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TECTONO-METAMORPHIC SETTING AND PARAGENETIC SEQUENCE OF Au-U MINERALISATION IN THE ARCHAEAN WITWATERSRAND BASIN, SOUTH AFRICA

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UNIVERSITY OF THE WITWATERSRAND

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ABSTRACT

The Witwatersrand Basin is a structural remnant of a once much larger depositional basin that was deposited between 3074 Ma and 2714 Ma in the south-central portion of the Kaapvaal Craton. The post-depositional history of the Basin is complex and long-lived. Compressional tectonics during subsidence and basin filling was followed by craton-wide extension and rift-basin formation which resulted in the covering of the Witwatersand succession by the Ventersdorp Supergroup. A prolonged period of subsidence ensued between ca. 2.5 - 2.2 Ga which resulted in the deposition of the Transvaal Sequence which also covered the Witwatersrand strata. The Craton was subjected to a major thermal perturbation at 2050 Ma, which resulted in the emplacement of the Bushveld and related igneous complexes. The prograde P-T path applicable to the Basin at this stage was catastrophically disrupted by an impacting bolide which resulted in geologically instantaneous exhumation of portions of the Basin at 2025 Ma.

A record of the above events is preserved in the metamorphic evolution of the Witwatersrand Basin as well as in the paragenetic sequence of mineralization recognized within the conglomeratic ore bodies which host the economic concentrations of Au and U. Many conglomerate "reefs" nevertheless preserve detrital accumulations of heavy minerals, such as pyrite, zircon, chromite, uraninite and gold, which were concentrated by placer processes in dominantly fluviodeltaic depositional systems. At least three stages of post-depositional mineralization are recognized. These are invariably associated with the primary, allogenic concentrations of heavy minerals. Pyrite and authigenic rutile were formed at ca. 2.5 Ga in a fluid circulation event that appears to be related to onset of Transvaal Sequence deposition. Circulation of hydrocarbon-bearing fluids and precipitation of bitumens by radiolytic polymerization followed at ca. 2.3 Ga. This event, possibly associated with deposition of the upper portion of the Transvaal Sequence, appears to have also been associated with mobilization of metals. Widespread fluid circulation and resetting of thermochronometers subsequently took place at 2050 - 2025 Ma during the Bushveld and Vredefort events, which resulted in precipitation of a number of sulphide phases and gold. Inference and logic support the contention that the bulk of fluid and metal involved in the formation of the post-depositional mineral paragenesis was derived from within the Basin, although the possibility does still exist, particularly with respect to the later events, that these may have been derived from outside the Basin.

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INTRODUCTION

The nature of the geological processes responsible for the enormous concentrations of gold and uranium in the Archaean Witwatersrand Basin of South Africa has been much debated ever since the turn of the century (Pretorius 1991). In a recent popular article in the weekly journal *New Scientist*, Davidson (1995) perpetuates the notion that Witwatersrand ore genesis has been the subject of diametrically opposed epigenetic and syngenetic viewpoints. Whilst it is of undoubted practical significance for mining and exploration to establish whether the Witwatersrand ores were concentrated either by the mechanics of fluvial placer formation or by precipitation from hydrothermal solutions, there is little doubt that the perceived intransigency of the debate is both overstated and depreciatory of much of the early empirical work that was carried out in the Basin. Robert Burns Young, for example, was the first to record the polyphase nature of mineralization in the Witwatersrand Basin, stating that "The conditions of deposition.....of the principal gold-bearing beds....were also the cause of the exceptional concentration of gold within them....At the same time the banket was the seat of complicated mineral changes....and these included...solution and reprecipitation of gold....solution and reprecipitation of pyrite....formation of chloritoid, sericite and chlorite....addition of metallic sulphides..." (Young 1917, p 116). Much later, Liebenberg (1955) and Ramdohr (1958), as well as many other ore petrographers, provided detailed documentation of ore textures and recognised that certain of the heavy minerals in the conglomerates were texturally consistent with an allogenic source, whereas others were undoubtedly authigenic and had been precipitated during the post-depositional history of the sedimentary rocks. Feather and Koen (1975) were the first to propose a formal paragenetic sequence in which the approximately 70 ore minerals were classified into three stages; these are the original accumulation of detrital minerals, followed by post-depositional pyrite mineralization and then remobilization of gold and other sulphide phases. Observations over several decades have, therefore, been consistent with the notion that mineralization is the product of a number of events that have superimposed authigenic minerals onto sedimentary accumulations of allogenic constituents.

A more accurate representation of the deficiencies in the understanding of ore genesis in the Witwatersrand Basin are the questions of whether (i) the paragenetically late gold - the most important commodity in the Basin - has been mobilized and reprecipitated *in situ* from an original sedimentary accumulation or introduced from an external source by hydrothermal solutions; and (ii) the existing paragenetic sequence can be refined and related to the known post-depositional history of the Basin such that predictions can be made regarding the origin and distribution of post-depositional gold in and around the Basin. This paper defines the paragenetic sequence in the Witwatersrand Basin, in terms of both rock-forming and ore minerals, and attempt to cast this in the framework of the post-depositional tectonic and metamorphic history of the Basin. The paragenetic sequence hypothesis will also be used to infer that post-depositional gold was more likely to have been derived by *in situ* remobilization than from an external source, although it is recognized that this aspect is difficult to quantify and, therefore, remains one of the outstanding issues in the Witwatersrand debate.

Geological Framework of the Witwatersrand Basin

The Kaapvaal Craton - one of the two continental nuclei of southern Africa - formed between about 3.7 to 2.7 Ga and comprises a granitoid basement that amalgamated with arc-like oceanic terranes represented by mafic/ultramafic volcanic and associated sedimentary rocks (De Wit et al. 1992). Growth of the craton was accompanied by further continental magmatic activity, possible Cordilleran-style accretion of composite terranes along the convergent margins of the proto-continent, and the formation of sedimentary basins. The Witwatersrand Basin is the structural remnant of what was originally a much more areally extensive depositional basin. It comprises a maximum of approximately 7500 metre of terrigenous sediment comprising mainly sandstone and mudrock, together with minor conglomerate (Figure 1). Historically it was considered to be early Proterozoic in age and, consequently, to have developed subsequent to the formation of the craton. It is now known to be Archaean in age and its formation is regarded as having been integral to the evolution of the Kaapvaal Craton.

The best exposed portion of Archaean basement on the Kaapvaal Craton is the Barberton region and Swaziland to the east of the Witwatersrand Basin (Figure 1). This area comprises a collage of amalgamated terranes each of which consists of tonalite-trondhjemite-granodiorite (TTG) gneisses and an associated assemblage of metavolcano-sedimentary supracrustal rocks (Lowe 1994).These terranes were mainly formed at ca. 3480-3440 Ma and 3250-3220 Ma (Armstrong et al. 1990; De Ronde & De Wit 1994; Kamo & Davis 1994), although isolated remnants of TTG gneisses and associated metavolcanics in the southwestern portion of the Barberton belt are as old as 3550-3530 Ma (Kröner et al. 1991). Greenstone belt formation and TTG plutonism was followed in the Barberton area by the emplacement of voluminous, sheet-like granodiorite-adamellite (or quartz-monzonite) batholiths at 3106 ± 3 Ma (Kamo and Davis 1994). Subsequent to these magmatic events an interval of epicontinental sedimentation (the Pongola Supergroup) and intracontinental rifting occurred which was proceeded, in the Barberton region, by at least two pulses of granite plutonism - an early period of discrete, S-type granite intrusions at 2820-2860 Ma, and then I-type intrusions at 2740-2690 Ma (Meyer et al., 1994).

To the north and west of the Witwatersrand Basin evolution of the Archaean basement is less well understood. An older generation of TTG gneiss (e.g. the 3170 ± 34 million year old Linden tonalite; Anhaeusser and Burger 1982) is intruded by ganodiorites and adamellites dated at 3174 ± 9, 3120 ± 5 Ma and 3086 ± 3 Ma (Armstrong et al. 1991; Robb et al. 1992). Younger, uraniferous, S-type granites were intruded at 3031 ± 11 Ma and 2880 ± 2 Ma (Robb et al. 1992). A large rapakivi granite-anorthosite-rhyolite complex in Botswana represented by the Gaborone Granite Suite and Kanye Formation (Figure 1), was emplaced at a high crustal level at 2785 ± 2 Ma (Moore et al. 1993; Grobler and Walraven 1993). I-type granite intrusions are also recorded adjacent to the Witwatersrand Basin and have been dated at 2687 ± 2 Ma (De Wit et al. 1993) and at 2727 ± 6 Ma (Robb et al. 1992).

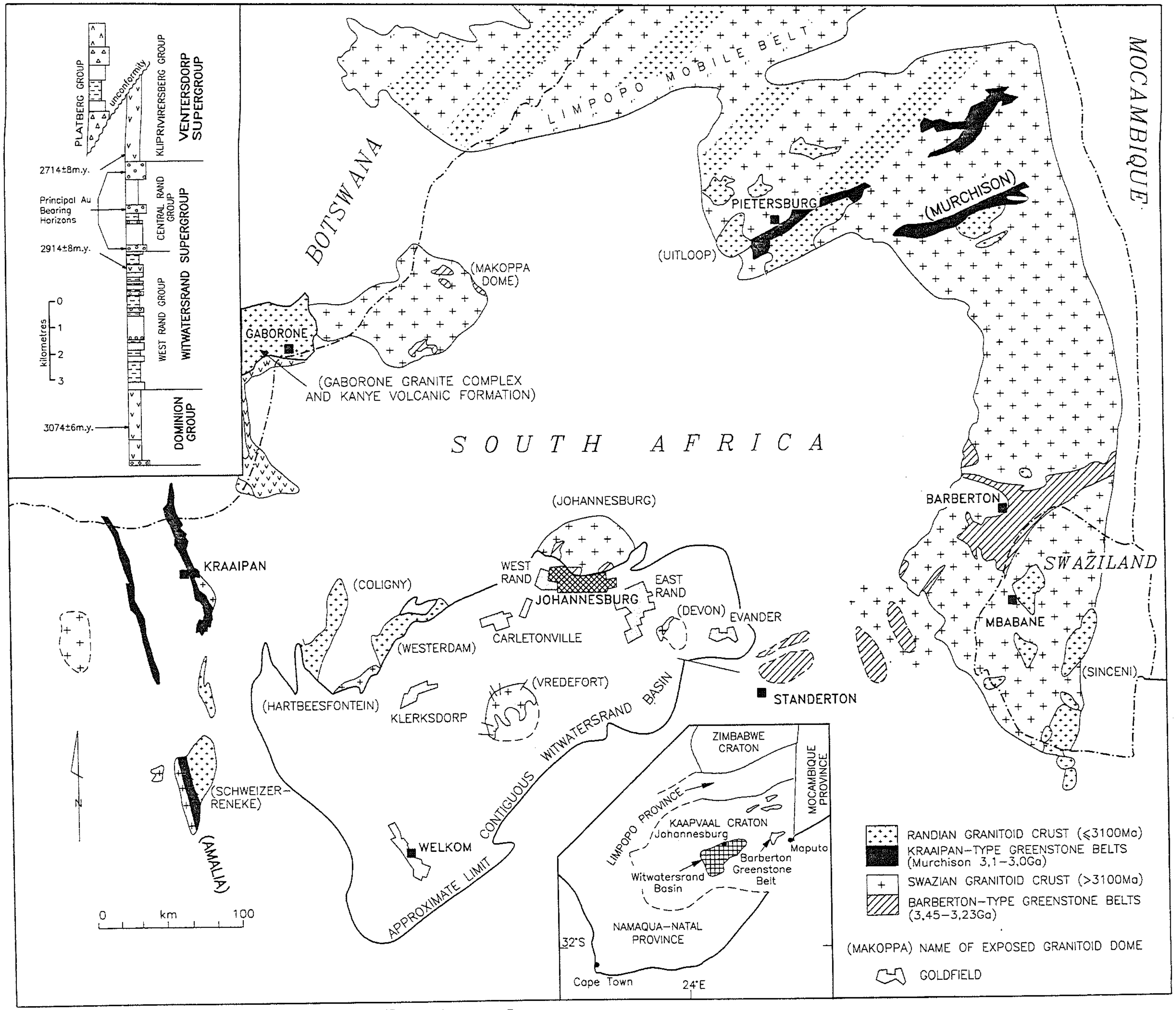


Figure 1: Simplified map showing the principal exposed components of the Witwatersrand Basin hinterland and the distinction between Swazian (> 3,1 Ga) and Randian (≤ 3,1 Ga) Archaean crust (modified after Robb and Meyer, 1990). A simplified stratigraphic column of the Witwatersrand Supergroup is shown inset.

Other significant components of the northern and western portions of the Craton are the linear array of greenstone belts which extend from the Murchison belt in the northeast, to the Amalia belt in the west (Figure 1). Recent single grain U-Pb zircon dating in the Murchison Belt indicates that it formed between 3.07 Ga and 2.97 Ga and may represent an arc terrane that was accreted onto the edge of the continent either prior to or during the Limpopo Orogeny (Poujol et al. 1997). The Limpopo Orogeny (or "mobile belt") refers to the belt of high-grade metamorphic rocks that occur along the northern margin of the Kaapvaal Craton and reflects the collisional processes that prevailed during progressive encroachment of the Zimbabwe Craton. The above age constraints suggest that the formation of the Murchison volcanic arc overlapped with the deposition of the Witwatersrand Basin. Although the geometric details are not yet clear it seems likely that accretion of the Murchison (and related greenstone belts to the west) volcanic arc onto the Craton might have been causatively linked with the formation of the Witwatersrand Basin (Vearncombe 1992).; the arc may also have represented a source of detrital gold that was eventually washed into the Basin as a significant proportion of the detrital zircon grains in the Witwatersrand strata have the same age as the magmatism associated with the arc (Poujol et al. 1997).

A profile through the granite-greenstone basement underlying the Witwatersrand Basin has been exposed in the core of the Vredefort Dome (Figure 1), which is interpreted, either as a meteorite impact site (Grieve et al. 1990; Leroux et al. 1994) formed at 2025$\pm$4 Ma (Kamo et al. 1995), or a post-Transvaal (i.e. <2550 Ma) push-up structure associated with a bend in a large strike-slip shear (Coward et al. 1995). The uplifted core of the structure exposes a segment of the Archaean basement which passes down from ca. 3100 million year old upper crustal potassic gneisses, through a magnetic discontinuity to a metamorphosed TTG-greenstone segment that is around 3500 million years old (Hart et al. 1991).

The development of the Kaapvaal Craton occurred over a prolonged (800 million year) period of Earth history and involved a number of tectono-magmatic events (Kamo & Davis 1994; De Wit et al. 1992). From the viewpoint of the Witwatersrand Basin, however, these events can be simplified into two periods: those that preceded Witwatersrand deposition (>3100 Ma) which are termed Swazian, and those associated with the development of the "Witwatersrand Triad" (i.e. the Dominion, Witwatersrand and Ventersdorp sequences deposited between 3100-2700 Ma), which are termed Randian. Among the Randian granites adjacent to the basin, several pulses of magmatism are recognized, namely at ca. 3090 Ma, 3030 Ma, 2880 Ma, 2780 Ma and 2730 Ma.

The availability of precise, single U-Pb zircon ages in and around the Witwatersrand Basin has resulted in a reasonably well constrained set of age limits to the various pulses of sedimentation that formed the Basin (Armstrong et al. 1991). Sedimentation in the Dominion Basin occurred over a relatively brief interval some time after 3086 Ma but before 3074 Ma. This was followed by what was probably an equally rapid pulse of bimodal volcanism at around and preceeding 3074 Ma. West Rand Group deposition (Figure 1, inset) commenced subsequent to 2970 Ma, indicating that a significant hiatus of some 100 million years appears to exist between deposition of the Dominion and West Rand Groups. Sedimentation in the West Rand Group was largely complete by 2914 Ma, the latter representing a tentative age for the Crown lava (Armstrong et al. 1991) which was extruded late in the sequence (Figure 1, inset). The onset of Central Rand Group deposition commenced some time after 2914 Ma and perhaps as late as 2894 Ma, the age of the youngest detrital zircon grain in the Elsburg reef. Sedimentation in the Witwatersrand Basin was terminated prior to 2714 Ma (Figure 1, inset) which is the published age (Armstrong et al. 1991) for the flood-basalts of the Klipriviersberg Group, which occur towards the base of the Ventersdorp Supergroup. The duration of Central Rand Group sedimentation, and the episodicity of its deposition, are not well constrained.

TECTONIC FRAMEWORK

Most tectonic studies of the Kaapvaal Craton now distinguish between the pre- to syn-depositional deformation of the Witwatersrand Triad and those deformational events that were superimposed during the Proterozoic evolution of the Craton. Originally thought to have been developed on a stable continental basement in an early-Proterozoic half-graben (Pretorius 1976), the Witwatersrand Basin is now believed to have developed in response to tectonic processes which occurred inboard of convergent margins of an ancestral continent during the Late Archaean. Details of the processes operative along the craton margins are, however, still poorly constrained, but involve convergence of the Zimbabwe and Kaapvaal cratons at *c.* 2700 Ma, formation of the Limpopo Orogeny (De Wit et al., 1992) and ultimate collision of the two cratons. Recent work in the Limpopo Belt (Rollinson, 1993) has, however, suggested the hypothesis that the major tectonic zones that make up the mobile belt were terranes each with their own distinctive geological history which were assembled by accretion processes. The intrusion of late- to syn- tectonic granites throughout all of the terranes constrains the timing of the accretion event to ca. 2600 Ma.

Tectonic models proposed by Burke et al. (1986) and Winter (1987) have regarded the Witwatersrand succession as a foreland basin. Clendenin et al. (1988) envisaged that the Witwatersrand Triad, as well as the 2550 Ma Transvaal Sequence, developed as successor basins along lines of pre-existing tectonothermal weakness which were responding to either compressional or extensional stresses generated by variable subduction geometries and collision between the Kaapvaal and Zimbabwe Cratons. The evolution of the Witwatersrand Triad in terms of a Wilson Cycle was suggested by Stanistreet and McCarthy (1991). The salient features of the latter model have been incorporated into a time-constrained depositional framework for the development of the Witwatersrand Triad by Robb et al. (1991). In this model, the major tectonic events associated with the development of the Triad are incorporated with the several pulses of magmatic activity, especially granitoid plutonism that accompanied the geological evolution of the region.

Various studies (McCarthy et al. 1986; Myers et al. 1990, 1992) indicate that a number of periods of deformation have affected the Witwatersrand strata: these can be described as:- (i) pre-Witwatersrand extension or Dominion-aged rifting; (ii) Witwatersrand-aged compression and block faulting; (iii) mid-Ventersdorp extension and graben development; and (iv) post-Transvaal deformation.

Dominion-aged Rifting

The Dominion Group immediately underlies the Witwatersrand strata and comprises a mixed volcano-sedimentary succession deposited nonconformably on Archaean basement granitoids. Petrogenetic studies of the bimodal basalt-rhyolite volcanic association of the

Dominion Group (Marsh et al. 1989; Jackson 1992) suggest that the succession was deposited in an intra-continental rift basin (the Dominion Basin) that was associated with north-northeast trending faults. Significantly, the lavas attain a maximum thickness of some 3 km within a basin which may have exceeded 20 000 km^2 in extent. The Dominion Group is overlain by the clastic sediments of the West Rand Group, although a hiatus of some 100 million years appears to exist between Dominion rifting and the onset of lower Witwatersrand sedimentation (Robb et al. 1991). This precludes any suggestion that the onset of Witwatersrand sedimentation is related to thermal relaxation associated with the rifting and volcanism of the Dominion event.

Witwatersrand-aged Compression

The nature of syn-depositional tectonics in the Witwatersrand Basin is recognized by variations in stratigraphic thickness and the occurrences of syn-sedimentary folding and faulting. Prominent northwesterly striking syn-sedimentary folds are, for example, developed across the northern margin of the basin (McCarthy et al. 1986) and major oblique-slip faults are well documented along the northern, western and southwestern margins of the basin. Marked thinning of Central Rand Group strata is noted away from the basin across these marginal structures. Stratigraphic thinning coincides with the traces of major faults that must have been active during deposition. In addition, deformation associated with basin margin structures indicate folding, overturning of strata and thrusting during Witwatersrand deposition. This faulting is believed to have had a reverse, oblique-slip character and is indicative of the existence of long-lived compressive stress in the region. Myers et al. (1990, 1992) suggest that the entire Witwatersrand Basin was intersected by east-west trending left-lateral, and north-south trending right-lateral, oblique slip faults that created a mosaic of independently moving fault-bounded blocks. These fault-bounded blocks were responsible for the generation of intra-fault stratigraphic accomodation, which controlled local sedimentation style and resulting variations in stratigraphic thicknesses. This style of faulting is similar to the Cenozoic Laramide-style of compressive block faulting in the foreland basins of the western USA (Myers et al.,1990).

Ventersdorp-aged Extension

An extensional stress regime and extrusion of the Klipriviersberg lavas at 2714 Ma effectively mark the termination of Witwatersrand sedimentation. Emplacement of the Klipriviersberg flood basalts has been attributed to tectonic escape-related extension and oblique-slip faulting associated with the collision of the Kaapvaal and Zimbabwe Cratons (Stanistreet & McCarthy 1991), or to oblique subduction processes involving slab roll-back (Clendenin et al. 1988). Northeast-southwest directed continent-continent collision is thought to have given rise to a large impactogenic rift (Burke et al. 1985; Stanistreet and McCarthy 1991) which formed a number of major graben particularly to the west of, but also within, the Witwatersrand Basin. In addition to the formation of new graben structures, this period of deformation was characterised by the formation of half-graben development along suitably oriented pre-existing reverse or thrust faults re-activated as extensional faults (Clendenin et al. 1988; Myers et al. 1992). The characteristics of sedimentary and volcanic fill in the graben are quite distinctive. Sedimentary rocks are typically coarse grained, poorly sorted, alluvial-fan deposits that are associated with minor rift-related bimodal volcanism (Buck 1980).

Transvaal-aged Subsidence

Following accretion of the Limpopo fragment to the Kaapvaal Craton at 2600-2550 Ma (Barton & Van Reenen 1992), gravitational collapse and erosion of the Limpopo Belt led to the development of rift basins and subsequent precursors to the Transvaal Basin (Eriksson & Clendenin 1990; Clendenin et al. 1988; Stanistreet & McCarthy 1991). Erosion over much of the Kaapvaal Craton produced extensive peneplanation . The Black Reef Formation was deposited as a thin sheet-like deposit of quartzites, with locally developed conglomerates and interbedded shales over an area of low relief. Thermal subsidence led to the formation of an epeiric sea over the Kaapvaal Craton, which covered much of the Witwatersrand Basin. This resulted in the deposition of the Chuniespoort Group, which comprises a thick succession of dolomites, minor shales and ironstones (Tankard et al. 1982; Clendenin et al. 1988; Martin et al. 1990). The Chuniespoort Basin was succeeded by the Pretoria Group, which is separated from the underlying sequence by regional unconformity marking a period of non-deposition and erosion. This hiatus indicates a major change in the nature of sedimentation as the siliciclastic sedimentary rocks of the Pretoria Group replaced the Chuniespoort carbonate sedimentation, and possibly reflects crustal rebound and uplift of the Limpopo Belt as a source for sedimentation (Clendenin et al. 1988). The available age determinations suggest that a major time break exists between the deposition of the lower Transvaal Sequence and the onset of deposition of the Pretoria Group (Figure 2).

Post-Transvaal Deformation

Vredefort-related deformation

The Vredefort structure is located in the centre of the present Witwatersrand Basin. Locally termed the Vredefort Dome, this sub-circular structure is delineated on its northern and western flanks by overturned and steeply dipping strata of the Dominion Group and the Witwatersrand, Ventersdorp and Transvaal successions. The eastern and southern flanks of the structure are obscured by the Permo-Triassic Karoo Supergroup. The core of this structure is approximately 40 km in diameter and is associated with a distinctive style of cataclysmic deformation represented by voluminous pseudotachylite breccias, shatter cones and high pressure silica minerals (e.g. coesite and stishovite). These data have been used to suggest that the Dome represents the site of an ancient impact site that is about 2025 million years old (Kamo et al. 1995; Reimold and Gibson 1996). This cataclysmic deformation event had a major effect on the disposition of Witwatersrand strata.

Although generally little deformed, McCarthy et al. (1986) have identified large-scale, open to overturned folds, a penetrative cleavage and faults in sedimentary rocks of the Transvaal Sequence overlying Witwatersrand and Ventersdorp strata. Analysis of these structures has shown that fabric orientations vary radially with respect to the Vredefort structure. These structures have been attributed to shear stresses that were directed outwards from the centre of the Basin and attributed to the emplacement of the Vredefort structure. These stresses caused folding, which decreases in amplitude away from the Vredefort structure, cleavage formation and low-angle thrust faulting (McCarthy et al. 1986). Along the northern margins of the Witwatersrand Basin and environs, northerly verging structures include a gentle south-dipping cleavage, a down-dip mineral lineation, bedding sub-parallel shear zones and open to tight folds. In localitities where the Black Reef Formation is absent,

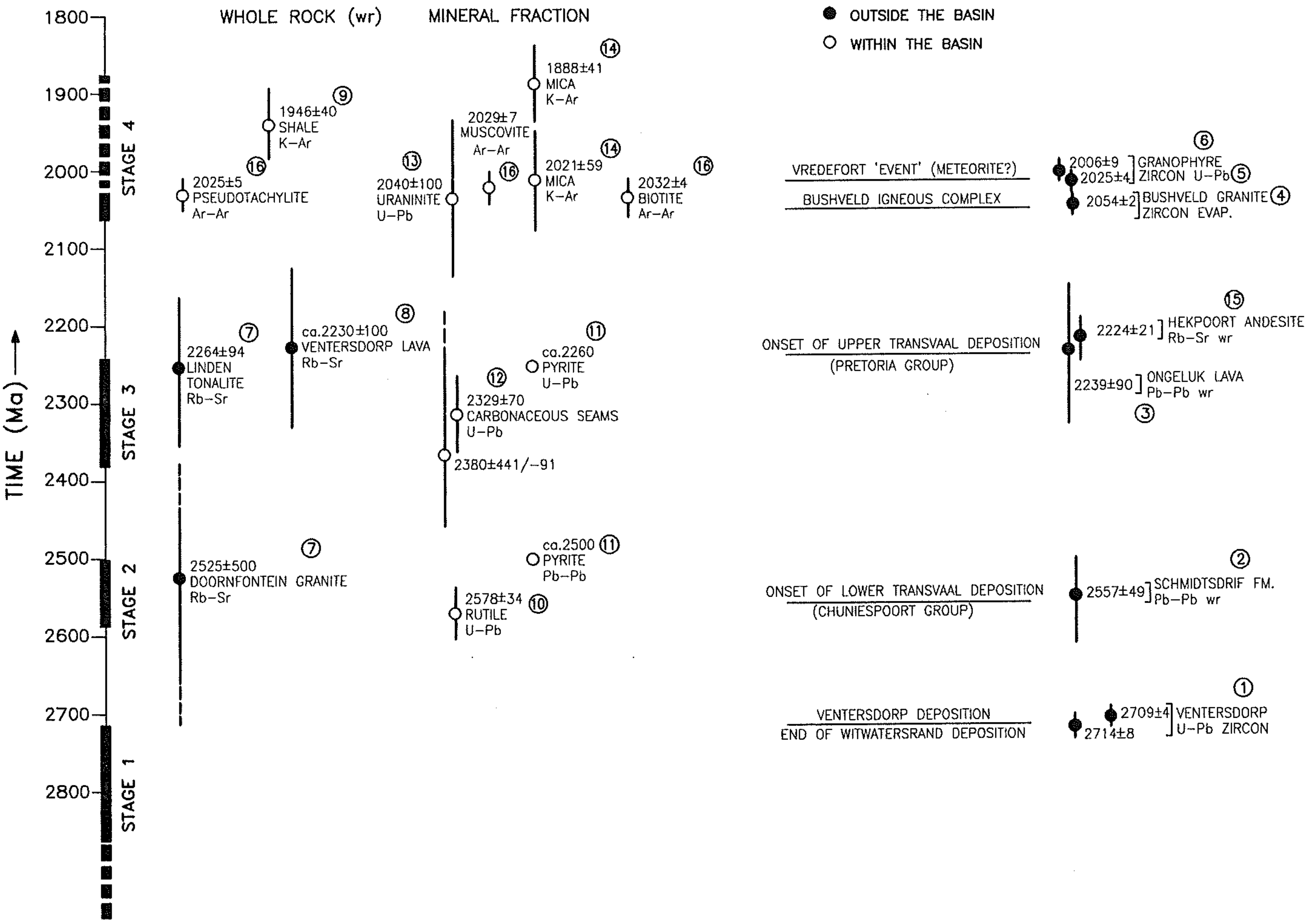


Figure 2: Figure depicting isotopic age data for post-depositional events affecting the Witwatersrand Basin. Data sources: 1. Armstrong et al., 1991; 2. Jahn et al.,1990; 3. Armstrong, 1987; 4. Walraven and Hattingh, 1993; 5. Kamo et al., 1995; 6. Allsopp et al., 1991; 7. Barton et al., 1986; 8. Walraven et al., 1990; 9. Layer et al., 1988; 10. Robb et al., 1990; 11. Giusti et al., 1986; 12. Allsopp et al., 1986; 13. Rundle and Snelling, 1977; 14, Zhao et al., 1995; 15. Van Niekerk and Burger, 1964; 16. Reimold et al., 1995.

the differentiation of pre- and post Transvaal structures is difficult, especially where they have a similar sense of vergence.

Other post-Transvaal deformation events

Recent work (Courtnage et al. 1995) has indicated that the structural features identified by McCarthy et al. (1986), and related to the Vredefort structure, are far more pervasive than previously thought. In a study between the Johannesburg Dome and the Bushveld Complex Courtnage (1996) has identified several additional phases of post-Transvaal deformation. The first is a phase of ductile deformation that produced a heterogeneously developed southerly verging cleavage in pre- to syn- Bushveld Complex times at 2050 Ma, which *predates* the Vredefort-related structures described above. In addition, other post-Vredefort events have been identified, notably, south-verging folds and thrusts which deform the Vredefort-related structures. Microstructural studies carried out by Courtnage (1996) on the porphryoblast -fabric relationships from shear-zone lithologies has confirmed a post-Bushveld Complex timing for this event. Although the origin for these structures has not been specifically identified, they may be similiar to bedding-parallel thrusts which verge away from the Bushveld Complex in the eastern Transvaal. These bedding-parallel thrusts have been attributed to rapid elastic subsidence that resulted from the emplacement of the Bushveld Complex and gravitational loading of the sedimentary pile into which the Bushveld Complex was emplaced (Harley and Charlesworth 1992). Notably, these bedding-parallel thrusts contain mesothermal gold-bearing quartz veins, best developed in the Pilgrims Rest goldfield of the eastern Transvaal (Harley and Charlesworth 1994; Boer et al. 1995 and which also occur along the southern flank of the Bushveld Complex. Moreover, significant tectonic duplication of the Transvaal Sequence by southward verging thrusts post-dating the Bushveld Complex and identified in vibroseismic profiles northwest of Pretoria (Andreoli 1990), may be related to this deformation event.

Courtnage (1996) has also identified other ductile structures such as east-verging folds and small-scale west-verging thrust duplexes, as well as an heterogeneously developed cleavage, that deform, and thus post-date, Vredefort-related structures. The absolute ages of these structures, however, are not clear. East-verging structures are known, however, along the western margins of the exposed Transvaal Basin, where the Transvaal Sequence was deformed during the early stages of the 2100-1800 million year old Kheis orogeny (Stowe 1986; Duane & Kruger 1991; Thomas et al 1994). These east-verging structures include recumbent folds and thrusts developed in a thin-skinned fold and thrust belt (Stowe, 1986). According to Duane and Kruger (1991), the Bushveld Complex intruded early in the history of this tectonic cycle (perhaps during its rift phase) and was subsequently deformed along its western margin during the Kheis Orogeny. West-verging structures have been identified along the northeastern margin of the Witwatersrand Basin (Roering et al. 1990) and attributed to compression during emplacement of the Bushveld Complex. Courtnage (1996), however, has provided evidence that these structures post-date the Vredefort-related deformation and suggested that they may be the result of post-Vredefort subsidence of the Bushveld Complex. The effects of the post-Vredefort related deformation, including that of the Kheis Orogeny, on the rocks of the Witwatersrand Triad are generally poorly understood.

Kibaran-aged deformation

Friese et al. (1995) have recently presented evidence for the occurrence of Mesoproterozoic tectonics and magmatic activity within the core region of the Kaapvaal Craton. Based on detailed structural studies from the Free State goldfield, in conjunction with partial Ar-Ar resetting ages of various fault lithologies and tectonites, two main cycles of localised tectono-magmatic activity and associated hydrothermal alteration processes have been suggested for the periods ca. 1450 - 1315 Ma and ca. 1280 - 1000 Ma. Both cycles have been related to Kibaran (i.e. Grenville) orogenic processes within the Namaqua-Natal Mobile Belt developed along the southern margin of the Craton (Thomas et al. 1994). The earlier period appears to be coincident with alkaline magmatic activity located along terrane boundary structures within the Craton. The later period, the main Kibaran orogenic phase (1200-1000 Ma), resulted in northwest-directed thrust tectonics into the core of the Kaapvaal Craton and Witwatersrand Basin. The Pilanesberg, and other associated alkaline igneous complexes, were emplaced along and associated with the formation of northwest directed fractures orthogonal to the Namaqua-Natal fold-thrust belt along the southern margin of the Craton. The effects of the Kibaran Orogeny on mineralization in the Witwatersrand Basin and its paragenetic sequence nevertheless appear to have minimal and it is unlikely that significant redistribution of metals occurred during the Mesoproterozoic.

METAMORPHIC EVOLUTION

The post-depositional thermal evolution of the Witwatersrand Basin is of particular interest due to the significance of thermal and hydrothermal events in the modification of Au-U mineralization. A variety of methods, including petrography of silicate and ore mineral parageneses, quantitative geothermometry, vitrinite reflectance, illite crystallinity, fluid inclusion chemistry and thermometry, stable isotope geochemistry, radiogenic isotope geochronology and palaeomagnetism, as well as the post-depositional tectonic history of the Basin, as discussed above, have been used to constrain the P-T-fluid evolution of the Basin. Several metamorphic events have been identified using these techniques.

Subsequent to the termination of Central Rand Group sedimentation, the Witwatersrand Basin underwent episodic subsidence between ca. 2700 Ma and 2200 Ma, during formation of first the Ventersdorp, and then the Transvaal, basins. It appears as though the thermal effects imposed by the Ventersdorp lavas were minimal as magmas were rapidly extruded and most heat was lost upwards. Evidence for this is the lack of an inverted metamorphic overprint beneath the Ventersdorp Contact Reef. There is, however, evidence of isotopic resetting at ca. 2550 Ma (Figure 2) which suggests a thermal perturbation possibly associated with deposition of the lower portion of the Transvaal Sequence (Frimmel 1994; Robb & Meyer 1995). In addition, U-Pb ages of 2330-2380 Ma for carbonaceous matter both in and adjacent to the Witwatersrand Basin (summarized in Robb et al., 1995) are interpreted as the timing of hydrocarbon circulation and subsequent polymerization of bitumens. These data suggest that temperatures in excess of ca. 150 °C, corresponding to the oil window, were only achieved significantly later than the onset of Transvaal deposition (Figure 2) and implies a relatively low geothermal gradient for 300-400 million years following cessation of Witwatersrand sedimentation and a slow rate of burial during that period. The interpretation of the isotopic data for carbonaceous matter is, however, equivocal and many questions remain regarding the source and secular evolution of the organic material that is now preserved within the Witwatersrand Basin. It is nevertheless apparent that numerous radiometric age data from throughout the region, which clearly represent isotopic resetting, cluster at ca. 2300 Ma (Figure 2). The widespread nature of isotopic re-setting on the Kaapvaal Craton suggests a thermal perturbation at this time (Phillips et al., 1989) which appears to coincide with deposition of the upper portion of the Transvaal Sequence (i.e. the

Pretoria Group).

There is a general consensus that the conglomeratic ore bodies in the goldfields experienced peak metamorphic conditions of 350±50 °C at pressures of between 1.5 and 3 kbar (Phillips & Law 1994; Frimmel 1994), as indicated by the coexistence of chloritoid and pyrophyllite. Similar peak temperature constraints have been obtained from fluid inclusions preserved in the reefs (Frimmel 1994; Boer et al. 1995) and indicate a regionally-extensive lower greenschist facies event. Higher-temperature, mid- to upper-greenschist facies assemblages involving biotite, cordierite and/or andalusite or kyanite are, however, locally developed in the goldfields (Schreyer & Bisschoff 1982; Tweedie 1986; Phillips & Law 1994). In addition, higher grades are recorded in the central parts of the Basin, in the collar of the Vredefort Dome. Here, metamorphic grade increases from mid-greenschist facies in the Central Rand Group to mid-amphibolite facies in the lower West Rand Group (Bisschoff 1982). Gibson and Wallmach (1995) obtained P-T estimates of 570-600 °C and 4.0-4.5 kbar from andalusite ± cordierite ± staurolite assemblages in West Rand Group metapelites.

A significant body of geochronological data, recently reviewed by Reimold et al. (1995), defines a cluster of ages at ca. 2000 Ma (Figure 2), whereas resetting of remnant magnetism (Layer et al. 1988) confirm that a major thermal event occurred at that time. These data do not, however, precisely define the age of the metamorphic event, which has led to proposals that the metamorphism was related either to the ca. 2060-2050 Ma Bushveld Complex event, or to the ca. 2025 Ma Vredefort diastrophism. Frimmel (1994) has suggested that the event indicated by these data was a younger retrogression unrelated to the peak event. However, several lines of evidence provide strong qualitative support for a syn-Bushveld Complex age for the greenschist to amphibolite facies metamorphism in the basin:

(1) The metamorphic peak predated the Vredefort event as ca. 2020 Ma pseudotachylitic breccias cut the metamorphic assemblages both in the goldfields and in the Vredefort Dome (Trieloff et al. 1994; Gibson & Wallmach 1995; Kamo et al. 1995);

(2) In the Evander goldfield, the metamorphic grade increases towards a gravity high, interpreted by Tweedie (1986) as a concealed offshoot of the nearby Bushveld Complex;

(3) The pressure estimates obtained from the metamorphic assemblages indicate an overburden of between 5 and 10 km overlying the Central Rand Group in the goldfields and of 14-16 km to the West Rand Group in the central parts of the basin. This requires, first, that the metamorphism predated the Vredefort event. Although the original thickness of the Ventersdorp succession prior to development of the Transvaal-related unconformity is not known, these estimates are consistent with the metamorphic peak having been achieved during the latter stages of, or after, the deposition of the Transvaal Sequence;

(4) The thermobarometric results indicate that the metamorphism was the product of an extreme upper crustal geotherm (>35-40 °C/km) and that the heat source was located below the levels of the Witwatersrand Basin. Such geotherms are typically regarded as the product of intraplating or underplating of mafic magmas into or below the crust. The development of voluminous felsic magmas associated with the Bushveld Complex is consistent with significant melting of the lower crust during such a magmatic event. Evidence of melting and the formation of restitic lithologies has recently been identified by Stevens et al. (1995) in

the Archaean basement in the Vredefort Dome; and

(5) P-T paths derived for the amphibolite facies West Rand Group metapelites and the basement granulites in the Vredefort Dome indicate concomitant burial of the central parts of the Basin by up to 4 km *during* the metamorphism (Gibson and Wallmach, 1995; Stevens et al., 1995). In the absence of evidence of significant tectonic thickening in the region during post-Transvaal times, these paths are best reconciled with magmatic thickening such as would be achieved by emplacement of the Bushveld Complex at shallow crustal levels.

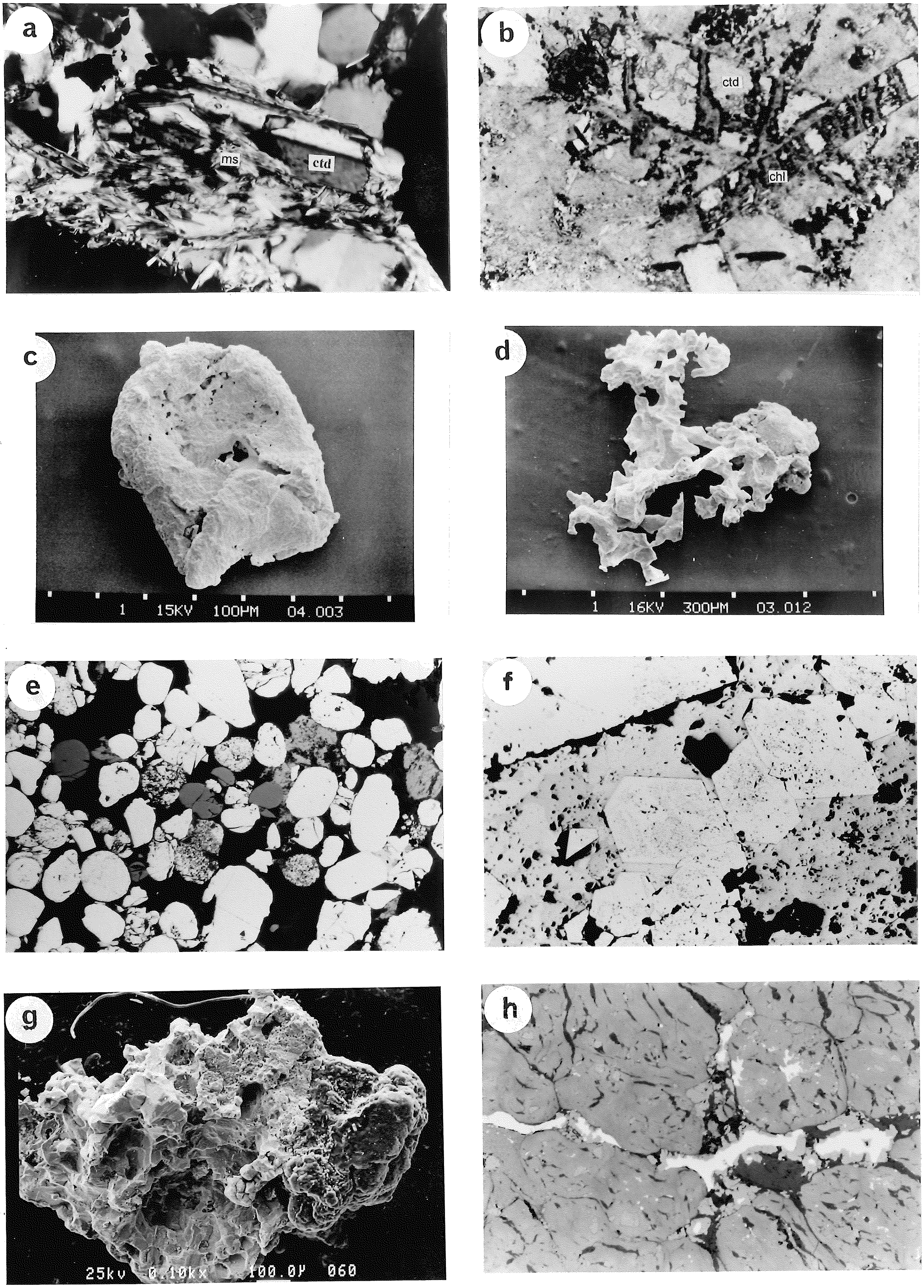
One explanation for the lack of definitive syn-Bushveld Complex radiometric ages from the metamorphic assemblages in the Witwatersrand Basin is that a significant retrogressive event followed the Vredefort diastrophism. According to Gibson and Wallmach (1995), this event was marked by a strong lateral thermal gradient in the Vredefort Dome, with temperatures in excess of 680-700 °C in the core (Stevens et al., 1995), 500-530 °C in the lower West Rand Group, and >400 °C in the upper West Rand Group in the collar. In the goldfields on the Basin margins, this event led to hydrothermally-induced sericitization of peak metamorphic assemblages and pseudotachylitic breccias (Wallmach and Meyer 1990; Trieloff et al. 1994; Zhao et al. 1995). Gibson and Wallmach (1995) attribute the retrogression to the combined effects of rapid differential uplift of incompletely cooled crust during the Vredefort event and heating caused by the release of shock energy and cooling of an impact melt sheet generated during the Vredefort meteorite impact event (see Reimold & Gibson 1996). Evidence of limited retrogression in the basin due to strong thermal activity at 1250-1060 Ma is provided by disturbed Ar-Ar age spectra (Reimold et al. 1995) and may be related to the Kibaran Orogeny to the south and west of the craton.

Detailed petrographic studies of the Witwatersrand Basin have also demonstrated the polyphase nature of its metamorphic evolution and a well-defined paragenetic sequence of authigenic phyllosilicate and related silicate mineral phases, including chlorite, pyrophyllite, chloritoid, white mica, kaolinite and illite/smectite, has been recognized (Table 1). Frimmel (1994), for example, identified several generations of chlorite in the Basin, namely, pseudomorphs after detrital biotite and garnet, fine-grained matrix material and discrete vein fillings. Chlorite varieties are distinguishable by their colour (i.e. distinctive green and Berlin-blue birefringence colours) or mineral associations; a variety of colourless chlorite appears to be restricted in its occurrence to seams of bitumen within the conglomerates. Chloritoid is typically present as fine- to medium-grained, prismatic, crystal aggregates, which display decussate textures and polysynthetic twinning. White mica occurs as isolated or aggregated, fine- to medium-grained flakes or laths, commonly displaying interstitial, decussate textures. Some varieties of white mica are distinguished by the presence or absence of chlorite. A third type of white mica generally shows an affinity for bituminous seams. In many conglomerates, pyrophyllite is the predominant phyllosilicate, to the extent that it forms the only matrix silicate. Veinlets of the mineral may be observed in fractures in quartz pebbles. Kaolinite and interstratified illite/smectite are generally restricted to bitumen seams where they typically occupy fractures in quartz pebbles embedded within the hydrocarbon.

Phyllosilicate minerals display complex replacement relationships. Chloritoid is commonly replaced by white mica (Figure 3a), and green chlorite is replaced by Berlin-blue chlorite which frequently also replaces white mica and chloritoid (Figure 3b). Prophyllite is

Figure 3: Microphotographs of ores and minerals from the Witwatersrand conglomerates:

a. Muscotive replacing chloritoid; X-Nicols, transmitted light, length of field of view = 0.5mm.
b. Chlorite replacing chloritoid; X-Nicols, transmitted light, length of field of view = 1mm.
c. Peaned micronugget of gold from the Basal Reef (SEM photo courtesy of W.E.L. Minter).
d. Crystalline gold extracted from the same sample of the Basal Reef as the micronugget above (SEM photo courtesy of W.E.L. Minter)
e. An assemblage of round allogenic grains of inter alia pyrite and chromite; reflected light, length of field of view = 2mm.
f. An assemblage of authigenic pyrite, pyrrhotite and chalcopyrite, reflected light, length of field of view = 1mm.
g. SEM microphotograph showing the association between nodular bitumen and crystalline pyrite and gold from a quartz vein
h. Bituminous seam containing numerous small fragments and partially replaced grains of uraninite transected by a veinlet of gold; reflected light, length of field of view = 0.2mm.


a
ms
ctd
b
ctd
chl
c
1 15KV 100µM 04.003
d
1 16KV 300µM 03.012
e
f
g
25kv 0.10kx 100.0µ 060
h

observed replacing chloritoid, Berlin-blue chlorite or white mica. It is also not uncommon, however, to observe white mica replacing pyrophyllite. According to Phillips (1987), the breakdown of chlorite and pyrophyllite to form chloritoid is an indication of peak metamorphic conditions. The replacement of chloritoid by Berlin-blue chlorite clearly indicates the existence of retrogression subsequent to the peak metamorphic condition. Likewise, the observation of low temperature chlorite (<250 °C; Tongu 1993) and its presence with kaolinite and illite/smectite in the bituminous seams, supports the view that retrogression may have followed development of these seams. A summary of the complex paragenetic sequence associated with the development of authigenic phyllosilicates in the Basin is presented in Table 1. The sequence points to a protracted history of fluid circulation through the Witwatersrand sequences but at this stage it is not yet clear how these events relate to the regional metamorphic P - T - t path. It seems likely, however, that the regional prograde path has been complicated by locally developed retrogressive stages which have important implications for the detailed pattern of fluid circulation in the Basin and resolution of the nature of the authigenic Au-U mineralization.

Table 1.

Paragenetic sequence for the development of the principal authigenic phyllosilicate phases in Witwatersrand conglomerates

Stage	**1**	**2**	**3**	**4**
Chloritoid		----------------		
Chlorite	-------------		---------	---------
White mica	------------		-----------	---------
Pyrophyllite	---------		--------	---------
Kaolinite				---------
Illite/Smectite				---------

(Note: The stages depicted here do not necessarily equate to the stages depicted in Figure 4)

In summary, the post-depositional thermal evolution of the Witwatersrand Basin indicates several discrete events at ca. 2550 Ma and 2350 Ma, which climaxed at ca. 2050 Ma during the Bushveld magmatic event. At that stage, the Witwatersrand sediments also reached their maximum depths of burial, having been covered successively by the Ventersdorp and Transvaal successions. The peak metamorphic event was closely followed by a variable retrogressive overprint associated with the Vredefort diastrophism, which also led to significant exhumation of the basin. The Bushveld and Vredefort events appear to be separated in time by about 30 million years, although improved resolution in the in the geochronological database is required to substantiate this distinction. Retrogression of equilibrium mineral assemblages may have accompanied each of the major metamorphic perturbations that affected the Witwatersrand strata, although widespread evidence for this will probably have largely been obliterated by subsequent increments of pressure and temperature.

MINERALIZATION PROCESSES AND PARAGENETIC SEQUENCE

The economically important Witwatersrand Au-U-sulphide ore bodies, or "reefs", are hosted by conglomerates of the dominantly fluviatile Central Rand Group (Figure 1, inset). This succession comprises numerous unconformity or disconformity bounded depositional sequences which accumulated in response to periodic tectono-magmatically induced uplift and subsidence. The depositional sequences are composed mainly of arenite, with lesser rudite, and were deposited in alluvial-fan and alluvial braid-plain environments. Ore bodies are associated with gravel facies and occur mainly in the form of very mature, scour-based pebble lag and gravel-bar deposits. The gravel facies are generally located on degradation surfaces, either on the basal unconformity of a depositional sequence or on retrenched degradation surfaces within such sequences (Minter 1978). The Witwatersrand conglomerate beds, nevertheless show a highly varied set of characteristics. A wide range of combinations of sand and pebble layers is present, extending from single layers of scattered pebbles to well-packed, thick conglomerate layers which tend to contain internal partings of pebbly pyritic arenite. In general, sedimentary features of the conglomerate beds can be expressed in terms of lithologies in modern braided stream sytems (Minter 1978). Gold and uranium in the Witwatersrand Basin is mined entirely from the conglomerates and associated coarse-grained arenites and there is no exploitation from other features such as faults or dykes. Nevertheless, the mineralization is complex and over 70 ore minerals displaying a variety of textural characteristics have been identified in the ore bodies. A paragenetic sequence for the principal ore minerals, modified after Feather and Koen (1975), is presented in Figure 4 and discussed in more detail below.

Stage 1 - Syn-sedimentary Mineralization

Since the advent of quantitative sedimentological studies in the Witwatersrand Basin in the 1960s, a demonstrable relationship between a variety of sedimentary characteristics and the presence of mineralization has been apparent. Widespread use is now made during mining and exploration of quantitative sedimentology as a tool in the prediction of the economic potential of conglomerates (e.g. Buck & Minter 1985; Els1990; Minter, 1978, 1981; Smith & Minter 1980). A correlation exists between mineralization and the presence of features such as unconformities, fluvial channels, cross-bed foreset laminae and deflation surfaces. The maximum concentration of detrital heavy minerals (including gold and uraninite) is in those conglomerates which have the best packing, the most resistant clasts, and an abundance of pyritic foresets.

The physical processes responsible for the concentration of heavy minerals were more complex than those predicted by simple Stokesian settling behaviour, and hydraulic equivalence in the conglomerates was the result of interaction between processes which probably included sediment entrainment, saltation suspension, bed load transport and shear

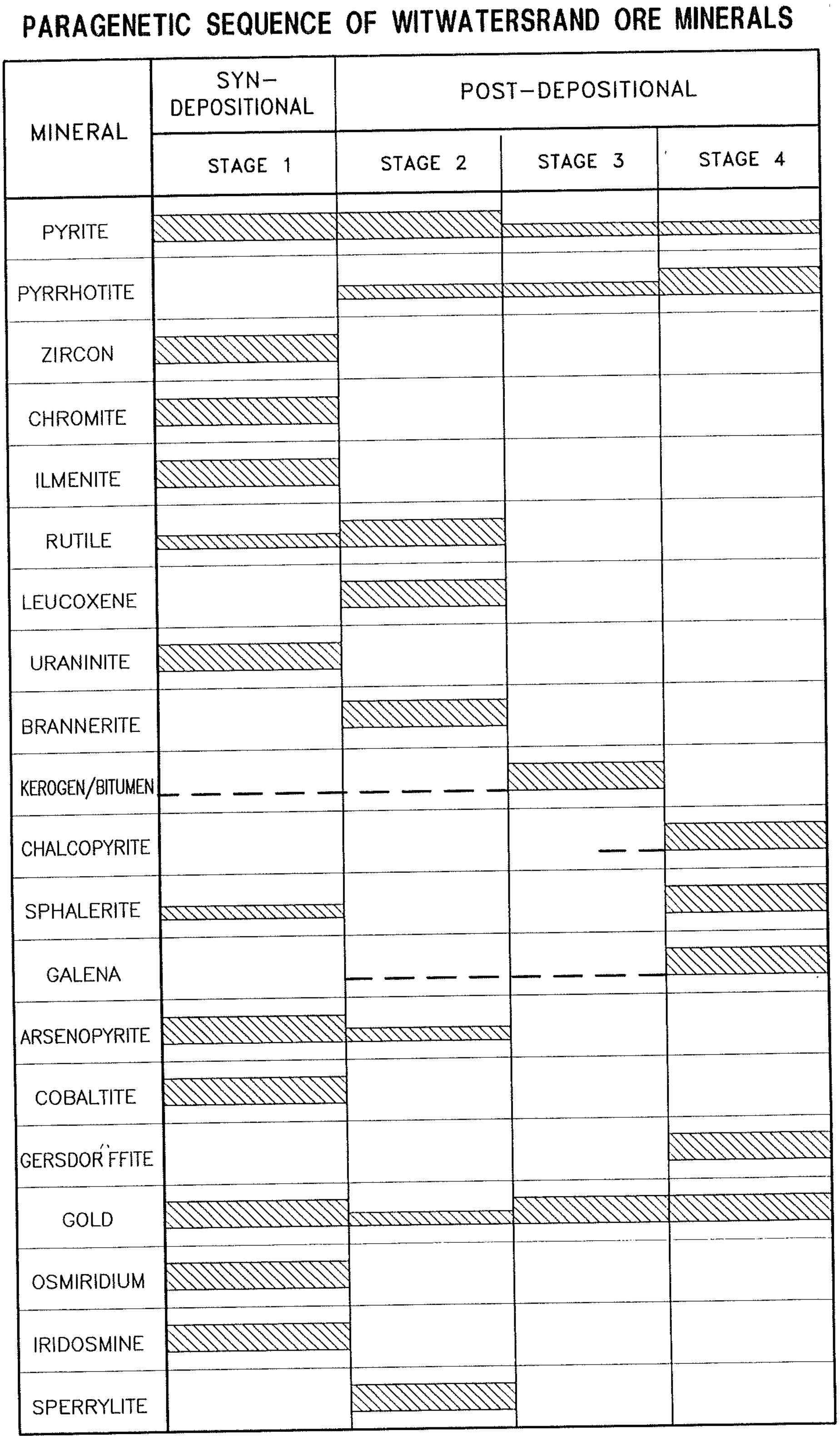


Figure 4: Diagram depicting the paragenetic sequence for the principal minerals located in the Witwatersrand conglomerates (modified after Feather and Koen, 1975). Details pertaining to each of the 4 stages are presented in the text. Thickness of the bars represents a qualitative estimation of the relative abundance of each mineral at a given stage.

sorting. It has now been established (James 1985) that, given the hydraulic conditions prevailing in the fluvio-deltaic environment applicable to the Basin, much fine-grained gold was transported in suspension. Sediment entrainment also appears to have played a pivotal role in the sorting of gold and other heavy minerals from their associated sediment load. Numerical modelling of sediment distribution, using the multi-parameter empirical equations of James (1985), predicts that in a channel-overbank system detritus would be transferred from the high-velocity channel and deposited in the overbank portions due to a reduced transport capacity of the flow. The process is verified in a comparison of actual and modelled gold distribution patterns for the Carbon Leader reef (Nami & James 1987). Figure 5 shows the excellent agreement between model distribution patterns and assayed gold grade distributions across two channel profiles of the Carbon Leader, which supports the contention that gold distribution patterns can be deterministically predicted by a fluvial model. The relationship does not prove that all gold was syngenetic, but, given that particulate gold did exist in the sediment load, points to the type of processes that resulted in its sorting and concentration.

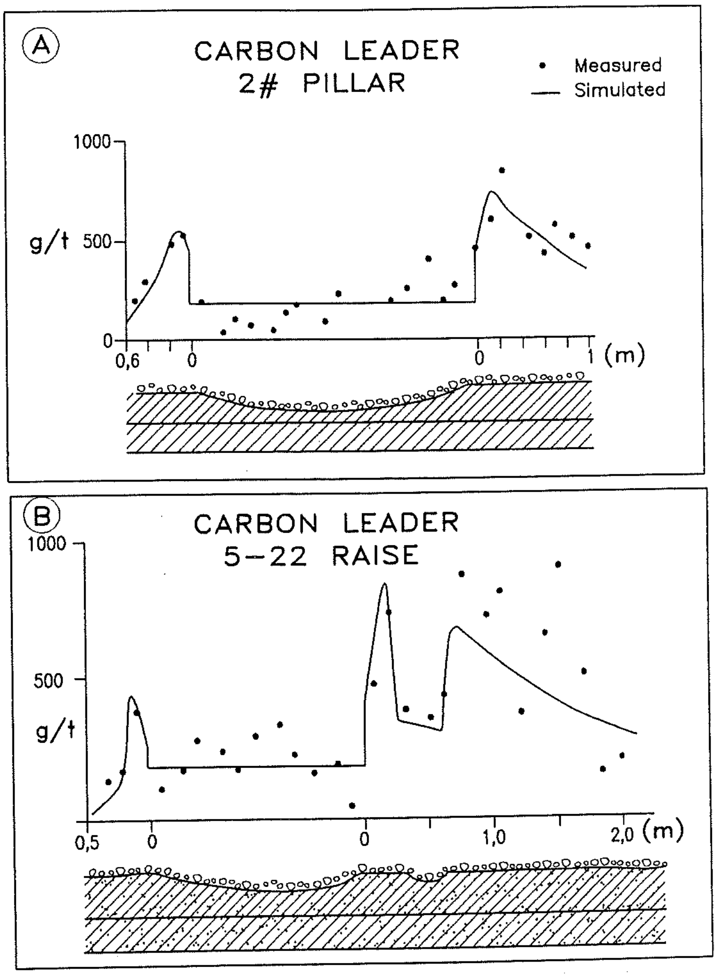


Figure 5: Gold distributions across channel sections of the Carbon Leader Reef at Blyvooruitzicht Gold Mine compared to numerical simulations of gold distribution for suspended and deposited material in a channel - overbank system using the criteria of James, 1985 (after Nami and James, 1987).

In addition to the primary sedimentary dispersion patterns, other indications for a detrital origin of many Witwatersrand ore constituents are provided by micromorphological and chemical studies which demonstrate that grain morphologies (including those of certain gold particles, uraninite and certain pyrites) are consistent with the shape of micro-nuggets which have been affected by abrasion during sediment transport and compaction during diagenesis (Viljoen 1963; Hallbauer & Utter 1977; Utter 1979, 1980; Schidlowski 1981; Minter et al. 1993). Detrital gold grains typically display flattened and edge-overturned morphologies (Figure 3c) and may be overgrown by authigenic pyrite. Uraninite is often concentrated along the basal contacts of conglomerate beds, or occurs as small subhedral grains in carbonaceous matter. In the first case, the abraded muffin-shape of individual grains is regarded as evidence for the allogenic nature of the mineral (Schidlowski 1981). This interpretation is supported by imprecise dating of uraninite which suggests ages in excess of 3000 Ma (Saager 1981; Rundle & Snelling 1977). Mineral-chemical analyses reveal highly variable ThO_2/UO_2 ratios, which suggests that uraninite originated from granitic and pegmatitic source rocks, and could not have formed within the Basin by low-temperature hydrothermal fluids, because the Th contents are too high (Feather & Glatthaar 1987). Round compact pyrite (Figure 3e) and arsenopyrite are often oscillatory zoned in terms of their As contents and the growth zones are truncated at grain boundaries, which indicates mechanical abrasion during transport (McLean & Fleet 1990). In addition, isotopic data for round pyrite, sphalerite and osmiridium grains suggest ages that are interpreted to be older than the maximum age of the Basin, suggesting that they originated as detritus from an external source (Saager 1981; Guisti et al. 1986; Hart & Kinloch 1989). Collectively, these features are regarded as convincing evidence that a significant proportion of the Witwatersrand ore minerals are allogenic and accumulated as placer particles.

Post-depositional mineralisation

Detailed mineragraphic and mineral-chemical analysis has shown that many of the constituents of the Witwatersrand ore-bodies, including gold, pyrite, sphalerite, rutile and cobaltite occur as both allogenic and authigenic phases. Other mineral associations such as cobaltite-arsenopyrite-gersdorffite, ilmenite-rutile-leucoxene and uraninite-brannerite-leucoxene represent assemblages which have formed from the *in situ* alteration and remobilization of labile constituents (Robb & Meyer 1991). Many other sulphide phases, including chalcopyrite, galena, pyrrhotite, cubanite, mackinawite, millerite, proustite and tennantite, are present only as authigenic minerals and display easily recognizable textural characteristics. Although detrital gold micro-nuggets are preserved in many conglomerate horizons, such as the Basal Reef (Minter et al., 1993) and the Vaal Reef, it is nevertheless clear that a significant proportion, perhaps even the majority, of gold grains display delicate filamentous and crystalline textures (Figure 3d) that could not have been preserved during sedimentary transport and deposition. It is important to note that both the allogenic and authigenic varieties of gold may be present *within the same sample*, as shown in a study of gold morphologies in the Basal Reef (Minter et al. 1993). The paragenetic sequence in Figure 4 shows that a number of the ore minerals were precipitated at one or more of the stages currently recognized in the sequence. It should also be emphasized that any discussion of post-depositional processes and paragenetic sequence in the Witwatersrand ores is hampered by the fact that earlier events, in particular during diagenetic stages of burial, have largely been obliterated by subsequent tectono-metamorphic overprints which are generally both severe and widespread.

Stage 2 - Early Pyrite Formation - ca. 2550 Ma

Although there is a paucity of detailed isotopic studies on the authigenic minerals of the Witwatersrand ore-bodies, the available published data are reasonably consistent in that they appear to identify episodes of fluid circulation and/or mineral growth that coincide with well-known, craton-wide geological events that have been superimposed onto the basin during its post-depositional history. For example, authigenic pyrite which from the Ventersdorp Contact Reef, has yielded a Pb-Pb model age of ca. 2500 Ma (Giusti et al., 1986). Authigenic rutile also formed at approximately this stage and, where sampled from the West Rand Group, has yielded an age of 2578 Ma (Robb et al., 1990). The Doornfontein granite along the northern margin of the Basin has yielded a very imprecise whole rock Rb-Sr reset age of about 2525 Ma (Barton et al. 1986). These ages coincide with the deposition of the dominantly carbonate succession of the 2550 Ma Chuniespoort Group (i.e. the lower Transvaal Sequence) and probably reflect an episode of crustal subsidence at that time. This event appears to have had a major influence on the Witwatersrand Basin and was almost certainly responsible for the development of an early stage of authigenic mineralization in the ore bodies.

Although it is apparent texturally that pyrite was the most voluminous authigenic phase to have formed at ca. 2550 Ma, it is not clear to what extent gold was also associated with the event. Since gold-thio complexes are very common in natural fluids under relatively reducing conditions and at low pH's, it seems likely that some gold was moving through the system at this stage. Moreover, since Ti was also labile and involved in precipitation of authigenic rutile, it is also conceivable that limited U mobility might have occurred, with subsequent precipitation of authigenic phases such as brannerite or uraniferous leucoxene.

It is interesting to note that very few isotopically reset ages are recorded at ca. 2700 Ma, which confirms the notion that the Ventersdorp Supergroup had a minimal thermal effect on the underlying Witwatersrand rocks, with the exception of the Ventersdorp Contact Reef. Although it may be argued that Ventersdorp-related re-setting might have been obliterated by subsequent events, it nevertheless appears, on the basis of the present data, that the earliest record of significant post-depositional modification of Witwatersrand ores occurred in response to the onset of Transvaal deposition and consequent burial of Witwatersrand strata.

Stage 3 - Maturation of Hydrocarbons - ca. 2350 Ma

It is well known that the Witwatersrand strata contain kerogen and/or bitumen which resulted from the maturation of primitive organic matter that existed in suitable environments, probably with the depository. The origin of the organic matter is controversial and opposing viewpoints for a syngenetic algal residue (Hallbauer 1975; Zumberge et al. 1981) and a radiolytically-polymerized hydrocarbon-rich fluid (Schidlowski 1981; Robb et al. 1994) have been put forward. It is clear, however, that progressive maturation of primitive algal material through diagenesis and metagenesis would have produced kerogen and released light hydrocarbons (CO_2, CH_4, C_2H_6, etc.), as well as oil, for migration within the Basin. It has also now been established from fluid inclusion studies that a population of CO_2-N_2-hydrocarbon-rich fluids existed in the Basin, supporting the suggestion of in situ maturation of organic matter.

Recent U-Pb dating of bituminous matter from various conglomerate horizons, as well as bituminous nodules in granites adjacent to the Basin, suggests that this material formed at ca. 2330-2380 Ma (Robb et al., 1994). It is also known that pyrite was precipitated at this time, Pb-Pb dating of which has suggested an age of ca. 2260 Ma (Giusti et al., 1986), and that the Ventersdorp lavas were also reset at ca. 2230 Ma (Figure 2). This time span broadly coincides with the onset of deposition of the upper Transvaal Sequence (Pretoria Group) which occurred at or soon after extrusion of the Ongeluk lavas at ca 2240 Ma (Figure 2). It is suggested, therefore, that the enhanced heat flow that accompanied the latter event, as well as deposition of the upper portion of the Transvaal Sequence, and the accompanying basin subsidence, stimulated production and circulation of aqueous and hydrocarbon-bearing fluids, not only through the Witwatersrand Basin, but other strata as well. It is not clear whether this was the only event related to hydrocarbon circulation in the region and more work is required to assess the possibility of both earlier (diagenetic) and later events. Existing evidence, however, indicates that organic matter in the Witwatersrand Basin was deposited during a discrete stage of the ore paragenetic sequence and is now represented mainly as bitumen resulting from radiolytic polymerization and accumulation around detrital uraninite lags. This notion is supported by the 2380 -2330 Ma "age" for the bitumen although this interpretation is equivocal and based on the assumption that this was the time that the isotope systems were last reset within the organic material (Robb et al 1994).

Decomposition of organic material rich in sulphur and nitrogen will release H_2S and N_2 into the fluid phase (Tissot & Welte 1978; Bottrell et al. 1988), which will enhance its metal carrying capacity. Moreover, methane and oil are known to be associated with the transport of a variety of metals (Saxby 1976; Hennet et al. 1988; Parnell & Eakin 1987). Hydrocarbon-bearing fluids within the Witwatersrand strata undoubtedly had the same potential for the formation of organo- and thio-metallic complexes and the transport of metals such as Au, U, Cu, etc. Evidence for organo-metallic complexation in the Witwatersrand Basin is provided by high-resolution element mapping of bituminous nodules which are intimately intergrown with cubic, striated pyrite and gold in fault-related quartz veins which cut through certain conglomerate horizons (Figure 3g). PIXE induced micromapping of these bitumen nodules show uniform distributions of metals such as Au, U, Fe, Cu, As, and Th throughout the hydrocarbon matrix (Figure 6). These metals appear to be present, either in elemental form (Au and U), or associated with minute sulphide phases (Fe, Cu and As). Gold, uranium and other metals were, therefore,transported in the same fluids as were the light hydrocarbons and may have been involved in the formation of a variety of chelate-type complexes. If the fluids themselves were derived from within the Basin during organic maturation then it is logical to infer that the metals involved in this event were also derived from within the Basin.

Stage 4 - Late Sulphide and Gold Precipitation - ca. 2050 Ma

The attainment of peak metamorphic conditions in the Witwatersrand Basin, associated with the events related to intrusion of the Bushveld Complex (2060-2050 Ma)and the subsequent but unrelated Vredefort catastrophism (2025 Ma), is considered to have had a major influence on the sediments and their contained mineralization. A large number of samples, both within and adjacent to the Witwatersrand Basin, yield Rb-Sr, K-Ar and Ar-Ar ages in the range 2050 to 1950 Ma which are thought to largely reflect the re-setting of temperature-sensitive isotope systems in older rocks and minerals during the above events (Figure 2).

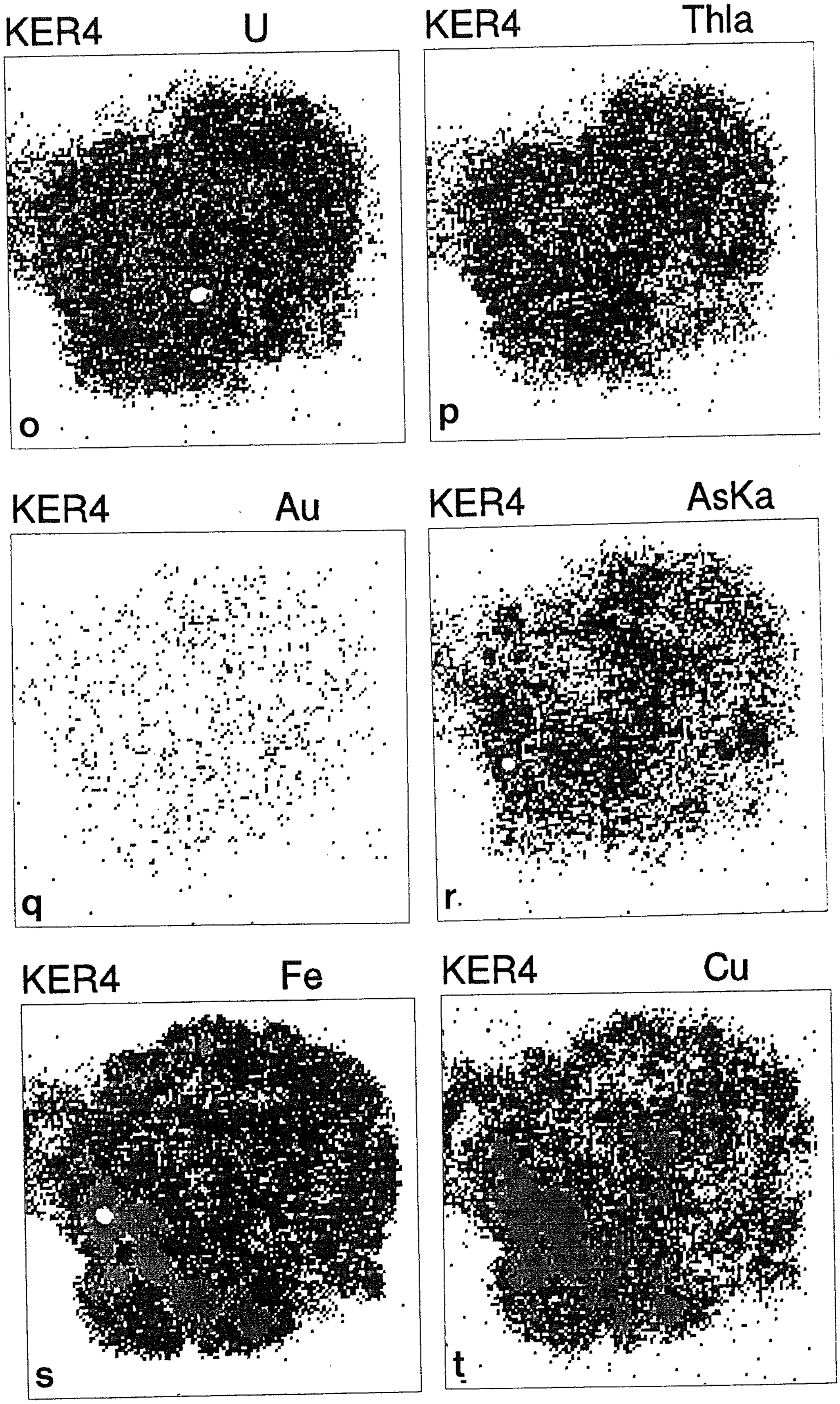


Figure 6: PIXE (proton-induced X-ray emission) induced micromaps showing the distribution of U, Au, Fe, Th, As and Cu in a bitumen nodule extracted froma quartz vein cutting through Witwatersrand conglomerate.

The Bushveld magmatic event resulted in the development of a major thermal anomaly over much of the central Kaapvaal Craton and this undoubtedly affected fluid flow within the Witwatersrand strata. The Vredefort bolide impact, and the cataclysmic exhumation of Witwatersrand strata associated with this event, is also likely to have had major repercussions for fluid circulation in the Basin. The effects of the Vredefort event are persistently recorded in ^{40}Ar-^{39}Ar plateau ages of minerals such as muscovite and biotite, as well as whole rock pseudotachylite samples, from the Witwatersrand strata. Muscovite ages of 2029 ± 7 Ma, biotite ages of 2032 ± 4 Ma and pseudotachylite ages of 2023 ± 6 Ma all point to a particularly focused and well-constrained fluid circulation event which is indistinguishable from the 2025 ± 4 Ma age obtained for the Vredefort impact event (Reimold et al. 1995). Although the bolide impact can be considered as geologically instantaneous, the effects of subsequent thermal re-equilibration are likely to have had an extended influence on fluid circulation and isotopic re-homogenization.

Although none of the paragenetically-late sulphide phases (Figure 3f), such as pyrrhotite, chalcopyrite, sphalerite, galena and gersdorffite, have been dated, it seems likely that their formation is associated with the Bushveld-Vredefort events. Late chalcopyrite and pyrrhotite in the Ventersdorp Contact Reef is associated with pervasive albite-chlorite-carbonate-sericite alteration; K -Ar dating of various 2M1 mica size fractions yield a variety of ages the majority of which fall between ca. 2050 Ma and 1900 Ma (Zhao et al. 1995). Uraninite grains from several conglomerate reefs have yielded "ages" of 2040 ± 100 Ma (Rundle & Snelling, 1977) suggesting a resetting of the U-Pb system in these grains that is also related to the Bushveld - Vredefort events. It is also pertinent to note that late gold is often observed on the margins of, or cutting through, bitumen seams (Figure 3h) and nodules which formed during an earlier stage of the paragenetic sequence (i.e. stage 3). This suggests that significant amounts of gold were in solution during the fluid circulation that accompanied the Bushveld and Vredefort events, and that gold was precipitated by redox reactions when these fluids encountered bituminous layers (Robb and Meyer, 1995).

DISCUSSION AND CONCLUSIONS

Ore genesis in the Witwatersrand Basin is clearly the result of two discrete processes, one syn-sedimentary and the other post-depositional. Gold and uranium mineralization within the conglomeratic components of the succession, and the intimate relationship between ore grade and sedimentological parameters, implies that the principles of hydrodynamic dispersion were responsible for the distribution and sorting of heavy mineralsduring sediment deposition. Gold, uranium and pyrite particles which are recognizably detrital on the basis of their morphological characteristics were concentrated together with other sedimentary particles with which they were in hydraulic equilibrium. Subsequent to deposition, however, the Witwatersrand strata were subjected to a prolonged, polyphase tectonic and metamorphic evolution which resulted in significant modification of the pristine mineralogy. Circulation of fluids, most of which are likely to have had connate or metamorphic origins, appear to have resulted in at least three major periods of authigenic mineral growth in the Basin.

In order to understand the post-depositional modifications of the placer ore-bodies, they must be related to known events which can be recognized both within and adjacent to the Basin itself. The present paper provides an attempt to relate the paragenetic sequence of ore and related gangue minerals to the Archaean and Palaeoproterozoic evolution of the

Kaapvaal Craton, for which a better understanding is now available through improved geochronological constraints from single zircon U - Pb dating. It appears that at least three major episodes of authigenic mineral growth affected the nature and distribution of mineralization in the Witwatersrand Basin.These are related to; (i) early burial of the Witwatersrand strata during early Transvaal Sequence deposition at ca. 2550 Ma; (ii) further burial during late Transvaal Sequence deposition at ca 2350 Ma; and (iii) a major thermal perturbation of the crust during Bushveld Complex intrusion at 2050 Ma. The latter event was followed some 30 million years later by a massive bolide impact into the centre of the Basin which resulted in geologically instantaneous exhumation of the ore-bearing strata and retrogression of the stable mineral assemblages present at that time.

During the various episodes of post-depositional alteration, it has been suggested that fluid conditions were such that the solubility of the various gold and uranium species was low, but mechanisms for the re-precipitation of these metals were very efficient (Robb & Meyer 1991). If correct this statement has implications for the question of whether the enormous concentrations of post-placer gold in the Witwatersrand ore-bodies were derived by remobilization and precipitation of gold that had already been concentrated by placer processes, or were introduced from a source external to the Basin. Palaeofluids trapped in quartz veins that cross-cut conglomeratic ore-bodies comprise two distinct types. One is H_2O-rich and is occasionally saturated with respect to salts, and the other is CO_2-rich and contains variable amounts (up to 90%) of CH_4, N_2, and heavier hydrocarbons such as ethane. Post-depositional aqueous fluids in the Witwatersrand Basin were typically acidic (pH 4-5 at 350 °C) with oxygen fugacities pertaining to the field of pyrite-arsenopyrite-pyrrhotite stability. These fluid parameters, together with solubility data for the $AuCl^-_2$, $Au(HS)^-_2$, $HAu(HS)^o_2$ and $U(OH)_4$ complexes, have been used to calculate Au and U solubilities for likely post-depositional fluids in the Basin (Robb & Meyer 1991). Total Au solubility, at a temperature of 350 °C, was unlikely to have been more than 10-30 ppb, whereas calculated U solubility was in the order of 20 ppb. The relatively low Au solubility argues against an introduction of the metal from an external source because such fluids would be unable to account for the enormous concentration of gold present without invoking excessively high fluid fluxes.

Although it has been suggested that alteration in the Witwatersrand Basin was fluid dominated (Phillips 1988; Harris & Watkins 1990), the widespread preservation of sedimentary features and the generally limited degree of very severe, pervasive alteration indicate that the post-depositional environment as a whole, with the possible exception of localized zones such as faults, was largely rock-buffered. If this is indeed the case, then the occurrence of gold that is late in the paragenetic sequence is likely to have been restricted to environments where; (i) fluid flow was maximised; (ii) where a ready source of gold already existed; and (iii) where a substrate for promoting the precipitation of gold out of solution was present. These conditions are best met in the conglomeratic horizons where palaeo-permeabilities were likely to have been significantly higher than in the enclosing sandstones, and where gold had already been concentrated by the mechanics of placer formation.

Precipitation of gold within the conglomerate horizons is considered to have been promoted a variety of factors which included; (i) the existence of redox barriers in the form of bituminous seams and nodules; and (ii) chemically zoned allogenic pyrite grains which are believed to have acted as micro-conductors that electrochemically precipitated gold from solution (Meyer et al. 1994).These precipitation mechanisms are regarded as having been relatively efficient and possibly explain why authigenic gold is located at the same sites within the conglomeratic ore bodies that the original placer gold was concentrated.

Detailed studies are still required in order to establish whether all the fluid populations recognized in the Witwatersrand Basin can be entirely related to dewatering and/or dehydration of the strata, or have come from some other source. Hydrocarbon-bearing fluids are related to maturation of sedimentary organic matter and it is generally believed that the source of this material was indigenous. The ability of these hydrocarbon fluids to transport both Au and U in solution, as suggested by the metal distributions observed in quartz vein-hosted bituminous nodules, supports the present contention that metals in the Witwatersrand Basin were largely redistributed internally rather than derived from an external source. The efficient precipitation mechanisms referred to above perhaps explain why the paragenetic sequence is characterised by the superimposition of both primary detrital and secondary authigenic mineralization. This notion is, however, more difficult to sustain when considering the origin of the latest fluids that migrated through the Basin, particularly those related to the Bushveld and subsequent Vredefort events. As long as the possibility exists that such fluids might have been derived from outside the Witwatersrand Basin, the suggestion that metals, and gold in particular, were also introduced by these fluids, and not simply remobilized in situ, cannot be entirely discounted.

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