Editor's note: This is the second of a two-part preview of an SEG-sponsored forum to be held in Reno, Nevada, on May 14, 2005. Meeting details are on p. 54.

Controversies on the Origin of World-Class Gold Deposits,

Part II: Witwatersrand Gold Deposits

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FOREWORD

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Similar to the previous article on Carlin-type deposits in the October *SEG Newsletter* (Muntean et al., 2004), this article serves as a preview to a discussion on the origins of the Witwatersrand gold deposits that will be part of an SEG-sponsored forum on the origins of gold deposits in the Carlin and Witwatersrand gold fields. The forum will be held in Reno, Nevada, on May 14, 2005, in conjunction with Geological Society of Nevada's Symposium 2005 – Window to the World. This article presents two clearly distinct explanations for the gold deposits of the Witwatersrand. In the first paper, Hartwig Frimmel presents the case for a modified placer origin. In this model, the gold was originally deposited in detrital form as placer deposits in coarse-grained clastic sediments. Once lithified, the gold was remobilized on a local scale by infiltrating hydrothermal fluids during the course of a complex postdepositional thermal history. In the second paper, Neil Phillips, Jonathan Law, and Russell Myers present an epigenetic hydrothermal model in which gold was introduced into the sediments after deposition. At the Reno forum, Frimmel will present the case for a modified placer origin and Phillips, the case for a hydrothermal origin. Their presentations will be followed by a panel discussion with audience participation.

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THE CASE FOR A MODIFIED PALEOPLACER MODEL FOR WITWATERSRAND GOLD

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INTRODUCTION

Situated within low-grade metamorphosed siliciclastic sediments of a Mesoarchean foreland basin in the Archean Kaapvaal craton of South Africa, the Witwatersrand gold fields (Fig. 1) have yielded close to 40 percent of all the gold ever mined and remain the world's largest repository of known gold resources. The orebodies are strictly stratiform within fluvial to fluvio-deltaic, predominantly pyrite rich (locally also uraninite-rich) quartz pebble conglomerates (reefs), which overlie regional unconformity surfaces. Because the gold grade and distribution are so closely controlled by sedimentary facies, a paleoplacer model for Witwatersrand's origin has been adopted by most exploration and mining geologists in the past. However, for almost as long as the gold has been mined, this model has been challenged because at a microscale the gold typically is associated with hydrothermal phases and occurs along microfractures. This paragenetically late position prompted a number of workers to postulate postdepositional introduction of gold into the host rocks by hydrothermal fluids (Phillips and Myers, 1989; Barnicoat et al., 1997). In view of the textural position of most of the gold, a paleoplacer model, sensu stricto, is not applicable. The question nevertheless remains as to whether the source of the currently observed hydrothermal gold particles was located within the host conglomerates in the form of original detrital grains (modified paleoplacer model), or whether it was located outside the host rocks. Clarification of this issue has far-reaching consequences for future exploration efforts to find new deposits of this particular type.

In the modified paleoplacer model, transport of gold grains into the host sediments is assumed to have taken place by fluvial processes, with subsequent short-range (micrometer- to meter-scale) mobilization of this gold, largely within the host rock, by infiltrating hydrothermal fluids and/or degradation of in situ hydrocarbon or hydrous phases in the course of a complex and polycyclic postdepositional burial and tectonic history (Frimmel and Minter, 2002; Frimmel et al., 2005).

In contrast, hydrothermal models explain the gold as having been introduced into the host rocks from an external source through the infiltration of postdepositional hydrothermal fluids. The presence of gold in the conglomeratic host rocks is inferred as a consequence of long-range, basin-wide fluid flow within permeable sedimentary horizons, combined with chemical and structural controls (Jolley et al., 2004). One hydrothermal model infers a separate origin for gold, uraninite, and hydrocarbons (Phillips and Law, 2000), whereas another seeks to explain these phases as cogenetic (Barnicoat et al., 1997). Infiltration of the inferred auriferous

to page 12 · · ·

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• • • from 7 Controversies on the Origin of World-Class Gold Deposits (Continued)

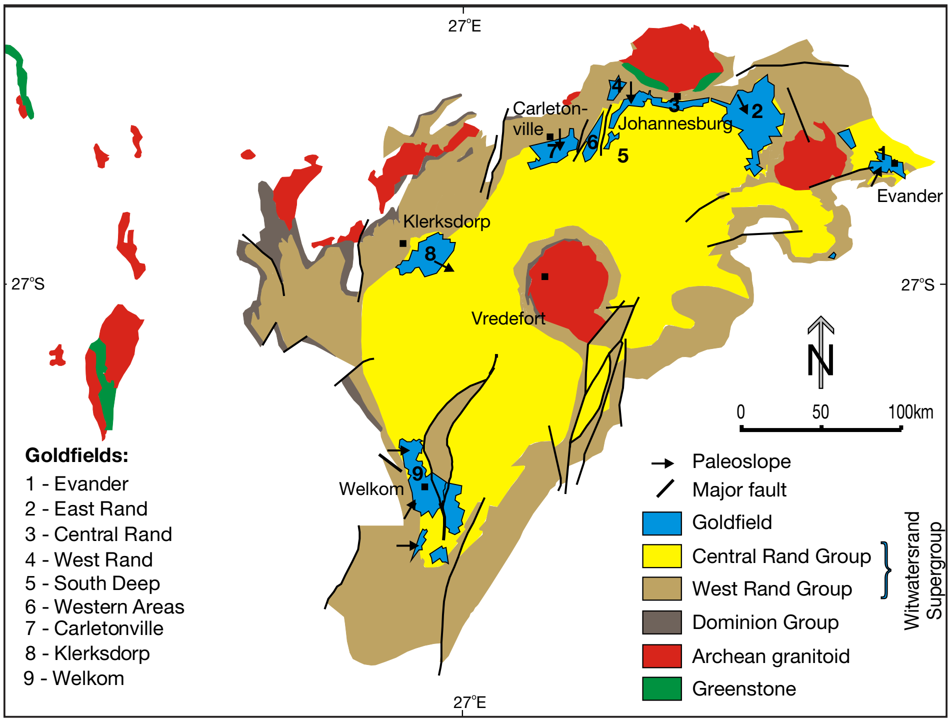

FIGURE 1. Simplified surface and subsurface geologic map of the Witwatersrand basin, also showing the distribution of Archean granitoid-greenstone terranes, the location of the gold fields, major faults, and paleocurrent directions of reefs in the Central Rand Group (from Frimmel and Minter, 2002).

hydrothermal fluids has been linked with several different events that range from Ventersdorp volcanism (Phillips et al., 1997) to regional metamorphism (Phillips and Myers, 1989), and the emplacement of the Bushveld Igneous Complex (Stevens et al., 1997).

Critical to the main arguments in support of either a hydrothermal or a modified paleoplacer model are textural, geochemical, and isotopic characteristics of the ore components on a micro- to mesoscale, as well as the macroscale distribution of the orebodies, as discussed below.

MICRO- TO MESOSCALE EVIDENCE

A major argument for a hydrothermal origin of gold in the Witwatersrand deposits is the observation that the bulk of gold grains are in or near microfractures filled with bitumen and secondary uraninite-brannerite, which postdate early, bedding-parallel pyrite-pyrrhotite-quartz-filled fractures that contain no gold (Fox, 2002; Jolley et al., 2004). Although this observation demonstrates the undisputed hydrothermal nature of the bulk of the gold particles in their current form, it does not address the distance of hydrothermal gold transport. Particularly relevant in this regard is the existence of spheroidal to torroidal gold particles interpreted as micronuggets that are spatially associated with secondary, locally remobilized, clearly hydrothermal gold (Fig. 2A, B). Although these inferred micro-nuggets are rare and have so far only been found in samples from the Basal reef, Vaal reef, B-reef, and Crystalkop reef (Minter et al., 1993; Frimmel and Minter, 2002), their existence gives a clear clue as to the primary process of gold enrichment in the Witwatersrand sediments. Strong support for such a sedimentary gold enrichment process also comes from Re-Os isotope data on gold (Kirk et al., 2002) from the Central Rand Group (upper Witwatersrand Supergroup), which hosts more than 95 percent of the Witwatersrand gold. These data indicate an age of 3.02 ± 0.11 Ga for the gold grains, similar to the Re-Os age of 2.99 ± 0.11 Ga for rounded pyrite (combined: 3.033 ± 0.021 Ga; Kirk et al., 2001), which is older than the age of host sediment deposition (2.902–2.780 Ga; Frimmel et al., 2005). Furthermore, the individual gold particles show a wide range in composition (Au/Ag/Hg ratio) with significant differences not only between reefs and within reefs, but even on a microscale between adjacent particles (Reid et al., 1988; Frimmel and Gartz, 1997). This would not be expected if they had precipitated from the same hydrothermal ore fluid.

The Witwatersrand gold differs from all other gold deposits studied so far by having unusually high Os concentrations (Kirk et al., 2002). This is inconsistent with a hydrothermal origin, based on the differing solubility of platinum-group elements in hydrothermal environments (Xiong and Wood, 2000), and is interpreted as a source-rock characteristic compatible with higher melting rates in a hotter Archean mantle (Frimmel et al., 2005).

If the gold was related to an infiltrating relatively reducing, sulfidizing, H_2O-CO_2-dominated fluid, as suggested by some advocates of a hydrothermal model (Phillips and Law, 2000), it should be cogenetic with the rounded pyrite (interpreted as reflecting sulfidized detrital Fe-oxides and Fe-pisolites), and by implication also with the rounded uraninite. Notwithstanding local evidence of sulfidation of Fe-Ti oxides, chert, and iron formation pebbles, the Re-Os data imply a detrital origin of the most abundant form of pyrite, namely the round allogenic variety. All of the above examples of sulfidation can be related to the same fluids that caused the formation of secondary pyrite at various stages throughout the complex postdepositional alteration history of the Witwatersrand sedimentary rocks. In many places, the gold occurs as inclusions within secondary, evidently hydrothermal pyrite, but gold inclusions in rounded pyrite—as expected if both were cogenetic—are conspicuously absent (Fig. 2D). Truncated zonation patterns with respect to As content in rounded pyrite (McLean and Fleet, 1989) and broken fragments of zoned, ooid-like pyrite particles (Fig. 2C) testify to mechanical abrasion during sediment transport. Furthermore, S isotope variations with both an increase and decrease in $\delta^{34}S$ values from core to rim in adjacent rounded pyrite grains speak for pyrite derivation from different source areas, and are inconsistent with precipitation from the same hydrothermal fluid (England et al., 2002).

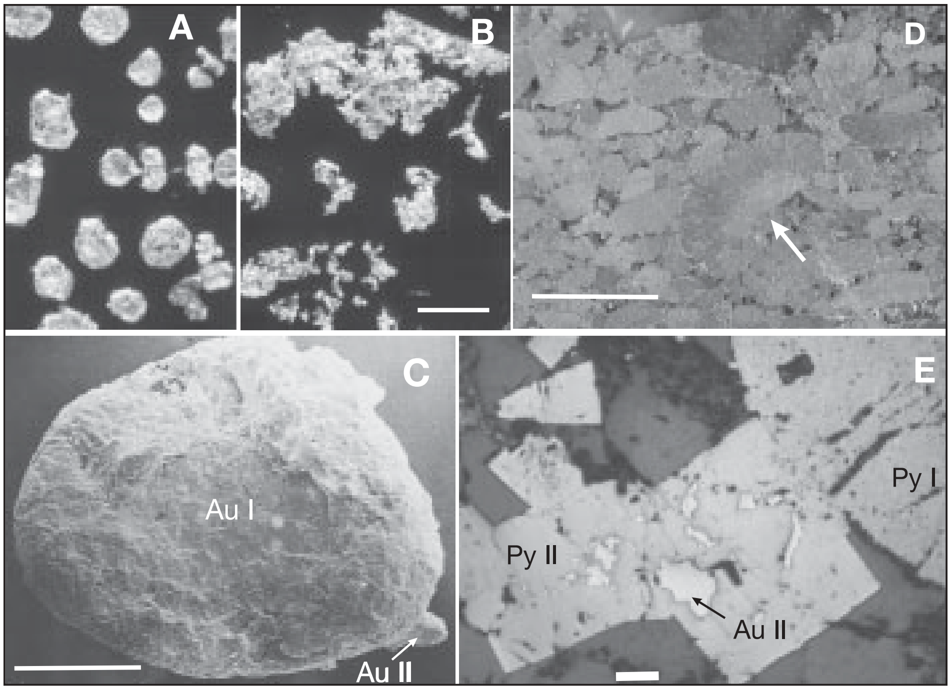

FIGURE 2. (A, B) Contrasting morphological types of gold particles occurring together on a millimeter-scale in a cross-bedded specimen of Basal reef, Welkom gold field (from Minter et al., 1993): rounded micronuggets (A) and hydrothermally mobilized, secondary gold (B); scale bar = 0.2 mm. Scanning electron microscope images of the following: (C) Spheroidal gold particle (Au I) with euhedral secondary gold overgrowth (Au II); scale bar = 0.1 mm; (D) Truncated, well-rounded, oolitic pyrite (arrow) within pyrite pebble lag in Basal reef, Welkom gold field, scale bar = 0.5 cm; (E) Gold inclusions within secondary, hydrothermal pyrite (Py II) overgrowths on rounded pyrite (Py I), B-reef, Free State Geduld mine, Welkom gold field; all images from Frimmel et al. (2005).

Similar arguments against a hydrothermal introduction into the Witwatersrand host rocks can be applied to uraninite, which occurs in some reefs at economic levels. A U-Pb age of 3050 ± 50 Ma obtained for uraninite from the Dominion reef (Rundle and Snelling, 1977) is older than the age of Witwatersrand sediment deposition but agrees well with the above Re-Os age for the gold and rounded pyrite, as well as with Re-Os model ages of 2.7 to 3.3 Ga for osmiridium grains in the reefs (Hart and Kinloch, 1989). Intergranular mineral chemical heterogeneity in uraninite, with variable and in places very high Th contents, is not compatible with a hydrothermal origin but is better explained by uraninite-derivation from a granitic-pegmatitic source (Feather and Glathaar, 1987).

One of the main pillars on which the hydrothermal models rests is the elemental correlation (or lack thereof) at the deposit to hand-specimen scale (Fox, 2002). In particular, a good correlation of Au with U and a very poor correlation with Zr have been used to infer a hydrothermal origin not only of the Au but also of the U, whereas the Zr is without doubt confined to detrital zircon. Comparison of similar studies (summarized in Frimmel et al., 2005) reveals, however, that elemental correlations vary from reef to reef, with some examples of very poor Au-U correlation, and others with moderately positive Au-Zr correlation. These variations, particularly for Au-U, may reflect a combination of hydraulic sorting of different detrital minerals during fluvial (and locally eolian) transport, and largely reef-internal dispersion of some elements, including Au, by postdepositional hydrothermal fluids.

MACRO- TO MEGASCALE EVIDENCE

If the gold was brought into the Witwatersrand basin during postdepositional fluid infiltration, extremely large fluid/rock ratios would be expected because of the low concentrations of gold in most hydrothermal solutions. The auriferous fluids would have had to flow preferentially along the conglomerate beds in order to explain the strong sedimentological control on the basin-wide ore distribution, because cross-cutting auriferous veins (feeders) are conspicuously absent. Although some evidence exists for bedding-parallel fluid flow (Jolley et al., 2004), mass balance calculations (Gartz and Frimmel, 1999) point to rather limited external fluid infiltration into the reefs. Only if all the pyrophyllite in the basin fill is explained by postdepositional H^+-metasomatism (Barnicoat et al., 1997), can a case be made for large-scale fluid infiltration. It has been shown, however, that the loss of alkalis on the scale of tens of meters into the footwall can be attributed to paleoweathering under an acidic atmosphere (Sutton et al., 1990; Frimmel and Minter, 2002), with much of the pyrophyllite resulting from the prograde metamorphism of a kaolinite-bearing protolith.

Bedding-parallel fluid flow in the Witwatersrand basin has been linked with compressional deformation, such as folding and thrusting, which has been documented particularly from the margins of the basin. There it has been related to both orogenic activity adjacent to the basin and gold mineralization within the basin (Jolley et al., 2004). Notwithstanding evidence of syndepositional thrusting during Central Rand Group sedimentation in a foreland basin (Frimmel and Minter, 2002; de Wit and Tinker, 2004), the large-scale dominant style of deformation is that of postdepositional block faulting.

A common gold-pyrite-carbon association (Phillips and Myers, 1989) and a striking paragenetic similarity makes comparison of the Witwatersrand deposits with orogenic gold deposits tempting. However, in addition to the microtextural, chemical, and isotopic characteristics mentioned above, there are also a number of fundamental differences in orogenic deposits at a larger scale (Frimmel et al., 2005). Both the tectonic setting and overall structure of the Central Rand basin, as well as the nature and scale of wall-rock alteration within the Witwatersrand gold fields, contrast with those of orogenic deposits. The inferred acidic alteration over distances of several hundreds of meters across stratigraphic boundaries in the Witwatersrand basin (Barnicoat et al., 1997) would be orders of magnitude more extensive than the alteration haloes around typical mineralized zones in orogenic deposits. Quartz (-carbonate) veins containing high Au grades are omnipresent in orogenic gold systems within quartz-rich sedimentary successions,

to page 14 · · ·

... from 13 Controversies on the Origin of World-Class Gold Deposits (Continued)

but are extremely rare in most Witwatersrand reefs, in spite of the almost exclusively siliciclastic nature of the basin fill.

Last but not least, gold mineralization must have taken place prior to or around 2.70 Ga, because Witwatersrand ore has been found as mechanically transported clasts within late-Ventersdorp diamictite (Phillips et al., 1997). Yet, the same style of mineralization marks the younger, post-Ventersdorp, 2.64 Ga Black reef. This clearly shows that more than one phase of mineralization affected the various conglomerate beds on the central Kaapvaal craton, which is more readily explained by the repeated accumulation of placer deposits than by a series of unrelated orogenic events.

CONCLUSIONS

Agreement exists that the Witwatersrand orebodies show evidence of interaction with hydrothermal fluids, some of which caused the precipitation of gold together with other phases, such as sulfides and bitumen. Although the evidence presented in favor of hydrothermal mineralization emphasizes the location of the gold in textural positions that can only postdate host sediment deposition, it does not give answers as to the ultimate source of the Au in the mineralizing fluid(s). In contrast, some of the evidence summarized here can only be reasonably explained by original introduction of gold, pyrite, and uraninite into the host conglomerates during sediment deposition, derived from a variety of sources that are older than the host sedimentary rocks. Consequently, a hydrothermally modified paleoplacer model is favored to explain the world's largest known accumulation of gold in the Witwatersrand basin.

HYDROTHERMAL ORIGIN FOR WITWATERSRAND GOLD DEPOSITS

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BRIEF HISTORY

There are many superlatives when one refers to the gold in the Witwatersrand basin of South Africa: the world's major source of gold for the last century, one of the largest geochemical anomalies in the Earth's crust, and with respect to its origin, *the greatest debate in the history of economic geology*.

The debate about the origin of the gold can be simplified to two end members (Phillips and Law, 2000; Frimmel and Minter, 2002): hydrothermal model or placer model.

The *hydrothermal replacement model* infers that the gold has been introduced into the Witwatersrand basin in an aqueous solution after burial (with associated hydrothermal alteration), and gold migration on the scale of a few kilometers is implied (Phillips et al., 1987; Barnicoat et al., 1997). Two significant precursors to the hydrothermal replacement model need to be acknowledged. First, Graton (1930) argued vehemently that the gold was hydrothermal. He favored a magmatic source with a diagenetic timing of fluid migration based on the secondary gold grain shapes, the associated hydrothermal minerals, and presence of quartz veining. Davidson (1965) also argued for a hydrothermal model with force and humor, and noted the abundance of uraninite and the difficulty of preserving this mineral through detrital transport in an atmosphere similar to that of today. Since 1986, hydrothermal models have suggested a deep-seated source for the gold-bearing fluids superimposed on a normal diagenetic assemblage. The source of the auriferous hydrothermal fluid is subject to the same uncertainties as those associated with other hydrothermal gold systems (slate belt; Archean greenstone; Carlin) but a metamorphic origin seems likely (Phillips and Law, 2000).

Both the unmodified and modified versions of the *placer model* infer that the gold was transported into the Witwatersrand basin in detrital form and deposited in response to sedimentary sorting processes. The *unmodified placer model* infers that very little has happened to the gold since burial, such that its geochemical composition, shape, and specific location are a reflection of these characteristics at the time of burial. After this model's loss of favor in the early twentieth century, there has been a pronounced shift back, since 1980, towards components and assumptions of the unmodified placer model; for example, several studies have assumed that the shape and/or composition of gold grains reflect the source terrain (Hallbauer, 1986; Minter et al., 1993; Minter, 1999; Kirk et al., 2002). The *modified placer model* invokes remobilization some time after burial that reconstituted the gold grain shapes and composition. Importantly, the scale of remobilization is suggested as a few centimeters only, so that broader relationships to enclosing host rocks have been maintained (Pretorius, 1981; Frimmel, 1997). The inferred mobilization of gold recognizes the compelling evidence for widespread alteration and secondary textures of gold that are commonly found in small-scale fracture networks (Barnicoat et al., 1997).

Conceptually, both placer and hydrothermal models are viable processes by which to form a giant gold deposit. Giant placer fields such as those of the Victorian gold fields in Australia contain individually in excess of 100 t Au each (e.g., Ballarat, Castlemaine, Bendigo), or collectively over 1,000 t in the case of the Sierra Nevada area of California (Hughes et al., 2004), and individual hydrothermal gold deposits can be a similar size (e.g., Kalgoorlie, 2,000 t; Homestake, 1,200 t). For the Witwatersrand, the perceived placer controls on gold distribution patterns led to the development of extensive flume tank and sedimentological modeling at the Chamber of Mines in Johannesburg in the 1980s (Nami, 1983; Kuhnle and Southard, 1990). At a similar time, a number of links were being made between different styles of hydrothermal gold mineralization (e.g., greenstone, slate belt, and Carlin; Phillips and Powell, 1993) and these links were extended to include the Witwatersrand gold in a foreland-orogenic model for major hydrothermal gold types (e.g., Law, 2004 a and b; Figure 3).

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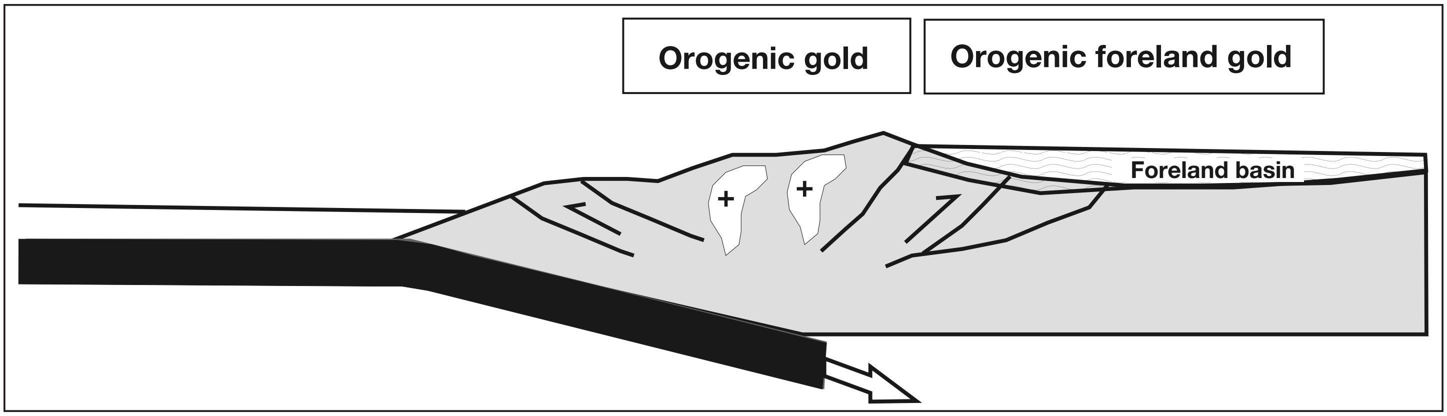

FIGURE 3. Schematic cross section of a continental margin, orogenic belt, and foreland basin showing the spatial juxtaposition of orogenic-type gold as represented in greenstone belts and slate belts, and orogenic foreland type gold as represented in the Witwatersrand gold fields (Law, 2004a and b).

HYDROTHERMAL REPLACEMENT MODEL FOR WITWATERSRAND GOLD

The hydrothermal replacement model postulates that conditions after burial of the Witwatersrand Supergroup led to the generation of metamorphic fluids at depth beneath the basin, and that these fluids had an H_2O-CO_2-H_2S composition conducive to transporting gold (Phillips and Evans, 2004). The fluids were channeled by the sedimentological and structural layering of the Witwatersrand Supergroup and by faults until they came in contact with particularly Fe- and/or C-rich layers where they precipitated gold (Fig. 4). The age of this hydrothermal event was probably syn- to post-Klipriviersberg Group, and pre-Platberg Group in age (both units are part of the Ventersdorp Supergroup dated at 2714 to 2709 Ma; see Fig. 5 for stratigraphic units). The inferred age of the alteration and mineralization remains controversial because of apparently contradictory observations. First, the Witwatersrand gold mineralization is truncated by Platberg-age extensional faults, and mineralized Witwatersrand boulders have been found in Platberg sediments. Second, the Black reef (in the Transvaal sequence; ~2.64 Ga in age) hosts mineralization very similar to that of the Witwatersrand Supergroup, so the gold would be inferred as post-Platberg in age. However, nowhere are we aware of Witwatersrand-style reefs (including “Black reef”) demonstrably overlying Platberg-age metasedimentary rocks, so we favor a pre-Platberg age for gold mineralization. This paradox has yet to be resolved.

Many of the components of this genetic model are common to other gold styles such as Archean gold in greenstone belts. Some parts of this hydrothermal replacement model are demonstrable by geological testing (regional metamorphic conditions, deep faults, H_2O-CO_2-H_2S fluids, alteration, sulfidation, replacement, gold solubility, association of gold with Fe- and C-rich horizons), and some components have not been conclusively demonstrated yet (a fluid source region, age of hydrothermal event). The uranium introduction is inferred to arise from synsedimentary meteoric water influx, analogous to younger uranium mineralization styles globally (see Fig. 4).

OBJECTIONS TO HYDROTHERMAL MODEL

It is interesting to take the reviews of the renowned Witwatersrand geologist Des Pretorius (e.g., 1981, 1989) as a starting point for the debate over the last quarter-century. In favoring a modified placer model for Witwatersrand gold, he provided five main reasons against the hydrothermal introduction of gold: (1) no fluid channelways; (2) gold is insoluble; (3) no mineralogical zoning; (4) no alteration; and (5) gold is closely linked to sedimentology.

The timing of his work was critical, because he was providing these five reasons just as research elsewhere in the world was in place to show that most of these reasons were not necessarily diagnostic, or were simply invalid. *Fluids in the Earth’s Crust*, by Fyfe et al. (1978), was a turning point in understanding how fluids moved through the Earth, and in appreciating that large volumes of fluid necessarily evolve during regional metamorphism and devolatilization. Subsequently, a vast network of fluid channelways has been demonstrated in Witwatersrand reef material (Barnicoat et al., 1997). Experimental work by Seward (1973) showed that gold is in fact quite soluble in aqueous fluids as sulfur-complexed species. Mineralogical zoning in the Witwatersrand reefs in both compositions and distribution was documented during the 1980s, but was interpreted within the placer paradigm of the day as down-slope mechanical sorting (e.g., Reid et al., 1988). Alteration was established at a similar time (Phillips, 1988; Barnicoat et al., 1997), but with the ironical twist that the alteration system was on such a large scale that most previous studies had never extended outside the alteration, and so never recognized that the alteration was present (an exception was Fuller, 1958, who recognized alteration in the Central Rand gold field). The close relationship of gold to sedimentology is no longer diagnostic of a placer origin, because the hydrothermal replacement model predicts the association of gold with detrital Fe-rich heavy minerals and migrated hydrocarbons in specific sedimentary facies.

Although the five objections to the hydrothermal model outlined by Pretorius are no longer valid, new “objections” have been raised (e.g., Frimmel and Minter, 2002; Groves et al., 2003). For example, Re-Os dating has suggested that gold in the Witwatersrand gold fields has an age of 3.01 Ga, which would make the gold grains

to page 16 · · ·

• • • from 15 Controversies on the Origin of World-Class Gold Deposits (Continued)

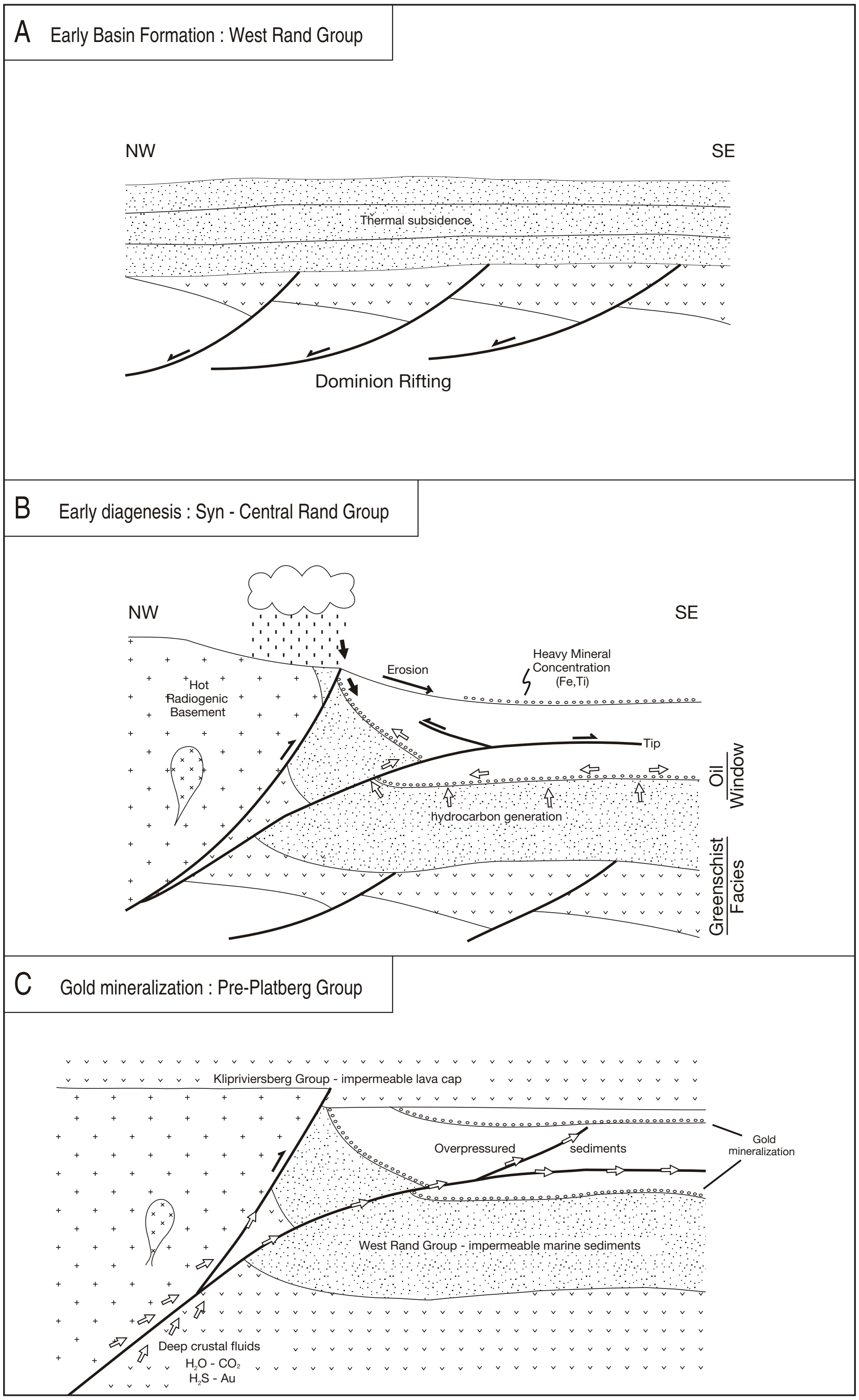

FIGURE 4. Schematic representation of the stages in the formation and mineralization of the Witwatersrand basin. (A) Thermal subsidence stage with deposition of the West Rand Group sediments; (B) early diagenesis, uplift of the basin margin with influx of meteoric waters deriving uranium from the granites in the hinterland, formation of unconformity surfaces, hydrocarbon migration, and deposition of the Central Rand Group sediments; (C) metamorphism leading to the liberation of H_2O-CO_2-rich auriferous fluids as recorded in fluid inclusions, and deposition of gold from the hydrothermal fluids in Fe- and C-rich locations. This stage is assumed to be pre-Platberg in age (see discussion in text).

older than the enclosing strata, and hence, placer in origin (Kirk et al., 2001). However, the inferred Re-Os "isochrons" are unlikely to reflect the age of the gold for at least two reasons. First, if the individual randomly selected gold grains from the complex source area existed in the Witwatersrand hinterland, they are unlikely to be derived from an isotopically homogeneous initial $^{187}Os/^{188}Os$ reservoir, which is a foundation requirement of isochron-based dating techniques. As an example, ages of detrital zircon grains in reefs span 100s of millions of years, implying a diverse age range of source lithologies in the hinterland. Second, if any detrital grains are mobilized as inferred by the modified placer model, they are unlikely to reflect the age of any original gold particles, but rather the accumulated Re-Os budget of the entire fluid-rock package. Walshe et al. (2004) point out the dilemma of either preserving an isochron through remobilization, or of generating a "possibly sensible" age from a diverse set of grains. Interpretation of the Re-Os data is complicated by the diametrically opposed interpretation of gold grain shapes and origins (compare Minter, 1999, and Barnicoat et al., 2001, working on the exact same sample of Basal reef from the Welkom gold field).

Uranium-lead dating provides another example of non-diagnostic data that have been over-cited in support of the placer model beyond the reasonable confidence level of the data. The pioneering work of Rundle and Snelling (1977) on the geochronology of uraniferous minerals in the Witwatersrand has been widely quoted in the literature in support of the placer model. These authors infer two discrete age groups: (1) an older population at 3050 ± 50 Ma that predates deposition of the Witwatersrand basin; (2) a younger population at 2040 ± 100 Ma that postdates the deposition of the Witwatersrand.

Rundle and Snelling note that "it would be virtually impossible to distinguish between disturbed detrital systems and disturbed systems with both detrital and authigenic components" (1977, p. 348). Nevertheless, the 3.05 Ga age is widely taken as the age of detrital Witwatersrand uraninite (e.g., Robb and Meyer, 1995) although the age actually refers to samples from the Dominion reef (which predates volcanic

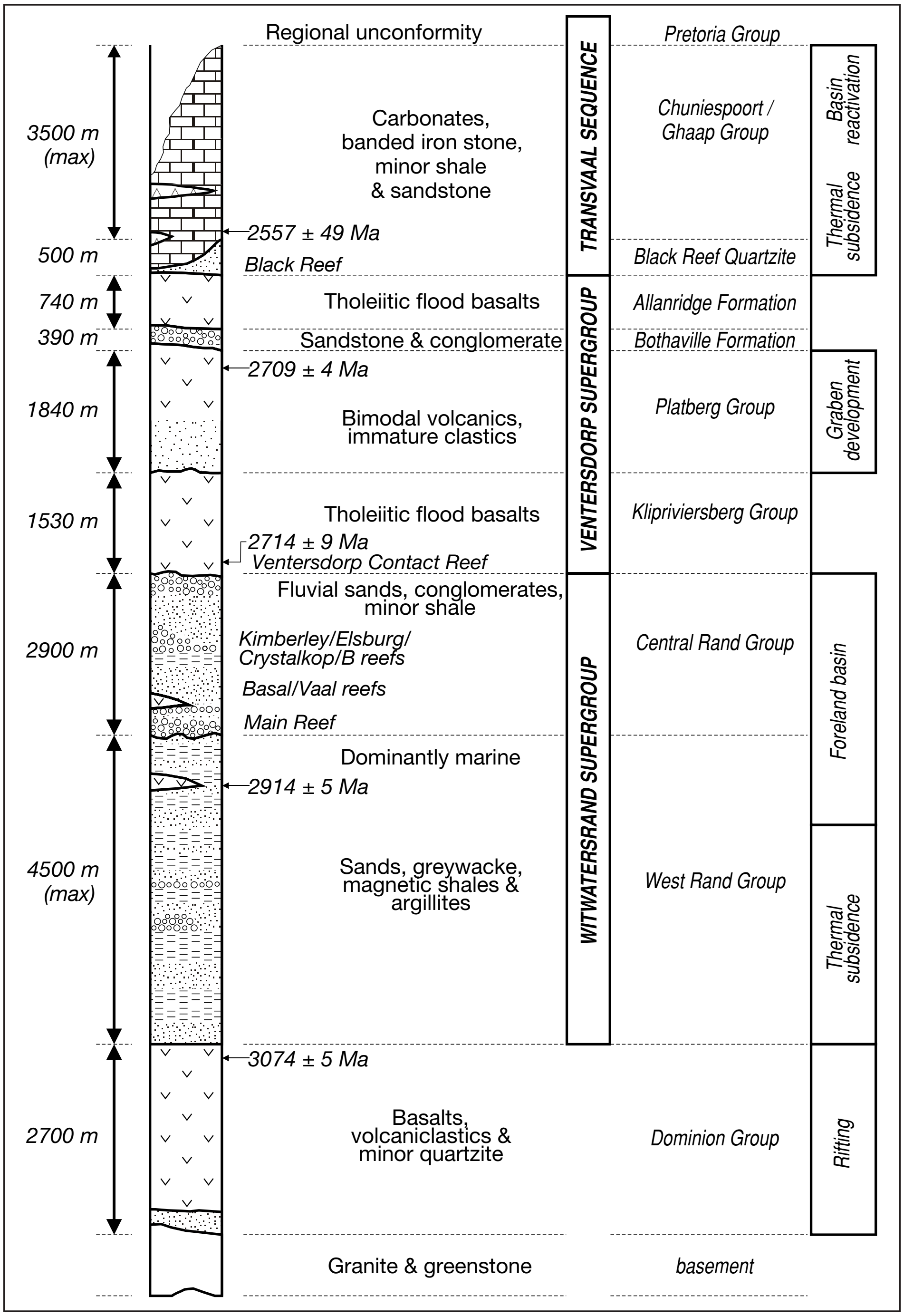

FIGURE 5. Stratigraphic column showing position of the Witwatersrand Supergroup relative to the Archean and early Proterozoic succession of South Africa. Uncertainties relating to the stratigraphic position of "mineralized Black reef" are discussed in the text.

rocks dated at 3.07 Ga; Armstrong et al., 1991). Given the error ranges, the uraninite age does not discriminate between hydrothermal and detrital mineralization for the Dominion reef.

CHALLENGES FOR THE PLACER MODEL

In providing this case for a hydrothermal replacement origin for Witwatersrand gold, it is worth laying out what appear to be the two key challenges for any placer model: the source of the gold, and the sedimentary sorting processes of gold and associated grains.

Source: All placer goldfields require a source of detrital gold, and at least in the major ones (e.g., Mother Lode, Victorian gold province), there is a close correspondence between economic primary goldfields, gold source, and placer deposits (Hughes et al., 2004). For these placer gold fields, there are realistic primary gold fields as potential source areas either known or reasonably expected on geological grounds within a kilometer or, at most, a few tens of kilometers. In the Victorian gold fields, there is a close spatial link between primary gold fields and major gold placers on several scales. For example, from global and continental scale (Goldfarb et al., 1998), through regional (Victoria within the Tasman fold belt, and the Ballarat zone within the Victorian gold province), to kilometer-scale downstream from auriferous quartz vein outcrops (e.g., Ballarat and Bendigo), there is a link between the settings of major primary gold deposits and major placer deposits.

Total production from the Witwatersrand gold fields exceeds 50,000 t of gold, so this is a bare minimum requirement for a source area in a placer model. To put this figure in perspective, this is more than twice the amount of gold produced in 6,000 years of mining on any single continent (excluding the Witwatersrand basin). If such an enormous gold source did exist in the Witwatersrand hinterland, then presumably it formed from some giant hydrothermal event before the evolution of the Witwatersrand basin. No such hydrothermal event is recorded in the hinterland, no viable alteration halo is known in any potential hinterland, and no gold deposit that is even 1 percent of the Witwatersrand has been found nearby. We may never be able to rule out categorically that the source for the 1,500 Moz of gold has been completely removed by erosion of the hinterland around the whole 300-km-long basin margin (noting the very limited unroofing of the basin itself), but this explanation does seem unlikely.

Sorting: Sedimentary sorting is regarded in the placer model as the means by which gold was concentrated in specific horizons, and in the case of quartz-rich conglomerate (banket ore), this might indeed be a viable mechanism if adequate gold is present in the hinterland. In a pioneering study of several auriferous rock types at East Driefontein mine, Krapez (1985) showed that the quartz-pebble-rich conglomerates do indeed have elevated gold abundances, but so also do other rock types, including matrix-supported conglomerates showing no apparent reworking that

to page 18 • • •

• • • from 17 Controversies on the Origin of World-Class Gold Deposits (Continued)

would have concentrated heavy minerals. As a result, he concluded that these differences in rock types reflected different gold-rich provenances rather than reflecting concentration by fluvial sorting processes. The issue raised by Krapez's data extends much further to all Witwatersrand reefs, because quartz-pebble conglomerates, lithic conglomerates, pyritic sandstones, carbon seams, and pyritiferous quartzites on unconformities are all mined for gold, and all represent very different sedimentary sorting environments. Such a range of gold host rocks makes it difficult to plead for special sorting processes during Witwatersrand basin sedimentation.

The interpretation of carbon seams has changed dramatically in the last 15 years. Carbon seams were thought to reflect the remnants of algal mats present in the depositional environment that trapped heavy minerals (notably gold and uraninite) in their filaments (Hallbauer, 1986). In contrast, recent studies have shown that the carbon seams reflect migrated hydrocarbons in bedding subparallel fracture networks that were not present at the time of sedimentary deposition. High gold grades in these seams must therefore reflect postdepositional processes.

Sedimentary sorting of the placer model has the challenging task of generating high gold values in a number of different rock types immediately above unconformities, while avoiding the formation of economic concentrations of gold in similar lithologic units elsewhere in the succession.

CONCLUSIONS

The hydrothermal replacement model builds on several independent lines of research that became available at the end of the 1970s. These included the role of fluids in the Earth's crust, the solubility of gold in a variety of high-temperature aqueous environments, and the efficacy of metamorphic processes to produce fluids capable of extracting, transporting, and depositing gold.

The close relationship between sedimentary facies and gold distribution lies at the heart of the placer model. However, the variety of sedimentary environments represented in the Witwatersrand reefs makes fluvial sorting an unlikely depositional mechanism to account for the enormous goldfield. In contrast, the chemical association of gold with Fe and C and with alteration is ubiquitous, and better explains the association of gold with specific rock types. Furthermore, the documentation of widespread hydrothermal alteration spatially related to Witwatersrand mineralization supports a hydrothermal model.

Inferred isochron "ages" for Witwatersrand gold grains require unrealistic assumptions to justify use of the isochron technique.

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REFERENCES

Armstrong, R.A., Compston, W., Retief, E.A., Williams, I.S., and Welke, H.J., 1991, Zircon ion microprobe studies bearing on the age and evolution of the Witwatersrand triad: Precambrian Research, v. 53, p. 243–266.

Barnicoat, A.C., Henderson, I.H.C., Knipe, R.J., Yardley, B.W.D., Napier, R.W., Fox, N.P.C., Kenyon, A.K., Muntingh, D.J., Strydom, D., Winkler, K.S., Lawrence, S.R., and Cornford, C., 1997, Hydrothermal gold mineralization in the Witwatersrand basin: Nature, v. 386, p. 820–824.

Barnicoat, A.C., Phillips, G.M., Law, J.D.M., Walshe, J.L., Phillips, G.N., and Fox N.P.C., 2001, Refuting the irrefutable—a new look at a well-known sample of Witwatersrand gold mineralisation: Economic Geology Research Unit, James Cook University, Townsville, Contribution 59, p. 16–17.

Davidson, C.F., 1965, The mode of origin of blanket orebodies: Institute of Mining and Metallurgy, London, Transcripts, v. 74, p. 319–338.

de Wit, M.J., and Tinker, J., 2004, Crustal structures across the central Kaapvaal craton from deep-seismic reflection data: South African Journal of Geology, v. 107, p. 185–206.

England, G.L., Rasmussen, B., Krapez, B., and Groves, D.I., 2002, Palaeoenvironmental significance of rounded pyrite in siliciclastic sequences of the Late Archaean Witwatersrand basin: Oxygen-deficient atmosphere or hydrothermal evolution: Sedimentology, v. 49, p. 1122–1156.

Feather, C.E., and Glathaar, C.W., 1987, A review of uranium-bearing minerals in the Dominion and Witwatersrand placers, *in* Pretorius, D.A., ed., Uranium deposits in Proterozoic quartz-pebble conglomerates: Vienna, International Atomic Energy Agency, Technical Document 427, p. 355–386.

Fox, N., 2002, Exploration for Witwatersrand gold deposits, and analogs, *in* Cooke, D. R., and Pongratz, J., eds., Giant ore deposits: Characteristics, genesis and exploration, University of Tasmania, CODES Special Publication 4, p. 243–269.

Frimmel, H.E., 1997, Detrital origin of hydrothermal Witwatersrand gold—a review: Terra Nova, v. 9, p. 192–197.

Frimmel, H.E., and Gartz, V.H., 1997, Witwatersrand gold particle chemistry matches model of metamorphosed, hydrothermally altered placer deposits: Mineralium Deposita, v. 32, p. 523–530.

Frimmel, H.E., and Minter, W.E.L., 2002, Recent developments concerning the geological history and genesis of the Witwatersrand gold deposits, South Africa: Society of Economic Geologists, Special Publication v. 9, p. 17–45.

Frimmel, H.E., Groves, D.I., Kirk, J., Ruiz, J., Chesley, J., and Minter, W.E.L., 2005, The formation and preservation of the Witwatersrand gold fields, the largest gold province in the world: Economic Geology, v. 100, in press.

Fuller, A.O., 1958, A contribution to the petrology of the Witwatersrand system: Geological Society of South Africa Transactions, v. 61, p. 10–50.

Fyfe, W.S., Price, N.J., and Thompson, A.B., 1978, Fluids in the Earth's crust: Elsevier, Amsterdam, 383 p.

Gartz, V.H., and Frimmel, H.E., 1999, Complex metasomatism of an Archean placer in the Witwatersrand basin, South Africa: The Ventersdorp contact reef—hydrothermal aquifer? Economic Geology, v. 94, p. 689–706.

Goldfarb, R.J., Phillips, G.N., Nockleberg, W.J., 1998, Tectonic setting of synorogenic gold deposits of the Pacific Rim: Ore Geology Reviews, v. 13, p.185–218.

Graton, L.C., 1930, Hydrothermal origin of the Rand gold deposits, Part 1: Economic Geology, v. 25, Supplement to no. 3, p.185.

Groves, D.I., Rasmussen, B., Krapez, B., and England, G.L., 2003. A comparison between the Witwatersrand and orogenic gold systems: A test of the hydrothermal Witwatersrand model: Mineral Exploration and Sustainable Development, v. 2, Orogenic hydrothermal systems, p. 727–730.

Hallbauer, D.K., 1986, The mineralogy and geochemistry of Witwatersrand pyrite, gold, uranium, and carbonaceous matter, *in* Anhaeusser, C.R., and Maske, S., eds., Mineral deposits of Southern Africa: Geological Society South Africa, p. 731–752.

Hart, S.R., and Kinloch, E.D., 1989, Os isotope systematics in the Witwatersrand and Bushveld ore deposits: Economic Geology, v. 84, p. 1651–1655.

Hughes, M.J., Phillips, G.N., and Carey, S.P., 2004, Giant placers of the Victorian gold province, SEG Newsletter, v. 56, p.1, 11–18.

Jolley, S.J., Freeman, S.R., Barnicoat, A.C., Phillips, G.M., Knipe, R.J., Pather, A., Fox, N.P.C., Strydom, D., Birch, M.T.G., Henderson, I.H.C., and Rowland, T.W., 2004, Structural controls on Witwatersrand gold mineralisation: Journal of Structural Geology, v. 26, p. 1067–1086.

Jolley, S.J., Henderson, H.C., Barnicoat, A.C., and Fox, N.P.C., 1999, Thrust-fracture network and hydrothermal gold mineralization: Witwatersrand basin, South Africa, *in* McCaffrey, K. J. W., Lonergan, L., and Wilkinson, J. J., eds., Fractures, fluid flow and mineralization, Geological Society, London, Special Publications, v. 155, p. 153–165.

Kirk, J., Ruiz, J., Chesley, J., Titley, S., and Walshe, J., 2001, A detrital model for the origin of gold and sulfides in the Witwatersrand basin based on Re-Os isotopes: Geochimica et Cosmochimica Acta, v. 65, p. 2149–2159.

Kirk, J., Ruiz, J., Chesley, J., Walshe, J., and England, G., 2002, A major Archean gold and crust-forming event in the Kaapvaal craton, South Africa: Science, v. 297, p. 1856–1858.

Krapez, B., 1985, The Ventersdorp contact placer: A gold-pyrite placer of stream and debris-flow origins from the Archaean Witwatersrand basin of South Africa: Sedimentology, v. 32, p. 223–234.

Kuhnle, R.A., and Southard, J.B., 1990, Flume experiments on the transport of heavy minerals in gravel-bed streams: Journal of Sedimentary Petrology, v. 60, p. 687–696.

Law, J.D.M., 2004a, Orogenic foreland gold: Linking orogenic and "Witwatersrand-style" mineralization [abs.], *in* Ashwal, L.D, ed,. Geoscience Africa 2004: Johannesburg, South Africa, University of Witwatersrand, Abstracts volume, p. 374–375.

——2004b, Potential for "Witwatersrand-style" gold in Phanerozoic sedimentary basins [abs.], *in* McPhie, J., and McGoldrick, P., eds., Dynamic Earth: past, present and future: Geological Society of Australia, 17th Australian Geological Convention, Hobart, Abstracts, v. 73, p. 92.

McLean, P.J., and Fleet, M.E., 1989, Detrital pyrite in the Witwatersrand gold fields of South Africa: Evidence from truncated growth banding: Economic Geology, v. 84, p. 2008–2011.

Minter, W.E.L., 1999, Irrefutable detrital origin of Witwatersrand gold and evidence of eolian signatures: Economic Geology, v. 94, p. 665–670.

Minter, W.E.L., Goedhart, M.L., Knight, J., and Frimmel, H.E., 1993, Morphology of Witwatersrand gold grains from the Basal reef: Evidence for their detrital origin: Economic Geology, v. 88, p. 237–248.

Muntean, J.L., Cline, J., Johnston, M.K., Ressel, M.W., Seedorff, E., and Barton, M.D., 2004, Controversies on the origin of world-class gold deposits, part I: Carlin-type gold deposits in Nevada, SEG Newsletter, no. 59, p. 1, 11–18.

Nami, M., 1983, Gold distribution in relation to depositional processes in the Proterozoic Carbon Leader placer, Witwatersrand, South Africa, *in* Collison, J.D., and Lewin, J., eds., Modern and ancient fluvial systems: International Association Sedimentology Special Publication, v. 6, p. 563–575.

Phillips, G.N., 1988, Widespread fluid infiltration during metamorphism of the Witwatersrand goldfields: Generation of chloritoid and pyrophyllite: Journal of Metamorphic Geology, v. 6, p. 311–332.

Phillips, G.N., and Evans, K., 2004, Role of CO_2 in the formation of gold deposits: Nature, v. 429, p. 860–863.

Phillips, G.N., and Law, J.D.M., 1994, Metamorphism of the Witwatersrand gold fields: A review: Ore Geology Reviews, v. 9, p. 1–31.

——2000, Witwatersrand gold fields: Geology, genesis and exploration: SEG Reviews, v. 13, p. 439–500.

Phillips, G.N., and Myers, R.E., 1989, Witwatersrand gold fields: Part II. An origin for Witwatersrand gold during metamorphism and associated alteration: Economic Geology Monograph 6, p. 598–608.

Phillips, G.N., and Powell, R., 1993, Link between gold provinces: Economic Geology, v. 88, p. 1084–1098.

Phillips, G.N., Myers, R.E., and Palmer, J.A., 1987, Problems with the placer model for Witwatersrand gold: Geology, v. 15, p. 1027–1030; v. 16, p. 1154–1155; v. 17, p. 92–93.

Phillips, G.N., Law, J.D.M., and Stevens, G., 1997, Alteration, heat, and Witwatersrand gold: 111 years after Harrison and Langlaagte: South African Journal of Geology, v. 100, p. 377–392.

Pretorius, D.A., 1981, Gold and uranium in quartz-pebble conglomerates: Economic Geology 75th Anniversary Volume, p. 117–138.

——1989, The sources of Witwatersrand gold and uranium: "A continued difference of opinion": Johannesburg, Economic Geology Research Unit, University of Witwatersrand, Information circular no. 206, 43 p.

Reid, A.M., le Roex, A.P., and Minter, W.E.L., 1988, Composition of gold grains in the Vaal Placer, Klerksdorp, South Africa: Mineralium Deposita, v. 23, p. 211–217.

Robb, L.J., and Meyer, F.M., 1990, The nature of the Witwatersrand hinterland: Conjectures on the source area problem: Economic Geology, v. 85, p. 511–536.

——1995, The Witwatersrand basin, South Africa: Geological framework and mineralisation processes: Ore Geology Reviews, v. 10, p. 67–94.

Rundle, C.C., and Snelling, N.J., 1977, The geochronology of uraniferous minerals in the Witwatersrand triad: An interpretation of new and existing U-Pb data on rocks and minerals from the Dominion reef, Witwatersrand and Ventersdorp Supergroups: Philosophical Transactions of the Royal Society of South Africa, v. 286, p. 567–583.

Seward, T.M., 1973, Thio complexes of gold in hydrothermal solutions: Geochimica et Cosmochimica Acta, v. 37, p. 379–399.

Stevens, G., Gibson, R.L., and Droop, G.T.R., 1997, Midcrustal granulite facies metamorphism in the central Kaapvaal craton: The Bushveld Complex connection: Precambrian Research, v. 82, p. 113–132.

Sutton, S.J., Ritger, S.D., and Maynard, J.B., 1990, Stratigraphic control of chemistry and mineralogy in metamorphosed Witwatersrand quartzites: The Journal of Geology, v. 98, p. 329–341.

Walshe, J.L., Ruis, J., Chesley, J., Barnicoat, A.C., Phillips, G.M., Hobbs, B.E., Regenauer-Lieb, K, and Ord, A., 2004, Hydrogen flux from the Earth's core: Origin of the Witwatersrand gold deposits and related phenomena through Earth history: University of Western Australia, Extended abstracts, Publication 33, p. 195–198.

Xiong, Y., and Wood, S.A., 2000, Experimental quantification of hydrothermal solubility of platinum-group elements with special reference to porphyry copper environments: Mineralogy and Petrology, v. 68, p. 1–28.