Quartz-Pebble-Conglomerate Gold Deposits

Chapter P of
Mineral Deposit Models for Resource Assessment

Scientific Investigations Report 2010–5070–P

U.S. Department of the Interior
U.S. Geological Survey

Cover. Sheared pyrite in a mylonitic contact between the Ventersdorp Contact Reef (main part of photograph) and the Ventersdorp lavas (uppermost part of photograph) at the Vaal Reefs mine in the Klerksdorp Gold Field, Witwatersrand, South Africa. Hammer for scale. Photograph by Cliff D. Taylor.

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By Ryan D. Taylor and Eric D. Anderson

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RYAN K. ZINKE, Secretary

U.S. Geological Survey
James F. Reilly II, Director

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
decimeter (dm)	3.937	inch (in.)
centimeter (cm)	0.3937	inch (in.)
micrometer (µm)	0.00003937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
	Area	
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Mass	
metric ton (t)	1.102	ton, short [2,000 lb]
metric ton (t)	0.9842	ton, long [2,240 lb]
	Density	
gram per cubic centimeter (g/cm^3)	62.4220	pound per cubic foot (lb/ft^3)

Datum

Vertical coordinate information is referenced to the World Geodetic System 1984 (WGS84).

Horizontal coordinate information is referenced to the World Geodetic System 1984 (WGS84).

Altitude, as used in this report, refers to distance above the vertical datum.

Quartz-Pebble-Conglomerate Gold Deposits

Ryan D. Taylor and Eric D. Anderson

Abstract

Quartz-pebble-conglomerate gold deposits represent the largest repository of gold on Earth, largely due to the deposits of the Witwatersrand Basin, which account for nearly 40 percent of the total gold produced throughout Earth's history. This deposit type has had a controversial history in regards to genetic models. However, most researchers conclude that they are paleoplacer deposits that have been modified by metamorphism and hydrothermal fluid flow subsequent to initial sedimentation.

The deposits are found exclusively within fault-bounded depositional basins. The periphery of these basins commonly consists of granite-greenstone terranes, classic hosts for lode gold that source the detrital material infilling the basin. The gold reefs are typically located along unconformities or, less commonly, at the top of sedimentary beds. Large quartz pebbles and heavy-mineral concentrates are found associated with the gold. Deposits that formed prior to the Great Oxidation Event (circa 2.4 giga-annum [Ga]) contain pyrite, whereas younger deposits contain iron oxides. Uranium minerals and hydrocarbons are also notable features of some deposits.

Much of the gold in these types of deposits forms crystalline features that are the product of local remobilization. However, some gold grains preserve textures that are undoubtedly of detrital origin. Other heavy minerals, such as pyrite, contain growth banding that is truncated along broken margins, which indicates that they were transported into place as opposed to forming by in situ growth in a hydrothermal setting.

The ore tailings associated with these deposits commonly contain uranium-rich minerals and sulfides. Oxidation of the sulfides releases sulfuric acid and mobilizes various metals into the environment. The neutralizing potential of the tailings is minimal, since carbonate minerals are rare. The continuity of the tabular ore bodies, such as those of the Witwatersrand Basin, has allowed these mines to be the deepest in the world. The extreme depths create engineering complications and safety issues for the miners, such as rock bursts as a result of pressure release.

The richness of these deposits makes them a desirable exploration target. However, the likelihood of future discoveries is minimal. Small deposits found in the United States include those found at Nemo in the Black Hills of South Dakota and Deep Lake in the Sierra Madre of Wyoming.

Introduction

Multiple hypotheses have been developed describing the genesis of quartz-pebble-conglomerate gold deposits. These various models have resulted from detailed studies of the world's largest gold province, in the Witwatersrand Basin in South Africa, which has oft-cited genetic models ranging from a modified paleoplacer origin to a hydrothermal origin. The majority of workers subscribe to the modified paleoplacer model, as it best describes the geology of, occurrence of metals in, and exploration criteria for the deposits. The host strata and many other features of these deposits resemble those of a paleoplacer. However, features such as the abundance of pyrite relative to detrital iron oxides, the large size of the deposits, and the presence of uraninite and kerogen make them distinct from modern placer deposits.

Quartz-pebble-conglomerate gold deposits represent some of the largest gold depositories in the world; in fact, the Witwatersrand Basin represents the largest resource of produced gold in the world (for example, Frimmel, 2002, 2008; Frimmel and Minter, 2002). Grains of native gold are found within coarse-grained sediment beds, either directly above erosion surfaces as heavy-mineral concentrates or at the top of individual beds left by winnowing. Some of these gold grains are of obvious detrital origin, but many are crystallized forms, which indicates hydrothermal emplacement caused by localized remobilization.

The current high price of gold is likely to increase exploration for the metal, but the likelihood of finding another quartz-pebble-conglomerate gold deposit as rich as the Witwatersrand deposits remains highly unlikely because of the confluence of features necessary to create such a large endowment of gold. However, some smaller occurrences do exist in the United States. Pyritic paleoplacers of sub-ore grade are found in the Deep Lake Group and Phantom Lake Metamorphic Suite in the Medicine Bow Mountains and Sierra Madre of Wyoming (Houston and Karlstrom, 1987) and at Nemo in the Black Hills of South Dakota (Redden, 1987).

This report is part of an effort by the U.S. Geological Survey Mineral Resources Program to update existing models and develop new, descriptive mineral-deposit models. It is intended to supplement the models previously published by authors such as Cox and Singer (1986).

Deposit Type and Associated Commodities

Name

Quartz-pebble-conglomerate gold deposits.

Synonyms

The most common synonym is Witwatersrand-type deposit, named after the world's largest geologic gold depository. Because the gold ore in the Witwatersrand Basin is located in ore "reefs," these deposits have also been coined quartz-pebble reef deposits. The almond shape of the quartz pebbles has also led these deposits to be referred to as banket-type (in Dutch, banket refers to a type of almond pastry). More generally, these may be classified by some workers as paleoplacer gold deposits or as fossil placers. Additionally, they have been referred to as conglomerate-hosted, quartz-pebble-associated, and quartz-arenite-associated gold deposits.

Associated Deposit Types

Similar geologic controls exist for modern placer deposits, and these have been successfully used to find additional ore zones within quartz-pebble-conglomerate gold deposits. These deposits concentrate gold along a bedrock surface because of the density of the gold particles relative to the matrix of coarser-grained quartz particles.

Primary Commodities

The primary commodities of quartz-pebble-conglomerate gold deposits are gold and uranium. Uranium has been recovered from many deposits such as those in the Witwatersrand Basin, but other deposits such as at Tarkwa, Ghana, do not contain recoverable uranium. Some deposits have abundant uranium and uneconomic concentrations of gold such as those in the Blind River-Elliot Lake district, Canada, and Bababudan, India (table 1).

Byproduct Commodities and Trace Constituents

Silver, platinum-group elements (PGE), diamonds, thorium, and pyrite may be byproduct commodities within these deposits (for example, Pretorius, 1976). Other metals such as rhenium, zinc, copper, chromium, arsenic, lead, molybdenum, osmium, and iridium may be enriched in associated heavy minerals and may be considered as anomalous trace constituents within these deposits.

Example Deposits

Gold deposits of this type are known on every continent except Antarctica (fig. 1). The most notable province is the Witwatersrand Basin in the Kaapvaal craton, South Africa, which accounts for nearly 40 percent of the world's gold, including produced, reserves, and resources (for example, Frimmel, 2008). The nine major gold fields within the Witwatersrand Basin include, from east to west, the Evander, East Rand, Central Rand, West Rand, South Deep, Western Areas, Carletonville, Klerksdorp, and Welkom Gold Fields (fig. 2). Other Witwatersrand reefs within the Kaapvaal craton of South Africa include the Ventersdorp Contact Reef, the Dominion Reef, and the Black Reef. Similar economic deposits elsewhere in the world are rather scarce. The second largest quartz-pebble-conglomerate gold system behind those in the Kaapvaal craton is found in Tarkwa, Ghana. Others of lesser importance include those at Jacobina and Moeda, Brazil; Roraima, South America; Blind River-Elliot Lake, Canada; Hamersley, Australia; and Bababudan, India. Recent studies of the Tertiary-aged deposit in Belle Brook, New Zealand, have inferred a similar origin (Falconer and others, 2006). Other smaller examples, in the United States, include deposits at the Nemo area in the Black Hills of South Dakota, and the Deep Lake paleoplacers in the Sierra Madre of Wyoming.

Historical Evolution of Descriptive and Genetic Knowledge and Concepts

The first discovery of a quartz-pebble-conglomerate gold deposit was in the Witwatersrand Basin in 1886, and mining began shortly thereafter. However, quartz-vein lode gold and alluvial placer gold had been discovered in the Witwatersrand Basin 18 years before this (Minter, 1977). Initial assessments hypothesized that the gold reefs would only extend underground to depths of 3 to 5 meters because they were thought to be simple, shallow alluvial deposits or narrow beach deposits that had been tilted (Pretorius, 1975). This was quickly realized to be an inaccurate assessment when bore holes drilled in 1889 and 1892 intersected the Main Reef at depth and geologic extrapolation defined extensions to what had been thought to be shallow ore bodies. Today, these mines are the deepest in the world and extend to greater than 3.5 km depth. The richness of this district led to abundant research and divergent and controversial opinions of the origin of its gold deposits. Most of the earliest geologists that studied this area firmly believed in a placer origin, and many compared it with marine placers of the Pacific Ocean (for example, Becker, 1897); however, other models were still offered. For example, shortly after the discovery of the Witwatersrand deposits, Penning (1888) observed features such as the homogeneous distribution of the gold within the conglomerate bed and perceived lack of correlation with heavy minerals and, based on these, suggested syngenetic precipitation of the gold from

Table 1. Geologic and production information on the major quartz-pebble-conglomerate deposits of the world.

[Ga, gigga-annum; Ma, mega-annum; n.d., no data; t, metric tonne; ?, uncertain]

Basin name	Location	Basin age (Ma)		Basin setting	Gold (Au) production	Iron (Fe) minerals	Significant uranium (U)	Significant hydrocarbon	Likely source	Hosting unit	Selected references
		maximum	minimum								
Witwatersrand	South Africa	2,970	2,714	foreland, retroarc, passive margin, intracratonic sag	>50,000 t	pyrite	yes	yes	3.1-3.0 Ga granite-greenstone	Central Rand and Western Rand Groups	Gregory, 1909; Pretorius, 1976, 1981a; Minter, 1977; Minter and others, 1993; Frimmel and others, 2005a
Tarkwa	Ghana	2,133	2,097	foreland	>280 t	hematite, magnetite	no	no	Paleoproterozoic greenstone	Tarkwaian Series	Sestini, 1973; Milési and others, 1991; Hirdes and Nunoo, 1994; Pigois and others, 2003
Jacobina	Brazil	2,086	1,883	foreland	>70 t	pyrite, hematite	no	yes	Archean-Eoproterozoic granite-greenstone	Serra do Córrego Formation	Ledru and others, 1997; Teixeira and others, 2001
Elliot Lake	Canada	2,450	2,219	foreland	negligable	pyrite	yes	yes	Archean granite	Huronian Supergroup	Fralick and Miall, 1989
Moeda	Brazil	2,800	2,200(?)	foreland	>10 t	pyrite	yes	minor	Archean granite-greenstone	Moeda Formation	Minter and others, 1990
Roraima	northern South America	2,000	1,900	foreland	n.d.	magnetite	no	no	2.3-2.1 Ga Guiana Shield granite-greenstone	Roraima Group	Santos and others, 2003; Frimmel and others, 2005b
Bababudan	India	2,900	2,600(?)	foreland	negligable	pyrite	yes	no	Archean granite-greenstone	Bababudan Group	Srinivasan and Ojakangas, 1986
Hamersley	Australia	2,780	2,630	graben	n.d.	pyrite	yes	yes	3.53-2.83 Ga Pilbara craton granite-greenstone	Mount Bruce Supergroup	Carter and Gee, 1987
Kaarestunturi	Finland	1,880	1,800	graben	prospect	magnetite, hematite	no	no	Lapland greenstone belt	Kumpu Group	Härkönen, 1984

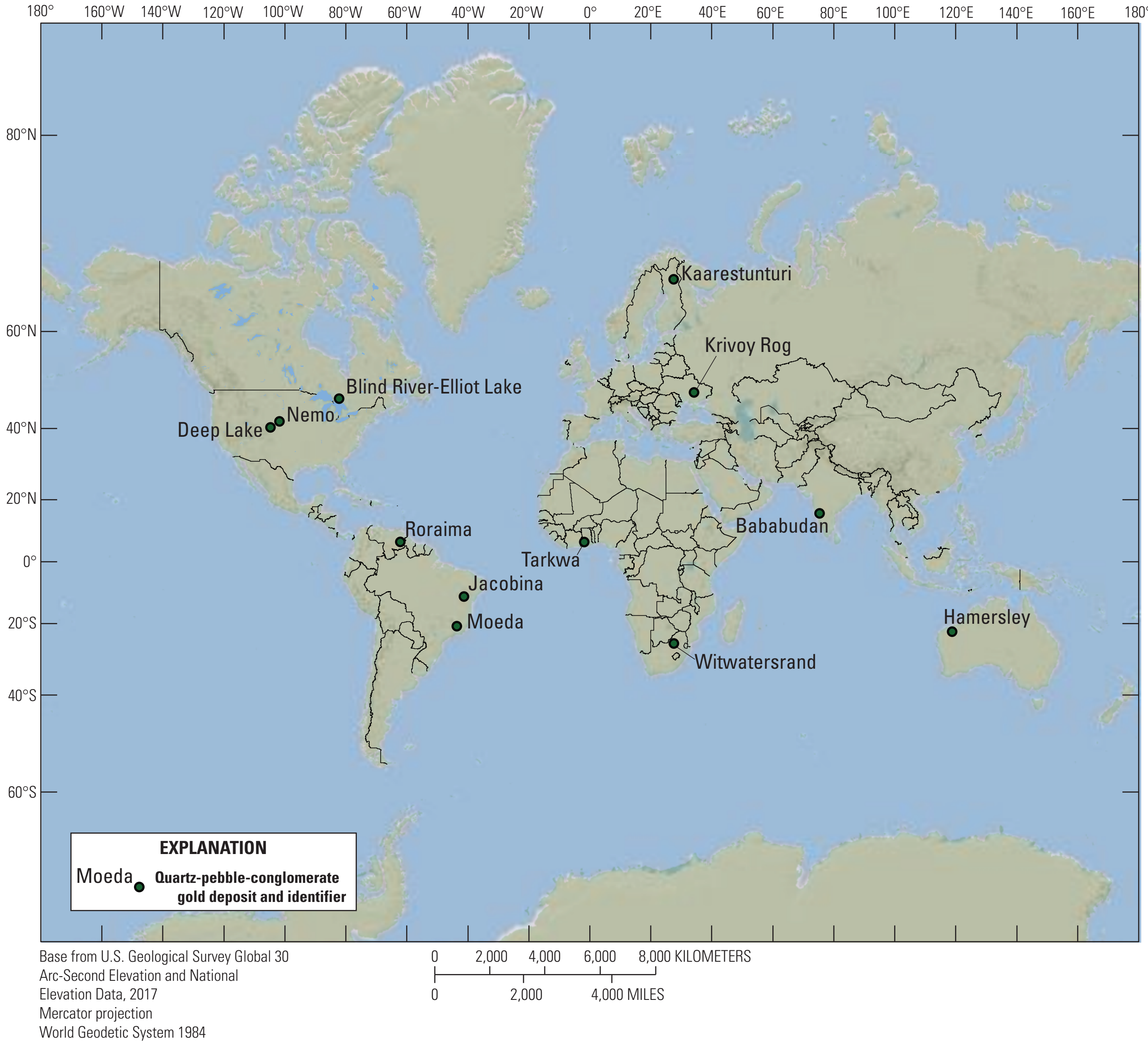


Figure 1. Global distribution of major quartz-pebble-conglomerate gold deposits.

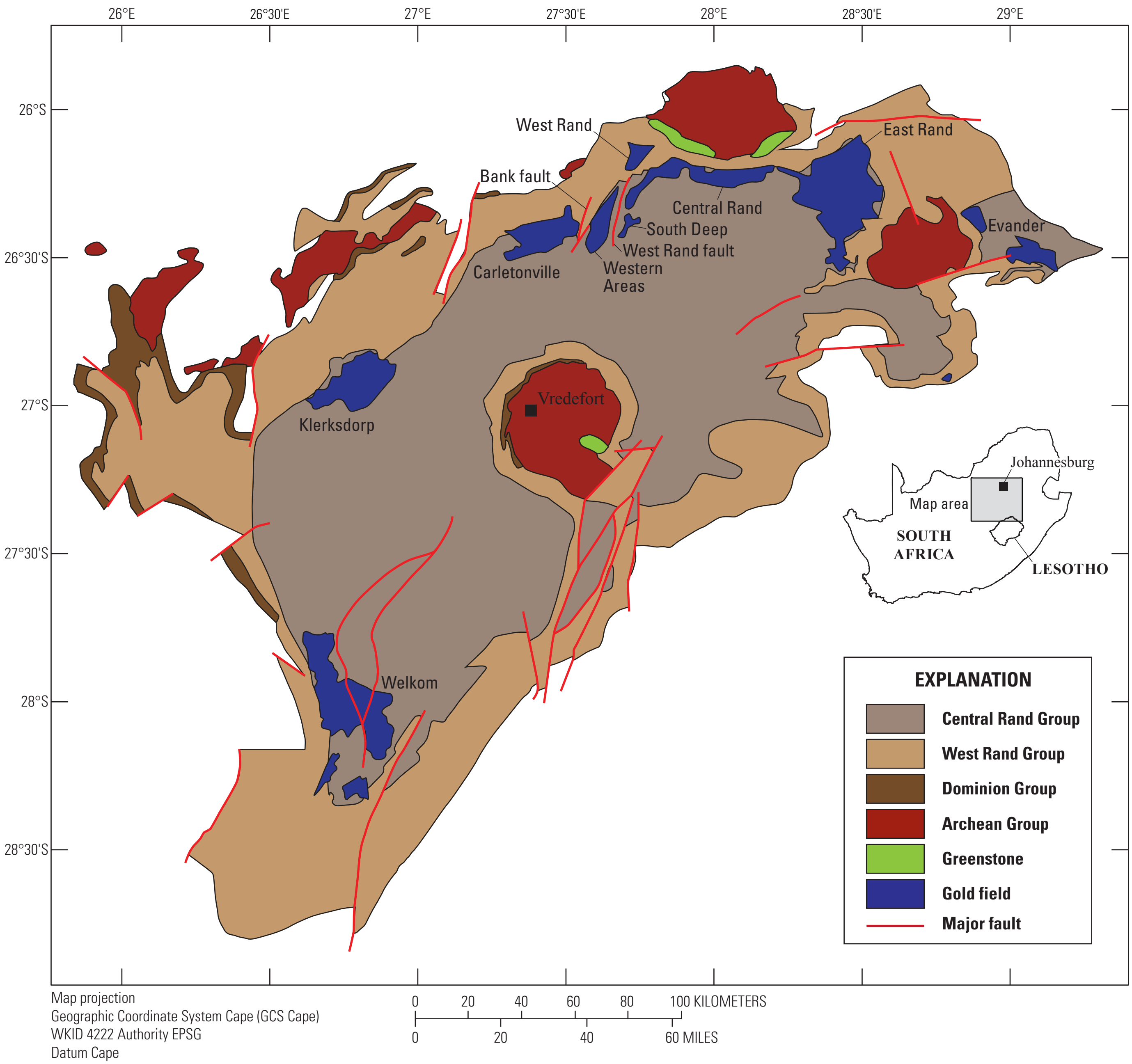


Figure 2. Simplified geologic map of the Witwatersrand Basin, South Africa. The gold deposits located in this basin make up the largest known concentration of gold. Modified from Frimmel and Minter (2002) and Frimmel and others (2005a).

gold-bearing waters. Shortly thereafter, a modified placer model was proposed, which suggested that an original marine placer contained black sands, which were converted to pyrite, and gold was simultaneously redistributed locally (Gregory, 1908, 1909). Young (1917) summarized three concepts for the formation of the gold deposits, including the “placer,” “infiltration” or hydrothermal, and “precipitation” models, of which variations now exist. In these early years, the placer and the hydrothermal models, just as today, were the most favored. The more favored placer model was questioned by Graton (1930) in a controversial manuscript, which presented evidence for a magmatic-hydrothermal model, although a similar model had been proposed even earlier (for example, the infiltration model of Hatch and Corstorphine, 1905). As he was one of the more famous geologists of his time, Graton’s work initiated a major discussion about the merits of the placer and hydrothermal models, with the local geologists still insisting on a placer model for exploration. The intense arguments over whether the Witwatersrand deposits formed as a placer or modified placer (for example, Mellor, 1916; Du Toit, 1939) or as a hydrothermal deposit (for example, Graton, 1930) continued into the 1940s, only to dwindle in intensity thereafter. These arguments again intensified in the mid-1950s with the interest in the occurrence and importance of uranium and carbon seams in these deposits.

The origin of the gold in the Witwatersrand Basin remains somewhat controversial to this day. Current analogs to Young’s (1917) divisions are the modified paleoplacer model (Frimmel and others, 2005a), the hydrothermal replacement model (Law and Phillips, 2005), and the modified syngenetic-precipitation model (Horscroft and others, 2011).

Analogous to the favored models for the Witwatersrand Basin deposits, models for deposits at Tarkwa, Jacobina, and Blind River-Elliot Lake have focused on the modified paleoplacer and hydrothermal models (for example, Pretorius, 1981a). Proponents for each model have used similar arguments as those that were invoked for the Witwatersrand deposits. For all of these deposits, the most popular and geologically consistent explanation seems to be the modified paleoplacer model.

Regional Environment

Geotectonic Environment

Quartz-pebble-conglomerate gold deposits all form in basins dominated by clastic sediments. Of the 12 significant Archean–Paleoproterozoic quartz-pebble-conglomerate gold-uranium-pyrite deposits that Frimmel and others (2005a) compare, those of the Kaapvaal craton have been interpreted to have formed in rift, passive margin, or intracratonic sag settings, whereas the other deposits are interpreted to have formed in foreland-basin settings. Some of the most famous deposits (those of the Central Rand Group in the Witwatersrand Basin and at Moeda, Blind River-Elliot Lake, Jacobina, Tarkwa, and Roraima; fig. 1) all formed in a foreland-basin tectonic setting. In the Witwatersrand Basin, the West Rand Group may have formed on a passive continental margin prior to basin formation. The Central Rand Group, which is the principal gold repository in the Witwatersrand Basin, likely formed in a foreland basin, but some prefer an interpretation of a passive margin setting resulting from thermal subsidence (de Wit and others, 1992). The foreland basin setting (either peripheral or retroarc) is also a common tectonic setting for modern placer deposits, in contrast to that of hydrothermal gold deposits that typically form in near-arc to arc settings (fig.3).

Conglomerates hosting the gold deposits consist of mature sediments that have undergone recycling and chemical weathering. This requires slow uplift and erosion, as high amounts of uplift and fast erosion rates in regions of high topography instead result in immature sediments; however, active uplift during sedimentation is still required. The source for the sediment and gold is upslope of the basin, in the hinterland.

Ore is most commonly associated with fluvial facies such as those deposited in channels, alluvial fans, braided streams, terraces, and shoreline environments. Local and basin-scale depositional facies can include those deposited in fluvial, deltaic, and near-shore environments that shifted across the basin in response to sea-level fluctuations. The quartz-pebble conglomerates in the Matinenda Formation at Blind River-Elliot Lake are interpreted to have formed in shallow braided channels (Fralick and Miall, 1989). Jacobina deposits formed in a Paleoproterozoic foreland basin with fluvial to fluvio-deltaic characteristics.

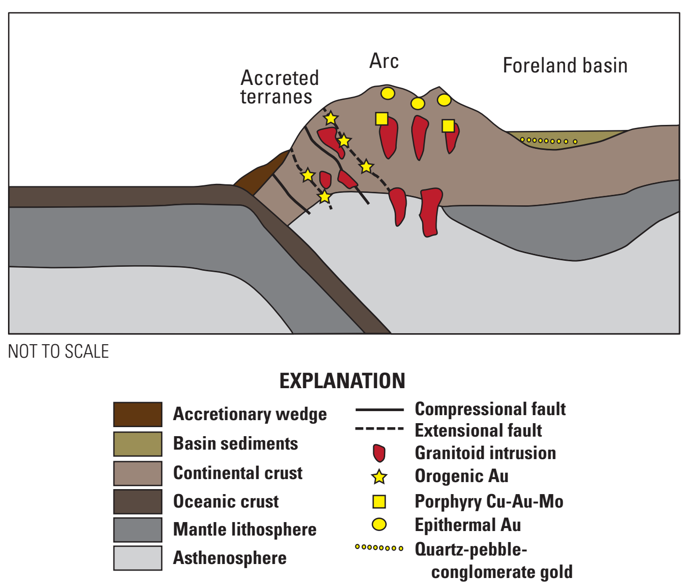


Figure 3. Schematic illustration of the geotectonic environments of formation for gold-bearing ore deposits. A foreland basin is shown with accumulations of placer gold, but a peripheral basin may also form seaward of the arc. Modified from Groves and others (2005). [Au, gold; Cu, copper; Mo, molybdenum]

Temporal (Secular) Relations

Quartz-pebble-conglomerate sedimentary rocks have formed throughout Earth's history, but the total number and the proportion of quartz-pebble conglomerates to total amount of conglomerates of a given age was highest in the Archean and Proterozoic and has steadily decreased through geologic time (Cox and others, 2002). This contrasts with the global age distribution of sedimentary rocks in general.

Presumably, paleoplacer and modern placer gold deposits have accumulated throughout Earth's history because of the formation and erosion of lode gold deposits. However, significant accumulations do not conform to this secular trend. Large quartz-pebble-conglomerate deposits such as those in the Witwatersrand, Tarkwa, and Jacobina basins are restricted to the Mesoarchean and Paleoproterozoic periods. Additional significant placer gold accumulation in gravels occurred during the Tertiary to Recent, but extensive placer gold in quartz-pebble conglomerates of this age is still exceedingly rare.

Relations to Structures

Uplift and associated faulting is necessary to create the erosion-prone hinterland that supplies the detritus that infills the basin. Thrust faulting is common in these regions and leads to flexural loading of the lithosphere that generates the foreland basin (fig. 4).

Many foreland basins are bounded on the side nearest the hinterland by thrust faults. In Witwatersrand, this basin-bounding fault was active during sedimentation of the foreland basin (Burke and others, 1986). Additional faults may bound the basin on the other sides. Normal faulting in the basin may also have contributed to some of the subsidence associated with basin formation.

Later deformation, including faulting, folding, and metamorphism, may occur after sedimentation but are not genetically related to the gold concentration. An understanding of these structures is of importance for tracing out extensions to the known ore reefs (fig. 5; Pigois and others, 2003).

Relations to Igneous and Metamorphic Rocks

Many quartz-pebble-conglomerate gold deposits have been variably metamorphosed, but this metamorphism is generally not assumed to generate the gold deposits. Instead, igneous and metamorphic rocks may host lode gold deposits in the hinterland that may become eroded and incorporated into the sedimentary units. Granite-greenstone terranes that commonly host orogenic lode gold deposits (Goldfarb and others, 2005) are found peripheral to or nonconformably underlying many quartz-pebble-conglomerate gold deposits. Archean granitoids and greenstones crop out up-paleoslope and form the basement rocks of the gold deposits of the Witwatersrand Basin. The Birimian Supergroup that underlies the gold field at Tarkwa is a granite-greenstone terrane (fig. 4). Archean granites and greenstones underlie the Proterozoic quartz-pebble conglomerates at Blind River-Elliot Lake. The deposits at Jacobina are also spatially related to greenstones.

Metamorphism of the gold-bearing beds, however, may locally remobilize the gold (Hayward and others, 2005). However, there is no relationship between the initial concentration of gold in the quartz-pebble conglomerates and later metamorphism.

Relations to Sedimentary Rocks

Quartz-pebble-conglomerate gold deposits are hosted in (meta-) sedimentary rocks. These basins are composed of clastic sedimentary rocks that vary from shales to sandstones to conglomerates. The vast majority of the gold is located within the conglomerate beds, with lesser amounts disseminated in quartzite beds. Total basin-fill thickness is on the kilometer scale. In the Witwatersrand Basin, the West Rand Group reaches a maximum thickness of 5.15 km and the Central Rand Group reaches a maximum thickness of 2.88 km (Frimmel and others, 2005a). Maximum total preserved thickness of the Witwatersrand Basin fill is 14 km (Pretorius, 1981a), although this basin is actually multiple tectonic basins whose fills are stacked on one another (Frimmel and others, 2009). These rocks are discussed in depth in the Petrology of Associated Sedimentary Rocks section.

Physical Description of Deposit

Dimensions in Plan View

The basins that contain quartz-pebble-conglomerate gold deposits are distinctly narrow and elongated, with their long axis parallel to the uplifted and eroded hinterland. Partial preservation of the basin may lead to shorter strikes, narrower widths, or preferential preservation of older and lower strata. Later metamorphism and deformation may further alter the shape of the basin by introducing folding and faulting that may give the basin an arcuate shape. The Witwatersrand and the Huronian Basins are arcuate in shape, whereas the Jacobina and Tarkwa Basins are more linear and narrower.

The Witwatersrand gold fields make up the largest and richest gold province in the world (fig. 2). The basin is elongate in the northeast-southwest direction, with dimensions of approximately 350 km by 200 km; the West Rand and Central Rand groups cover an area of approximately 80,000 square kilometers (km^2) (Boyle, 1979; Pretorius, 1981b). The narrow Jacobina Basin is 200 km long and 10–25 km wide and trends N-S.

Vertical Extent

The underground mines of the Witwatersrand constitute the deepest mines on Earth, with some extending to depths greater than 3.5 km and some approaching 4 km

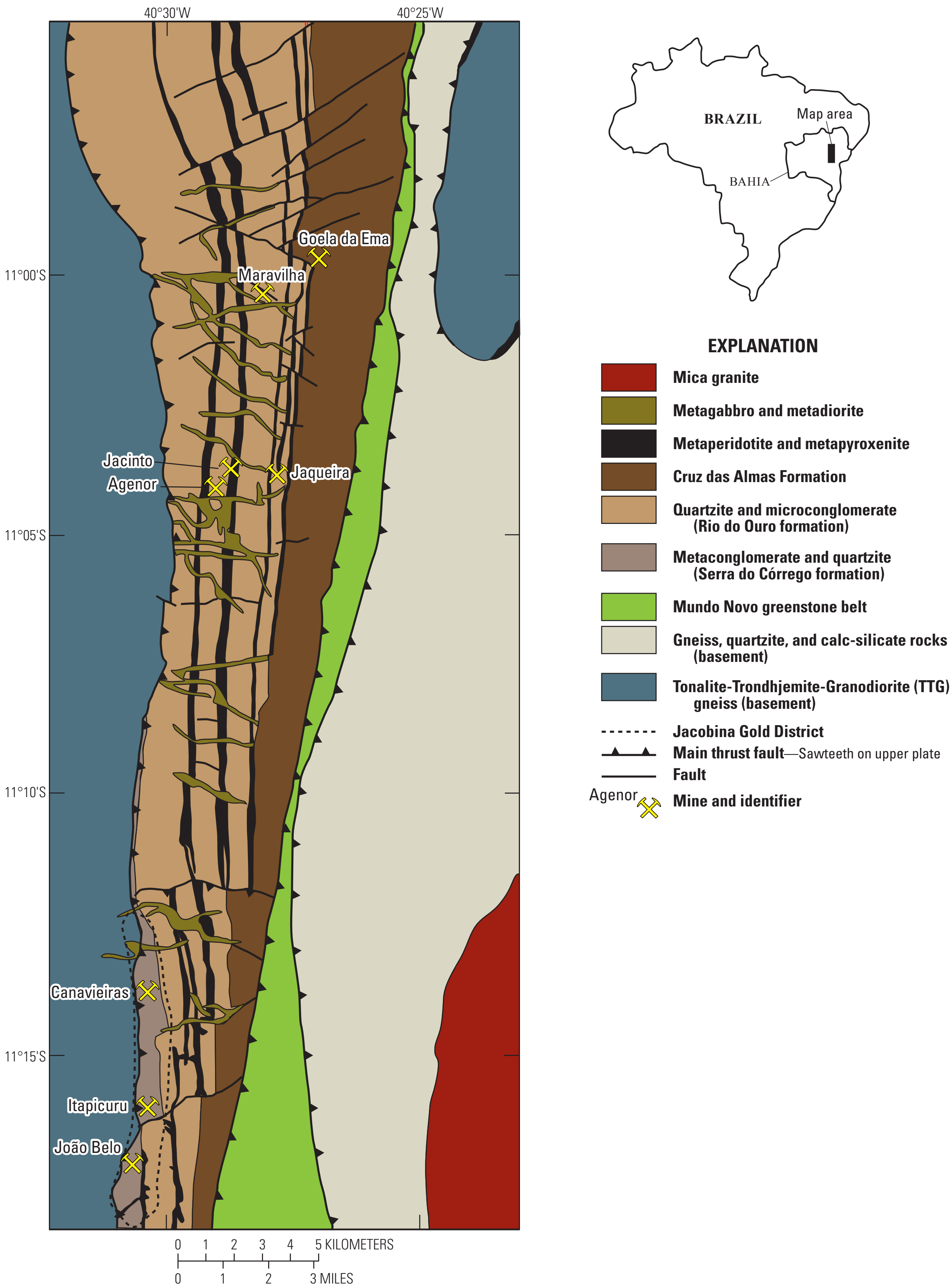


Figure 4. Simplified geologic map of the Jacobina region, Brazil. The gold-hosting basin is located between large thrust faults. Modified from Teixeira and others (2001).

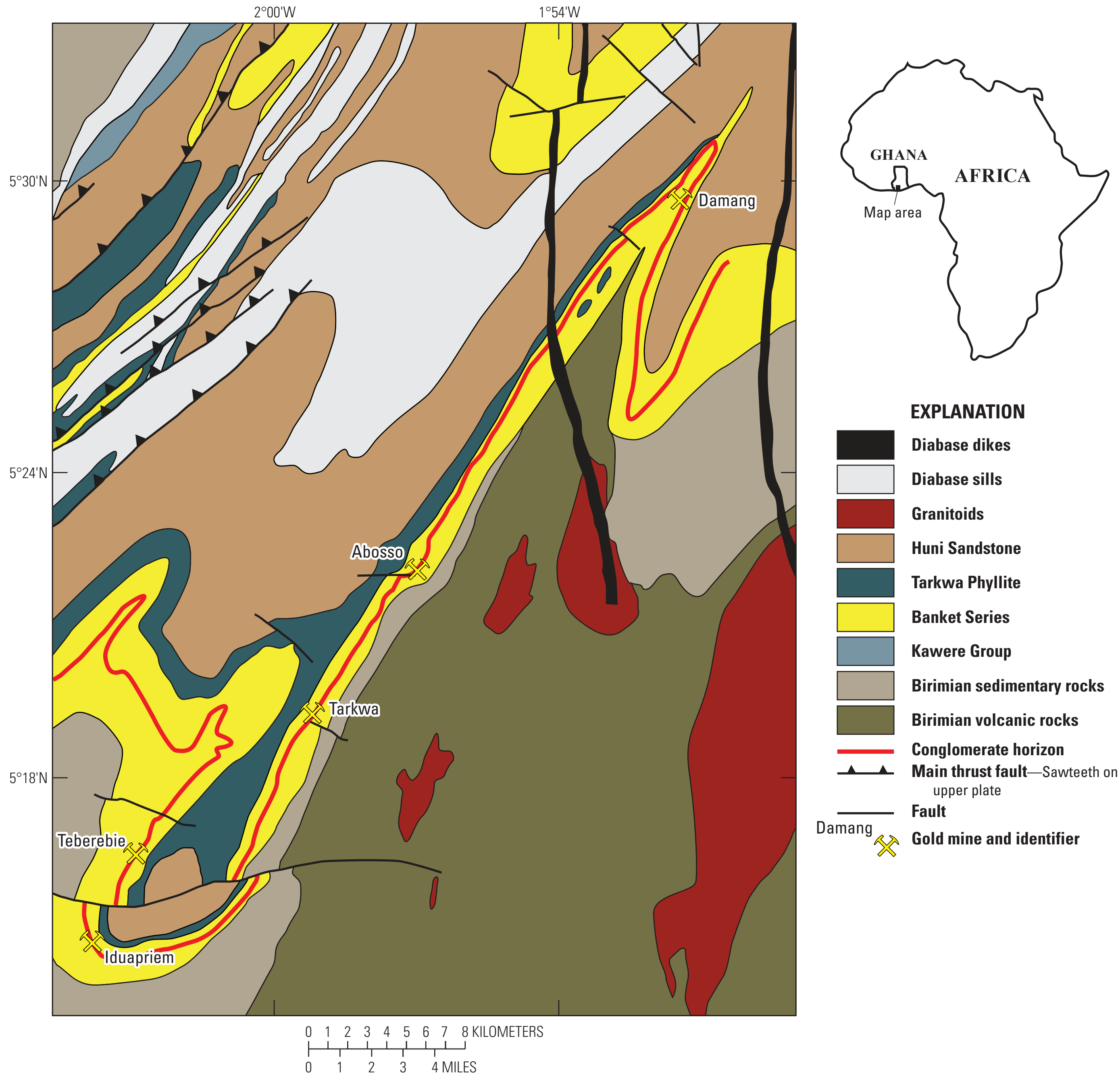


Figure 5. Simplified geologic map of the Tarkwa gold district, Ghana. Significant folding and faulting has led to a convoluted geometry of the ore body. Modified from Pigois and others (2003).

deep. Continued mining is planned to approach 5 km depth (Grodner, 2001), although many technical problems exist for mining at such extreme depths.

As stated above, the sedimentary rock sequences that make up the basin fill are on the kilometer scale. Of the four basins that host major quartz-pebble-conglomerate deposits, the sedimentary rock fill of the Tarkwa Basin is the thinnest, with a maximum preserved thickness of 2.5 km, and that of the Huronian Basin is one of the thickest, at 15 km (Pretorius, 1981a). Gold-bearing conglomerate beds are not necessarily restricted to certain positions in the sedimentary pile and can be found at various stratigraphic levels. The most prolific beds in the Witwatersrand Basin are located in the middle to upper portions of the basin fill, but are mostly found stratigraphically within about a 4 km section between the highest level and lowest level gold-bearing bed. The richest beds in the Jacobina Basin span slightly less than 1 km of stratigraphy but are focused in the lowest stratigraphic formation of the basin. However, the conglomerate beds tend be located at or near the base of each sedimentation cycle (Pretorius, 1976).

Form and Shape

Tabular ore bodies are concordant with sedimentary bedding. The individual gold-bearing conglomerate beds range from single-pebble thickness to meter-scale. Some beds are laterally extensive, persisting for tens to hundreds of kilometers. In the Witwatersrand Basin, these beds have a lens-like geometry defined by fluvial-bar or channel bedforms.

Host Rocks

As suggested by their name, these deposits are hosted by quartz-pebble conglomerates. The hosting conglomerates are beds contained within thicker sedimentary sequences that infilled basins, typically foreland basins.

Structural Setting(s) and Controls

These basins are fault bounded, with an active fault that separated the basin from the uplifting hinterland during sedimentation. The source area of the sediments, the hinterland, was continuously uplifted, which leads to continued erosion and sedimentation and reworking and maturing of the sediments. Foreland basin formation is related to flexural subsidence driven by thrust-sheet loading in the hinterland (DeCelles, 1996).

Geophysical Characteristics

Modern geophysical methods employed at multiple scales are useful during exploration for paleoplacer gold deposits. An up-to-date review (as of 2018) of geophysical methods for mineral exploration is provided by Dentith and Mudge (2014) and is the basis for the method descriptions presented here. We discuss several geophysical methods and provide examples of their utility in the exploration for paleoplacer gold systems.

Geophysical methods are successful only when the target rocks, structures, or ore bodies have physical properties that differ from their surroundings. Thus, these methods are most sensitive to changes in the physical properties of rocks (or minerals), including magnetism, density, electrical resistivity, radioactivity, and elasticity.

Unique geological characteristics of paleoplacer gold deposits occur at multiple scales, from the basin in which they occur down to the deposit itself. Correspondingly, geophysical data are collected at multiple scales and can be effective for imaging differing parts of the gold system. At a regional-scale, the crustal architecture in which paleoplacer gold deposits occur can be imaged using aeromagnetic, gravity, and two-dimensional (2D) seismic techniques. These methods are effective for mapping favorable lithologies at depth, as well as structures. At the deposit scale, geophysical methods such as aeromagnetic, gravity, radiometric, and three-dimensional (3D) seismic techniques can be useful in delineating lithology and structures.

Optical Remote Sensing Signature

Optical remote sensing measures the way in which incident light from the sun reflects off surface material and has long been used in mineral exploration (Sabins, 1999; Kokaly and others, 2016). These data are acquired by scanners on aircraft or satellites orbiting Earth. In addition, infrared spectroscopy using hand-held spectrometers can measure reflectance on outcrops, hand samples, and drill cores, providing a rapid means for material characterization. Combining airborne and ground-based imaging spectroscopy can provide a swift characterization of geology and hydrothermal alteration in three dimensions (Kruse and others, 2012). In mineral exploration, the measured wavelengths typically range from visible to shortwave infrared regions of the electromagnetic spectrum. These data are capable of differentiating lithologic units and minerals or mineral groups that yield unique spectra on a plot of wavelength versus reflectance. The spectra can be compared to spectral libraries for material identification. Band ratios can be used to enhance various features in the data sets. One drawback of optical remote sensing using airborne detectors is that only surficial material is mapped, which limits utility in geological or mineralogical studies in covered or concealed terrains.

Optical remote sensing data sets can be grouped into hyperspectral and multispectral data types. A recent review of these data types is provided by van der Meer and others (2012). Hyperspectral data have narrow and contiguous spectral bands, providing greater certainty in material identification. These data are generally acquired and processed by service companies and, therefore, can be costly and are not typically publicly available. Multispectral data have wider spectral bands and can be useful in distinguishing alteration mineral groups such as hydrous clays and iron oxides. These data are maintained by government agencies and are relatively inexpensive and have nearly global coverage. The most commonly used data sets for mineral exploration include Landsat Enhanced Thematic Mapper (ETM) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER).

Multispectral data were used to better understand the distribution of gold-bearing conglomerate units in the Marble Bar Basin, Western Australia (Box, 2013). The gold-bearing conglomerate units lie beneath basalts and sedimentary rocks, making direct detection of the conglomerate units with remote sensing difficult. Using band ratios, researchers were able to differentiate sedimentary and igneous rocks, as well as highlight the quartz-rich rocks, using ASTER data. Ground investigation showed that the ASTER data were highly effective in locating prospective conglomerate horizons.

Magnetic and Gravity Signature

The magnetic and gravity methods, commonly referred to as potential field methods, are often interpreted together. Both methods involve measurements that can be made on the ground or from aircraft. These data are commonly available from government geological surveys at little or no cost and can provide a nearly continuous set of unbiased observations over relatively large areas. Magnetic and gravity anomalies are non-unique in that there are an infinite number of possible source distributions that may create the observed anomalies. For more meaningful anomaly interpretations, the integration of additional data sets, such as physical property measurements, additional geophysical data sets, and geology maps, is essential.

Magnetic data provide information on the distribution of magnetic minerals, mainly magnetite, within the crust. These data can be used to uncover patterns and trends that may reflect differing lithologies and structures proximal to paleoplacer gold deposits. These data can map geology at depth under surficial cover such as glacial deposits, forests, sands, and weathered material.

Magnetic susceptibility measurements can be made on both outcrop and drill core. Rocks with larger concentrations of magnetite have high magnetic susceptibilities and produce magnetic-anomaly highs when compared to rocks with low magnetic susceptibilities. In general, igneous rocks have higher magnetic susceptibilities than sedimentary rocks. However, the ferruginous shale units within the Witwatersrand Basin have relatively high susceptibilities such that they produce prominent magnetic anomalies (Roux, 1967). Magnetic susceptibilities are highly variable, spanning several orders of magnitude for a single rock type (fig. 6).

Gravity surveys measure small variations in rock density. In general, igneous rocks have higher densities than sedimentary rocks and mafic igneous rocks tend to have higher densities than felsic rocks (fig. 7). Gravity data are commonly collected on the ground at relatively coarse resolution. However, recent advances in airborne geophysical survey techniques allow for gravity information to be obtained in moving aircraft at spatial resolutions that may exceed existing ground surveys.

Magnetic surveys can be effective when exploring for placer gold deposits (Doyle, 1986; Gunn and Dentith, 1997). Paleochannels may contain detrital magnetite or basalt flows that can give rise to magnetic anomalies if they occur at relatively shallow depths and the data are of high enough resolution. Because hematite and magnetite are commonly found with the paleoplacer deposits in the Tarkwa Basin quartz-pebble conglomerates (Sestini, 1973; Strogen, 1988; Hirdes and Nunoo, 1994), magnetic surveys may prove useful during exploration. However, as depth-to-deposits increases, these methods become less effective.

Gravity and magnetic methods have helped researchers understand the structure of the Witwatersrand Basin, Africa (Roux, 1967; Doyle, 1986; Corner and others, 1990). The extent of the basin has been mapped in detail using both gravity and magnetic methods (Corner and others, 1990), which provides a first-order constraint for exploration. Ferruginous shale units in the West Rand Group, which stratigraphically underlie the gold-bearing conglomerates of the Central Rand Group, produce prominent magnetic highs along the basin margin (Roux, 1967). The magnetic method images these rocks to depths as great as 1,000 meters (m) (fig. 8). The magnetic anomalies help establish the position of the gold-bearing conglomerates of the Central Rand Group beneath cover rocks (Roux, 1967). A Bouguer-gravity-anomaly high is observed over the basin and localized lows are observed over the ore-bearing conglomerate rocks proximal to the edge of the basin (fig. 8). The interpretation of the gravity anomalies is calibrated using density measurements on rocks throughout the basin (Roux, 1967). The granite basement has relatively low density, around 2.63 grams per cubic centimeter (g/cm^3). The rocks of the West Rand Group are stratigraphically above the basement and include ferruginous shales and slates, which have relatively high densities, ranging from 2.8 to 3.85 g/cm^3, and quartzites, which have densities around 2.63 g/cm^3. The intrusions within the West Rand Group have measured densities around 2.9 g/cm^3. The ore-bearing rocks of the Central Rand Group, composed predominantly of quartzites, shales, and conglomerates, have relatively low densities, averaging around 2.65 g/cm^3. The rocks that lie stratigraphically above the Central Rand Group have densities around 2.85 g/cm^3. Thus, the rocks of the Central Rand Group that host the paleoplacer deposits are less dense than the rocks stratigraphically above and below them. The density contrast is imaged by local Bouguer-anomaly lows near the perimeter of the basin (fig. 8). Together, the magnetic highs associated with the ferruginous shale units, coupled with coincident gravity and magnetic lows over the ore-bearing Central Rand Group, helped guide early exploration in the Witwatersrand Basin (Roux, 1967; Doyle, 1986). However, the potential field methods become less effective with depth and do not provided the necessary detail needed to effectively explore for relatively deep gold resources.

Radiometric Signature

Radiometric methods measure the potassium, uranium, and thorium concentrations of rocks or surface material. These measurements can be made in aircraft, on the ground, or down boreholes. All measurements have limited penetration depths of a few centimeters. Potassium, uranium, and thorium are the three most abundant naturally occurring radioactive elements that are present in various proportions in all rocks and soils. It is important to note that a measured point from airborne data is an average element concentration over a specified surface area, so absolute, localized concentration measurements are not possible unless a ground-based instrument is used. Depending on survey design (mainly line spacing), these data can be examined on either a profile basis or as concentrations interpolated to form a continuous surface. Radiometric data should be interpreted in terms of surface chemistry using maps of individual elements or maps with the ratio of two elements (Dickson and Scott, 1997). The elemental distribution can help with mapping geologic units. Linear features within the data may indicate the presence of faults or structures.

Radiometric methods have been helpful for understanding paleoplacer deposits in South Africa and Brazil. The paleoplacer deposits are commonly enriched in uranium and therefore can be effectively mapped using radiometric methods where the host sedimentary rocks crop out. In South Africa, downhole

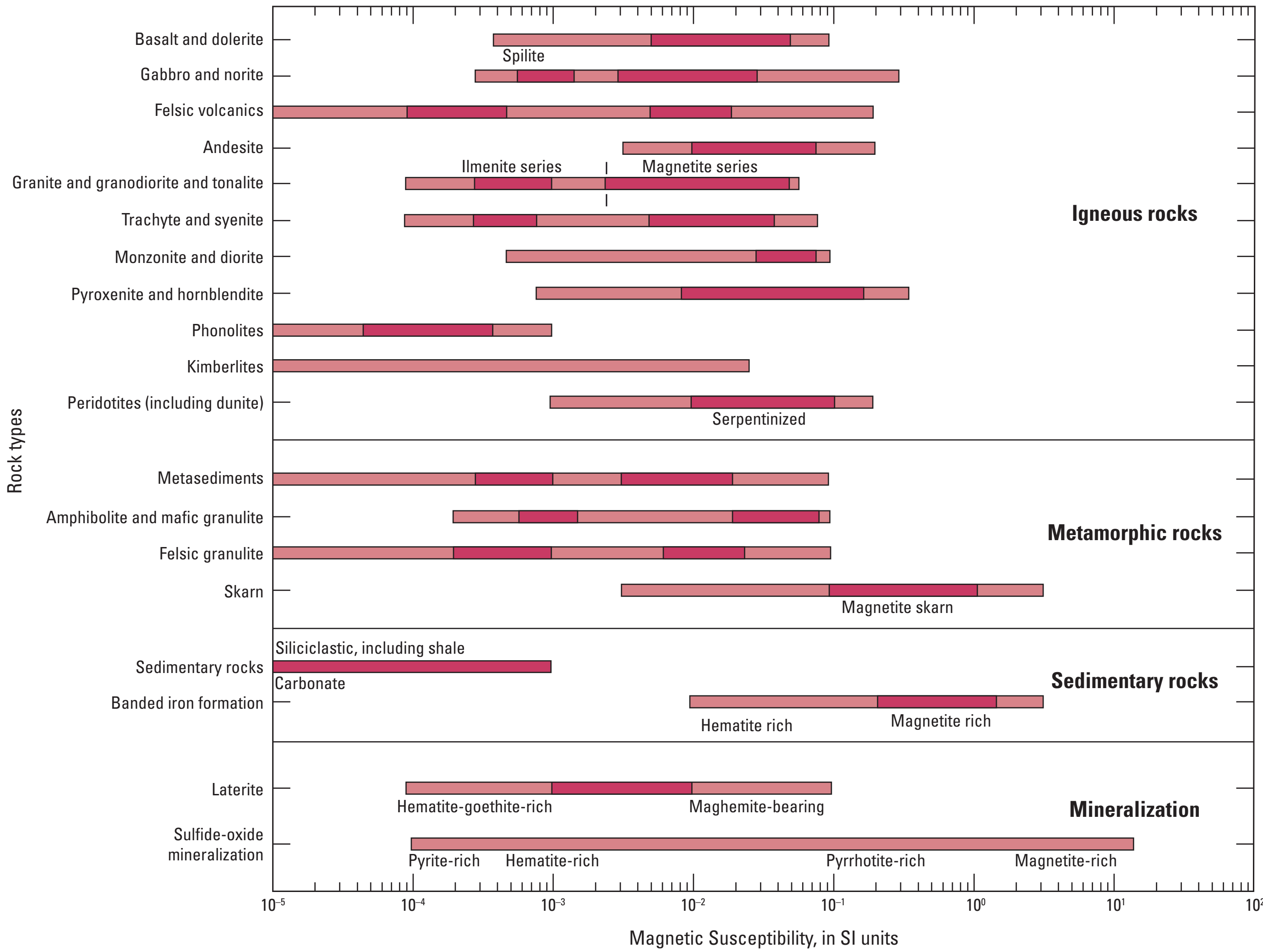


Figure 6. Magnetic susceptibility ranges for common rock types. The dark red shading indicates the most common ranges. Bimodal distributions, with two bars of dark red shading for a given rock type, typically reflect the presence or absence of ferromagnetic minerals; in these cases, the leftmost dark red bar represents rocks that lack magnetite but contain ilmenite (ilmenite series) and the rightmost dark red bar represents rocks containing magnetite (magnetite series). Modified from Dentith and Mudge (2014). [SI, International System of Units]

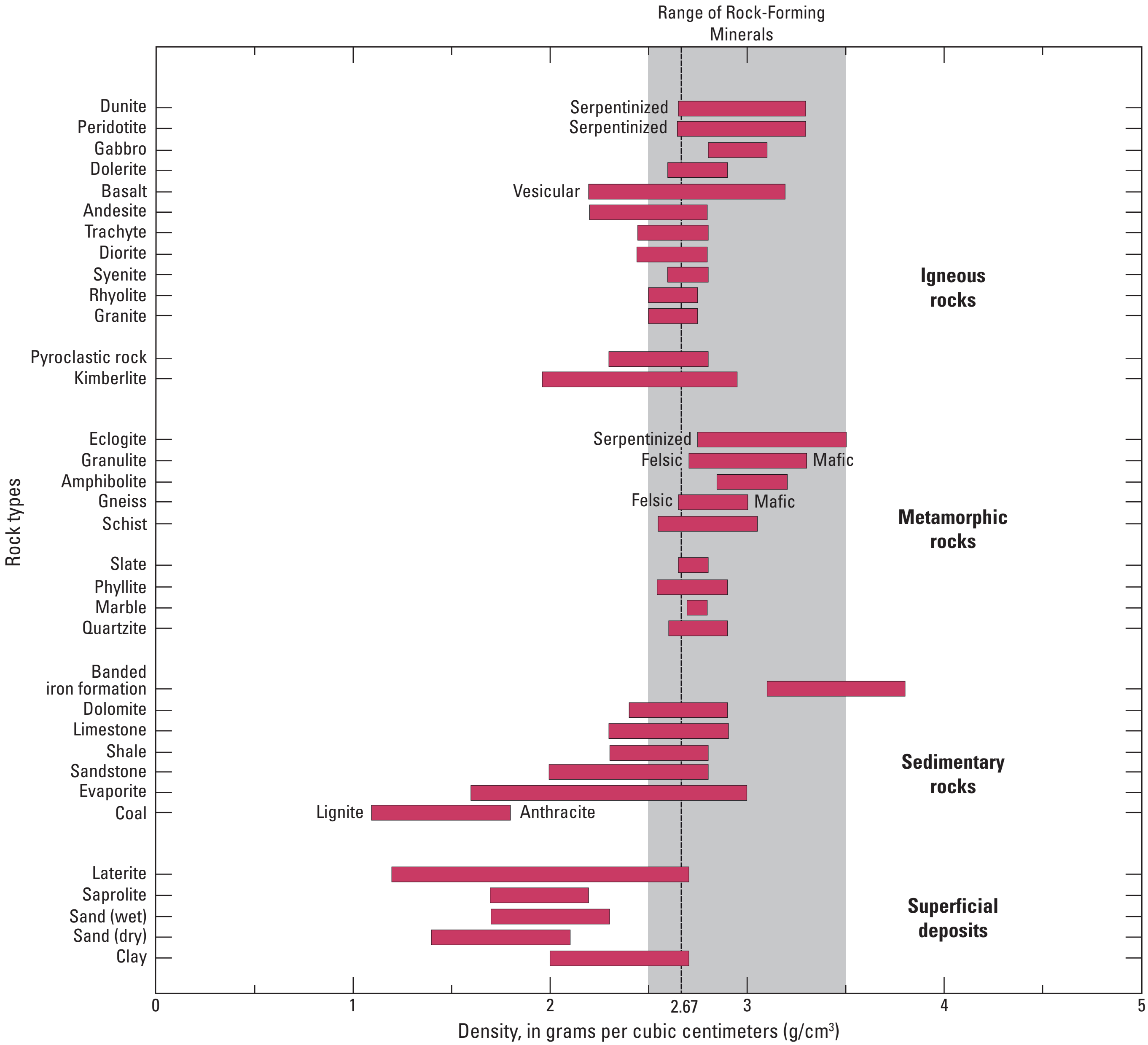


Figure 7. Density ranges for common rock types. Modified from Dentith and Mudge (2014).

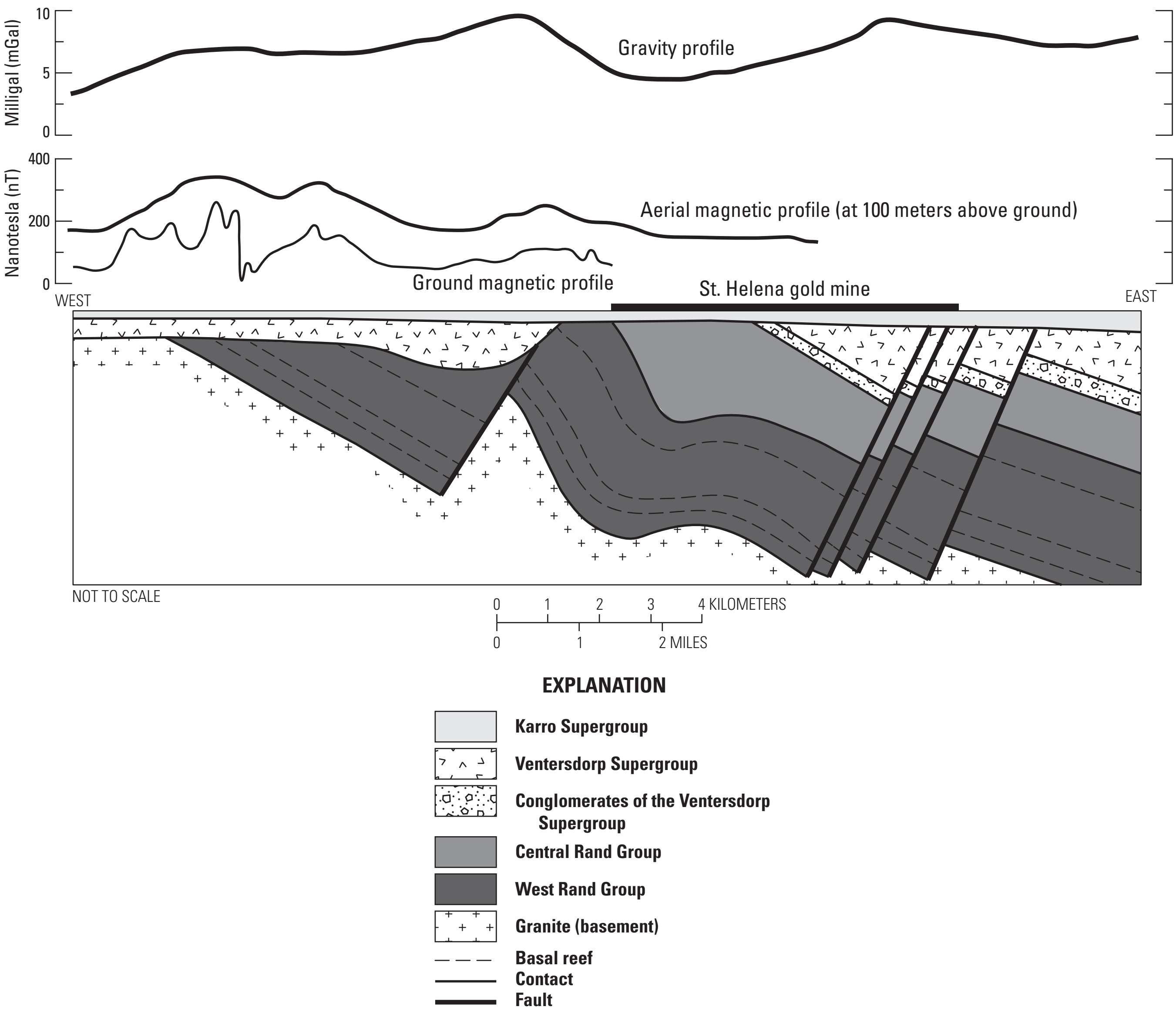


Figure 8. Magnetic and gravity anomalies juxtaposed above a cross section near the St. Helena gold mine, South Africa. Strong magnetic anomalies are associated with ferruginous shales in the West Rand Group. A gravity low occurs over the eastward-dipping Central Rand Group, whereas a moderate gravity high is coincident with magnetic highs associated with the ferruginous shales. Such observations helped lead to discovery during early gold exploration in the Witwatersrand Basin, South Africa. Modified from Roux (1967).

radiometric logs across the Witwatersrand Basin have been used to correlate stratigraphy and locate gold- and uranium-bearing conglomerates (Simpson, 1951). In Brazil, reconnaissance gamma spectrometry was used to map anomalies around the Canavieiras mine (Ferreira and others, 1979).

Electrical and Electromagnetic Signature

Electrical and electromagnetic (EM) methods respond to the electrical conductivity of rocks and minerals. The electrical conductivity (reciprocal of resistivity) of rocks and minerals can span many orders of magnitude, but in general, sedimentary rocks are more conductive than crystalline rocks, a fact that can be used to trace geologic units within deposits (fig. 9). The resistivity properties are mainly controlled by rock porosity and the nature of what occupies the pore space. Resistivity is lowered when saline fluids occupy pore space or fractures in rocks. In addition, the presence of conductive clays, graphite, and metallic ore bodies can lower bulk resistivities.

Electrical and EM survey designs are fundamentally different. A summary of these techniques is provided by Dentith and Mudge (2014). Smith (2014) discusses recent advancements in EM methods in the mining industry. Electrical surveys are exclusively ground based, as they require electrodes to be placed into the ground. The self-potential (SP) method is passive and may be the most basic electrical survey. Self-potential methods involve a series of measurements of the natural variation of electrical potential between two electrodes. Active electrical-resistivity surveys are achieved

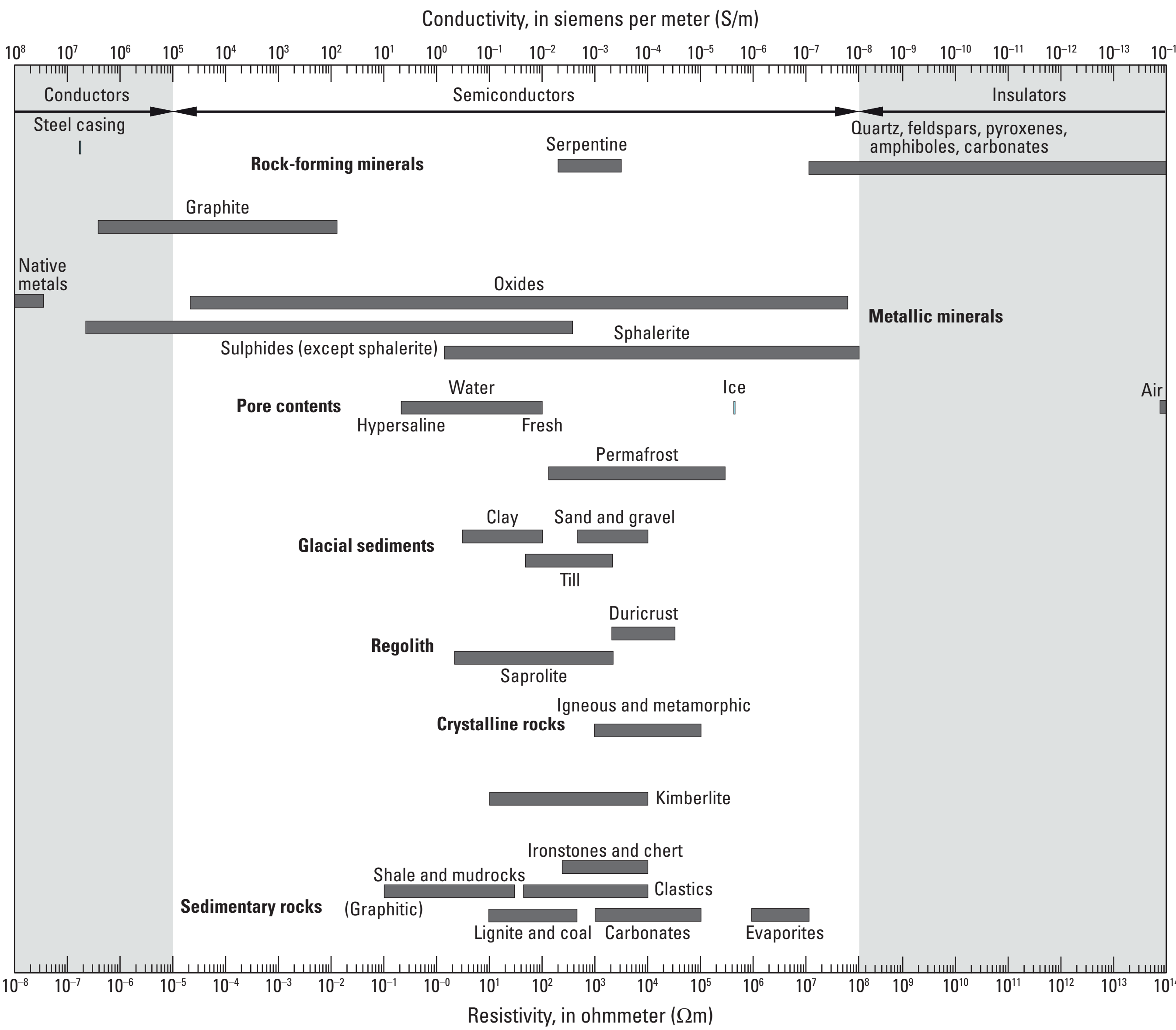


Figure 9. Ranges for conductivity and resistivity values for common rock types. Modified from Dentith and Mudge (2014).

by injecting current into the ground using a pair of electrodes and measuring the voltage at another pair of electrodes. The induced-polarization (IP) method, which is often employed concurrently during resistivity surveys, measures the voltage decay (chargeability) after the current has been interrupted. Changing the geometry of the electrodes allows for the 3D resistivity structure to be mapped.

Electromagnetic methods can be carried out on the ground or in aircraft. Electromagnetic surveys transmit an EM field that penetrates the ground and produces a secondary field when conductive material is encountered. The secondary field is then measured by a receiver. The technique can be performed in both frequency and time domains. The magnetotelluric electromagnetic method is passive and utilizes natural EM fields to investigate the resistivity structure to mantle depths. The controlled-source-audio-frequency-magnetotelluric method, commonly used in mineral exploration, utilizes an artificial signal source to investigate resistivity structure to crustal depths, around 1 km (Zonge and Hughes, 1991).

Seismic Signature

The seismic method has traditionally been used in petroleum exploration but is seeing an increased use in the search for mineral deposits under cover (Malehmir and others, 2012, 2014; Dentith and Mudge, 2014). Seismic methods include reflection and refraction, both of which investigate the travel times of seismic waves through the Earth. Seismic reflection surveys are capable of mapping changes in geology down to tens of kilometers depth, whereas refraction surveys are generally limited to shallower depths. Seismic surveys are most effective in sedimentary basins where the lithologic units are laterally continuous and subhorizontal. The seismic method is sensitive to the elastic properties of rocks. The strength of a seismic reflection is dependent upon the acoustic-impedance contrast between two layers, where high contrasts yield stronger reflections.

Since the 1980s, seismic methods have been routinely used in the exploration for gold resources within the Witwatersrand Basin (Durrheim and others, 1991; Coward and others, 1995; Stevenson and Durrheim, 1997; Gibson and others, 2000; Pretorius and others, 2000; de Wit and Tinker, 2004; Malehmir and others, 2012, 2014; Manzi and others, 2012a, 2012b). The first seismic investigations were 2D surveys designed for subsurface structural mapping. In the 1990s, 3D seismic surveys began to be used and were focused on mine planning and development. The seismic method does not directly detect gold but does image structure and marker beds within the stratigraphic section that help guide exploration.

Seismic surveys in the Witwatersrand Basin image several rock packages and contacts in the stratigraphic column (fig. 10). At the broadest scale, the seismic data image the Witwatersrand Supergroup on granitic basement, with underlying Moho at around 40 km depth

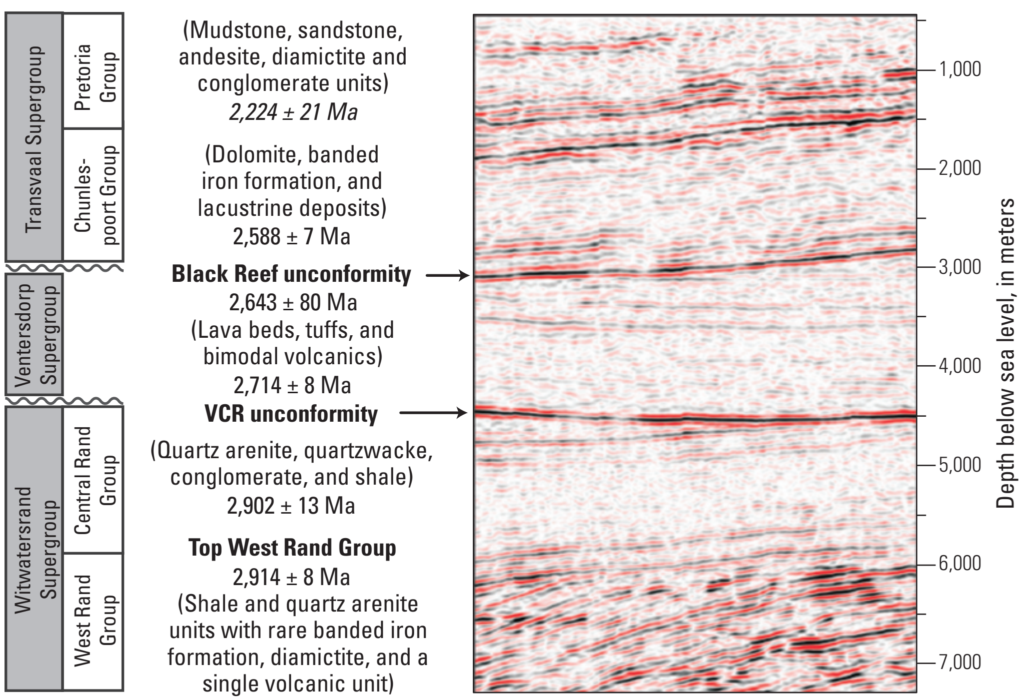


Figure 10. Generalized stratigraphy and seismic reflection section from the West Wit Line Gold Field, South Africa (modified from Manzi and others, 2012b). Marker horizons such as the Ventersdorp Contact Reef (VCR) and Black Reef unconformities help make seismic methods an effective exploration tool within the Witwatersrand Basin. Geochronological data and geology modified from Dankert and Hein (2010). [Ma, mega-annum]

(de Wit and Tinker, 2004). The basement rocks are generally seismically transparent, and most reflectors are found in the overlying sedimentary sections. The shales, lavas, and quartzites within the West Rand Group that overlies the basement show strong, continuous reflections (fig. 10). The rocks in the Central Rand Group are not particularly well imaged with the seismic data. However, the contact between the Central Rand Group and overlying basaltic lavas in the Ventersdorp Supergroup is known as the Ventersdorp Contact Reef (VCR) and shows strong reflection throughout the basin. The contact between the dolomite rocks of the Transvaal sequence and the underlying lavas of the Ventersdorp Supergroup produce strong reflections. The shales in the Transvaal sequence are characterized by strong, continuous reflections. Structural interpretation of these data can identify where potential ore bodies occur at minable depths and where such resources may be preserved.

Early 3D reflection seismic data proved effective for mapping gold resources in the Klerksdorp (Pretorius and others, 2000) and Welkom (Stuart and others, 2000) Gold Fields (fig. 2). In both areas, the seismic data accurately delineated the 3D structure of the VCR at depths ranging from 1,000 to 3,500 m. In addition, fault offsets in the range from 20 to 1,200 m were imaged in the Klerksdorp Gold Field (Pretorius and others, 2000). Seismic attributes such as reflective amplitude, instantaneous frequency, instantaneous phase, dip magnitude, and azimuth of dip revealed details of fault geometries with as little as 10 to 20 m of offsets (Stuart and others, 2000).

Three-dimensional reflection seismic methods play an important role during gold exploration and mine planning in the West Rand and Carletonville Gold Fields, 80 km southwest of Johannesburg, South Africa (Gibson and others, 2000; Malehmir and others, 2012, 2014; Manzi and others, 2012a, 2012b). A contiguous seismic volume was generated by merging legacy and newly acquired seismic reflection data. Advanced signal processing and seismic attribute analysis on this volume led to an improved understanding of the continuity of faults and their geometries (Manzi and others, 2012b). With the results, researchers were able to confidently map faults with 25 m of throw and, using attribute analysis, they imaged with relatively high confidence faults with offsets as small as 10 m (Manzi and others, 2012b). In addition, these data facilitated mine planning by helping researchers map hazardous zones associated with unstable lithologies and faults that may have provided conduits for groundwater and methane gas migration (Manzi and others, 2012a). The seismic data clearly imaged the VCR, marking the contact between mafic and ultramafic rocks of the Klipriviersberg Group and the underlying gold-bearing conglomerates of the Central Rand Group (fig. 10). At a broad scale, the seismic data mapped the north-south-trending, west-dipping West Rand and Bank faults (fig. 2) that were shown to have offsets of as much as 2 km. This information, combined with locations of footwall units to the VCR, helped researchers identify prospective areas for additional gold resources.

Ore Characteristics

Mineralogy

Deposits emplaced during the Archean through the early part of the Paleoproterozoic, such as those that mostly formed prior to the Great Oxidation Event at approximately 2.3 Ga in the Jacobina and Witwatersrand Basins (Holland, 2002), contain gold and uraninite along with sulfides. Gold deposits that formed later during the Paleoproterozoic subsequent to the Great Oxidation Event, such as those at Tarkwa, contain oxides instead of abundant sulfides, as do the younger Phanerozoic deposits. These younger deposits contain minor sulfide with no uraninite.

Over 70 ore minerals have been identified in the reefs of the Witwatersrand Basin (Feather and Koen, 1975). The most significant of these are native gold, pyrite, and uranium-bearing minerals such as uraninite, brannerite, and leucoxene.

Mineral Assemblages

Gold, uranium minerals, and pyrite are spatially associated with other detrital heavy minerals within the beds. This is especially the case with heavy minerals that are concentrated along the basal surfaces of individual beds. Much of the gold in the Witwatersrand deposits is also associated with carbonaceous material and pyrite. Gold displaying hydrothermal textures is commonly associated with chlorite, bitumen, and hydrothermal pyrite. Other, more oxidized deposits such as those at Tarkwa have gold associated with hematite and magnetite instead of pyrite and bitumen, along with other similar heavy minerals such as zircon and rutile.

Gold occurs most commonly as free gold and as inclusions within pyrite. At Tarkwa, gold is also found as inclusions within quartz pebbles, which provides strong support for the idea that the gold is derived directly from the erosion of orogenic gold-bearing quartz veins (Frimmel, 2014).

Textures and Structures

Even within the same sample from the Witwatersrand, gold can occur as rounded detrital grains or as crystalline secondary gold (fig. 11; Minter and others, 1993). The proportion of detrital to hydrothermal gold grains in the Witwatersrand deposits seems to greatly vary between local areas. Spheroidal or flattened, disc-like gold grains with compaction marks, overturned rims, folds, and other deformation textures indicate a detrital origin, and textures mark transportation, compaction, and burial. The surfaces of many of these detrital grains from the Witwatersrand deposits also have impact areas and even other heavy detrital minerals that are embedded into the rounded gold grains. At Roraima, the degree of rounding of the gold increases down paleoslope, as would be expected to result from extended transport of detrital gold grains (Frimmel and others, 2005b); however, even these detrital grains may

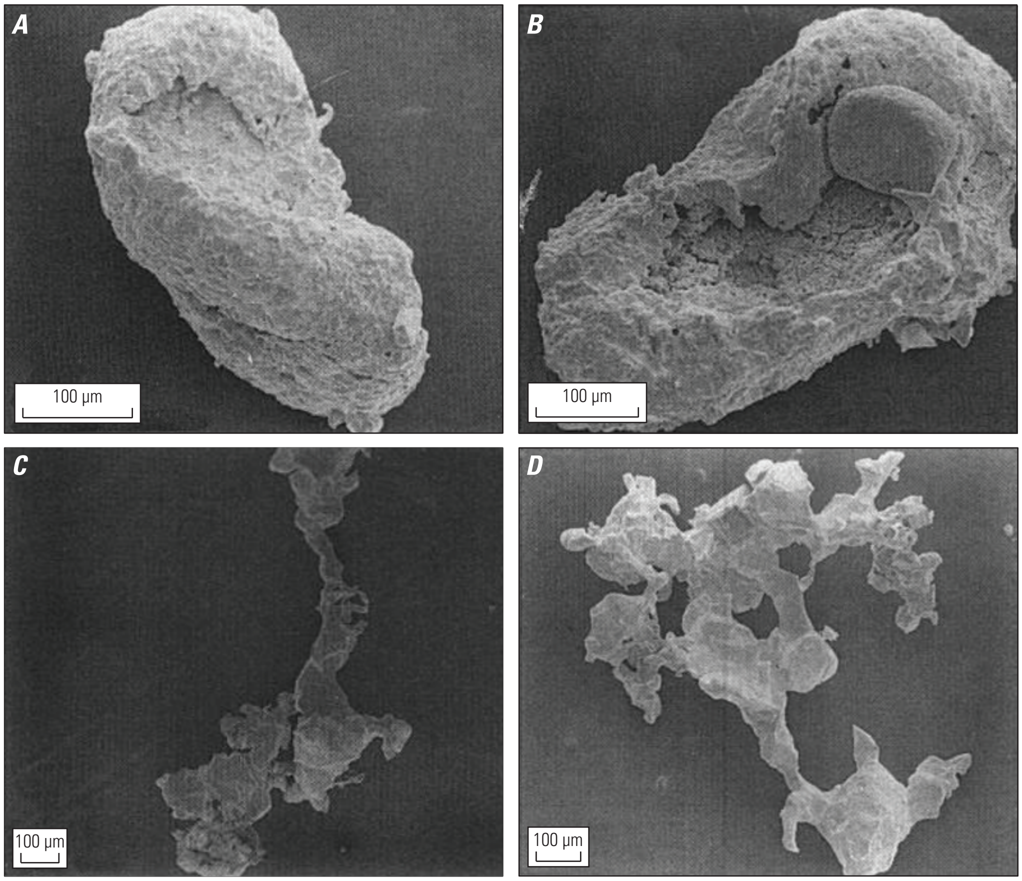


Figure 11. Photomicrographs of gold grains from Witwatersrand Basin deposits, South Africa (adapted from Minter and others, 1993). *A*, Rounded and folded gold grain. *B*, Rounded gold grain with a rounded pyrite crystal embedded within it. *C* and *D*, Secondary crystalline gold grains. [µm, micrometer]

show an overgrowth of secondary crystalline gold, indicating local gold remobilization by hydrothermal processes (Frimmel and others, 2005b, their figure 1*C*).

Many gold grains are unquestionably of secondary origin, although the extent and distance of primary gold remobilization and movement into secondary form cannot be determined. These irregularly shaped crystals lack surfaces with indentations or other markings and are commonly found within microfractures, indicating that they formed after transport of the surrounding detritus.

Gold and other heavy minerals are commonly richest along the bottoms and tops of the pebble beds, which are the bottom degradation surface and the top winnowed surface, respectively. These are locations that support initial concentration via sedimentary processes.

Various forms of pyrite are found within the reefs (for example, see England and others, 2002, their figures 3–9). In the Witwatersrand deposits, pyrite is divided into multiple types based upon texture, mainly classified as rounded or euhedral to subhedral (fig. 12). Here, the rounded pyrite crystals are further subdivided into rounded compact and rounded porous forms. The rounded compact pyrites are the most abundant form of pyrite in the vast majority of reefs and have truncated growth banding along the edges of the crystals as a result of abrasion during mechanical transport, conclusively proving their detrital origin (MacLean and Fleet, 1989). These textures would be infeasible if the grains were originally heavy, detrital, black sands that were subsequently sulfidized in situ to pyrite, as some previous researchers had contended (for example, Phillips and Myers, 1989). The rounded porous pyrites may show a wide variety of internal structures and has been further subdivided by England and others (2002) into six forms: aggregated pyrite, concretionary pyrite, oolitic-colloform pyrite, dendritic pyrite, banded pyrite, and miscellaneous forms of pyrite. All of these forms of rounded porous pyrite have been interpreted to also be detrital in origin, except for some of the aggregated pyrite, which may be diagenetic in origin or show textures indicative of multiple generations, such as pore-filling pyrite cement between aggregates of pyrite.

The euhedral to subhedral authigenic pyrite crystals formed during hydrothermal alteration, metamorphism, and (or) diagenesis. Some of these pyrite crystals are wholly authigenic, whereas others may have euhedral overgrowth around a core of rounded pyrite or may form larger crystals that nucleated around fractured pyrite.

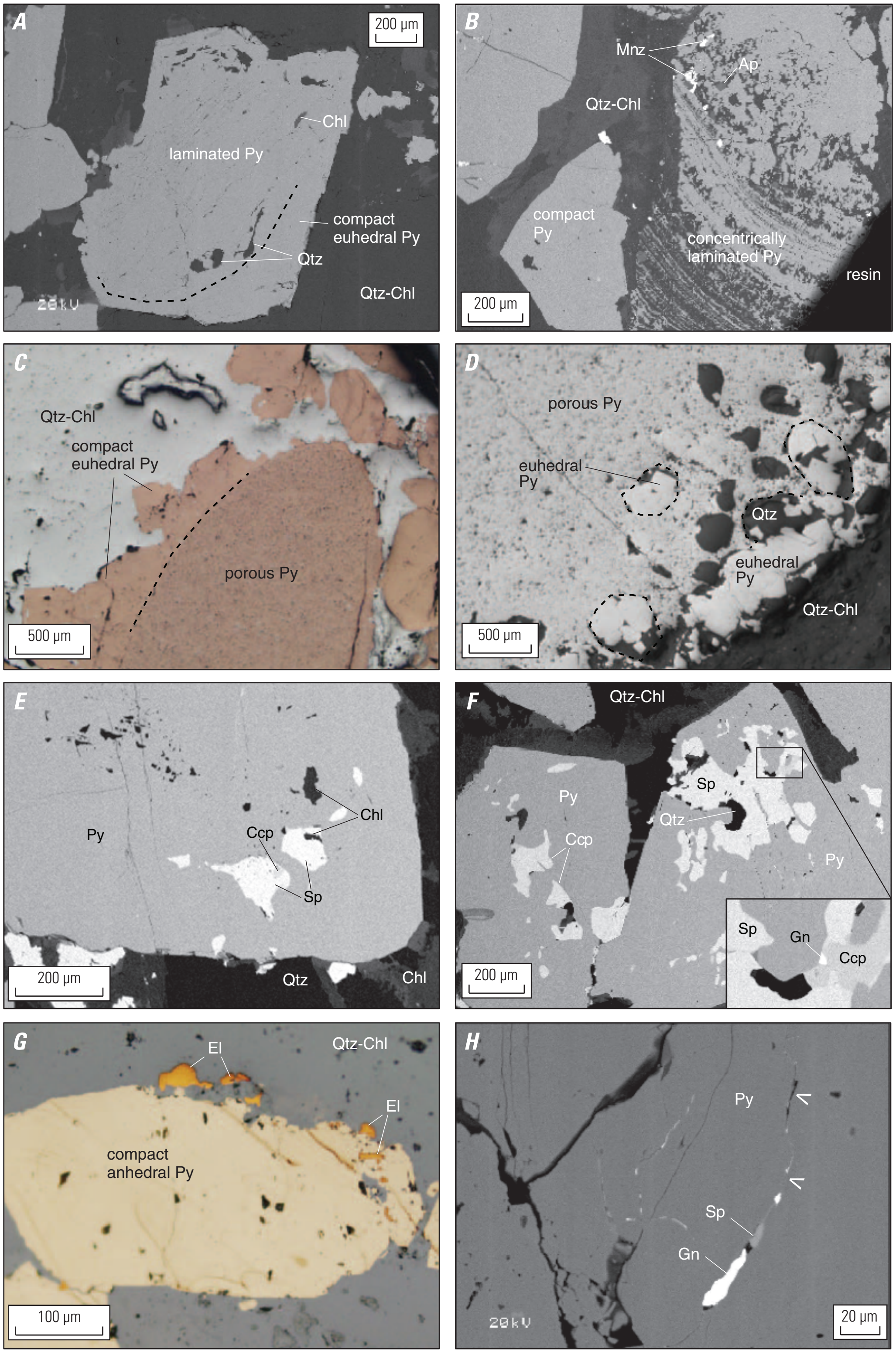


Figure 12. Optical microscope (*C*, *D*, and *G*) and backscattered electron (*A*, *B*, *E*, *F*, and *H*) images of pyrite textures from Witwatersrand deposit ore samples. From Agangi and others (2013). *A*, Laminated pyrite grain with quartz, chlorite, and compact euheral pyrite overgrowth. B, Fragmented laminated and compact pyrite within a quartz and chlorite matrix. Pyrite contains apatite and monazite inclusions. *C*, Rounded, porous pyrite crystal with a compact euhedral pyrite overgrowth. *D*, Large, rounded, porous pyrite with round domains (possibly former voids), which include compact euhedral pyrite and quartz. *E*, Association of chalcopyrite, sphalerite, and chlorite inclusions in pyrite. *F*, Sphalerite, galena, chalcopyrite, and quartz inclusions in compact pyrite. *G*, Electrum inclusions hosted in compact anhedral pyrite and in the quartz-chlorite matrix. *H*, Galena and sphalerite inclusions located along a crack (arrows) in secondary pyrite. [µm, micrometer; kV, kilovolts; Qtz, quartz; Chl, chlorite; Py, pyrite; Mnz, monazite; Ap, apatite; Ccp, chalcopyrite; Sp, sphalerite; Gn, galena; El, electrum]

Grain Size

Coarse gold is typically not present in this type of deposit, and the vast majority of the gold is on the submillimeter scale. In the Witwatersrand deposits, gold that is greater than 1 millimeter is almost always attached to coarse pyrite crystals (Hallbauer and Joughin, 1973). Submicrometer gold is also found. The size of detrital gold grains within the Evander Gold Field in the Witwatersrand Basin (fig. 2) was noted to decrease exponentially to the northeast, which has been interpreted to be a result of decreasing energy levels within the sedimentary environment (Hirdes, 1979). The largest gold grains at Tarkwa are a bit over 100 micrometers, but most are between 1–40 micrometers (Hirdes and Nunoo, 1994; Pigois and others, 2003).

Hydrothermal Alteration

Hydrothermal events most certainly remobilized detrital gold, but only over very short distances. Many workers agree that metamorphic fluids infiltrated the sedimentary rock pile after burial and diagenesis to remobilize gold and precipitate hydrothermal mineral assemblages (for example, Robb and Meyer, 1995). However, disagreement as to the extent and quantity of minerals originating from hydrothermal processes continues to exist between those who believe that these deposits are formed as modified placers and those who believe they are formed entirely by hydrothermal processes. Gold can be associated with many hydrothermal minerals, such as secondary pyrite, uraninite, and bitumen, but also has forms, textures, and mineral associations that are clearly detrital in origin. Barnicoat and others (1997) surmised that basinwide distribution of pyrophyllite, chloritoid, chlorite, and other assemblages resulted from acidic hydrogen metasomatism that also introduced the gold mineralization. Others have interpreted this assemblage to be a product of chemical weathering under acidic conditions (Frimmel and Minter, 2002).

The origin of the carbon in these deposits is important because of its close association with gold. Gray and others (1998) believe that the carbon in the Witwatersrand Basin represents liquid hydrocarbons that migrated by hydrothermal processes, whereas Mossman and others (2008) show that elementary geologic evidence indicates the syndepositional nature of some carbon seams, as they are truncated by erosional channels within the sedimentary rock pile and can be found along crossbed foresets. The pyrobitumen in the Witwatersrand is preferentially located in rocks deposited in low-energy, distal environments, whereas it is noticeably absent from rocks deposited in high-energy, proximal environments (Frimmel, 2005); this distribution is in agreement with the interpretation that the pyrobitumen represents the remnants of algal mats. However, just as with the gold, pyrobitumen fills fractures and likely represents local remobilization during a later hydrothermal event. The pyrobitumen likely was formed by the reaction of the original hydrocarbon with the radioactive uraninite grains.

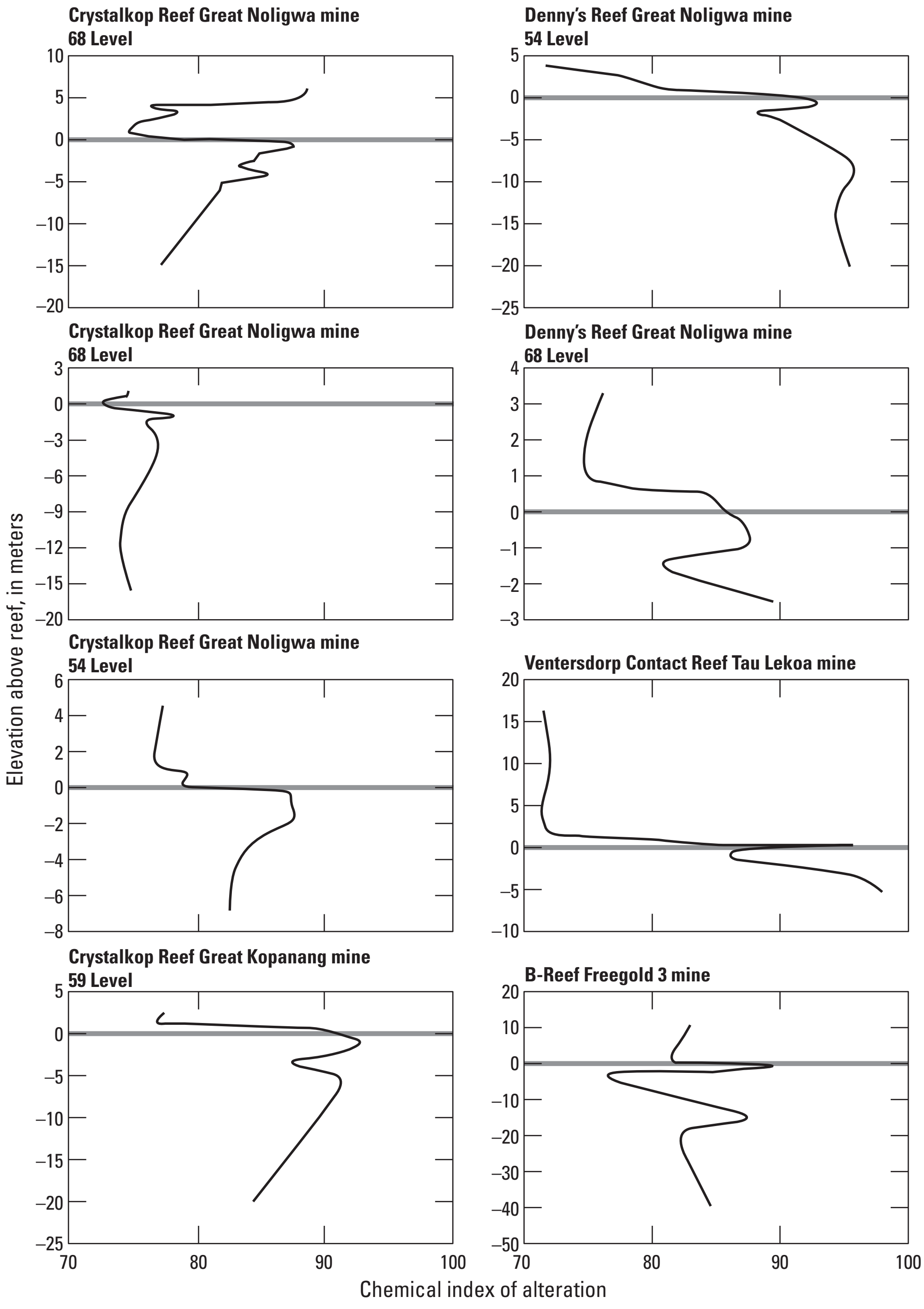
Various other hydrothermal phases are present in other quartz-pebble conglomerates around the world. In deposits at Jacobina, alteration phases of either metamorphic or hydrothermal origin include sulfides, fuchsite, muscovite, and lesser amounts of andalusite, rutile, chromite, and tourmaline (Ledru and others, 1997). In deposits at Tarkwa, pyrite, bitumen and uranium-bearing minerals are rare, but gold and other minerals were remobilized during greenschist-facies metamorphism (Pigois and others, 2003). The gold deposits in the Roraima Supergroup of South America show no significant hydrothermal alteration but still contain secondary crystals, including gold formed by local remobilization and recrystallization (Frimmel and others, 2005b).

Some of these paleoplacers also show overprinting sericitic or chloritic alteration (Robert and others, 1997). However, the lack of hydrothermal alteration in some quartz-pebble-conglomerate deposits and the detrital origin of ore in others that have a hydrothermal overprint indicate that hydrothermal alteration is not necessary in the development of this type of deposit.

Weathering and Supergene Processes

Formation of pyrophyllite and other alteration products in the Witwatersrand Basin is ascribed to acidic conditions. Although some researchers prefer to think that H^+ metasomatism through hydrothermal alteration has led to this alteration, the acidic alteration is more likely the result of weathering in an acidic atmosphere. Testing whether systematic changes in bulk, whole-rock chemistry across an erosional unconformity (or reef) exist or whether there is no significant change in chemistry can clarify this question.

Large-scale changes in the chemical index of alteration (CIA; defined as $Al_2O_3/(Al_2O_3+CaO+Na_2O+K_2O)$ by Nesbitt and Young, 1982) across the profiles of numerous reefs have been attributed to extreme paleoweathering subsequent to sediment deposition (Frimmel and Minter, 2002). During weathering, sodium and calcium are removed during the initial stages, and potassium is removed during the latest stages as minerals such as feldspars weather to aluminous clays (Nesbitt and Young, 1984; Nesbitt and Markovics, 1997). The highest CIA values can be seen in the footwall, just below the contact with the hanging wall, which has much lower values; this would not be expected if the alteration were the product of reef-parallel hydrothermal fluid infiltration (fig. 13). If these large-scale chemical differences were the result of hydrothermal fluid flow, they would be expected to be dispersed within both the footwall and hanging wall. However, it is likely that minor, small-scale (centimeter to decimeter) trends of CIA immediately around individual reefs reflect metasomatism by reef-parallel hydrothermal fluids in a post-depositional environment (Frimmel, 2005). Aggressive weathering conditions within an acidic atmosphere may have led to the intense weathering of source rocks for the gold, leaving the inert gold intact for substantial concentration and transport into the sedimentary systems.



Figue 13. Spatial trends in the Chemical Index of Alteration (CIA, defined as $Al_2O_3/(Al_2O_3+CaO+Na_2O+K_2O)$) with distance to gold reefs in the Witwatersrand Basin gold province, South Africa. All data are for argillic to arenitic siliciclastic rocks except for the hanging wall of the Ventersdorp Contact Reef, which is a metabasalt that leads to a lower CIA. Modified from Frimmel and Minter (2002) and Frimmel (2005).

Supergene alteration and weathering lead to oxidation and subsequent mobilization of uranium content. Detrital uraninite clasts may weather to brannerite or coffinite. Excessive oxidation may lead to leaching of uranium. At Moeda, pyrite has been noted to have oxidized to limonite or to have been completely weathered out, leaving relict holes where the original detrital pyrite was located (Minter and others, 1990). Supergene covellite may result from alteration of chalcopyrite.

Geochemical Characteristics

Trace Elements and Element Associations

A positive correlation between gold, silver, and uranium exists for some reefs (for example, Frimmel and Minter, 2002; Frimmel and others, 2005a), but this elemental signature is not always consistent. Gold particles from the Carbon Leader Reef in the Witwatersrand Basin have a uniform fineness and can have significant amounts of mercury (up to 6 percent; Oberthür and Saager, 1986). A weak positive correlation between gold and zirconium has been used to argue both for and against the modified placer model. Those researchers who prefer the hydrothermal model suggest that a stronger correlation should be seen if both gold and zircon crystals are detrital in origin; however, this logic is flawed in that the predominant source for each one would be different and the availability of these sources would control any correlation. Zircon crystals would likely erode from felsic sources, whereas the gold would likely be sourced from veins in mafic greenstone belts, and thus, the proportion of detritus from each type would dictate how well gold and zirconium correlate.

Zoning Patterns

Elemental zoning patterns have been observed (for example, Fox, 2002), but these patterns are derived from subsequent hydrothermal alteration or weathering. They are not related to any sedimentary processes responsible for detrital gold deposition.

Stable Isotope Geochemistry

The oxygen isotope composition of quartz pebbles varies from reef to reef, and even between adjacent pebbles from the same hand sample. Huronian quartz pebbles related to uranium mineralization have a normal distribution of values centered on a stable oxygen isotope ($\delta^{18}O$) value of 10 permil (‰), which is consistent with a granitic source for the quartz pebbles (Vennemann and others, 1992). The same authors also analyzed quartz pebbles from the Witwatersrand but noted a broad distribution of values, ranging from about 9 to 15 ‰, skewed toward higher values than the Huronian samples and also consistent with derivation from an Archean granite-greenstone terrane with components of hydrothermal vein quartz. Vennemann and others (1992) used these data to interpret that uranium-rich deposits such as those in the Huronian are sourced from granites, whereas more gold-rich deposits such as those in the Witwatersrand have gold sourced from greenstones.

Some authors contend that rounded pyrite grains within the conglomerates of the Witwatersrand deposits are the sulfidized replacement of primary detrital iron oxides (for example, Barnicoat and others, 1997); however, the heterogeneous nature of the sulfur isotopes within rounded pyrite samples is problematic for the model of precipitation or replacement by hydrothermal fluids. Rounded pyrite grains have a rather large range of sulfur-isotope values (-4.7 to +6.7 ‰) even at the centimeter scale (England and others, 2002). Eldridge and others (1993) noted large variations (-7 to +32 ‰) within single crystals and between populations of crystals of differing morphology.

Radiogenic Isotope Geochemistry and Geochronology

Rhenium-osmium (Re-Os) isotopic studies of gold from the Witwatersrand deposits found that the gold has low Re/Os (≥32 parts per billion Re, up to 10,350 parts per billion Os) and unradiogenic $^{187}Os/^{188}Os$ values (0.1056–0.1099), which refute a hydrothermal origin for the gold and provide further validation of the modified paleoplacer model (Kirk and others, 2001). Rhenium-depletion ages derived from these isotopic data (3.5 to 2.9 Ga [giga-annum]; Kirk and others, 2001) are older than the basin, suggesting that the gold formed prior to basin formation and was later eroded and deposited as detrital grains. Significantly higher radiogenic $^{187}Os/^{188}Os$ values would be expected if the gold were derived from hydrothermal sources at a more recent time than basin formation. A Re-Os isochron age from rounded pyrite (2.99±0.11 Ga) from the Vaal Reef in the Klerksdorp Gold Field of the Witwatersrand Basin is also older than the age of sedimentation (Kirk and others, 2001). An even more precise Re-Os isochron age from gold and rounded pyrite from the Vaal Reef (3.03±0.02 Ga, mean square of weighted deviates is 1.06) is older than the Central Rand Group host rocks dated between 2.89 and 2.76 Ga (Kirk and others, 2002). Figure 14 summarizes ages derived from minerals of the Witwatersrand Basin.

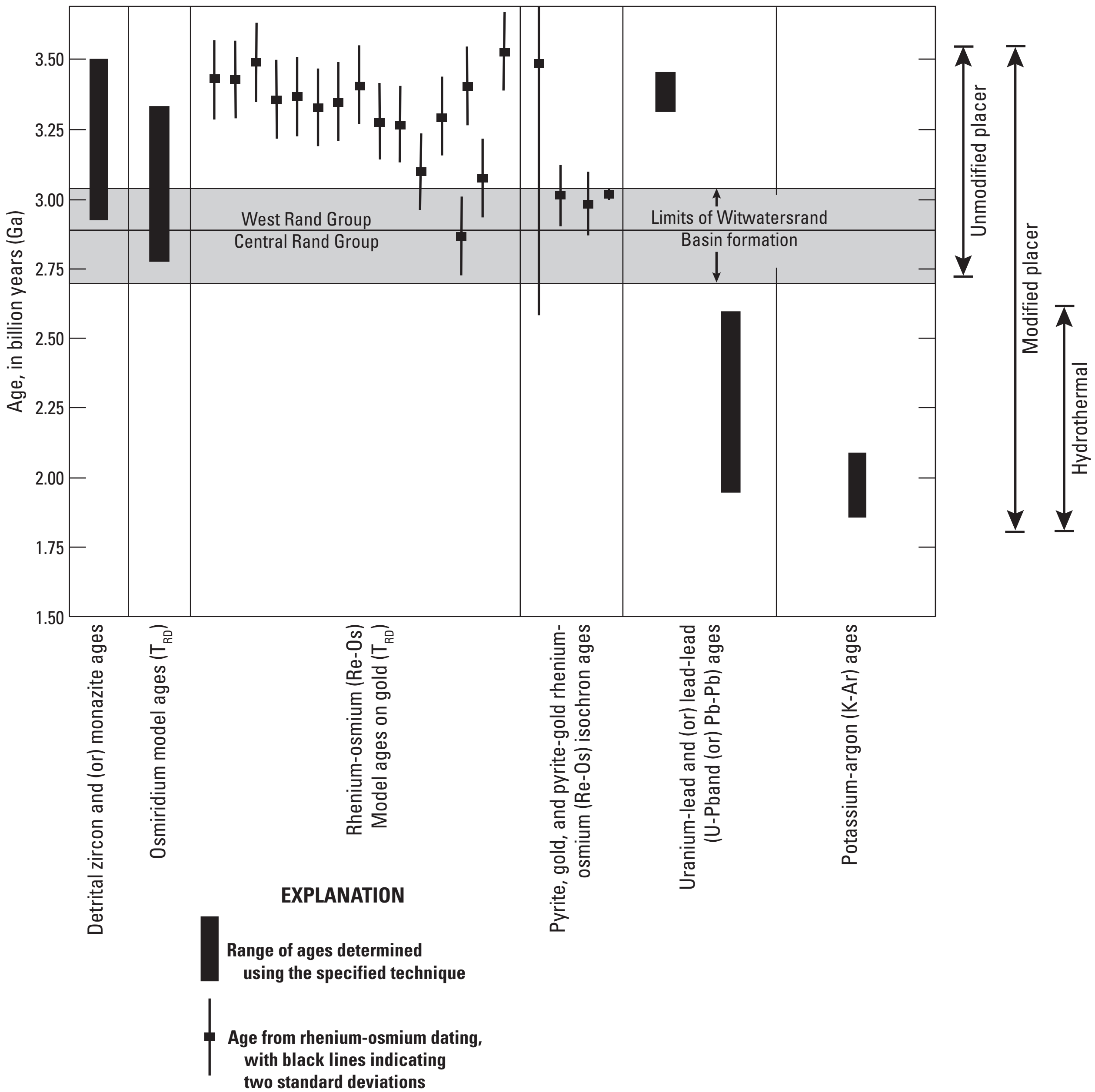


Figure 14. Geochronological comparison for the Witwatersrand Basin, South Africa, paleoplacer gold deposits. Igneous zircon ages from overlying and underlying volcanic units provide the age constraints on basin formation and an igneous zircon age of the Crown lava located just below the stratigraphic transition between the West Rand and Central Rand Groups. All ages from sources summarized within Robb and Meyer (1995) and Zartman and Frimmel (1999) except osmiridium ages (Hart and Kinlock, 1989) and rhenium-osmium (Re-Os) isochron ages (Kirk and others, 2001, 2002). Two distinct groupings of uranium-lead (U-Pb) and (or) lead-lead (Pb-Pb) ages derived from pyrite, sphalerite, rutile, uraninite, and carbonaceous seams are shown; the older group of ore-related minerals is representative of detrital grains that form part of the sedimentary fill, and the younger group, whose isotopic systems closed millions of years after basin sedimentation, are not detrital in origin and formed due to later geologic events that affected the basin. Potassium-argon (K-Ar) ages derived from clays, shales, and micas. Arrows on the right side of the diagram represent the range of ages that would be expected for each model of gold mineralization. The range of ages more closely matches the modified placer model than the unmodified placer and hydrothermal models. Modified from Kirk and others (2001). [Ga, giga-annum; T_{RD}, rhenium-depletion model ages]

Petrology of Associated Sedimentary Rocks

Importance of Sedimentary Rocks to Deposit Genesis

Unlike modern placers, these paleoplacers are contained within lithified sediments (fig. 15). Oligomict conglomerates are the dominant lithology within paleoplacer deposits (Edwards and Atkinson, 1986). These clastic sequences form in extensive depositional basins over cratons. Sedimentary strata are a necessary requirement for the formation of these deposits, and they form as depositional beds with heavy minerals derived from minerals and metals eroded and transported from a peripheral source.

Mineralogy

The conglomerate pebbles chiefly consist of quartz, with less abundant clasts of chert, quartzite, and slate and only minor amounts of other clast types. The majority of the quartz clasts originated as vein quartz. Clasts of granite and volcanic rocks are notably rare or absent. An exception to this is the Steyn Reef in the Welkom Gold Field of the Witwatersrand Basin, which has deposits with up to 30 percent of the sand- and pebble-sized fractions being quartz porphyry clasts (Frimmel and Minter, 2002). Within the Witwatersrand as a whole, the compositions of pebble assemblages average 85 percent vein quartz, 12 percent chert, 2 percent quartz porphyry, and 1 percent metamorphic clasts (Frimmel and Minter, 2002). The matrix usually consists of fine-grained quartz, sericite, chlorite, chloritoid, pyrophyllite, and other minor minerals.

Pyrite and pyrrhotite are the dominant iron minerals in some deposits, such as those in the Witwatersrand Basin and at Jacobina and Blind River-Elliot Lake, and are the most abundant detrital heavy minerals. In the Witwatersrand deposits, pyrite composes 90 percent of the sulfide abundance (Minter, 1977). In younger deposits, such as at Tarkwa, iron oxides are found rather than iron sulfides. Deposits associated with iron sulfides tend to also be associated with uranium, thorium and rare-earth minerals, whereas the iron-oxide-bearing deposits typically are not, because of the oxidizing conditions prevalent at the time of deposition (Boyle, 1979). Uranium minerals include uraninite and its alteration products brannerite and coffinite. High carbon content is common. Other pervasive heavy minerals in the paleoplacers include chromite, ilmenite altered to leucoxene, and zircon.

Textures

Most economically important beds are highly sorted and characterized by clasts displaying thorough abrasion. Rounded pebbles may have been subsequently flattened through metamorphism and folding, making them ellipsoidal. A fine-grained

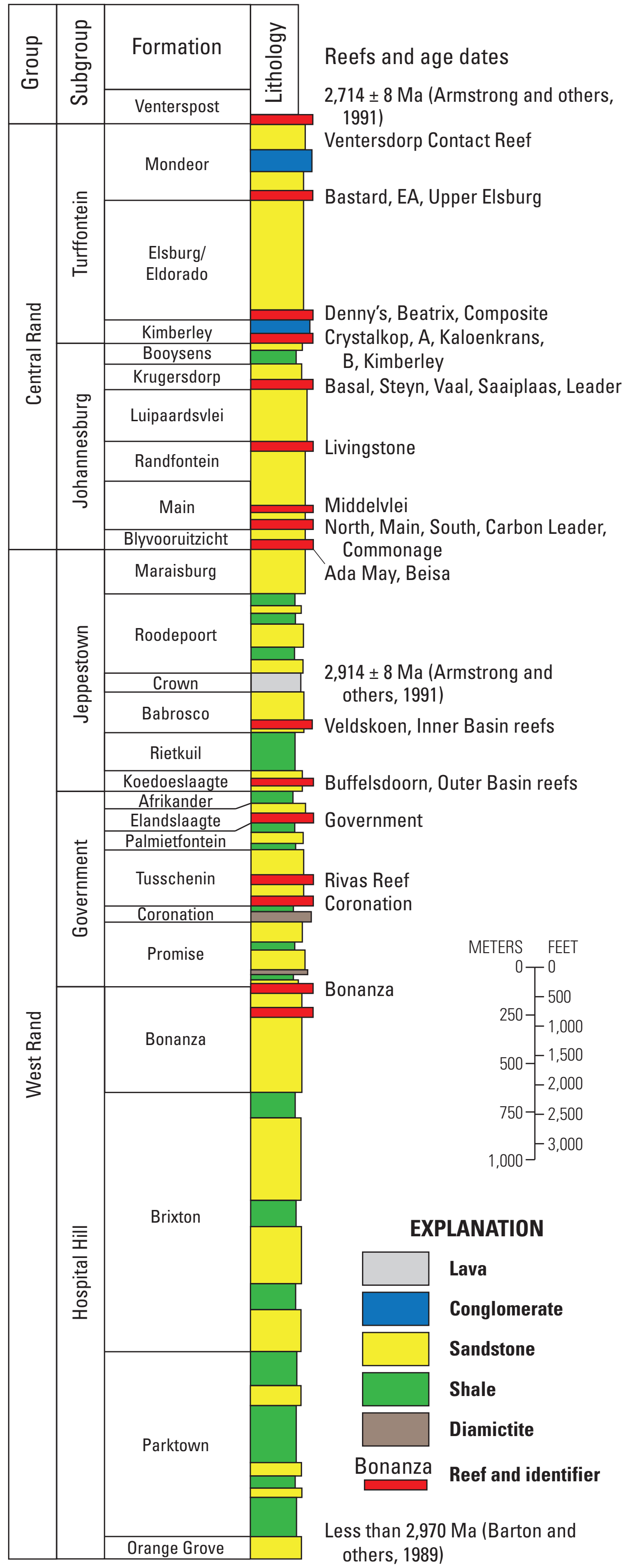


Figure 15. Generalized stratigraphic column for the Witwatersrand Supergroup, South Africa, and the position of the main auriferous conglomerate reefs. Modified from Frimmel and Minter (2002) and Minter (2006). [Ma, mega-annum]

matrix is found between the larger clast-supported pebbles. Many of the gold-bearing reefs in the Witwatersrand are found in pebbly bases of thin sandstone beds. These thin pebble sheets may extend for great distances down the paleoslope.

Internal textures within the individual beds typically display trough or planar crossbeds. Gold can be concentrated along these surfaces. The direction of paleoflow or drainage can be determined based on these features and the direction of imbrication in imbricated pebbles.

The quartz pebbles are well-rounded spheroids that occasionally show ventifacts. This likely indicates that the quartz pebbles were rounded by fluvial processes, with additional eolian modification.

Grain Size

Rounded quartz pebbles up to 40 centimeters in diameter have been recorded in the Witwatersrand deposits, which have been interpreted to be part of a mid-fan deposit (Minter, 1977). In each bed, the majority of the detrital minerals seem to be in hydraulic equilibrium with each other; denser grains are smaller and less dense material is larger. At Tarkwa, the economic intervals of gold mineralization occur within conglomerate horizons that are separated by barren layers of sandstone (Milési and others, 1991). The conglomerate beds only make up a small percentage of the basin sedimentary fill. Within the Central Rand Group of the Witwatersrand Basin, conglomerates only make up 600 m of the 7,200 m of sediments.

Environment of Deposition

Typically, reefs are found at the bottom or, less commonly, at the top of an individual depositional sequence. The gold-bearing bed is typically separated from the underlying bed by a disconformity along which the gold has collected. A coating of carbon along this disconformity has been interpreted as the residue of organic matter (Mossman and others, 2008) or as hydrocarbon that has infiltrated along the disconformity after deposition and reef formation (Gray and others, 1998). In facies where sediment movement dominated over preservation, only mature sediments with high concentrations of heavy detrital minerals remained at the very base of each bed; they were likely held in place by pebble accumulations and sticky algal mats that eventually formed carbon seams associated with gold mineralization (Minter, 1977).

Many of the quartz-pebble gravels are interpreted to have been deposited in proximal fluvial environments. The depositional environment for much of the gold and uranium in the Witwatersrand deposits is interpreted to be alluvial fans, fan deltas, and braid plains (Pretorius, 1976). Other depositional environments for quartz-conglomerate or sandstone sediments in these basins can locally be lacustrine, eolian, tidal, or shallow marine (for example, the Roraima Supergroup; Santos and others, 2003). The most extensive of these paleoplacers in the Witwatersrand Basin were formed by braid deltas associated with shorelines, such as in the Basal (Welkom Gold Field), Steyn (Welkom Gold Field), Vaal (Klerksdorp Gold Field), and Carbon Leader (Carleton Gold Field) Reefs (fig. 16;

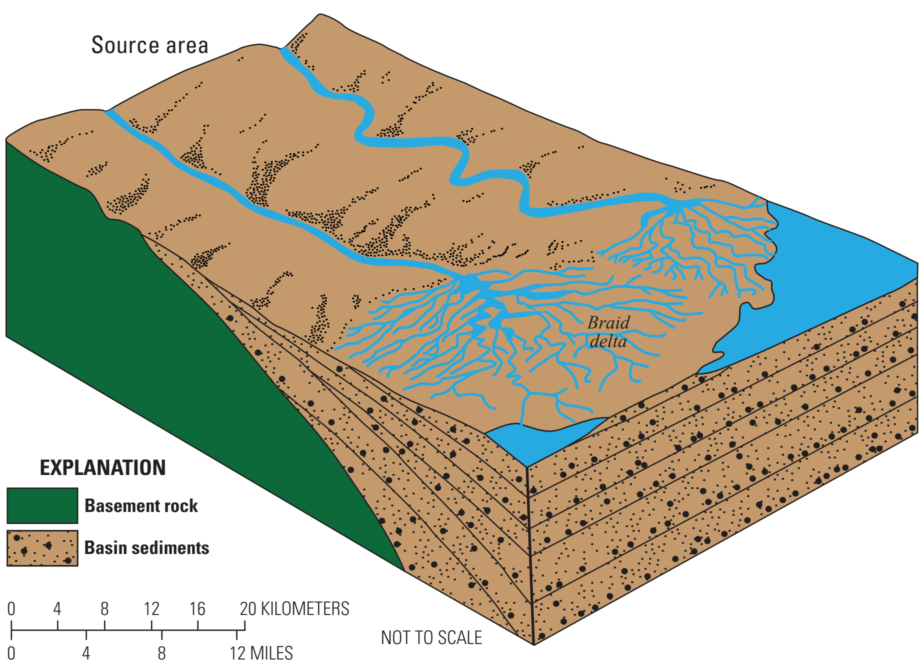


Figure 16. The braid-delta model of coalescing alluvial fans as envisioned for the Basal and Steyn placers of the Witwatersrand Basin, South Africa. Modified from Minter (1991). [km, kilometer]

Minter, 2006). These sedimentary rocks unconformably overlie older granite-gneiss and greenstone basement units. Large and extensive source areas for the sediment and heavy minerals are required to account for the large volumes of sediment and metal found in these basins.

The paleotopographic relief in these deposits is generally minor, and the drainage channels along unconformities are of low sinuosity (Minter, 1991). For example, the Vaal placer of the Klerksdorp Gold Field in the Witwatersrand Basin is found along a paleostrike length of 14 km, yet the deepest channel within it is only 1 m deep and 1 km wide (Minter, 1976). This suggests that braid deltas of shallow water transported and deposited the placer sediments in braid plains and deltas.

Theory of Deposit Formation

The first step in developing a quartz-pebble conglomerate is the formation of a source for the detrital material. Lode gold veins may develop in association with greenstone belts or with intrusions. Both are probable, as the uraninite grains are likely sourced from granitic sources and the gold from greenstone-hosted quartz veins; adequate sources are common components of Archean granitoid-greenstone terranes. The abundance of quartz-vein clasts in the conglomerates of the Witwatersrand Basin (Frimmel and Minter, 2002) supports the interpretation that gold and quartz are derived from lode veins.

The only reef with a known source of gold is the Ventersdorp Contact Reef of the Witwatersrand Basin. Gold within this reef is only found where the reef truncates gold-bearing portions of the Central Rand Group, and was produced by erosion of earlier placers and redeposition of the gold (Laznicka, 2006). However, lode gold veins within the hinterland of these deposits are commonly assumed to be the source for the gold within these deposits. The uplift and erosion of this gold source would lead to transport of detrital gold particles into a peripheral basin. Slow rates of uplift and erosion of the source area will lead to mature sediments that have a higher proportion of heavy minerals concentrated in the depositional basin. Initial concentration of heavy detrital minerals during high-velocity flow conditions may be followed by further concentration through winnowing away of some of the less dense mineral phases, which effectively concentrates the smaller, denser grains (Slingerland and Smith, 1986). This winnowing may have occurred by bedload transport or eolian deflation of the smaller and less dense grains.

Subsequent metamorphism or infiltration of hydrothermal fluids may locally remobilize the gold and other metals, but this is not a necessary component in their formation. The remobilization of the gold is on the centimeter scale and does not affect exploration and mining, which is based upon the original sedimentary features. For example, the Witwatersrand Basin was subjected to a series of events that led to a complex alteration history. The Witwatersrand has undergone leaching by meteoric waters, multiple episodes of metamorphism through burial and intrusion of the igneous Bushveld Complex, and infiltration of hydrothermal fluids possibly resulting from the Vredefort impact or some other tectonic events, which resulted in local remobilization of gold crystals taking euhedral or dendritic forms (Frimmel and others, 2005a, 2005b). In contrast, the Roraima Supergroup conglomerates were only subjected to subgreenschist-facies metamorphism, and the gold grains retain rounded edges formed during mechanical transport (Frimmel and others, 2005b).

The start of the about 2.4 Ga Great Oxidation Event (Holland, 2005) approximately separates the formation of older pyritic paleoplacers like those in the Witwatersrand Basin from younger iron-oxide-bearing paleoplacers like those at Tarkwa. However, some pyritic paleoplacers have minimum ages that extend beyond 2.4 Ga.

Exploration and Resource Assessment Guides

Regardless of any remaining controversy about the genetic model for quartz-pebble-conglomerate gold deposits, the most effective guide for exploration and mine development is to treat the deposits as paleoplacers; within the Witwatersrand Basin, no significant ore bodies have been found that crosscut the sedimentary fabric (Frimmel, 2014). However, no new deposits of this type have been discovered within the last six decades. Quartz-pebble-conglomerate gold deposits formed mainly in Archean through Paleoproterozoic sedimentary successions dominated by mature, quartz-rich units formed by multiple cycles of erosion and deposition. Tectonic paleoconditions favorable for formation of quartz-pebble-conglomerate gold deposits are similar to what is necessary for the formation of modern placers: high-energy environments where hydraulic sorting concentrates heavy minerals. The cost of separating the gold in these lithified sediments is more than the cost of separating gold from unconsolidated fluvial detritus, and thus the concentration of gold needs to be larger than in modern placers for the deposit to be considered economic.

Deposits older than 2.4 Ga will most likely have pyrite as an associated heavy mineral. Rust stains on weathered bands of conglomerate may indicate the presence of weathered pyrite.

Potential source terranes for the gold need to be found peripheral to the sedimentary basin. The most promising of possible source terranes are granite-greenstone terranes that may contain lode gold veins. This is true for both paleoplacer deposits and modern placer deposits.

Geologic observations in outcrop, drill core, and mine openings should provide evidence for the direction of paleoflow. Defining this feature for exploration allows for targeting of strata that may contain coarser clasts suitable for heavy-mineral concentration, defining proper proximal to mid-fan depositional environments and extending reef targets.

Geoenvironmental Features and Anthropogenic Mining Effects

Soil and Sediment Signatures Prior to Mining

The pre-mining soil and sediment signatures of quartz-pebble-conglomerate gold deposits are dependent upon host-rock mineralogy, ore mineralogy, climate, topography, and the effectiveness of secondary fluid flow through the deposit; these all relate to the weathering and breakdown of the ore deposit. Ore from the Witwatersrand Basin is compositionally uniform, containing 70–90 percent quartz and 10–30 percent phyllosilicate minerals such as sericite, muscovite, chlorite, and pyrophyllite (Feather and Koen, 1975; Tutu and others, 2008). Pyrite is the dominant ore-related mineral (3–5 percent). Amounts of uraninite, arsenopyrite, pyrrhotite, nickel and cobalt sulfarsenides, and base metal sulfides are less (Phillips and Law, 2000), and all of these can have negative environmental consequences. Arsenic, iron, nickel, cobalt, silver, thorium, platinum-group elements, rhenium, zinc, copper, chromium, lead, molybdenum, osmium, and iridium, may be anomalously enriched in soils and sediments derived from these deposits.

Drainage Signatures

Contaminated waters can be discharged into the environment from different sources, leading to the pollution of local waters and soils. Tailings piles will contain elevated concentrations of pyrite and other sulfides that can oxidize and form acid mine drainage. Besides waste piles, polluted water can decant directly from mine adits or other mining structures, or be pumped out of the underground workings for dewatering purposes. Acid mine drainage can be characterized by low pH and high levels of heavy metals, dissolved solids, and SO_4.

Even though acid-producing minerals are fairly dilute within these tailings piles, concentration of minerals capable of neutralizing any produced acid is even lower. The primary acid-producing mineral is pyrite, and the neutralizing minerals are primarily carbonates. Silicate minerals have limited importance as neutralizing agents if the neutralizing potential of any of the carbonates is depleted.

Acid-base accounting of the acidity potential and the neutralization potential of mine waste is used to assess the potential production of acid mine drainage. Sulfuric acid is commonly produced through the interaction of iron sulfides with water and oxygen (Singer and Stumm, 1970). As pyrite is the dominant sulfide within quartz-pebble-conglomerate gold deposits, the first acid-producing reaction involves its oxidation:

$$FeS_2 + 7/2O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ \quad (1)$$

The Fe^{2+} produced in reaction 1 can be oxidized to Fe^{3+} (reaction 2), the stability of which is dependent upon acidic conditions (Tutu and others, 2008). The rate of this oxidation reaction can be increased by a factor of 100,000 in the presence of the iron-oxidizing bacterium *Acidithiobacillus ferrooxidans* (Singer and Stumm, 1970).

$$Fe^{2+} + 1/4O_2 + H^+ \rightarrow Fe^{3+} + 1/2H_2O \quad (2)$$

This Fe^{3+} can act as another oxidizing agent of pyrite (reaction 3), that allows oxidation at a higher magnitude than oxidation by oxygen (Chandra and Gerson, 2010).

$$FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+ \quad (3)$$

The most effective neutralization reaction involves carbonates, notably calcite (reaction 4). Downstream improvement in water quality may occur if the drainage interacts with carbonate beds and to a lesser extent with feldspar-bearing rocks.

$$CaCO_3 + 2H^+ \rightarrow H_2CO_3 + Ca^{2+} \quad (4)$$

Other sulfide minerals such as arsenopyrite and pyrrhotite can produce acid through interaction with both oxygen and ferric iron (Plumlee, 1999). The oxidation of these and other trace minerals may lead to the release of other dissolved metals. Surface waters near mine tailings in the Witwatersrand Basin have been reported to contain elevated concentrations of cyanide, cadmium, cobalt, copper, iron, nickel, manganese, lead, radium, uranium, and zinc (Marsden, 1986).

Polluted drainage from waste piles in the Witwatersrand Basin accounts for up to 20 percent of stream discharge in the area (Naicker and others, 2003). Heavy metals also coprecipitate with iron and manganese in these streams. During the winter months in the Witwatersrand Basin, a white crust of gypsum containing elevated concentrations of cobalt, nickel, and zinc forms along the banks of the streams (Naicker and others, 2003). Oxygenated rainwater percolates through these waste piles, ultimately creating polluted groundwater plumes that reemerge at the surface, feeding the streams that drain from these point sources. Any gypsum containing heavy metals will dissolve during the rainy months, further contributing to the pollution of the local streams and soil.

In the uranium-bearing ores, a radiological risk is present. In the Witwatersrand Basin, it took until 1952, nearly seven decades after initial mining, for uranium to be produced from the ores as a byproduct. Those early tailings piles contained mobile uranium and associated radionuclides that were released into the soils and streams. Uraninite can react with acidic solutions, such as are produced through oxidation of pyrite waste, to produce soluble uranium ions (Hansen, 2015), according to

$$UO_{2(s)} + 4H^+ + 2H_2O + U^{4+} \quad (5)$$

As uranium and other heavy metals are not biodegradable, they tend to accumulate in the local environment. Acid mine drainage with a pH of 2.6 from a waste pile in the Klerksdorp Gold Field of the Witwatersrand Basin was found to have high concentrations of many dissolved metals, such as uranium (30.1 parts per million [ppm]), arsenic (36.3 ppm), copper (7.3 ppm), nickel (21.6 ppm), zinc (31.0 ppm), and iron (1162 ppm) (Winde and Sandham, 2004). Near-neutral (pH of 6.85) seepage from a waste pile in the Welkom Gold Field of the Witwatersrand Basin only contained uranium concentrations of 0.11 ppm, which emphasizes the degree to which the acidity of the seepage correlates with its ability to leach metals into solution from the waste rock (Winde and Sandham, 2004).

Climate Effects on Geoenvironmental Signatures

The effect of climate factors on the geoenvironmental signatures of quartz-pebble-conglomerate gold deposits typically relates to temperature and total precipitation, and thus, how arid, temperate, or tropical the climate is. These factors can influence chemical-reaction rates and the chemical characteristics of waters that interact with the ore and waste materials. Wetter climates increase the amount of water available to interact with sulfidized rock, but drier climates are likely to produce waters that are more acidic and metal rich, partially because of evaporative effects that create metal-rich and soluble salts or other precipitates. The influence of metal-rich dust particles from waste piles will also be magnified in arid climates.

Volume and Footprint of Mine Waste and Tailings

The total area affected by mining operations is larger for surface mining than it is for underground operations, which includes areas affected by mine pits, shafts, adits, waste piles, cyanide heap leach pads, cyanide tank leaching operations, and other infrastructure used to support mining activities. The size of waste piles for a deposit largely depends on the size of the deposit and the stripping ratios. More than 6,000,000,000 tonnes of tailings covering an area of 400 km^2 has been produced in the Witwatersrand Basin over the 100 years of mining activity (Robb and Robb, 1998; Winde and Sandham, 2004). An area of 63,000 km^2 is taken up by the tailings dam of a single mine at Tarkwa (Akabzaa and Darimani, 2001). Slimes dams in the Witwatersrand reach heights of nearly 50 m (Winde and Sandham, 2004).

Mining Methods

Most deposits, such as those at Witwatersrand and Jacobina, are mined by underground methods. The Tarkwa operation exploits six open-pit mines. The underground mines in the Witwatersrand are some of the deepest in the world, with some exceeding 3.5 km depth. The extreme depth of these mine shafts creates new challenges because of increased cost of mining and health and safety issues. In particular, rock burst caused by pressure release from excavating at such depths is a serious safety concern. Geotechnical difficulties caused by “squeezing” of the rock into the tunnels at this depth are a serious concern to the development and maintaining of mining tunnels. At the Hartebeestfontein mine, Klerksdorp Gold Field, in the Witwatersrand Basin, tunnel closure rates from “squeezing” are up to 50 centimeters per month, because of rock failure and slip along bedding planes (Malan and Basson, 1998). The additional cost of rehabilitating the tunnels to remediate this process can be significant.

Ore Processing Methods

Initial ore processing of shallow, oxidized ores during the early years of production in the Witwatersrand was done using mercury amalgam. Upon deeper mining that intersected pyritic ores, the cyanide extraction method was used (Tutu and others, 2008); this is the method currently used to recover gold from ore deposits. In the Witwatersrand, gold recovery of over 90 percent has generally been attained through milling of the rock, followed by gravity separation for coarser gold particles and cyanide extraction for the rest (Fleming, 1992).

Cyanide extraction is accomplished on finely crushed and milled ore to produce cyanide complexes. A low-concentration sodium cyanide solution leaches gold from the ore according to the Elsener equation from Smith and Mudder (1999):

$$4Au + 8NaCN + O_2 + H_2O = 4NaAu(CN)_2 + 4\,NaOH \quad (6)$$

The alkaline cyanide solution is necessary for safe and efficient extraction of the gold, and usually has a basic pH near 10 (Tutu and others, 2008). However, the resultant alkaline tailings are typically insufficient to neutralize the acid-generating capacity of the tailings.

Extraction of gold from solution may be done in one of two fundamental ways. One method involves adding pulverized zinc dust to the solution. The zinc causes gold precipitation and zinc dissolution through replacement reactions. The cost and inefficiency of this operation led to development of the other method of extraction, using activated carbon (Fleming, 1992).

Two variations of the carbon-leaching process exist, the carbon-in-pulp (CIP) and the carbon-in-leach (CIL) processes. In the CIL process, the activated carbon is added to the cyanide solution where gold-cyanide complexes form and sorb to the carbon essentially coevally. In the CIP process, the carbon is added later to the downstream slurry tanks such that gold-cyanide complexation is followed by sorbtion to the carbon.

Both the mercury-amalgam and cyanide extraction methods are highly selective for gold and silver. As a result, much of the remaining ore minerals and their metals remain intact and are transported to the mine waste dumps. Oxidation of these remaining ore minerals then leads to adverse chemical characteristics of water draining from these point sources.

Potential Ecosystem Impacts

Adverse effects on the ecosystem resulting from mining can result from ore processing or from chemical reactions involving waste rock. Acid mine drainage and any associated dissolved metals will impact the local aquatic ecosystems, such as through the precipitation of iron hydroxides in the stream environment resulting from oxidation of iron sulfides. Regions with wetting and drying cycles promote the development of efflorescent metal sulfate salts. Enrichment of heavy metals along stream banks from precipitation and dissolution of heavy-metal-bearing gypsum and capillary action from polluted groundwater affects vegetation. In parts of the Witwatersrand, these processes have led to a zone along stream banks that does not support plant life (Naicker and others, 2003). These metals would also likely cause acute toxic effects to local fauna.

The processing of gold ores utilizes cyanide, and examples of cyanide release into the environment are commonly high-profile events because of the public perception of the chemical. Hydrogen cyanide gas can volatilize and be released into the air. Metal-cyanide complexes may dissociate to form free cyanide and metals that may pose toxicological concerns; free cyanide is the most toxic form of cyanide.

Potential Health Issues

Some of these deposits are found in populated regions and subject local inhabitants to the environmental pollutants and radiation associated with mining these deposits. In some instances, contaminated water is used for agricultural purposes, allowing uranium and heavy metals to enter the human food chain (Winde and Sandham, 2004). This is especially true in the Witwatersrand Basin since uranium was not considered a resource in the Witwatersrand until the 1950s and was dumped along with other tailings into waste piles.

The depth at which mining may occur in the Witwatersrand Basin also presents issues related to human health. Rock burst can pose a serious risk to the lives of those mining at extreme depth.

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