A Review of the Witwatersrand Basin -
The World’s Greatest Goldfield

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The world’s greatest deposit of gold is hosted by the Archaean Witwatersrand sedimentary basin, situated in the central portion of the Kaapvaal Craton of South Africa. The geological setting of this remarkable clastic sedimentary deposit, which has yielded more than one third of all the gold ever produced on the planet, is discussed. The stratigraphy and structure of the Witwatersrand Supergroup is reviewed together with the sedimentology, mineralogy and geochronology of the more important auriferous conglomerate (reef) horizons. Geophysical methods of exploration are discussed briefly.

The Witwatersrand Basin was formed in response to a series of crustal plate movements from the north and west in a foreland basin setting. Deposition commenced in a shallow marine environment with quartzite and shale, including prominent iron rich shale horizons forming the West Rand Group (WRG). The overlying dominantly arenaceous Central Rand Group (CRG) was deposited in a basin which regressed as it filled. Important gold deposits formed on braided fluvial plains which sometimes terminated in a shoreline. Gold reefs at the base of the CRG show evidence of later marine reworking. Higher in the sequence, fluvial deposits become dominant. The focus of this paper is the Central Rand Group where most of the gold mineralisation occurs. Detrital gold (largely within sulphides) and uranium (as uraninite) were originally concentrated along with placer minerals such as chromite and zircon, at the base of fluvial cycles. In addition to the placer mineralisation, prokaryotic bacteria flourished and provided carbon-rich material that was highly effective in the concentration of non-detrital gold. Although most of the lithologies, including reef horizons, have great continuity and can be correlated across much of the Witwatersrand Basin, discrete entry points of reef material, with distributary channels and associated ore shoots, can generally be clearly defined.

Three major events reshaped and metamorphosed the Witwatersrand. Lateral crustal plate movements caused severe faulting and folding, especially along the western and northern sides of the Basin. The second event was the catastrophic Vredefort meteorite impact which struck the centre of the basin. The resulting fluid movement which pervaded the Witwatersrand strata caused widespread metasomatic alteration. Localised alteration and remobilisation of the gold mineralisation is thought to have been in partial response to this event. The third major event was the emplacement of the Bushveld Complex, which is the largest layered igneous intrusion of its kind on Earth. The heat generated by this intrusion certainly exceeded that of the Vredefort event, also making it an important agent of mineral alteration and remobilisation, especially along the northern flank.

The “Great Debate” on the origin of the gold has been the subject of heated discussions for decades. The three main points of view are a placer source, a hydrothermal source and a combination of the two called the modified placer theory. Recognition of the problem was realised soon after the discovery of the gold and continues to this day. Evidence has been presented in favour of all arguments, lending more credence for the modified placer process. Although the Witwatersrand is a mature goldfield with declining production, it is estimated that it still contains six times more gold than the world’s second largest goldfield. Much of the remaining resource occurs at considerable depths; however, there are still opportunities for extracting some of this resource, as well as generally somewhat lower grade mineralisation, at moderate to shallow depth. The Basin thus remains a major exploration target.

Gold mining in the Witwatersrand Basin has been responsible for the creation of the metropolis of Johannesburg and many thriving mining towns and has

DOI: 10.18814/epiiugs/2016/v39i2/95771
had a major influence in the shaping of South Africa. It still plays an important role in the country’s economy.

Introduction

The Witwatersrand Basin is the largest goldfield in the world having yielded over 52,000 tonnes of gold (~1,672 Moz.) to the present time, representing more than one third of all gold ever produced on Earth. It is estimated that an inferred resource of about 30,000 tonnes (~965 Moz.) remain in the basin.

A white quartzite ridge named the Orange Grove Quartzite, forms the lowermost stratigraphic layer of the basin. This prominent feature forms the northern scarp edge of the Witwatersrand plateau in the Johannesburg area. A number of streams have their origins on the plateau and have given rise to waterfalls which cascade over the escarpment edge (Figure 1). The combination of white quartzite and white water has resulted in the appropriate name of Witwatersrand (White Waters Ridge).

Brothers Fred and Harry Struben discovered the first gold in quartz veins along this Ridge, but also noted the presence of traces of gold in a quartz pebble conglomerate as well. In 1886 their associates George Harrison and George Walker, discovered and sampled the rich Main Reef Leader conglomerate on the farm Langlaagte, near present day Johannesburg. The subsequent gold rush attracted worldwide attention and capital investment flowed into the area amid feverish activity. Wealthy nations and entrepreneurs alike rushed in to secure a stake in the bonanza, leading to huge opportunities and wealth creation, together with a number of inevitable conflicts (Antrobus, 1986).

The Witwatersrand Supergroup is a 2.9 Ga old, Archaean, intra-cratonic, sedimentary succession, occupying a central position on the Kaapvaal Craton of South Africa. The lower or West Rand Group mainly comprises iron rich shale and quartzites, while the gold bearing conglomerates occur almost exclusively in the dominantly arenaceous upper, or Central Rand Group. The Witwatersrand sediments are underlain by metamorphosed volcanics and minor elastic sediments of the Dominion Group, which in turn overlie an older granite-greenstone basement (Figure 2). Much of the Witwatersrand is overlain by the extensive volcano-sedimentary Ventersdorp Supergroup, the dolomitic and quartzitic Transvaal Supergroup, and sediments of the Karoo Supergroup. The Pontola Supergroup, straddling the border between Swaziland and Kwazulu-Natal, has been correlated with the Witwatersrand but no substantial gold mineralisation has been found in this sedimentary sequence.

After its discovery, the outcrop of the Main Reef Group, which hosts the most important gold-bearing conglomerate reefs of the Witwatersrand, was soon traced along the Central Rand for some 40 km, from the Durban Roodepoort Deep mine in the west, to the East Rand Propriety Mines (ERPM) in the east (Wermüller, 1986). Shortly thereafter, the West and East Rand Goldfields were discovered. The search for the continuation of the gold-bearing strata beneath a cover of lava, dolomite and quartzite (sometimes in excess of 2,000 m thick), commenced in earnest during the first half of the 20th century and seven major goldfields were delineated within the Witwatersrand Basin over this period (Figure 3). A detailed history of these discoveries is given in Antrobus (1986) and Mendelsohn & Potgieter (1986).

A number of exploration methods have been used in the search for the extensions to the Witwatersrand conglomerate reef under younger cover. Geophysical surveys in particular, in the form of magnetics and gravity and more recently seismics, have played an important role. Exploration diamond drilling on the Witwatersrand began as early as 1889 using a steam driven Sullivan drill rig (Denny, 1900). Denny stated that “It is a well-established fact that the only reliable and satisfactory method of drilling prospect holes is by means of diamond core drills”. This remains true to this day, with diamond drilling having played a major role in unravelling the Witwatersrand story. Exploration is time consuming and requires meticulous work to be done. In the case of four of the seven major goldfields, it took close to fifty years of endeavour, before the first significant gold mine was established.

Sedimentological and geostatistical studies have played a major role in mine exploration and the evaluation of individual conglomerate reefs and together with rock mechanics studies, have guided the planning of underground development and mining. Parameters such as conglomerate thickness, total thickness of quartzitic zones within the reef (internal waste), gold content (the product of reef width and grade), together with sedimentological data, have been important in predicting lateral and vertical variations of gold grade and in identifying ore shoots and grade trends.

The South African gold mining industry was controlled for many years by six major mining houses - Anglo American, Anglovaal, General Mining/Union Corporation, Gold Fields, JCI and Rand
Mines. The first mining house was that of Gold Fields of South Africa, established in 1887 by the entrepreneurs Cecil Rhodes and Charles Rudd. Although many of the mining houses have been restructured or have disappeared over the last two decades, active exploration is still taking place, particularly by a number of new players and the Witwatersrand Basin still remains one of the world’s prime gold exploration targets.

Historical and technical detail regarding the Witwatersrand is given by Haughton (1964), Antrobus (1986), Mendelsohn & Potgieter (1986) and Handley (2004). More recent overviews include those by McCarthy (2006), Frimmel et al. (2005) and Robb & Robb (1998). The literature on the Witwatersrand is vast and exceeds well over 1,000 references.

**The Goldfields**

The gold-bearing conglomerate reefs of the Witwatersrand are mined in seven major goldfields, and a few smaller occurrences, which extend for over 400 km in what has been called “The Golden Arc”. The arc is centred on the conspicuous Vredefort Dome (Figure 3). This feature is thought to be a major meteorite impact site, fortuitously located in the centre of the Witwatersrand Basin (Therriault et al., 1997). The diameter of the original astrobleme is estimated to have been 300 km. A central core of up-domed granitic basement is rimmed by steeply dipping upturned beds of the overlying Witwatersrand Supergroup strata. The present granite core is some 60 km in diameter at surface (Figure 3).

After the discovery at Langlaagte, the gold bearing “reefs”, as they became known, were soon traced to the east and west leading to the establishment of the Central Rand Goldfield (Figure 3). Further east, across a break in continuity of the reef horizons known as the “Boksburg Gap”, gold bearing reefs were again located. They occur in a large adjacent basin that became known as the East Rand Goldfield. The western limit of the Central Rand Goldfield is defined by a major horst structure known as the Witpoortjie Break. Exploitation commenced towards the end of the 19th century on a large number of conglomerate reefs, which lie to the northwest of this break and which constitute the West Rand Goldfield (Figure 3).

To the southwest of the West Rand Goldfield, Witwatersrand strata are covered by progressively thicker, younger sediments of the Transvaal and Karoo Supergroups. It took another forty years to unravel the position of the gold bearing reefs in this area with painstaking geophysical surveys and diamond drilling, leading ultimately to the establishment of the West Wits Goldfield. This goldfield consists of an Eastern sector comprising
the Venterpost, Libanon and Kloof mines and is separated from the Carletonville sector by a conspicuous structural feature known as the Bank fault or break (Figure 3).

Gold was discovered in the Klerksdorp area very soon after the discovery on the Central Rand (Chapman et al., 1986). Most of this gold however was found in low grade conglomeratic reefs of the West Rand Group. It was nearly 50 years after these early discoveries that the important Vaal Reef was revealed. This became the principal gold reef of the Klerksdorp Goldfield. This goldfield lies to the southwest of the West Wits Goldfield on the southwestern side of a feature known as the Potchefstroom Gap (Figure 3).

The discovery of the Welkom Goldfield to the south of Klerksdorp, across the Bothaville Gap, followed. This goldfield also lies entirely beneath younger cover sequences. The most recent of the major goldfields to be discovered was the Evander Goldfield in the northeast (Figure 3), also lying entirely below younger cover. It was discovered with the aid of geophysics in the 1950s.

Stratigraphy

The Witwatersrand Supergroup comprises a lower “West Rand Group” and an upper “Central Rand Group” (SACS, 1980). The formations which comprise the latter are shown in Figure 4. The continuity of the major geological units, marker horizons and individual conglomerate reef horizons around the auriferous northern and western basin edges, is a feature of the Witwatersrand as exemplified by the major stratigraphic units of the Central Rand Group.

The stratigraphic nomenclature of the Witwatersrand has undergone several revisions. A chronostratigraphic scheme was proposed by Mellor (1915) and used for many years. He divided the Witwatersrand into an “Upper Witwatersrand System” and a “Lower Witwatersrand System”. These units were revised to fit a more appropriate lithostratigraphic scheme (SACS, 1980), where the essential unit is the Formation. The Central Rand is taken as a type section (Figure 4) and the strata in all of the goldfields can be related to this stratigraphy, albeit with minor departures. However in the Welkom, Klerksdorp and Evander Goldfields in particular, local nomenclature has prevailed, often combining formations where they could not be unequivocally defined. Figure 4 shows the stratigraphic position of the important gold reefs in relation to the type formations and to each other.

West Rand Group

The lower or West Rand Group (WRG) sediments accumulated in response to rapid episodes of mechanical subsidence related to a pull-apart basin developed under trans-tensional rifting conditions (Maynard & Klein, 1995). Quartzites and iron-rich shales prevail in roughly equal proportions (Pretorius, 1974). Many of the quartzites...
are shallow marine shelf sand bodies (Eriksson et al., 1979; Beukes & Nelson, 1995). The WRG comprises the lower Hospital Hill Subgroup; middle Government Subgroup and upper Jeppesfontein Subgroup. The shales of the WRG are characterised by the presence of magnetite bearing interlayers. These layers played a significant role during deep basin exploration, as they were used as magnetic markers.

**Central Rand Group**

The overlying Central Rand Group (CRG) is a dominantly arenaceous sequence comprised of quartz-pebble conglomerates, quartzites, quartzwackes and minor shales. The quartzite to shale ratio is 12.6:1 (Pretorius, 1974), as opposed to a ratio of only 1:1 for the WRG.

The CRG contains by far the bulk of the gold mineralisation. It is divided into a lower Johannesburg Subgroup and an upper Turffontein Subgroup. These Subgroups are separated by the Booyens Shale Formation, often called the “Upper Shale marker” in the Welkom Goldfield.

The Central Rand Group comprises a number of formations which, although varying in thickness, can be traced and correlated, with a few exceptions, in all the goldfields (Figure 4). The gold-bearing conglomerate reefs tend to occur in clusters which are informally referred to as “reef groups”. As seen in Figure 4, the economically important reef names vary from one goldfield to another and these are highlighted in red.

All of the important gold reefs lie on prominent unconformity surfaces, many of which can be traced around the entire basin. Compressional tectonic episodes with significant strike movement (Beukes & Nelson, 1995), led to periodic uplift in the hinterland of the basin which was a necessary trigger mechanism for the development of each of the placer gravels.

**Venterstpost Formation**

The Venterstpost Contact Reef, commonly called the “VCR”, is the basal conglomerate of the overlying Venterstpost Formation at the base of the Venterstpost Supergroup. This is a volcanic dominated sequence, and therefore is not, *sensu stricto*, a part of the Witwatersrand Supergroup. It is nevertheless spatially related to the underlying auriferous reefs of the Witwatersrand and from a practical mining point of view, is considered to be part of the Witwatersrand.

The formation contains significant lava debris and generally occurs in proximity to the underlying Elsburg Reefs. Basinward, the Elsburg and VCR Reefs develop an almost conformable relationship. The VCR was deposited in a tectonically active environment, with debris flow deposits and incised channels attesting to this (Hall et al., 1997).

**Black Reef Formation**

The Black Reef Formation lies at the base of the overlying Transvaal Supergroup. Although not a part of the Witwatersrand Supergroup, Black Reef conglomerates which occur within the confines of the Witwatersrand Basin, always carry gold in close proximity to footwall Witwatersrand gold-bearing conglomerates. This suggests a localised origin, related to erosion of Witwatersrand conglomerates, although this simplistic view has recently been questioned.

**Structure**

Despite the large amount of mining and geological research that has taken place over the years, the complex, basin-wide structural character of the Witwatersrand Basin has not yet been fully compiled. The main source of information on structure has come from the mapping and compilation of data from underground workings by mine geologists, surveyors and samplers. Detailed structural maps of all the major goldfields exist and provide a picture of complicated faulting and folding, particularly along the northwestern margin of the basin (Dankert & Hein, 2010). More recently, several 3D-seismic surveys have been undertaken providing a significantly improved record of the major faulting. The base of the Venterstpost lavas against the underlying Witwatersrand strata, provides a very strong seismic reflector which shows that blocks of ground defined by normal and reverse faults have moved relative to each other, disrupting the continuity of the reef horizons and posing many challenges for mining and mine design. Folding and basin edge faulting have been important controls for sediment deposition and gold distribution patterns within the basin and fold trends have been employed in many instances, such as the Central Rand Goldfield, in evaluating the economic viability of various reef horizons.

Detailed structural studies at a stope scale (Jolley et al., 1999) have recorded mineralised thrust-related fracture systems at major rheological interfaces, as seen for example in the Venterstpost Contact Reef (VCR), which lies between Witwatersrand footwall sediments and overlying Venterstpost volcanics. In certain instances the VCR has been imbricated by zones of minor thrust movement along reef contacts, with the formation of dilatant sites. Bedding-parallel shear zones at the base of certain reefs may have been conduits for the introduction of hydrothermal fluids which introduced or modified the gold during a compressional phase. Such sites are thought to be associated with hydrothermal fluid flow and local precipitation of gold. A strong correlation between elevated gold grades and fracture densities has been reported in places and supports a hydrothermal fingerprint for some of the mineralisation. The extent to which these fluids actually brought in the gold and to which they remobilised in situ gold, is difficult to quantify.

Three main deformational episodes relating to gold mineralisation have been recognized by Myers et al. (1990) and McCarthy (2006) (Figure 5a, b and c). An additional stage has been incorporated into Figure 5b as outlined below.

**a. Early Syndepositional deformation:** This phase commenced during the Johannesburg Subgroup times and occurred under regional compression (Figure 5a). The basin became fragmented into a number of domains which had a direct influence on the sedimentation patterns. Incipient basement domes, basin edge faults and uplifted blocks provided material to create conglomerate layers and the folding patterns also played an important role in the channelling of sediment and its deposition in the basin. The notion was developed that the Central Rand Group accumulated in topographic lows between basement “domes” (Brock & Pretorius, 1964). This is supported by the presence of auriferous reef development with proximal areas near a series of pronounced domes along the northwest flank of the Witwatersrand Basin. This constitutes what has been
termed the Rand Anticline (Pretorius, 1974) (Figure 5a).

b. Late syndepositional deformation: This phase commenced during the Turffontein subgroup times with progressively more rapid uplift along the marginal thrusts which led to an upward coarsening of the basin fill, culminating in the predominantly conglomeratic Mondeor Conglomerate Formation at the top of the Central Rand Group. Additional faulting took place basinwards resulting in the formation of further erosional entry points. In part, the faults controlled the formation of the Kimberley Reefs but, more importantly, the Elsburg and Mondeor conglomerate formations (Figure 5b). This stage was particularly active in the West Rand South Goldfield and in the western and southwestern parts of the Welkom Goldfield.

With the relaxation of the previous compressive stresses, thrust faults were reactivated as normal faults together with new, major, normal faults culminating in post-Klipriviersberg (upper Venterdorp) times and creating the Platberg Group sediments and volcanic strata. This stage was particularly active along the western edge of the basin (Klerksdorp and Welkom Goldfields) and in the Evander Goldfield in the east. The Venterdorp magmatic activity provided a heat source for the introduction of hydrothermal fluids into the Witwatersrand (Wilson, pers. comm.). Venterdorp age dykes and sills served as conduits for the mineralising fluids and late-stage quartz veining associated with this deformation also hosted fluids which remobilised gold. Fluid inclusion data obtained from these veins suggest that hydrocarbon-rich fluids were also associated with remobilisation of gold (Drennan et al., 1999; Drennan & Robb, 2006).

c. Post-Transvaal Age deformation: The major deformation in this period was associated with the emplacement of the Vredefort

![Image](image_url)

**Figure 5.** (a) Early syndepositional structures which were active during Johannesburg Subgroup sedimentation, showing major entry points of reef material. (b) Late syndepositional structures active during the Turffontein subgroup sedimentation and middle Venterdorp times, showing major entry points of reef material. (c) Structure of the Vredefort impact rim synclinorium in relation to the underlying Witwatersrand beds. Karoo and Venterdorp strata have been stripped off to reveal the underlying strata (Modified after McCarthy, 2006).
Dome (McCarthy et al., 1986), (Figure 5c). The Dome represents an area of significant (~60 km) structural uplift within the central parts of the Witwatersrand Basin. The gold-bearing strata were tilted and in places overturned, and experienced at least two metamorphic events at ca. 2 Ga. These are explained by the formation of a large, 250-300 km diameter, meteorite impact structure, the extent of which closely correlates with the present day limits of the Witwatersrand Basin (Gibson & Reimold, 1999). Perhaps the most surprising aspect of the Witwatersrand was that the meteorite struck a rotating planet Earth precisely in the centre of the Witwatersrand Basin - this leaves much food for thought.

A large synclinorium developed around the up-domed core of the vredefort structure, which are associated regionally extensive, concentrically disposed, low amplitude folds. In addition, a number of low-angle thrust and normal faults developed tangentially to the structure. These are developed in some of the goldfields as bedding-parallel thrust faults. This infolding around the rim of the vredefort structure is largely responsible for the preservation of the Witwatersrand Basin in that the depressed strata were protected from significant erosion (McCarthy et al., 1990).

**Sedimentology**

A clear relationship between gold mineralisation and sedimentation has been observed in the Witwatersrand. Sedimentological studies have played an important role in the understanding of gold distribution patterns and the economic evaluation of various reef horizons. Research has focussed mainly on the conglomerate reefs of the Central Rand Group. A number of macroscopic, microscopic and geochemical studies have also been undertaken, mostly between 1960 and 1990, with numerous papers and review articles being published on the subject ( Pretorius, 1964 and 1974).

Burke et al. (1986) proposed that the sediments of the Witwatersrand include a lower flysch-type sequence (West Rand Group) and an upper molasse type facies, (Central Rand Group), both of which contain abundant siliceous volcanic detritus. They noted that the strata are thicker and more proximal on the northwestern side of the basin which is, at least locally, bounded by thrust faults. These features indicate that the Witwatersrand strata may have been deposited in a foreland basin and a regional geological synthesis suggests initial deposition on the craton-ward side of an Andean-type arc.

Most of the sediments of the Johannesburg Subgroup of the CRG were deposited in a fluviatile environment with evidence of marine incursions in places and sub-aerial exposure in others (Figure 6). Many of the important conglomerate reefs are fairly thin and sheet-like, a characteristic that may in part be due to marine reworking of incursions in places and sub-aerial exposure in others (Figure 6). These are explained by the formation of a large, 250-300 km diameter, meteorite impact structure, the extent of which closely correlates with the present day limits of the Witwatersrand Basin (Gibson & Reimold, 1999).

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The overlying Turffontein Subgroup is more clearly fluviatile in nature, the quartzites being characterised by distinct channels and related sedimentary structures. In some cases, particularly in the Welkom Goldfield, diamicittes and quartzwackes with polymictic clasts were deposited in response to rapid dumping in an influx stage. Such sediment generally lacks obvious sedimentary structures such as bedding planes or cross-bedding. The matrix is usually sericitic, giving the rock a moderate to dark yellowish-green colour.

Fluvial channels have characteristics which are common to several Witwatersrand quartz pebble conglomerates and are particularly well defined in the Kimberley and Elsburg conglomerates of the Turffontein Subgroup (Figures 5, 7 and 8).

Channel formation was initiated by nearby tectonic uplift with high flow rates resulting in new sediment being washed into the basin. This initial stage is characterised by cross bedded arenite units which form the lower portions of channels (Figure 7C). The sand is a pale grey colour as a consequence of the clay fraction having been flushed out. This resulted in the development of siliceous, often cross bedded, grey quartzites. Basal heavy mineral and pebble lags are usually present on a scoured basal contact of such sand filled channels (Figure 7B), which rest on a footwall of sericite rich, yellowish grey argillaceous quartzite to quartzwacke (Figure 7A). A yellowish grey footwall is a feature of several Witwatersrand reefs including the Carbon Leader of the West Wits Goldfield (Figure 12), the Commononage Reef on Hartebeestfontein Mine in the Klerksdorp Goldfield and the May Reef on Winkelhaak Mine in the Evander Goldfield.

The second stage of reef formation involves the development of laminar gravel bars and thin siliceous sands deposited in a protracted period of winnowing and degradation, above the siliceous cross bedded quartzites (Figure 7D). In certain instances, superimposed gravel bars merged to form thicker conglomerate packages. The individual gravel bars are seldom thicker than a few centimetres. As the flow rate decreased, pebbles were no longer transported and a final heavy mineral layer was deposited on top of the conglomerate, at the base of the younger overlying siliceous quartzite (Figure 7F). In the case of the U1E/a (Elburg) Reef of the West Rand, this process created the “U-Seed”, a widespread 2 cm thick pyritic heavy mineral placer, particularly enriched in sand-sized uraninite, chromite, zinc, arsenopyrite and gold (Figure 7E).

These two stages of reef formation give rise to a typical, “composite” Witwatersrand reef.

**Figure 6:** Oligomictic quartz pebble conglomerate with white to dark grey quartz pebbles in a pyritic matrix. The dark-rimmed dreikanter pebble near top right attests to aeolian processes on the braid plain (Kimberley Reef) (Photo by C. Pais, Anglovaal Ltd.).
rivers cut down and created knick points, possibly on incipient fault zones, which served as the locus for the apex of successive alluvial fans. At the foot of the fans and beyond, net erosion formed a scoured pediment where at times the UE1A (Composite Reef) was reduced to a 1 mm thick contact. Further downstream braided fluvial deposition created substantial high amplitude sand bars (trough cross bedding) which winnowed gravel and heavy minerals down to the toes of the sand bars (see Figures 7 and 8). In the proximal areas the conglomerates were very thin with very little sand. Down the palaeoslope, as the fluvial energy diminished, more sand and less gravel was deposited.

Mineralogy

Over 140 mineral species have been reported from the Witwatersrand sediments, most of them occurring in the conglomerate reefs where placer concentration took place. The introduction of hydrothermal fluids followed, modifying the assemblage and in places introducing new minerals. The nature and genesis of some of the more important minerals is discussed below.

Gold

The origin of the huge quantities of gold, largely confined to conglomerate layers in the Witwatersrand Basin, has been a contentious issue. The “Great Debate” concerning the syngenetic as opposed to the epigenetic origin of the gold has raged since shortly after the discovery and the various ideas put forward by De Launay (1896) summarised by Master (2003) are still being debated today.

Many workers and notably geologists actually working on the various gold mines, have favoured the placer model for the concentration of gold in the conglomerates. Sedimentological studies which commenced in the 1960s have largely supported the placer model and led to a better understanding of the depositional environments and controls for gold mineralisation.

Some gold particles clearly show water-laid features, such as rounded gold nuggets (Minter, 1999) and grains deposited as a heavy mineral concentrate on small cross bed foresets (Figure 9). The most likely source of this detrital gold is from older, Archaean, lode gold deposits which are present in all the greenstone belts of the Kaapvaal Craton. This source is inferred by a comparison of the $\delta^{18}O$ distributions in quartz pebbles and quartz sands (Vennemann et al., 1995). In addition rhenium (Re) - osmium (Os) isotopes of particles of gold and pyrite from the Witwatersrand give results which are consistent with detrital deposition. Osmium data suggests minor hydrothermal remobilisation and/or overprinting of hydrothermal gold on pre-existing gold grains but does not support the introduction of gold solely by hydrothermal fluids (Kirk et al., 2001).

Post depositional mobilization of gold is evident in many instances, for example in cross cutting veins containing carbon (Frimmel et al., 1993) (Figure 13). Some workers believe that the origin of most of the gold was hydrothermal as suggested by the alteration of conglomerate reefs (Law & Phillips, 2005) and their surrounding environment (Barnicoat et al., 1997).

The Hydrothermal Model proposes that much of the gold and pyrite were deposited from hydrothermal fluids which infiltrated barren conglomerates long after deposition. Phillips and Powell (2011, 2015) have suggested a metamorphic devolatilisation-hydrothermal replacement model which favours introduction of gold into the basin much later. Large shear zones such as the “Master Bedding Fault” of the Carletonville Goldfield are cited as
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probable pathways along which the gold was introduced.

A Precipitation Model suggests that gold and pyrite were deposited from solution during deposition of the conglomerates. The Modified Placer Model envisages gold being washed into the basin from pre-existing gold-bearing source rocks (Minter, 1978), followed by regional metamorphism and post depositional fluid flow throughout the basin (Phillips & Law, 1994). There is general agreement that the majority of the gold particles seen today are indeed hydrothermal precipitates and the modified placer model suggests that primary gold was mobilized by fluids which migrated over short distances (Frimmel, 2005). Fluids which either carried or mobilized gold have been attributed to the Ventersdorp, Bushveld and Vredefort events.

A connection between structure and the origin of the gold has been invoked by Jolley et al. (2004) and Dankert & Hein (2010). These workers have shown that significant fluid movement attributable to the Bushveld Intrusion has influenced the carbon and gold distribution patterns in various reefs, particularly along the northern margin of the basin. The Beisa Reef in the Welkom Goldfield is typical of the Au-U-C association where late stage fluids have carried hydrocarbon rich fluids (Drennan et al., 1999 and Drennan & Robb, 2006.).

The Modified Placer Model is now widely favoured and accounts for most of the observed phenomena. However there is evidence of further gold concentrating processes having been operative and primitive bacterial processes are thought to have been important in this regard.

Uranium

Uranium occurs in the conglomerate reefs mainly as the mineral uraninite (UO₂) which, due to oxidation, contains a certain proportion of UO₃. The decay of radioactive uranium has led to the formation of radiogenic lead which is often present as small specks of galena (Figure 10). Most rounded grains of uraninite appear to be of detrital origin and are believed to have originated in certain more evolved volatile rich granitic source rocks. Size analysis of uraninite, zircon and chromite grains by a number of workers, has shown sympathetic variations suggesting that these minerals are in hydraulic equilibrium (Koen, 1961). This gives credence to the placer origin of the uraninite.

Uranium is also frequently associated with carbonaceous matter in the reefs (radiogenic hydrocarbon), where uraninite is intimately associated with layers of columnar carbonaceous material (as for example in the Carbon Leader Reef) (Figure 12) and as allogenic uraninite grains in a quartzite matrix (Hallbauer, 1986 and Koen, 1961). Figure 10 shows an interesting rounded uraninite grain with equally rounded detrital chromite, pyrite and other minerals in a well-rounded mud-ball (Tucker, 1980). The interstitial pyrite appears to be a late stage infill of earlier species in this example, perhaps cemented during diagenesis.

The Witwatersrand has been a major producer of uranium, with some 28 mines having been producers in the past. The Bird Reefs of the West Rand and Klerksdorp Goldfields have been the most important sources and production has varied greatly, depending on the demand and price cycle.

Pyrite

Pyrite is ubiquitous in the Witwatersrand gold-bearing conglomerates and in certain quartzites and is often enriched in gold. Several forms of pyrite are present and attest to a range of formation processes (Viljoen, 1963; Utter, 1978; Tucker, 1980; Guy, 2012). Four main types of pyrite are recognised:

a. Allogenic, rounded, compact pyrite usually occurs in association with detrital zircon and chromite and is considered to be a primary detrital mineral.

b. Syngenetic, rounded porous pyrite is thought to have originated as mud-balls by the process of colloidal precipitation of iron sulphide gels in abandoned channels on braided fluvial plains. This form of pyrite is therefore sensu stricto not allogenic and is often associated with higher gold grades. Agangi et al. (2015), proposed concurrent biogenically-mediated pyrite formation and Au trapping by microbial activity. Koglin et al. (2010), in a trace element study of Witwatersrand and other pyrites, report that high Co/Ni ratios and low Au concentrations are typical of post-sedimentary pyrite which is hydrothermal in origin, while low Co/Ni ratios and high Au contents characterise pyrite grains which are syn-sedimentary in origin.

c. Diagenetic pyrite formed in the sediment before lithification.

Figure 9: Rounded Gold grains lying on small-scale cross bed foresets and regarded as evidence of a primary placer origin. Basal Reef, Free State Geduld Mine (W.E.L. Minter, 1990).

Figure 10: A water-worn Pyritic pebble with inclusions of uraninite (1), radiogenic galena (2), chromite (3), allogenic pyrite (4), interstitial secondary pyrite (5), chlorite (6) and pyrrhotite (7). The pebble edge is indicated by (8) (R.F. Tucker, 1980).
and metamorphism (Guy, 2012 and Tucker, 1980).

d. Epigenetic, often well crystallised euhedral to subhedral pyrite is interpreted as having formed during a metamorphic or hydrothermal event. This crystalline pyrite is generally younger and does not appear to be associated with the bulk of the gold mineralisation. Large et al. (2013), suggested that a significant proportion of the pyrite and gold was intrabasinal, derived from pre-existing Witwatersrand shales. They dated detrital pyrites between 2750 and 2950 Ma, with much younger hydrothermal (epigenetic) overgrowths between 2100 and 2020 Ma “demonstrating that both of the two main competing theories for the origin of the Witwatersrand gold reefs are likely to be correct”.

Some of the best gold values in Witwatersrand reefs occur when dull, porous, “buckshot” pyrite is present. Mineralogical examination of this pyrite reveals that the dull lustre and porous appearance is due to the presence of chlorite, either dispersed throughout the matrix or often in fine layers (Tucker, 1980). The latter is thought to be due to a laminated pyritic mud, which was subsequently ripped up and rolled into well rounded mud balls.

Size-sorted, dull, porous pyrite grains have accumulated at the toe of foresets (Figures 7 and 11). These grains appear to have not confirming a placer origin for gold in Witwatersrand Au-U ores, the palaeo-environmental significance of rounded pyrite largely negates its link to large scale hydrothermal introduction.

Guy et al. (2014), in a sulphur isotope study, concluded that “the majority of the buckshot pyrite grains were derived from a sedimentary provenance and that a wide range of pyrite morphologies are characteristic of sedimentary pyrite”. This implies a significant contribution of continentally derived sulphur for most of the pyrite grains in the Witwatersrand conglomerates.

**Carbon**

Carbonaceous material is ubiquitous in the gold bearing Witwatersrand conglomerates. It occurs mainly as thin black seams varying from a few millimetres to a few centimetres in width. It is particularly common in the Carbon Leader of the Carletonville Goldfield (Figure 12) and the Vaal, Basal and Elsburg Reefs. Carbon also occurs as small black specks, known as fly speck carbon, in many Witwatersrand reefs (Figure 13). As with gold and uranium, there has been considerable debate concerning the origin of the carbon and reasons for its close association with gold in particular.

Acid leaching of samples to dissolve the silica matrix suggests...
that the columnar structure of the carbon seams is the result of primitive algal growth (Hallbauer, 1986 and Tucker, 1980), (Figure 14). More recent work however suggests that the columns are related to structure and grew in dilatant zones in certain reefs. This carbon is thought to have been introduced by early hydrothermal fluids which may have been sourced from the underlying West Rand Group carbonaceous shales (Jolley, 2004; Large et al., 2013). Hydrocarbon rich fluids are generally late and are, according to Drennan et al. (1999) and Drennan and Robb (2006), unequivocally associated with metal redistribution.

Mossman & Dyer (1985), Ebert et al. (1990), Drennan and Robb (2006) and Mossman et al. (2008), suggest that the carbon originated as a prokaryotic life form, while England et al. (2002a), suggest that the source of the carbon was from ancient oil which is found in inclusions in quartz grains. The latter authors conclude that the oil “was derived from multiple source areas, with the principal source probably being shales within the West Rand Group”. It has also been proposed that the carbon is not of bacterial origin at all but has a fine mesophase texture that has previously been wrongly attributed to plant (algal) morphology (Gray et al., 1998). The latter authors conclude that “the combination of hydrocarbon, radiation and hydrothermal fluid flow, distinguishes Witwatersrand Basin pyrobitumens as being different from conventional oil”.

It has been proposed that diagenetic maturation of primitive bacterial material released hydrocarbons that were able to migrate through the sediments in a process perhaps similar to the origin and migration of oil in sedimentary deposits. Over pressure created the fracture network that hosted the oil and also introduced Uranium as uranyl ions. Polymerisation of the carbon occurred due to ionizing radiation in the proximity of detrital uranium grains during catagenesis (Drennan & Robb, 2006). On meeting a reducing agent (oil), uraninite precipitated, stabilizing the oil by polymerization. Further hotter hydrothermal flux then ‘coked’ the bitumen to the familiar fibrous (spindle-shaped) mesophase. Wanger et al. (2012), show that while carbon spheres in the Witwatersrand contain a suite of alkane, alkenes and aromatic compounds, consistent with organic-rich carbon seams within the auriferous reef horizons, they do not retain any true structural, fossil information and were formed by an abiogenic process.

Carbon seams are developed in lower energy environments adjoining higher energy fluvial distributary channels in more proximal reaches. Such areas constituted ideal sites for these remarkable early life forms to live, grow, and trap passing minerals, notably gold and uranium, either physically, chemically or biologically. However, carbon seams in the Beisa Reef of the Welkom Goldfield are late stage features, as the carbon bifurcates its way through the conglomerate. Drennan (pers. comm.) concluded that there are at least 4 generations of hydrocarbon. Woods, Drennan and Durbach (in preparation) indicate that the precipitation of carbon from hydrocarbon gas phases is quite possible and that not only uranium, but Fe and Cu may act as electron donors that result in carbon precipitation.

Recent thermodynamic modelling and mass balance calculations have shown that chemical transport and precipitation of gold could have taken place in anoxic surface waters in an oxygen free atmosphere some three billion years ago (Heinrich, 2015). It is suggested that sulphurous gases from volcanic eruptions created acid rain that enabled the dissolution and transport of gold in surface waters as sulphur complexes. Precipitation of this dissolved gold onto organic material in shallow fluvial overbank areas could have been triggered by chemical reduction. It is concluded that the precipitation of much of the gold in the Witwatersrand Basin could only have taken place during the Archaean, after the emergence of continental life but before the increase of oxygen levels in the atmosphere (Heinrich, 2015).

Besides gold and uraninite, a number of heavy minerals and a variety of base metal sulphide minerals such as chalcopyrite, skutterudite, arsenopyrite and limnaeite, are frequently associated with the carbon.

**Diamonds**

Diamonds constitute a relatively abundant heavy mineral constituent of certain reefs such as the Nigel Reef of the East Rand Goldfield. They were extracted commercially in the early days by the Klerksdorp and Modderfontein Gold and Diamond Mining Companies and at a number of other mines, prior to the advent of fine milling of the ore, necessary for the cyanidation process.

The yellow-green colour of many of the diamonds is thought to be as a result of exposure to radiation, while their presence suggests that diamond bearing kimberlites existed over 2.8 Ga ago on a thickened Kaapvaal Craton.

**Detrital Oxides**

The most common detrital oxides in Witwatersrand reefs are chromite, zircon and ilmenite/titute, the latter usually being altered to leucocene (Figure 15). Abraded detrital chromite and zircon grain sizes are typically 50 to 200 µm (Utter, 1978) and a number of studies have shown that their sizes decrease from proximal areas of sediment input to more distal areas (Viljoen, 1963). Chromite and zircon are commonly seen to be associated with the finer grained allogetic compact pyrite (Tucker, 1980). These grains all have similar diameters and are likely to have been in hydraulic equilibrium with each other and with pyrite.
Age determinations have provided critical evidence in helping to resolve the great placer - hydrothermal debate on the origin of the Witwatersrand gold. Important events are listed in chronological order in Table 1. The age of the base of the Witwatersrand Super group has been fixed at 2.970 Ga, while the top of the Central Rand Group has been dated at 2.714 Ga, which is the age of commencement of Ventersdorp volcanism. The emplacement of the Ventersdorp lavas and Bushveld complex at 2.05 Ga and the Vredefort event (2.02 Ga) are thought to have been important for the mobilization of gold and other elements.

Principal Gold Reefs

While spasmodic tectonic events caused uplift which triggered the formation of most of the conglomerate reefs, protracted periods of tectonic stability resulted in long periods of low energy degradation of the conglomerates. The development of unconformities and the concomitant placer winnowing of heavy minerals was active during these periods. This resulted in the primary concentration of gold. Highly productive gold reefs in the Witwatersrand are commonly related to such unconformities, which are most pronounced towards the basin edge to the north and west, the areas of the most intense tectonic activity. A number of cycles often followed within relatively short time periods, resulting in groups of closely spaced reefs which correspond to the various conglomerate formations. The overlying Venterspost Formation (Figure 4) and the Black Reef Formation at the base of the overlying Transvaal Supergroup, are included on account of their significant gold mineralisation and geographical proximity to the Witwatersrand.

Main Reef Group

The Main Reef Group (MRG) of conglomerate reefs lies at the base of the Johannesburg Subgroup of the Central Rand Group, in the Blyvooruitzicht and Main Formations (Figure 4). The Main Reef, Main Reef Leader and South Reef and their equivalents in other goldfields are the most important reefs in this cluster and have been extensively mined along the northern edge of the basin in the East Rand, Central Rand and West Wits Goldfields. Reef names vary from one goldfield to another as shown in Figure 4. These reefs become progressively eroded to the east. In the East Rand Goldfield they are collectively reduced to the Nigel Reef while they are not present in the Evander Goldfield (Figure 4).

The Main Reef and overlying Main Reef Leader (MRL) were the first reefs to be mined. They were discovered by Harrison and Walker in 1886 (Werdmüller, 1986) and the discovery site can still be seen at Langlaagte to the west of downtown Johannesburg (Figures 16 and 17). One of the very early stopes on the Main Reef Leader on Village Main Mine, as well as the underlying unmined Main Reef, was unearthed and can be viewed in the basement of the Standard Bank building in downtown Johannesburg.

Main Reef

The Main Reef is the lowermost of the economically exploitable reefs. It is generally a poorly sorted conglomerate with relatively large pebbles (typically up to 5 cm in diameter) and occasional boulder filled channels. It is usually composed of a number of pebble bands which coalesce as the reef package thins from over 4 m to less than 2 m as seen on the western and eastern faces, respectively, at the Discovery site on Langlaagte (Figure 17). The reef has been sporadically mined along strike in the CRG, particularly where it is thinner and has higher grades. A substantial resource averaging just less...
than 4 g/t (using a 3 g/t cut-off) is still present in the Main Reef on the Central Rand and is currently being exploited by Central Rand Gold.

The Carbon Leader Reef is the correlative of the Main Reef in the Carletonville Goldfield (Figure 4). It is characterised by an abundance of carbon with visible gold and very high gold grades. A number of lithofacies have been established. A channel facies with conglomerate bands and intervening sands (quartzite), forms a channelized, thick (up to 3 m), multiple-band facies representing areas of major sediment input (Figure 18). Channel edges are characterised by narrower composite conglomerates, often with significant carbon and very high gold values. Away from the channels, in a broad overbank area, near the centre of the goldfield, the Carbon Leader often reduces to a single gold-rich columnar carbon seam. An erosional channel facies consists of reworked channels with proximal areas to the north. Sediment input directions for the Carbon Leader are from the north, with the development of thin sandy facies type reef in the distal area to the south (Figure 18).

The equivalent of the Main Reef in the Welkom Goldfield is the Beisa Reef which lies at the base of the Central Rand Group in the southern part of this goldfield (Figures 4, 19 and 20). The Welkom Goldfield is structurally complex with major north-south trending faults dividing it into numerous blocks of various sizes. Faulting, together with upturning (and overturning in places) along the western edge, has had an important bearing on the distribution of the various reefs in this goldfield (Figure 20). While the intense faulting has made mining difficult, it has resulted in the reefs being up-faulted to the east. If this had not been the case, much of the Welkom Goldfield would have soon become too deep to mine.

**Pyritic Quartzite and Chloritoid Bearing Channels**

After the deposition of the Main Reef and Carbon Leader, a number of erosion channels incised into, and in places removed, the Main Reef in the East Rand, Central Rand and Carletonville Goldfields (De Jager, 1986), (Wagener, 1972). In the Central Rand on the Village Main and City Deep Mines, such channels are termed the “Pyritic Quartzites” or “PQ’s”. A number of PQ’s are sporadically gold bearing, with very high but erratic values. On the West Rand, equivalent channels are filled with chloritoid-rich shale known as the Cab or Black Bar. In the West Wits Goldfield, the Green Bar is a spatially very persistent chloritoid-rich, massive siltstone which is on average 2 m thick and deposited about 2 m above the Carbon Leader (McCarthy, 2006; Toens & Griffiths, 1964). The basal contact (and on occasion the top contact) can be laminated and is often marked by bedding parallel shearing with quartz veining. In a few instances the Green Bar channels eroded down and eliminated the underlying strata as deep as the North Leader Reef (about 15 m below the Carbon Leader). These channels are not common and only in rare instances are the reworked sediments economic (M Wilson, pers. comm.). These thick cross-stratified arenites
are reminiscent of the thick cross-stratified lower unit comprising a part of the “E9G/d” Reef on Cooke Section (Figure 7).

On the East Rand, scoured channels occur below the Nigel Reef. The channels are filled with slumped conglomerates, quartzites and auriferous pyritic quartzites (De Jager, 1986).

Main Reef Leader

The Main Reef Leader (MRL) is an extensive, thinner and sheet-like conglomerate which overlies the Main Reef, Black Bar and the Pyritic Quartzite channels on the Central Rand. It was the most prolific gold producer of the Central Rand Goldfield and one of the most important reefs of the entire Witwatersrand Basin. The reef averages 40 cm in thickness, often with gold grades in excess of 50 g/t. It has been mined continuously for over 40 km along strike, for 6 km down dip and to vertical depths in excess of 3 km.

The MRL is generally a well-sorted and well-packed conglomerate with a dark coloured matrix, due mainly to the presence of chlorite and chloritoid derived from the Black Bar footwall. The pebbles are larger (up to 8 cm in diameter) and better sorted than those of the Main Reef, with higher grades. The remarkable continuity of this reef is considered in part to be due to marine reworking during a transgressive event.

Compilation of data including reef width (Figure 21), percentage internal quartzite and grade parameters for the Main Reef Leader on the Central Rand show a fluvial depositional pattern (W. Stear, pers. comm.). A well-defined major entry point is evident just north of the Village Main Mine. Further entry points are seen along the northern basin edge at Consolidated Main Reef Mine (CMR) to the west and Simmer & Jack to the east (Viljoen, 2009), (Figure 21). The prevalent southeasterly orientation of the channels and associated pay shoots appear to be controlled by a gentle set of NW-SE trending synclinal and anticlinal folds.

In places east-west trending ore shoots lying parallel to strike, have been interpreted as marine reworking along an ancient shoreline (W. Stear, pers. comm.). It is estimated that a resource of over 900 tonnes of gold still exists in the major channel at depths below 2,900 m (Figure 21).

South Reef

In the Central Rand Goldfield the South Reef lies 80 m above the Main Reef Leader. It has similar characteristics to the latter reef but is less well sorted and is usually comprised of a number of pebble bands (Viljoen, 2009). It has been a major producer of gold along most of the Central Rand.

The Nigel Reef is a stratigraphic equivalent of the South Reef in the East Rand Goldfield. It is a composite conglomerate reef which has cut into and incorporated the Main Reef Leader and Main Reef sediments to the east of the Boksburg Gap that separates the Central Rand and East Rand Goldfields. The reef is considered to have
Figure 20: Section through the southern Welkom Goldfield showing the recumbent basin edge fold and the position of various reef horizons (see Figure 19 for location) (after McCarthy, 2006).

Figure 21: Main Reef Leader sedimentary channels and related ore shoots largely controlled by NW-SE trending folds and highlighted by a reef isopach plan. Central Rand Goldfield (R.P. Viljoen and M.J. Viljoen).
acquired its gold content by a placer process and has been the major producer of gold in the East Rand Goldfield.

In the 1920s, Dr. Leopold Reinecke and mine geologists, defined payshoots on the Nigel Reef, together with a proximal entry point of reef material into the basin. These palaeocurrent trends were later refined by Minter & Loen (1991). The importance of NW-SE trending anticlinal folds in controlling sedimentation has been demonstrated by Stear (pers. comm.) and payshoot patterns for the Nigel and Kimberley Reefs in the East Rand Goldfield are shown in Figure 22 (Minter & Loen, 1991). The determination of palaeocurrent trends and payshoot patterns has been an important factor in the evaluation and understanding of Witwatersrand reefs.

The South Reef is present as a narrow band on the West Rand Goldfield where it was mined sporadically. It is a much wider and more important reef in the eastern sector of the West Wits Goldfield where it is known as the Middelvlei Reef on Libanon and Kloof gold mines and on the mines of the Carletonville sector of the West Wits Goldfield (Figure 4).

An artist’s impression of the landscape at the time of deposition of the Main Reef Group is shown in Figure 23. In the background, an eroding mountain range comprised of granites and greenstones constitutes the source region for both gold and uranium. Winnowing on the flat pediment by a braided fluvial system concentrated the gold on the flat-lying fluvial braid plain at the foot of the mountains. The cross-section in front of the picture shows a number of styles of typical gold-bearing conglomerate layers of the types described.

Mats of cyanobacteria (primitive green and amber algae) flourished in the quieter regions of the system and gave rise to the carbon seam facies of the Carbon Leader Reef. While carbon (i.e. bacteria) could conceivably grow in distal low energy environments, carbon is also seen in shallow channels in proximal areas which were abandoned due to avulsion, much like an ox-bow lake, but with a much lower sinuosity (Tucker, 1980).

**Bird Reefs**

The Bird Reefs occur in the Krugersdorp Formation and can be correlated, with a few exceptions, throughout the Witwatersrand and are generally characterised by uranium enrichment compared to other reef groups. The nomenclature of the Bird Reefs in the various goldfields is shown in Figure 4 with the economically important ones highlighted in red.

The Bird Reefs have been mined for uranium in the West Rand Goldfield on the Randfontein Estates Gold Mine (Hocking, 1986), where gold at one stage was considered to be a by-product of uranium, and on a more limited scale in the Central Rand Goldfield where large but isolated ore shoots are a feature. The Bird Reefs are the predominant gold source in the Klerksdorp and Welkom Goldfields. In the Klerksdorp Goldfield the correlative of the Bird Reef is termed the Vaal Reef. Usually less than 50 cm thick, it is well mineralised with nodular and crystalline pyrite, gold, uraninite and carbonaceous matter, concentrated along the base of the conglomerate (Robb & Robb, 1998). The provenance of the Vaal Reef was from the north and northwest. Like other important reefs, it lies on an erosional surface that was covered by fluvial drainage during a transgressive stage. In 1985 the Vaal Reef accounted for 22% of South Africa’s gold production, together with significant amounts of uranium. Gold production from the Vaal Reef amounted to just over 10% of the World’s production at the time.

In the Welkom Goldfield the Bird Reef is termed the Basal Reef and is developed across the northern two thirds of the goldfield (Figures 4, 19 and 20). It has a palaeocurrent direction towards the east. In the southern part of the goldfield a lateral equivalent known as the Steyn Reef was deposited from the south. Both the Basal and Steyn Reefs lie on unconformities. The oligomictic Basal Reef is slightly older than the less mature,
polymictic, Steyn Reef which has eroded the Basal Reef. Both of these placers were deposited on a braided fluvial plain which was subsequently inundated and reworked by a marine transgression (Minter, 1976).

**Kimberley Reefs**

The Turffontein Subgroup which is more fluvial in nature than the Johannesburg Subgroup, comprises three formations. The lowermost is the Kimberley Conglomerate Formation which overlies the Booyssens Shale (or Kimberley Shale) and hosts a number of variably mineralised conglomerate reefs (Figure 4). It is the only formation which has been mined in all of the Goldfields of the Witwatersrand, albeit on a lesser scale than some of the other reef groups.

The Kimberley Reefs are thinnest along the basin edge, where unconformities are most pronounced. In more distal areas, the conglomerates attenuate and the strata become conformable. The most pronounced unconformities, and the best gold mineralisation, lie at the base of each of the four main conglomerate/sandstone cycles of the Kimberley Formation.

Well-defined payshoot patterns have been mapped out in the East Rand Goldfield and have similar orientations to the underlying Nigel Reef. This suggests a common control through time for payshoot formation (Figure 22).

The Kimberley Reefs are well mineralised in the Sun project area of the northern Welkom Goldfield where they are referred to as the Big Pebble Reefs. These reefs yielded high gold grades (Anglovaal Limited, 1992). Detailed correlation between adjacent boreholes proved extremely difficult however, due to the rapid coalescing of the conglomerates towards the more proximal (west) side of the Basin.

**Elsburg Reefs**

The Elsburg Quartzite Formation, that overlies the Kimberley Formation, is composed mainly of quartz arenite and lies in the middle of the Turffontein Subgroup (Figure 4). The quartzite is pale grey, fine grained and siliceous with a few slightly more argillaceous zones. A prominent basal unconformity is associated with an extensive gold bearing conglomerate which has been given different names in various regions of the goldfield (Figure 4).

The Elsburg Formation strikes east-west in the Central Rand where the large pebble conglomerates in it are unmineralised. To the west, the formation swings southward near the Roodepoort/Panvlakte Fault that forms the southern margin of the Witpoortjie Break (Figure 3 and 24). This fault defines the western limit of the Central Rand Goldfield. Within this structural setting the Elsburg conglomerate becomes well mineralised and is known as the UE1A Reef on the Cooke Section of Randfontein Estates Gold Mine (REGM), with the same Middle Elsburg Reefs being mined on the Western Areas mine to the south (Figure 24). The Elsburg Reef is present in the West Wits Goldfield where it is called the Kloof No.2 Reef. The Denny’s Reef in the Klerksdorp Goldfield and the VS5, or Beatrix Reef of the Welkom Goldfield, also lie at the base of the Elsburg Quartzite Formation.

A cross section through the Cooke Section of REGM highlights the structural setting of the Central Rand Group and the UE1A Reef of the Elsburg Formation in relation to the Panvlakte fault which is marked by a wedge of overlying Ventersdorp lava (Figure 25). The UE1A Reef is confomal over much of Cooke Section but it thins rapidly towards the west where it transgresses the underlying Kimberley Formation, including the mineralised E8 and Kimberley conglomerates. In this proximal area the reef suffered net erosion and is present as a thin discontinuous scoured pediment facies as it approaches the Panvlakte fault, before being truncated by the overlying wedge of the Klipriviersberg lava.

The UE1A Reef immediately overlies the EG9/d Reef which is now considered to be the top of the underlying Kimberley Formation. On the Cooke Section of REGM, where the UE1A and EG9/d Reefs are mined together, they are referred to as the Composite Reef (Tucker, 1980; Tucker & Viljoen, 1986).

A strong braided fluvial pattern with a well-defined, generally east-west trending payshoot pattern is revealed by an isochron map of gold content of the Composite Reef (Figure 26) (Tucker, 1980; Viljoen, 1994), while the inset on figure 26 is a photograph of highly mineralised Composite Reef in a proximal ore shoot area on the Cooke Section of Randfontein Estates Mine.

High gold grades generally persist for a few hundred metres down the palaeoslope in the Cooke 1 area. In the Cooke 2 area further to the south, the main ore shoots have good gold values for a distance of more than 1 km down the palaeoslope. A distinct increase in the uranium/gold ratio down the palaeoslope is evident on the Cooke Section of REGM. This is also the case with other Witwatersrand reefs, for example the Basal Reef in the Welkom Goldfield (Minter et al., 1986), supporting the hypothesis that gold was preferentially deposited in more proximal areas because of its higher specific gravity compared to detrital uraninite.

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**Figure 24: Regional setting of the Elsburg and Mondeor Reefs on the West Rand South Goldfield with mineralisation flanking the Panvlakte Fault (M.J. Viljoen).**
Figure 25: East-West cross section through the Cooke 2 Section of Randfontein Estates Gold Mine on the West Rand South Goldfield. The E9G/d, precursor to the UE1A/a, has been eroded away in the western half of the section where the transgressive UE1A/a has been reduced to a scoured pediment overlying the whole Kimberley Formation and from which most of its gold and pebbles have been flushed out (M.J. Viljoen).

Figure 26: A well-defined west-east paysheet pattern for the Elsburg Composite Reef on Cooke Section corresponds with fluvial entry points in the vicinity of the Panvlakte fault to the west. Inset. Well mineralised highly pyritic composite conglomerate containing buckshot pyrite and large quartz pebbles with individual grades exceeding 100g/t, occurs in the proximal areas of these ore shoots (M.J. Viljoen).
Mondeor Reefs

The Mondeor Conglomerate Formation is the uppermost formation of the Witwatersrand Basin. The type locality is situated south of Johannesburg on the Central Rand where resistant, well-developed conglomerates and coarse-grained quartzites are overlain by Ventersdorp volcanics (Figure 27). The conglomerates are unmineralised along the length of the Central Rand and as in the case of the UE1A (often called just “UE1A”), at the base of the Elsburg Formation, become well mineralised as they swing southwards, parallel to the major Panvlakte Fault to the west (Figure 24). Correlatives of the Mondeor Conglomerate Formation are present around the Witwatersrand Basin (Figure 4); probably reflecting a period where increasing tectonic activity was a precursor to the Ventersdorp lava event.

The relationship of the Mondeor conglomerates to the underlying Elsburg Formation conglomerates and the overlying Venterdorp lava at Western Areas Gold Mine is depicted in Figure 28a. At the South Deep and Western Areas gold mines, the Mondeor Conglomerate is divided into two groups - the “Individuals” and the overlying “Massives” (Figure 28a). The new world-class South Deep gold deposit of the West Rand Goldfield is based on these Mondeor conglomerates and contains a resource of some 2,000 tonnes of gold.

The Mondeor Reefs comprise several conglomerates with intervening quartzites which wedge open down the palaeoslope, eastward from the subcrop. The subcrop positions of the Massives and Individual Reef groups on these mines are colloquially called “shorelines” (Figure 28a), but this does not imply that these reefs were deposited in a marine or littoral setting. Each of the conglomerate layers has its own channel distribution pattern and related primarily east-west trending ore shoot pattern.

In the Welkom Goldfield a series of fluvial “fans” also correspond to discrete entry points along a western, structurally controlled basin edge at Target Mine, which now incorporates the old Loraine Gold Mine. Higher aggregate gold content is recorded near the apex of each of these fans (Camisani-Calzolari, 1996). The intervening quartzites thin out westward towards the subcrop position and the conglomerates coalesce, resulting in the conglomerate reefs becoming sufficiently close to each other to be mined together as a single unit in massive open stopes (Figures 29 and 30).

Exploration borehole ERO1 had a remarkable Elsburg Reef intersection on the Target property with several stacked reefs near the apex of a fan giving an aggregate grade of 6.5 g/t Au over 128 m (true width), close to where this photograph (Figure 30) was taken. The Elsburg sequence in the Aandenk discovery borehole “WE1”, just over 4 km to the south east, intersected only quartzites with virtually no Elsburg Reefs developed in this more distal setting. It is clear that the gold is almost exclusively associated with conglomeratic, fluvial distributary channels. At Target Mine, steepening of the EA Reefs occurs to the extent that the package becomes over folded and unconformably overlain by a diamictite facies called the “Boulder Beds”.

The area to the west of the subcrop of the Mondeor formation has been scoured into by the VCR and represents a scoured pediment facies where the net erosion exceeded the deposition (Figure 8).

Economic concentrations of gold in the Elsburg and Mondeor conglomerates, whether due to a late stage hydrothermal source or a syngenetic placer source, are related to a basin-edge structure. At
Cooke Section Randfontein Estates Gold Mine this is the Panvlakte Fault and in the case of the Elsburg and Mondeor Conglomerates of the northern Welkom Goldfield, it is the so-called Border Fault. Fluvial entry points appear to be constrained by structural features transverse to these faults (Tucker, 1980; Camisani-Calzolari, 1996). Continued activity of such structural features resulted in successive entry points being superimposed on each other. These entry points are often called “fans” on the Witwatersrand but they are fluvial braid-plain entry points rather than true alluvial fans.

**Vengersdorp Contact Reef (VCR)**

The Vengersdorp Contact Reef (VCR) is the basal conglomerate of the Vengerspost Formation. It lies unconformably on the Witwatersrand Supergroup and is spatially closely linked to the underlying Witwatersrand gold placers. Degradation of Witwatersrand material and the development of a network of fluvial channels and terraces strongly suggest that concentration of gold and heavy minerals occurred by fluvial placer processes.

Economically mineralised VCR occurs along the tectonically active northwestern and western margins of the Witwatersrand Basin in the West Rand, West Wits and Klerksdorp Goldfields. More recently the VCR has been discovered to the north of the Welkom Goldfield by Anglovaal Limited (1992).

Six main lithofacies of the VCR were recognised by Krapez (1985). These include a debris flow facies and five stream flow facies. These fluvial deposits were controlled by the palaeotopography which included a complex array of terraces and channels (Krapez, 1985; McWha, 1988; Henning, 1993).

An analysis of S, O and H isotopes from the VCR by Zhao et al. (2006), demonstrates that metamorphic fluids “were probably derived from the Basin itself, and allogenic sulphides in the Vengersdorp Contact Reef were reconstituted during this fluid circulation during peak metamorphic conditions. Accordingly, gold appears to have been locally remobilized and possibly derived from pre-existing placer concentrations”. Extensive mine mapping has shown that economic concentrations...

[Figure 28b. Coarse pebble conglomerate of the “Massives” displaying channelling within the conglomerate package (M.J. Viljoen).]

[Figure 29: Section through Eldorado Fan conglomerates showing gold grade distribution on Target Mine, Welkom Goldfield. “EA” and “DK” refer to informal “Elsburg” and “Dreyerskuil” zones of the Mondeor (formerly Eldorado) Formation as used on Target Mine (R.F. Tucker, AvGold Limited).]
VCR is preferentially developed where it lies directly on or close to underlying gold-bearing Witwatersrand reefs, as seen in the Carletonville and West Rand South Goldfields (Engelbrecht et al., 1986), (Figure 31).

Left uncovered the VCR may eventually have degraded to a uniform conglomerate layer. However, the outpouring of the Venterdorp volcanics sealed the system with pillow lavas overlying VCR conglomerates in places, precluding further degradation or winnowing (Figure 32).

The VCR has been a major source of gold production particularly in the West Wits Goldfield and in the past has produced up to 18% of the annual gold production of South Africa.

**Black Reef**

The Black Reef Formation lies at the base of the much younger, 2.65 Ga. Transvaal Supergroup (Eriksson et al., 2006). It is essentially a pyritic quartz pebble conglomerate in a fluvial setting with a black, carbonaceous shale from whence its name. Conglomerate-filled channels occur near the base of the succession and in places contain well-developed coarse buckshot pyrite and carbonaceous material, especially in the vicinity of underlying gold-bearing Witwatersrand reefs (Figure 33).

At the Randfontein Estates Gold Mine in the West Rand Goldfield, the Black Reef unconformably overlies Venterdorp and Witwatersrand Supergroup strata. As with the VCR described in the previous section, a clear spatial association of gold-rich Black Reef conglomerates and underlying Witwatersrand conglomerates exists.

Black Reef conglomerates were deposited in linear channels trending roughly north-south, which cut into less resistant sediments in close proximity to underlying outcrops of Main, Bird and Kimberley Reefs. This strongly suggests that the source of the gold was from these underlying Witwatersrand reefs (Figure 33).

Recent microprobe analyses of pyrite from the Black Reef have revealed a trace element signature which differs from that of the underlying Witwatersrand reefs (Fuchs et al., 2016). These workers suggest that while the depositional environment was similar to that of the underlying Witwatersrand clastic sediments, hydrothermal alteration by circulating aqueous and hydrocarbon fluids (oils), deposited large volumes of native gold, uranium minerals and pyrobitumen. Their work indicates that while the pyrite was not the
result of reworking of the underlying Witwatersrand strata, the close spatial association suggests strongly that gold and uranium were hydrothermally recycled from the underlying Witwatersrand reefs. It is thus likely that the Witwatersrand reefs were the proto-ore of the Black Reef and that later hydrothermal activity remobilised the gold and changed its character and appearance.

Black Reef conglomerates were exploited at the Government Gold Mining Areas, Geduld Proprietary and Modderfontein mines in the East Rand Goldfield and to a lesser extent from the West Rand and Klerksdorp Goldfields. In excess of 30 Mt of ore was extracted from Black Reef conglomerates (Robb & Robb, 1998).

**Gold Production**

The Witwatersrand was, for over a century, (late 1800s to 2006) the largest producer of gold in the World. To date Witwatersrand gold production has exceeded 52,000 tonnes. This is more than one third of all the gold ever produced on earth. The Witwatersrand still contains the largest resource of gold in the World, estimated to be in the order of some 30,000 tonnes. This is five times more than the remaining resource in the world’s second largest goldfield, the Carlin district of northern Nevada in the USA.

Gold has been mined down to 4,000 m and the resource has still not bottomed out. Major capital is however required to mine at these great depths. In the early years, the high cost of deep level mining was a major factor leading to the formation of the big South African Mining Finance houses such as Anglo American and Gold Fields of South Africa.

The Rand Refinery was opened in 1921 to refine South Africa’s gold which had previously been refined in London. The refinery, which was rebuilt in the late 1980s, is the world’s largest and has refined over 40,000 tonnes of gold in its history (Handley, 2004).

Table 2 is a summary of the gold production for each of the main goldfields for each of four groups of reefs. The greatest amount of gold has been extracted from the East Rand Goldfield (over 9,500 tonnes) while the Carletonville, Central Rand and Welkom Goldfields have each produced well over 7,000 tonnes of the metal. Together with the East Rand Goldfield, these have been the mainstay of the gold mining industry in South Africa. Most of this gold has come from the Main Reef Group of conglomerates at the base of the Johannesburg Subgroup, which has produced over 50% of the total quantity of gold produced from the entire Witwatersrand Basin.

The largest amount of gold from the Welkom and Klerksdorp Goldfields in the western portion of the basin has been won from the Bird Reef Group of conglomerates while the Ventersdorp Contact Reef at the top of the sequence has been an important contributor in the Carletonville and to a lesser extent, the Klerksdorp Goldfield.

Relatively small amounts of gold have been produced from the reefs in the Kimberley, Elsburg and Mondeor Formations of the Turffontein Subgroup, although more and more gold is now being produced from these reefs. The average grade of gold mined from all of the Witwatersrand reefs in all the gold fields is 8.4 g/t. The highest average grade is 12.6 g/t in the West Wits Goldfield, due largely to the incredibly rich Carbon Leader Reef.

Table 2 gives an earlier summary of gold production. Regrettably the old Chamber of Mines source of this data is no longer able to supply an update. Thus, even though the figures have not been brought up to date, they do provide an idea of relative significance and productivity of the various reef groups and goldfields.

**Exploration on the Witwatersrand**

In the early years, prospectors easily followed the important outcrops of gold-bearing reefs along the Central and West Rand from the discovery site. While sophisticated exploration was unnecessary, diamond drilling played an important role from early on and was
used effectively to establish the down-dip continuity of the reefs from outcrop (Denny, 1900).

In December 1889 drilling commenced on the Village Main Reef property, just a few hundred metres south of where downtown Johannesburg now lies. The South Reef was intersected at 158 m yielding 15 g/t over 76 cm and the Main Reef Leader at a depth of 177 m with 19 g/t gold. In 1891 the Rand Victoria borehole was drilled near present day Germiston, nearly 1.5 km south of the outcrop. It intersected the Main Reef Group at a depth 729 m, returning a value of 60 g/t over 122 cm (Borchers, 1964). The results of this intersection injected renewed confidence into the Rand mining community as it confirmed that the discovery site was merely the tip of a huge iceberg. More sophisticated methods were however required to trace the Witwatersrand reefs under younger cover rocks, prior to drilling. In this regard, geophysical techniques came to the fore and still play an essential role in Witwatersrand exploration.

**Magnetics**

The magnetic signature of the iron-rich shales and ironstones of the West Rand Group has been of fundamental importance in tracing marker beds below cover rocks. By extrapolation, the position of the overlying non-magnetic gold bearing reefs of the Central Rand Group

### Table 2: A conservative estimate of gold produced from the principal gold fields, on the major reef horizons (Handley, 2004 and Robb & Robb, 1998).

<table>
<thead>
<tr>
<th>Reef Group</th>
<th>VCR</th>
<th>Kimberley &amp; Elsburg</th>
<th>Bird Reefs</th>
<th>Main Reefs</th>
<th>Total</th>
<th>Reefs</th>
<th>Major Mines</th>
<th>Avg. Grade</th>
<th>% per Goldfield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold Field</td>
<td>t Au</td>
<td>t Au</td>
<td>t Au</td>
<td>t Au</td>
<td>n</td>
<td>n</td>
<td>g/t</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>Welkom</td>
<td>-</td>
<td>450</td>
<td>6,900</td>
<td>-</td>
<td>7,350</td>
<td>- 32</td>
<td>17</td>
<td>9.4</td>
<td>18%</td>
</tr>
<tr>
<td>Klerksdorp</td>
<td>650</td>
<td>64</td>
<td>4,200</td>
<td>8</td>
<td>4,923</td>
<td>- 12</td>
<td>19</td>
<td>10.1</td>
<td>12%</td>
</tr>
<tr>
<td>West Wits</td>
<td>2,400</td>
<td>500</td>
<td>-</td>
<td>4,800</td>
<td>7,700</td>
<td>12</td>
<td>11</td>
<td>12.6</td>
<td>19%</td>
</tr>
<tr>
<td>West Rand</td>
<td>31</td>
<td>760</td>
<td>99</td>
<td>1,100</td>
<td>1,990</td>
<td>35</td>
<td>16</td>
<td>5.2</td>
<td>5%</td>
</tr>
<tr>
<td>Central Rand</td>
<td>-</td>
<td>200</td>
<td>230</td>
<td>7,200</td>
<td>7,630</td>
<td>5</td>
<td>46</td>
<td>8.3</td>
<td>19%</td>
</tr>
<tr>
<td>East Rand</td>
<td>-</td>
<td>500</td>
<td>-</td>
<td>9,000</td>
<td>9,500</td>
<td>4</td>
<td>31</td>
<td>8.4</td>
<td>24%</td>
</tr>
<tr>
<td>Evander</td>
<td>-</td>
<td>1,200</td>
<td>-</td>
<td>1,200</td>
<td>2,400</td>
<td>1</td>
<td>4</td>
<td>7.4</td>
<td>3%</td>
</tr>
<tr>
<td>Metric tonnes</td>
<td>3,081</td>
<td>3,674</td>
<td>11,429</td>
<td>22,107</td>
<td>40,292</td>
<td>98</td>
<td>146</td>
<td>9.0</td>
<td>100%</td>
</tr>
<tr>
<td>% per Reef</td>
<td>7.6%</td>
<td>9.1%</td>
<td>28.4%</td>
<td>54.9%</td>
<td>100.0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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*Figure 34: Magnetic markers in the West Rand Group delineated by Krahmann (1936), the blueprint for the discovery of the West Wits Goldfield (after Kramann, 1936).*
could be inferred. This concept was used to great effect in the early 1930s by the Gold Fields team of Rudolf Krahmann (geophysicist), Leopold Reinecke (consulting geologist) and Guy Carleton Jones (consulting mining engineer).

The iron-rich shales in the West Rand Group provided the basis for the location of the westerly, under cover, extension of the overlying gold-bearing Central Rand Group reefs, leading directly to the discovery and establishment of the West Wits Goldfield (Figure 34). This developed into one of the world’s greatest goldfields. Magnetics has played an important role in the definition of a number of the other goldfields over the years, including the Welkom Goldfield (Figure 35). Aeromagnetic surveys have provided an important mapping tool in defining the extent and geological setting of the entire Witwatersrand Basin, based largely on the magnetic signature of West Rand Group strata.

Gravity

Gravity surveys have provided valuable information regarding the regional structural setting of the Witwatersrand Basin, as well as delineating the position of low density basement granite domes and higher density rocks (Figure 35). Gravity combined with magnetics played an important role in the discovery of the Welkom Goldfield where ground magnetic profiles indicated the position of prominent marker beds in the West Rand Group, while a low-gravity signature over the buried Central Rand Group, revealed the location of lower density central group quartzites below Karoo cover (Figure 35). This work was instrumental in guiding the subsequent drilling programme that delineated the extent of the Welkom Goldfield.

Regional magnetic and gravity maps over the Witwatersrand Basin are shown in Figures 36a and 36b.

Seismics

Since the early 1980s the seismic method has played an important role in both regional and on-mine exploration in the Witwatersrand Basin. Excellent seismic velocity contrasts occur between crucial marker beds such as the Black Reef contact at the base of the Transvaal
Super group and Witwatersrand strata and overlying Venterdorp lava, with the VCR having developed on this contact. Additional seismic marker beds include the Booysens Shale and various marker units in the West Rand Group (Figure 37).

More recently, 3D seismic surveys have vastly improved the precision of structural interpretation which has provided invaluable information on reef dislocations, essential for detailed mine layouts, with faults for example being located to within 15 metres.

Conclusions

The great mineral deposits of the world appear to have formed as a result of a fortuitous combination of events which have often not been repeated in the course of geological history. Crustal processes occasionally interact at a particular point on the earth’s crust in such a way as to form metal concentrations that are virtually unique (Robb & Meyer, 1995). To form the enormous high grade gold deposits of the Witwatersrand, three critical elements were essential. There needed to be a source of gold, concentrating mechanisms and preservation events.

The primary source for the Witwatersrand gold was the surrounding Archaean granite-greenstone terrain of the Kaapvaal Craton. Gold grains in the Witwatersrand dating back to this time unequivocally point to these greenstone belts and in some cases hydrothermally altered granites, as being significant contributors of the gold. Later stage remobilisation in the conglomerate reefs certainly occurred and may be linked to the Venterdorp lavas, Vrededorp impact and/or the Bushveld intrusive events. The preservation of the Witwatersrand is considered to be largely due to the Vrededorp impact event.

Besides sedimentary processes, “carbon”, now shown to be largely the remains of prokaryotic bacteria, has been important in the concentration of gold and uranium. Geochemical studies show an excellent correlation between carbon, gold and uranium, suggesting a strong genetic association. Algal mats on the base of avulsed channels would have provided ideal and convenient locations for such concentrations to occur. Some carbon has been radiogenically polymerised due to contact with uraninite. The carbon may have been remobilised and introduced as oil into suitable horizons associated with certain reefs, then crystallised in tensional sites with the formation of distinctive columnar forms closely associated with gold.

The “Great Debate” regarding the placer versus hydrothermal origin of the Witwatersrand gold continues. Following an increasing number of academic studies, it is now more widely accepted that both schools contain elements that are in essence, correct. Gold and uraninite grains which predate the commencement of Witwatersrand sedimentation have been identified. The coarser gold particles, which account for the bulk of the available gold, were washed into the system by placer processes whilst some fine grained gold might have been carried in suspension or solution and precipitated by organic material. There is also clear evidence that some gold has undergone post depositional reworking and re-distribution. The ultimate question is “was the gold introduced by the hydrothermal fluids or did these fluids remobilise placer gold, leaving behind red herrings as to the true origin?” The jury is still out on this one.

An in-depth understanding of the many geological disciplines is needed to understand this remarkable ore deposit. Sedimentology has been of fundamental importance in the geological modelling and evaluation of Witwatersrand reefs. Such studies when combined with geostatistical techniques, have allowed for more meaningful resource estimates of the gold reefs.

The Witwatersrand has been by far the largest producer of gold in the world. In 1970 the goldfield produced 1,000 tonnes of gold,

Figure 37: 3-D seismic section highlighting the base of the Venterdorp lava and the Booysens Shale and defining the faulting pattern. (Sun Exploration, northern Welkom Goldfield).
or over 68% of world production. It was the world’s number one producer for over 100 years, up to 2006. Production then steadily declined to less than 200 tonnes of gold per annum, with the higher grade resources having been depleted or being too deep to be mined economically at the current level of technology and price. 

In 2014 production had fallen to only 15% of the total world output. The life of the Witwatersrand is however by no means over and after 130 years of mining an estimated resource of some 30,000 tonnes of gold still exists, much of it below depths of 3,000 m but some, still at surprisingly shallow depths. Mining at great depth with high temperatures and pressures presents a huge challenge that is being met by new technologies such as chilled hydropower, backfill and the use of robotics in the mining of narrow reefs at depth. The future of the goldfield is indeed still a very bright one.

Acknowledgements

Rod Tucker would like to thank the Publications Committee of the LOC of the 35th IGC for inviting him to compile this review chapter and assisting substantially in the compilation. The literature is vast and many important contributions have been consulted and we are grateful for their help. Understanding the Witwatersrand has been an enormous team effort and through our professional association with the goldfield, which has spanned many decades. We hope to have portrayed some of the most important attributes of this great African mineral field.

The authors acknowledge the many geologists with whom we have had hours of debate, and from whom we have learnt a great deal. Thanks go to our former employers JCI, Randfontein Estates, Anglovaal, Avgold, Gold Fields of South Africa and Snowden Mining Consultants. We have benefitted greatly from our association with the School of Geosciences at the University of the Witwatersrand and particularly the Economic Geology Research Institute and the late professor Des Pretorius who facilitated our long association with the greatest goldfield in the world and afforded us the privilege of having worked on it is acknowledged. Particular thanks go to Mike Wilson, Gillian Drennan and George Henry who offered substantial improvements to this contribution.

The Viljoen’s would like to acknowledge the mineral exploration companies VMI and Bushveld Minerals for the considerable support given to them in contributing to this paper. Lyn Whitfield and Margaret Sherwood prepared many of the figures and diagrams while Timothy Marais, Makabele Fosa and Samukeliso Mnkandla typed several drafts of this chapter. Their assistance is gratefully acknowledged. Understanding the Witwatersrand has been an enormous team effort and through our professional association with the goldfield, which has spanned many decades. We hope to have portrayed some of the most important attributes of this great African mineral field.

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Richard Viljoen is Co-President of the 35th IGC. Subsequent to extensive research studies in Archaean terrains, he spent most of his career in the mining industry. He was an Honorary Professor at the University of the Witwatersrand and is now a consultant for VM/ Bushveld Minerals. He is a fellow of five international and national Geoscience Societies and is the recipient of a number of awards including the Draper medal of the Geological Society of South Africa and the Lindgren award of the Society of Economic Geologists.

Rodney Tucker worked in base metal exploration before embarking on a career primarily focused on Witwatersrand gold. He was a production mine geologist on Randfontein Estates Gold Mine before completing a research project on the sedimentological, mineralogical and geochemical aspects of the Composite “E1A/a” gold and uranium reef, for which he attained an MSc under the guidance of Dr. Richard Viljoen and the late Professor Des Pretorius. He was appointed Group Sedimentologist for Anglovaal Limited and later Exploration Manager for Avgold Limited, before joining Snowden Mining Industry Consultants as Divisional Manager, Exploration for Africa. Rod is a Life Fellow and was President of the Geological Society of South Africa in 1997.


