerogen. Colonies of microbiota might have developed on the unconformity surfaces that represent hiatuses in sedimentation. Rapid sediment aggradation at these sites would have preserved and fossilized this material, although it seems doubtful that it played a significant role in the concentration of heavy minerals within the conglomerates. The basin was deposited on what had, by 2700 Ma, become a relatively stable proto-continental core and was subjected to slow and protracted subsidence over the following 700 Ma. The duration of oil and gas generation would probably, therefore, have been long-lived (in the order of 10^1-10^2 Ma), while the elapsed time between the end of sedimentation and the onset of major hydrocarbon production/bitumen formation appears to have been about $3\text{-}4 \times 10^2$ Ma. Liquid and gaseous hydrocarbons produced during this period might have migrated some distance from the source rock, had it not been for the significant concentrations of detrital uraninite that characterized the Witwatersrand conglomerates, often in sites not too distant from, or even overlapping, those where kerogens themselves had formed. Bitumen fixation was achieved by radiolytic polymerization, which also had a pronounced affect, through time, on the alteration and maturation of the carbonaceous matter.

Evolution of hydrocarbons and paragenetic sequence

Post-depositional ore modification in the Witwatersrand Basin took place for at least 700 Ma after termination of sedimentation at 2700 Ma and probably occurred during three main events at around 2500 Ma, 2300 Ma and 2000 Ma. Pb-Pb isotopic data from authigenic pyrite suggest that a major event of sulphide remobilization took place at around 2500 Ma and this apparently preceded bitumen formation according to both petrographic evidence and U-Pb dating of carbonaceous matter. Bitumen appears, therefore, to have formed subsequent to early sulphide remobilization at 2500 Ma, but prior to the final authigenic event at ca. 2000 Ma. The latter event is believed to be associated with the attainment of peak metamorphic conditions in the basin and also the remobilization of late sulphides and gold. The presence of abundant gold associated with, but *post-dating* carbonaceous matter, indicates that a substantial amount of the metal was precipitated late in the paragenetic sequence. The precipitation of gold around carbonaceous matter would appear, therefore, to have largely been the result of redox control.

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LOW-PRESSURE GRANULITE FACIES METAMORPHISM IN THE CORE OF THE VREDEFORT DOME: GETTING TO THE ROOT OF THE PROBLEM

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INTRODUCTION

The many exceptional geological features associated with the formation of the Vredefort Dome at 2025 ± 4 Ma (Kamo *et al.*, 1995) attest to high intensity processes (the Vredefort catastrophe). To date these processes have largely been ignored in metamorphic modelling of the Witwatersrand Basin and the gold fields within. However, there is a growing recognition that metamorphism in the rocks of the Vredefort Dome may hold the key to an understanding of processes that potentially impacted on the entire basin (e.g. Phillips and Law, 1994; Gibson and Wallmach, 1995). This study aims to examine metamorphism in the high-grade core of the dome with a view to deriving information on the evolution of the Archaean basement to the Witwatersrand Basin during Vredefort times. In the core, the timing of the catastrophe and dome formation is marked by the development of pseudotachylite veins in granulite-grade assemblages. Pseudotachylite is, in turn, overprinted by the subsequent growth of new high-grade assemblages. These features have been recognised in previous studies (Schreyer and Abraham, 1978; Schreyer, 1983) and have been used to infer that the basement beneath the dome was at elevated temperature prior to the dome-forming event. This appears irrefutable and this study builds on this polymetamorphic model.

METAMORPHIC EVOLUTION OF THE VREDEFORT CORE

A mid-crustal anatectic event

The earliest discernible metamorphic textures in the metasedimentary granulites exposed in the core record an anatectic event that occurred close to the peak of metamorphism. Some exposures are extensively migmatised and large garnet and cordierite crystals have been produced in conjunction with stromatic leucosomes of quartz, plagioclase and K-feldspar. The growth of new, coarse-grained, largely anhydrous, phases in association with leucosome development has been described from many anatectic terranes (e.g. Powell and Downes, 1990; Stevens and Van Reenen, 1992; Srogi *et al.*, 1993). In metapelites, such evidence indicates incongruent melting involving biotite breakdown producing an H_2O-undersaturated granitic melt and a mafitised, residual, crystalline assemblage. Reactions of this type are generally multi-variant and migmatised exposures represent rocks that equilibrated at *P-T* conditions within the melting reaction field (Fig. 1).

Rocks from other exposures are not migmatised. Rather, they have the mineralogical and chemical composition of melt-depleted restites. In such samples the temperature of peak metamorphism must, thus, have exceeded the maximum for biotite - H_2O undersaturated melt coexistence. Experimental calibration of biotite melting in appropriate bulk compositions indicates that this temperature lies between 880 and 910°C for a wide range of crustal pressures (Stevens *et al.*, 1994). In the case of these rocks, the melt and the H_2O component dissolved within it have left the high-grade environment and migrated to higher crustal levels. Conventional geobarometry applied to the peak assemblages indicates a pressure of approximately O.5 GPa (5 kbar) for the anatectic event (Fig. 1).

The diagnostic high-temperature, low-pressure assemblage of spinel + quartz (Waters, 1991) occurs as inclusions in some anatectic generation garnets. This possibly provides a clue to the pre-peak metamorphic conditions and suggests a period of significant pressure increase as the rocks evolved towards the metamorphic peak (Fig. 1).

Cooling from the metamorphic peak

P-T evolution during this period is marked by the development of a retrograde reaction texture in the migmatised rocks. Cordierite, produced by the biotite melting reactions, has been partially replaced by biotite and sillimanite through a crystallisation-hydration reaction (Melt + Crd = Bt + Sil + Qtz) driven by rising aH_2O in the melt during the cooling and partial crystallisation of the leucosomes. The involvement of an externally derived fluid, causing a general rise in aH_2O, is unlikely as cordierite in restistic rocks that lost all their melt is often in contact with K-feldspar and quartz, yet has not reacted to biotite. These textures suggest a period of cooling (Fig. 1), although the exact *P-T* range represented by the reaction is difficult to define, due to a lack of data on the thermodynamic properties of granitoid melt.

Metamorphism after the Vredefort catastrophe

The well-documented Vredefort shock metamorphic features are also manifested in the rocks of the present study, the most typical and obvious elements being pseudotachylite veinlets. These veinlets are, in turn, overprinted by metamorphic textures developed after the formation of the dome. Pseudotachylite formation clearly pre-dates the formation of second-generation cordierite and orthopyroxene coronas around garnet, as well as the replacement of the sillimanite + cordierite assemblage that resulted from the crystallisation-hydration reaction by a spinel + orthopyroxene assemblage. In some cases garnet crystals that have been partially replaced by the cordierite + orthopyroxene coronas are compositionally zoned towards more Fe-rich rims and a reasonable case can be made for an approach to equilibrium. In these examples the same geobarometry techniques as applied to the peak metamorphic assemblage yield pressures of approximately O.25 GPa, i.e. some 0.25 GPa lower than that experienced during the peak metamorphic episode (Fig.1). The two metamorphic textures overprinting the shock features are remarkably fine-grained ($<15\mu m$). This lack of textural equilibration must represent extremely rapid cooling after the decompression that these textures document.

IMPLICATIONS FOR THE EVOLUTION OF THE KAAPVAAL CRATON

Two features of the data are important:

(1) the Vredefort catastrophe, with its attendant shock metamorphism and deformation, post-dates the partial retrogression of the granulite-grade assemblage. Thus, it is unlikely that the granulite-grade event is in any way related to the Vredefort catastrophe. The granulite-grade metamorphism represents a "normal" mid-crustal anatectic episode. The process that produced the shock metamorphism halted this natural metamorphic evolution and initiated a period of rapid decompression and cooling, thus providing a mechanism for exhuming the core granulites to the presently exposed level; and

(2) crustal temperatures high enough for complete biotite breakdown by anatectic processes are not possible without a substantial mantle heat contribution (Clemens, 1990). Thus, the peak temperature of >900°C at 0.5 GPa is only compatible with granulite formation in an environment dominated by the intraplating of mantle-derived magmas. The fact that the granulite terrane was still at elevated temperature at the time of the 2025 Ma Vredefort catastrophe appears to be compatible with the intraplating of Bushveld-related magmas as the heat source (Gibson and Stevens, 1995). The resultant metamorphism would not have been restricted to the rocks now exposed at Vredefort. This suggests the presence of an unrecognised granulite terrane underlying a large portion of the Kaapvaal Craton.

IMPLICATIONS FOR METAMORPHISM AND FLUID-FLOW IN THE WITWATERSRAND SUPERGROUP

The data presented here confirm the idea proposed by Gibson and Wallmach (1995) and Gibson and Stevens (1995) that heat from below (as opposed to heat from the overlying Bushveld Complex) is likely to be the major driving force behind metamorphism of the Witwatersrand Supergroup in Bushveld times. The deeper portions of the basin could have been exposed to mid-amphibole facies conditions during the mid-crustal granulite-facies event, resulting in prograde dehydration reactions, fluid production, and potential gold redistribution.

Another aspect to consider is the uplift of the hot Vredefort core into proximity with the relatively cool, hydrous metapelite-dominated lower levels of the Witwatersrand succession at 2025 Ma. This also has the potential to drive fluid producing reactions in the Witwatersrand rocks in the immediate vicinity of the Vredefort Dome, although the volume of fluid produced by this mechanism may be secondary to that derived directly from the granulite core. Quenching textures in leucosomes in the metasediments and in the hosting granitoid basement suggest that residual peak-metamorphic melts quench-crystallised during, or shortly after the decompression (Fig. 1). Prior to decompression the melts would have contained >4.5 wt% H_2O (Nekvasil and Burnham, 1987). Thus, if the granulite-grade basement contained 10% partial melt at 0.5 GPa and 700°C, then the entire core would have lost approximately 0.5 wt% H_2O upon decompression. This pulse of fluid would have mobilised out of the system by moving down thermal gradients. The bedding-parallel thrust system that already existed in the Witwatersrand sediments (Roering and Smit, 1987) would have provided a convenient plumbing system for fluid evacuation, as would have the brittle-ductile structures developed during the Vredefort catastrophe.

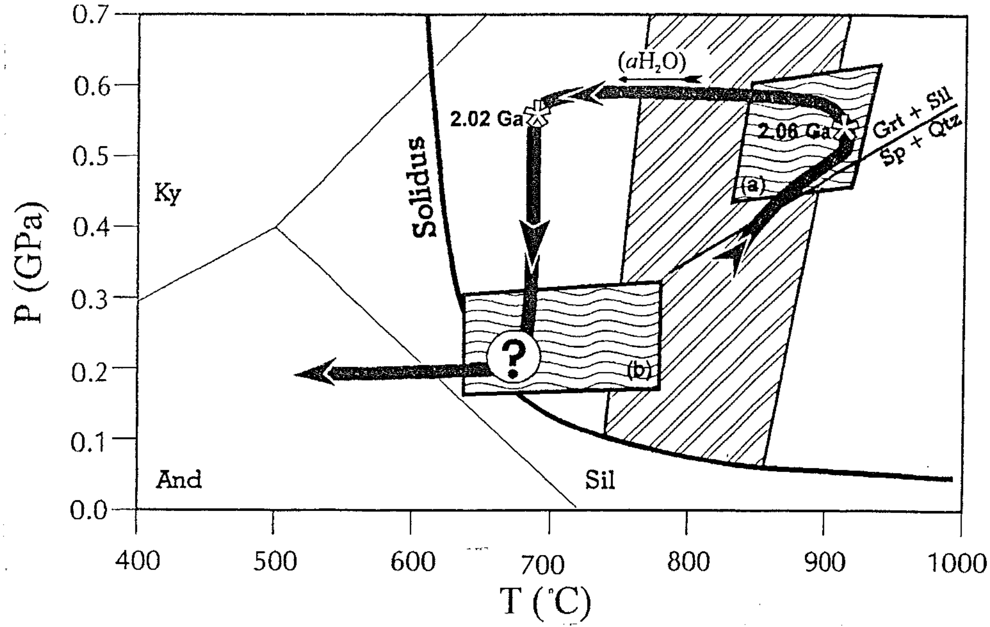

Figure 1: The proposed P-T loop for the Vredefort granulites. The form of the loop and the magnitude of the peak conditions constrain the mechanism of granulite formation to intraplating of mantle-derived magmas. Boxes (a) and (b) represent the P-T conditions calculated for the granulite and post-pseudotachylite assemblages, respectively. The large diagonally hatched field is the experimentally determined field of biotite-melt co-existence from the data of Stevens et al. (1994). Uplift and cooling after the Vredefort catastrophe at 2.02 Ga must have been extremely rapid, but the exact temperature at the time of equilibration of the assemblages represented by box (b) is difficult to constrain due to the minute equilibration domain size during this event.

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EVIDENCE OF DIFFERENT TYPES OF FLUID ACTIVITY IN WITWATERSRAND ROCKS AS INFERRED FROM MINERALOGICAL OBSERVATIONS

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INTRODUCTION

Several thousand polished sections were systematically scanned mainly to define the deportment of the minerals to be recovered. This work led to interesting observations regarding the influence of fluid activity during Witwatersrand time.

CHEMICAL DOMAINS

Three major geochemical domains can be recognised in the stratigraphic interval encompassing the West Rand Group to the Venterspost Conglomerate Formation.

The first domain is the West Rand Group, characterised by contents of Ca, Mg, and CO_2 that are high in comparison to the Central Rand Group.

The second chemical domain is the Central Rand Group that has remarkably and consistently low contents of Ca, Mg, and CO_2 and generally depressed levels of Al_2O_3. Mineralogical and textural evidence will be presented to show that, while the depressed level of Al_2O_3 relates to the primary sedimentary environment, the anomalously low levels of CaO and MgO are overprinted features.

The third chemical domain is the Ventersdorp conglomerate formation that again has levels of Ca, Mg and CO_2 that are high compared with the Central Rand Group.

FLUID SYSTEM TYPE 1

Figure 1 shows an example of a set of fractures acting as the locus for the formation of chloritoid. The metamorphism has highlighted the chemical zonation emanating from these fractures by creating the new mineral chloritoid. Chloritoid becomes the stable alumina-rich mineral under the conditions that governed the metamorphism in the Witwatersrand rocks when the chemical environment is depleted in Ca and Mg compared with Fe. The importance of the whole-rock chemistry for the formation of chloritoid is illustrated by Figure 2. In this diagram the Fe and Mg contents are plotted for chloritoid-bearing and chloritoid-free Witwatersrand samples. The chloritoid-bearing samples have lower levels of Fe and Mg and a lower Mg/Fe ratio than the chloritoid-free samples.

Slightly younger pyrite is now filling the set of fractures that acted as loci for the distribution of chloritoid. This close spatial association between pyrite and chloritoid links these minerals to the same source.

The study of several occurrences similar to the one just discussed has shown upward migration of fluids along near-vertical fractures. The timing of this metasomatic event will be discussed later, but the liquids are postulated to be acidic, anoxic fluids of diagenetic origin, leaching Ca and Mg from the basin-floor sediments and stabilising sulphide minerals.

FLUID SYSTEM TYPE 2

The mineralogical expression of the activity of this system is the replacement of rutile by sphene and of pyrite by pyrrhotite, showing the introduction of Ca and Fe. The alteration front for System 2 was not observed to follow channels, but is clearly related to the unconformable contact between the Ventersdorp Supergroup and the Central Rand Group. The rutile to sphene change is independent of the host stratigraphy but, where studied, always occurred less than 10m below the base of the lava. The change from pyrite to pyrrhotite was observed to follow a similar pattern but here the distance below the lava was generally 10 to 20m.

TIMING OF THE EVENTS

Normally, the downward introduction of Ca and Fe is overprinted on strata that have previously been depleted in Ca and Mg. In a very few instances, however, the place of the ubiquitous sphene in the Ventersdorp lava is taken by rutile, suggesting that in these cases fluids of System Type 1 were active after the extrusion of the Ventersdorp lava. The current interpretation of the timing of events is that fluid systems of Type 1 were associated with the process of diagenesis and active on a cyclic basis over the entire period of deposition of the Central Rand Group.

Textural evidence shows that pyrite precipitation took place during several successive periods. This periodic crystallisation is displayed in Figure 3, which shows a pebble consisting of younger pyrite cementing older pebbles of pyrite. From the relationship just described, it can be deduced that a period of erosion was followed by a period of pyrite precipitation that, in turn, was followed by at least one erosive event before the final lithification. Similar pebbles were observed which also had a matrix of pyrite but with enclosed detrital grains consisting of zircon and chromite unaccompanied by "black sand" type heavy minerals. This particular heavy mineral assemblage is typical of Witwatersrand conglomerates. It is, therefore, concluded that the pyrite of the matrix was precipitated within a Witwatersrand age conglomerate. It is further concluded that the heavy minerals, set in their pyrite matrix, were subsequently eroded to provide a pebble for deposition in a younger Witwatersrand conglomerate. The above cited evidence, with the well-known overgrowth of rounded pyrite in Witwatersrand reefs by younger pyrite, shows that pyrite precipitation and conglomerate deposition were closely linked processes in Witwatersrand time.

CONCLUSION

Two types of fluid movement were inferred from microscope studies on Witwatersrand rocks. The upwardly mobile Type 1 fluid systems, which helped the dissolution of Ca and Mg, and also the precipitation of pyrite, were active during the final stages of conglomerate formation. Type 2 fluid systems were active only during the initial stage of the extrusion of the Klipriviersberg Group.

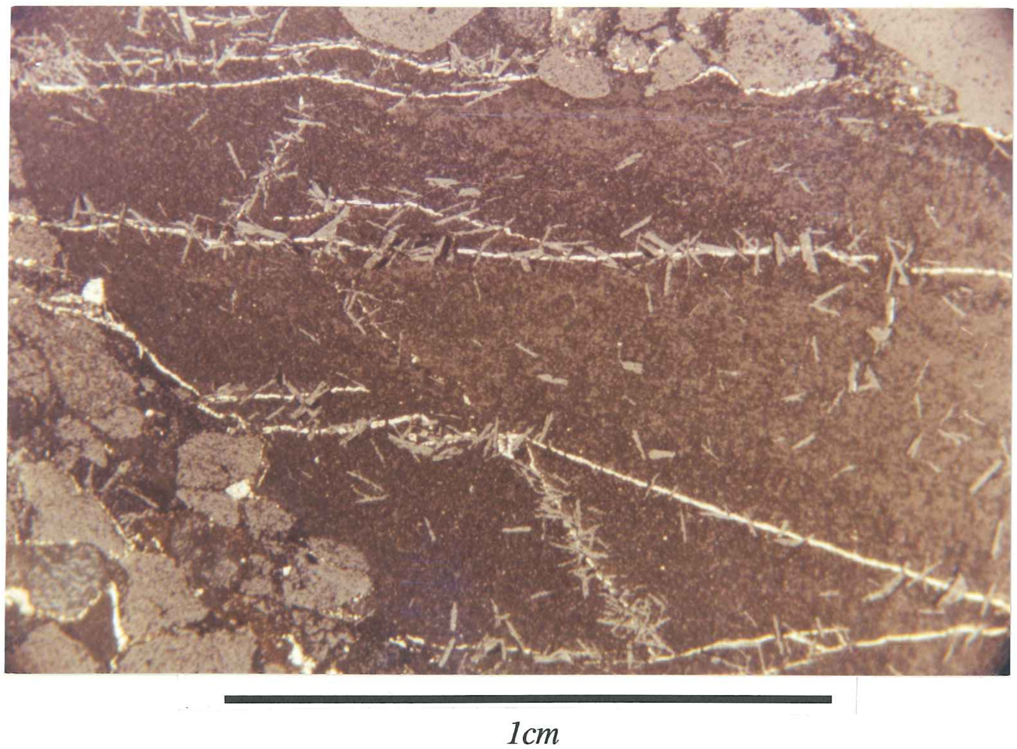

Figure 1: Laths of chloritoid are spatially associated with a set of subparallel fractures. These fractures, which are now filled with pyrite, were oriented approximately at right angles to bedding.

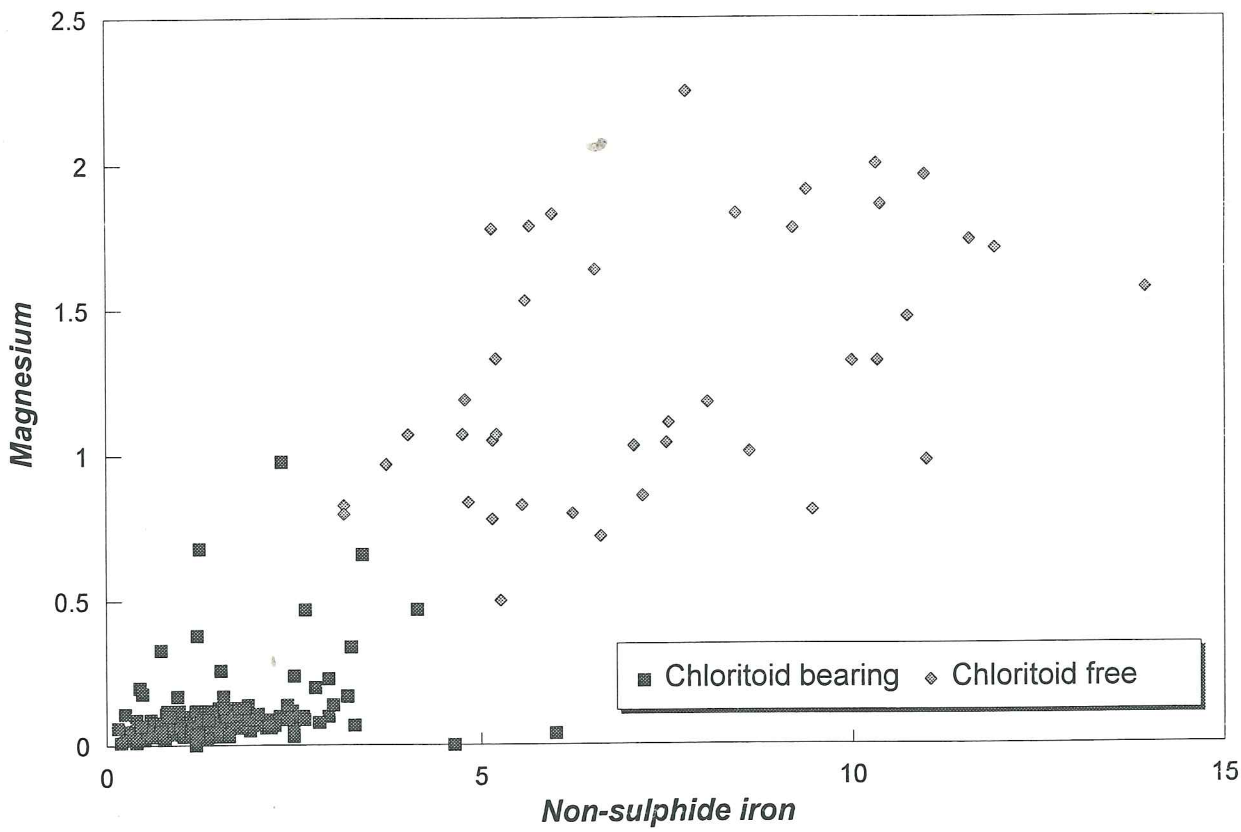

Figure 2: Mg plotted against Fe for chloritoid-bearing and chloritoid-free samples.

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Figure 3: *Photomicrograph (reflected light) showing a pebble of pyrite composed of older pyrite pebbles in a matrix of younger pyrite.*

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THE TIMING OF METAMORPHISM, HYDROTHERMAL ALTERATION AND MINERALIZATION IN THE VENTERSDORP CONTACT REEF, WITWATERSRAND BASIN

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INTRODUCTION

Samples in this study came from the Ventersdorp Contact Reef (VCR)at the Western Deep Levels South Mine (WDLSM). The purpose of this study was to date the metamorphism/ hydrothermal alteration and associated authigenic gold mineralization in this reef using K-Ar dating and related mineralogical studies.

GEOLOGICAL BACKGROUND

The VCR package sampled for this study comprises basaltic lava of the Klipriviersberg Group in the hanging-wall, Elsburg quartzite of the Turffontein Subgroup and Booysens shale in the footwall, and the conglomerate of the Venterspost Group. The Central Rand Group was deposited between 2 840-2 714 Ma , while the overlying Klipriviersberg Group lavas have been constrained, by zircon dating, at 2 714±8 Ma. The VCR is associated with zones of intense alteration in both hanging-wall and footwall; seven distinct alteration zones have been recognized at WDLSM on the basis of alteration mineral assemblages and coloration. These are believed to be a useful indicator for tracing auriferous reefs during mining. Alteration involves albitization, chloritization, carbonation, sulphidization and muscovitization; mica is the most abundant phase produced during the alteration and the most suitable material for K-Ar dating. Four types of mica were recognized through optical microscope and electron microprobe study and substantiated on the basis of paragenetic sequences and grain sizes. Coarse-grained (>200 μm) detrital muscovite is often deformed, banded and replaced by chlorite. The medium-grained (100-200 μm) muscovite has a tabular texture and overgrows quartz grains, or occurs as interstitial filling with albite and chlorite. The fine-grained (>10 μm) muscovite is also tabular and replaces feldspar detritus. Extremely fine-grained mica (<10 μm) comprises the matrix of the sediments and also occurs as an alteration product of lava. Electron microscopic examination has revealed that most of the mica has an authigenic morphology. Ore sulphides are often replaced by authigenic phyllosilicates, an event that appears to be associated with remobilization of gold. Because of the episodic nature of the alteration, radiometric dating on accurately separated micaceous material is considered to be potentially useful in obtaining further insights into the duration of metamorphism, hydrothermal alteration and gold mineralization in the VCR.

SAMPLE DESCRIPTION

Samples were chosen from different lithologies in the VCR package and were also selected to be representative of the different alteration zones, especially in the footwall quartzite. All of the samples can be be considered to have been metamorphosed in the greenshist facies with chlorite-muscovite-albite-carbonate-(epidote-) sulphide assemblages present. Chlorite is abundant in the samples of lavas, and dark grey quartzite, while muscovite is abundant in grey quartzite zones and shale samples. Epidote is preferentially present in the samples of lavas, while carbonate phases are present in most samples.

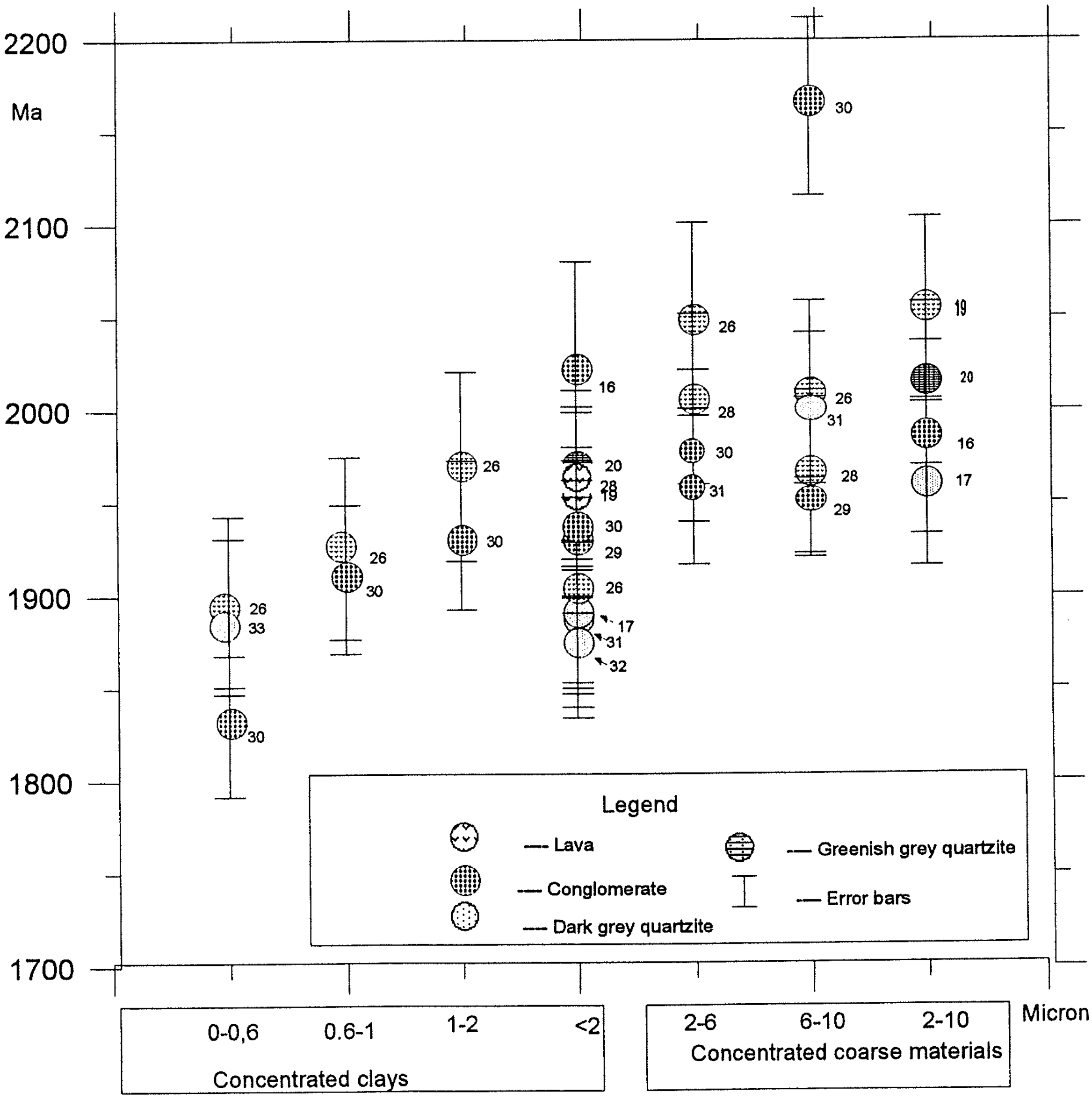

Figure 1: Plot of K-Ar age versus size fraction for samples from the VCR at WDLSM.

TECHNIQUES

The SEM was utilized for the identification of mineral components and assessment of rock texture, pore and pore fillings, grain morphologies, paragenetic sequences and mineral chemistry. Powder preparation was facilitated by heating-freezing techniques and gentle crushing. Natural sedimentation and centrifugal techniques were used to separate different grain size fractions. XRD was extensively used for the determination of mineral components, polytypism, crystalinity, and relative abundances. TEM was specifically used for examining separated single mineral components and lattice dimensions. Pure separates were prepared for K-Ar dating and other purposes. Argon was extracted from an argon line through two stages of purification and analyzed in a mass spectrometer. Potassium was analyzed using a flamephotometer with an accuracy of 1%.

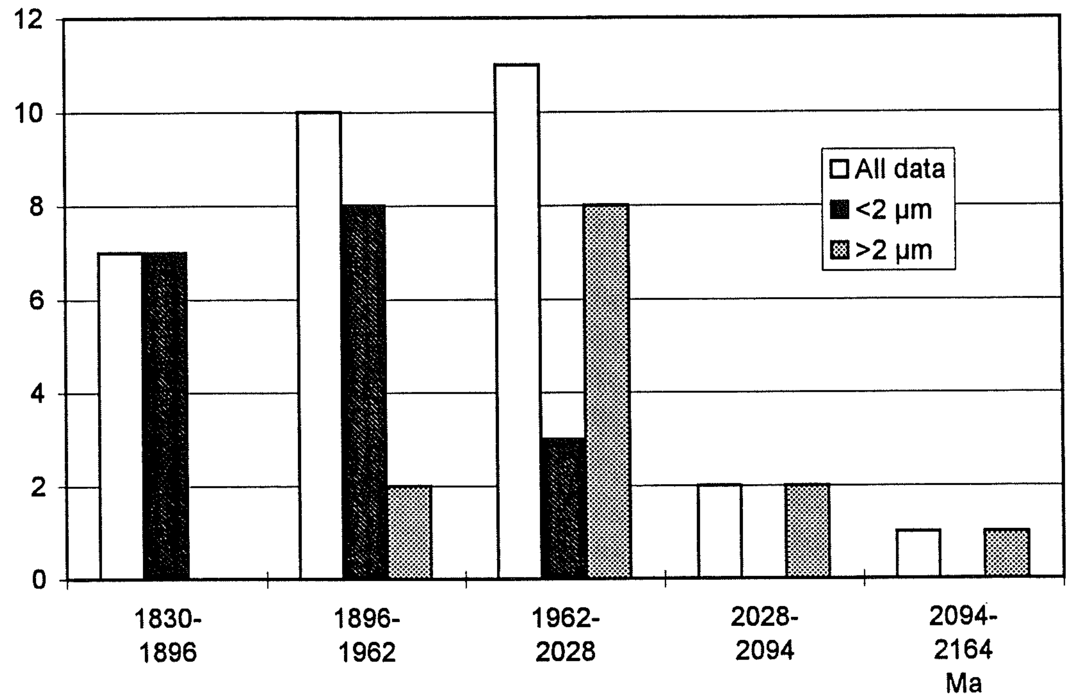

Figure 2: Histogram summarizing the distribution of K-Ar dates from micaceous fractions separated from the VCR at WDLSM

RESULTS AND DISCUSSION

A total of 31 K-Ar isotopic age determinations of various 2M1 mica size fractions define a range between 1830±38 Ma and 2164±48 Ma (Figure 1). Only one date is older than 2054 Ma (2164±48 Ma) and only a single age is as low as 1830±38 Ma; the majority of the data fall between 2050 Ma and 1850 Ma and are believed to reflect the final, and possibly most important stage of alteration/metamorphism in the Witwatersrand Basin. This event, at least in the VCR, played a major role in the recrystallization of reef components, neo-formation of silicates, carbonates and sulfides, and also gold remobilization.

With respect to the >2 μm size fractions, 92% of the K-Ar dates have a range of 1959±42 Ma - 2054±50 Ma. By contrast, the <2 μm size fraction is characterized by distinctly younger ages, mainly in the range 1875±41 Ma to 1940±40 Ma. As evident in Figure 1, there appears to be a positive correlation between grain size and age. When plotted on a histogram (Figure 2) the age data are skewed with a weighting towards the younger ages in the range. The highest proportion of ages falls in the interval 1962-2028 Ma.

The K -Ar ages recorded in this study clearly reflect a major isotope resetting event related to either, or both, the emplacement of the Bushveld Complex at 2054 Ma and the Vredefort catastrophism at 2025 Ma. However, the ages persist for some 200 Ma after these events with a distinctive peak at 1900-2000 Ma. This suggests that the ages more correctly reflect an extended period of retrograde metamorphism and hydrothermal alteration during post-Bushveld/Vredefort times. This suggests that the smaller size fractions are either paragenetically later than coarser fractions, or were not able to retain Ar as efficiently until lower closure temperatures. In either case, the extended range of K -Ar ages point to a a long-lived period of retrograde metamorphism and hydrothermal fluid circulation subsequent to the Bushveld and Vredefort events, and that these effects were particularly prevalent in the ubiquitously altered Ventersdorp Contact Reef. Earlier events of metamorphism/hydrothermal alteration do not appear to be recorded in the K -Ar isotopic systems in the VCR and there is little evidence for events at 2700, 2500 and 2300 Ma, as is sometimes the case elsewhere in the Witwatersrand Basin. The VCR in particular records the effects of extensive fluid circulation at 2000-1900 Ma, a feature which is consistent with the dominantly authigenic nature of the ore components.

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