A review of the Birimian Supergroup- and Tarkwaian Group-hosted gold deposits of Ghana

Albertus J. B. Smith^{1,2*}, George Henry^{1,2} and Susan Frost-Killian³

¹ DST-NRF Centre of Excellence for Integrated Mineral and Energy Resource Analysis, Department of Geology, University of Johannesburg, Auckland Park, 2006, South Africa. *Corresponding author e-mail address: bertuss@uj.ac.za

² Palaeoproterozoic Mineralisation Research Group, Department of Geology, University of Johannesburg, Auckland Park, 2006, South Africa

³ The MSA Group, 20B Rothesay Avenue, Craighall Park, 2196, South Africa

DOI: 10.18814/epiugs/2016/v39i2/95775

Ghana is the largest producer of gold in West Africa, a region with over 2,500 years of history with regards to gold production and trade. Modern exploration for and mining of gold in Ghana dates from 1874 with the establishment of the British Gold Coast Colony, which was followed in 1957 by the independence of Ghana and increased gold production since the early 1980s through Ghana's Economic Recovery Plan. At the time of writing, gold production (108.2 tonnes or 3.48 million ounces [Moz] in 2014) accounted for approximately one-third of Ghana's export revenues, with 36% of gold production coming from small-scale mining.

The majority of the gold occurs in two styles of mineralisation, namely mesothermal quartz vein-hosted and associated gold in metavolcanics and metasediments and modified palaeoplacer gold in conglomerates. These styles of mineralisation occur in the Palaeoproterozoic Birimian Supergroup and Tarkwaian Group that make up Ghana's mainly southwest to northeast trending Birimian belts. Significant gold resources also occur as hydrothermal mineralisation in basement-type granitoids which show some geological association with the Birimian Supergroup-hosted mesothermal mineralisation. The majority of the gold mineralisation is believed to have formed between approximately 2.15 and 2.06 Ga during the Eburnean orogeny.

The mesothermal quartz vein gold mineralisation is usually confined to tectonic corridors within the Birimian belts and is strongly associated with shear zones and fault systems. The quartz veins show multiple stages of formation and are steeply dipping, with the gold mineralisation occurring either as free gold within fractures in the veins or as invisible gold within disseminated sulphides in the host rocks surrounding the

veins. The vein- and sulphide-hosted gold is strongly associated with deformational fabrics formed by the Eburnean extensional and compressional events, respectively, suggesting that disseminated sulphide mineralisation predates quartz vein-hosted mineralisation. The fluid from which the gold precipitated is believed to have been of metamorphic origin and carbon dioxide (CO₂) dominated, with lesser water (H₂O) and nitrogen (N₂) and minor methane (CH₄). Gold precipitation was probably caused by decrease in pressure, temperature and CO₂-H₂O immiscibility, at depths of between 7 and 11 km.

The palaeoplacer gold mineralisation shows some hydrothermal modification and occurs mostly within the conglomerates and to a lesser extent within the interbedded quartzite of the Banket Series of the Tarkwaian Group. The gold occurs as free gold in the matrix of the conglomerates and as intergrowths and overgrowths on and inclusions in, other heavy mineral grains. Based on strong evidence for palaeoplacer mineralisation, the gold was likely deposited with the conglomerates in alluvial fans and braided tributary channels. Because the Eburnean compressional event associated with the Birimian Supergroup-hosted mesothermal gold mineralisation also overprinted the gold-bearing Banket conglomerates, the former gold occurrences could not have acted as the source for the palaeoplacer gold.

Hydrothermal gold mineralisation occurs in the Palaeoproterozoic belts and basin granitoids that intrude the Birimian belts, as well as in the sedimentary basins occurring between the belts. Gold mineralisation within the granitoids occurs as micro-inclusions in sulphides in small, steeply dipping stockworks and as sulphide

disseminations concordant with regional faults and shears. A gold-bearing fluid similar to that for the Birimian Supergroup-hosted quartz vein gold mineralisation, but with a larger H₂O component, is proposed to have formed the granitoid-hosted gold mineralisation.

Introduction

The mining and trade of gold in West Africa has a long history, possibly dating as far back as 500 BC (Ellis, 1893; Ward, 1967). Of all the countries producing gold in West Africa, the largest and most prominent past and present producing mines are located in Ghana (which has more than 1,500 tonnes of cumulative gold production; Eisenlohr, 1992; Oberthür *et al.*, 1995). Before the discovery of the Witwatersrand gold reefs in South Africa in 1886, Ghana was the top gold producer on the African continent (Pigois *et al.*, 2003). Today, mining contributes more than one-third of Ghana's export revenues and gold contributes 95% of this mining revenue (2.63 Moz and 3.48 Moz gold produced in 2013 and 2014 respectively; Ghana Chamber of Mines, 2014; GCM-ICMM, 2015).

The majority of Ghana's gold is hosted in the Paleoproterozoic rocks of the Birimian Supergroup and the overlying Tarkwaian Group, which generally occur collectively in deformed, southwest to northeast trending belts that have been intruded by granites (Fig. 1). These belts, generally referred to as the Birimian belts or Ghana's principal gold belts, are from southeast to northwest, the: Kibi-Winneba Belt; Ashanti Belt; Manso Nkwanta/Asankrangwa Belt; Sefwi Belt; Bui Belt; Bole-Navrongo Belt (Fig. 1); Wa-Lawra Belt (Griffis *et al.*, 2002); and Julie Belt to the north of the area shown in Fig. 1 (Amponsah *et al.*, 2015b). The two main types of mineralisation occurring in these belts are mesothermal quartz-vein associated gold and palaeoplacer gold (e.g. Eisenlohr, 1992; Oberthür *et al.*, 1995; Griffis *et al.*, 2002; Pigois *et al.*, 2003).

This contribution aims to review and summarise the main aspects related to gold in Ghana as available in literature, namely: the history of gold exploration, mining and production; the occurrence and general geological features of the main gold deposit types; the timing and genesis of the main gold deposit types; the exploration potential for gold; and the future potential for gold mining in Ghana. The general geological setting of Ghana will also be summarised. The majority of the focus will be on the geological aspects of the gold deposits.

History of gold exploration, mining and production in Ghana

The history of gold mining in Ghana is intricately linked to the general regional development of West Africa which has more than 2,000 years of recorded

history. This history can essentially be divided into three periods: early regional development from 300 BC to 1500 AD; European trade from 1500 AD to the mid-nineteenth century; and the modern mining period from the mid-nineteenth century to the present day. These periods are briefly summarised below. More complete reviews on the history of gold mining, trade and production in Ghana can be found in Griffis *et al.* (2002) and Hilson (2002). It is important to note that in older literature, present day Ghana was referred to as the Gold Coast (e.g. Ellis, 1893; Junner, 1940; Ward, 1967), the name given to the British and other European colonies established in the region in the 1800s, and was renamed Ghana when the country won independence in 1957.

Early regional development

Although it is hard to establish the earliest record of gold mining in the West Africa region and more specifically Ghana, it is likely

Figure 1: Simplified geological map of southwestern Ghana showing the gold-bearing belts as well as the location of the most well-known mesothermal and palaeoplacer gold deposits (adapted from Pigois *et al.*, 2003).

that by between 500 BC and 300 AD there was sustained gold production in the region. This is indicated by: possible trade with Carthaginian, Phoenician and Greek expeditions between approximately 500 and 100 BC (Ellis, 1893; Ward, 1967); re-established northern trade routes between West Africa and the Arab world by 500 BC and the minting of gold coins by the Roman Empire on the coast of modern day Tunisia by 300 AD (Illife, 1995; Griffis *et al.*, 2002).

Trade expanded in the West African region from the third century onwards due to the introduction of camels from Asia, and from this time many accounts of gold-rich kingdoms across the region were recorded, which included the Ancient Kingdom of Ghana (Griffis *et al.*, 2002; Hilson, 2002). The latter was at the peak of its influence by 1000 AD, through control of the upper reaches of the Niger and Senegal Rivers and its control over the Bambouk goldfields, which are situated in the area known today as the Kedougou-Kenieba Inlier, the site of the present day Sadiola goldfields in Mali. The Mali Empire became the most influential force in the region in the late 11th century AD after the Ancient Kingdom of Ghana was conquered by its Berber Muslim neighbours. The Mali Empire was followed by the Songhay Empire, centered in the city of Gao, until the latter was overthrown in the late 1500s by forces from Morocco (Griffis *et al.*, 2002). The main external influence in West Africa would remain the Islamic world (Hilson, 2002), until the arrival of Portuguese merchants in the late fifteenth century (Griffis *et al.*, 2002).

Although little is known about the precise mining techniques employed in ancient Ghana, the majority of gold is thought to have been recovered by collecting and panning material in alluvial settings (Hilson, 2002). Shallow pit and deeper shaft mining are also thought to have been practiced to lesser extents. Gold production in West Africa has been estimated to have been 2,000 to 5,000 ounces per year from 0 to 500 AD, 5,000 to 10,000 ounces per year from 500 to 1000 AD and 15,000 to 25,000 ounces per year from 1000 to 1500 AD (Griffis *et al.*, 2002).

European trade

Due to general shortages of gold on the European continent during the fifteenth century, European interest in gold in West African gold grew rapidly (Hilson, 2002). The first formal European visit to present day Ghana was made by a Portuguese envoy in 1471, which was shortly followed by the erection of the Sao George castle along the coast, as well as other castles, during the early sixteenth century. The main Portuguese focus during their occupation of West Africa was gold trade with local tribes and independent African states (Griffis *et al.*, 2002), although two gold deposits were mined by the Portuguese themselves during the early seventeenth century (Hilson, 2002). Gold production during the Portuguese occupation of West Africa between 1493 and 1600, is estimated to have been approximately 8.2 million ounces (Addy, 1998).

Although their trading in West Africa commenced in 1595, the Dutch became more aggressive in their trading policies in West Africa during the early seventeenth century, leading to the establishment of several trading forts as well as the removal of the Portuguese from some of their castles. During this time the slave trade became the dominant European interest in West Africa, and although the gold trade was still significant, gold production in Ghana declined from 1600 to 1900. Dutch dominance was short-lived due to renewed trade and competition from England in 1632, which led to a 150 year power

struggle in West Africa between these two nations. Other European nations that had trade interests and settlements in the region were France, Denmark and Prussia. From 1601 to 1900, Ghana's gold production is estimated to have been approximately 14.4 million ounces (Ellis, 1893; Addy, 1998; Griffis *et al.*, 2002; Hilson, 2002).

The period of strong European gold trade in West Africa was also marked by the rise of the Ashanti Nation in Ghana in the mid-1600s, through the collaboration of numerous clans close to present day Kumasi. Mining of gold within their region led to great wealth and control of a region larger than present day Ghana by the end of the eighteenth century. The Ashantis were also involved in bedrock mining of gold-rich quartz veins by the early nineteenth century (Griffis *et al.*, 2002). Friction between the Ashanti Nation and Great Britain grew in the nineteenth century due to the latter's control over trade and their desire to reduce slavery in West Africa, which culminated in hostilities. The British defeated the Ashantis in Kumasi in 1874, leading to the Gold Coast formally being declared a British colony (Ellis, 1893; Griffis *et al.*, 2002).

Modern mining

The declaration of the Gold Coast as a British Colony in 1874 led to a more direct interest in exploration and mining, through new technologies, of Ghana's gold deposits by foreign companies (Griffis *et al.*, 2002). French entrepreneur Marie-Joseph Bonnat learned of gold workings in Tarkwa (Fig. 1), during the time he was held captive by the Ashantis (Hilson, 2002) from 1871 to 1874. This led him to lease a small mining concession near Tarkwa from the Wassa chief in 1878, followed by the first mining activities at Tarkwa by the African Gold Coast Company (Fig. 2) (Griffis *et al.*, 2002). There were also mass gold rushes in the region (Hilson, 2002). Although the discovery of gold in the Witwatersrand in South Africa in 1886 renewed interest in Africa's gold potential, it had no immediate effect on production in Ghana. Only with the start of the Anglo-Boer War was there an outflow of capital from South Africa, followed by re-investment in Ghana. The majority of the mining and prospecting during the late nineteenth century was concentrated at Tarkwa (Fig. 2) and Prestea (Griffis *et al.*, 2002; Hilson, 2002) (Fig. 1). The mines exploited by European companies in the late nineteenth century were located by local inhabitants who, after sampling soils and determining the gold contents, guided foreigners to the sites (Hilson, 2002).

The late nineteenth century also marked the first large scale gold mining at Obuasi (Fig. 1), from 1895 onwards (Griffis *et al.*, 2002), which led to a significant increase in gold production in Ghana (Ward, 1967; Hilson, 2002). These deposits had previously been exploited by the Denkyera and the Ashantis (Ward, 1967; Hilson, 2002). Ashanti Goldfields Corporation Limited was listed in 1897 by Cade and his Gold Coast partners and by 1902 the company was producing 20,000 ounces of gold per year (Griffis *et al.*, 2002).

Gold production during early European involvement in Ghana was the lowest recorded up to that point with 360,000 ounces produced between 1880 and 1900. However, from 1902 onwards, mining in the region grew so that by 1914 the annual production of gold from Ghana was approximately 410,500 ounces, the majority coming from underground mines in Tarkwa, Obuasi and Prestea (Fig. 1). Due to Britain dropping the gold standard following the First World War, gold production in Ghana decreased and stagnated from 1918 to 1929 (~ 200,000 ounces per year average). This, in turn, was followed by a mining boom in the 1930s caused by the stock market crash of

Figure 2: A picture of Tarkwa Mine taken in the early 1900s (Stokes, 1908).

1929 and investors returning to gold for financial refuge (Griffis *et al.*, 2002). By 1933-1934, annual production in Ghana had climbed to 336,065 ounces (Hilson, 2002) and, by the end of the 1930s, it was 819,000 ounces (Griffis *et al.*, 2002). This mining and exploration boom also led to great advances in the documentation of the geology and gold deposits of the then Gold Coast (e.g. Junner, 1935; 1940).

The Second World War (1939-1945) had a highly detrimental effect on gold mining in Ghana due to declining availability of sea tankers, fuel and skilled workforce shortages, which resulted in decreasing annual production to 541,000 ounces by 1945. Following the war gold production fluctuated due to political unrest related to local workforce unhappiness and widespread calls for Ghana's independence from Great Britain. The latter was achieved in 1957. Following Ghana's independence, the gold mining sector reached peak production of approximately one million ounces per annum by the early 1960s. However, State intervention in the mining sector and nationalisation of the majority of the gold mines led to a steady decline in gold production over the next two decades, reaching a 50-year low point of 232,000 ounces in 1982. This coincided with a general decline in Ghana's economy during the 1960s and 1970s. The Quashie report, submitted to the Ghana government in 1980, highlighted the poor status of Ghana's gold sector and made recommendations on how to overhaul the mining sector. This was also followed by Ghana's Economic Recovery Plan (ERP) in 1983, with assistance from the International Monetary Fund (IMF), World Bank and other creditors (Addy, 1998; Griffis *et al.*, 2002; Hilson, 2002; Tsikata, 1997).

Ghana's mineral sector underwent significant recovery and growth from 1986 onwards following the ERP reforms in the Country's mineral policies and the establishment of the Minerals Commission. These changes, which included the implementation of the Minerals and Mining Law, made investment for foreign mining companies more attractive through tax breaks as well as royalties and mineral rights

advantages (Addy, 1998; Griffis *et al.*, 2002; Hilson, 2002; Tsikata, 1997). Between 1983 and 1998 an estimated US\$ 4 billion was invested in Ghana's mining sector, the majority of that spent on gold exploration and mining (Aryee, 2001; Hilson, 2002). By 2002 some 237 companies were exploring for gold and an additional 18 companies had operating gold mines in Ghana (Hilson, 2002). New gold exploration and mining concessions over this period included Konongo, Bogosu, Bonte River, Abosso, Obotan and Yamfo (Griffis *et al.*, 2002). From the low point in 1982, gold production in Ghana rapidly grew to somewhere between 975,000 and 998,000 ounces in 1992, and between 1,707,460 and 1,758,000 ounces in 1997 (Tsikata, 1997; Aryee, 2001; Griffis *et al.*, 2002; Hilson, 2002), peaking at between 2,590,000 and 2,852,000 ounces in 1999 (Griffis *et al.*, 2002; Hilson, 2002).

Gold production since 2000

By 2001 Ghana's gold production had declined to 2,369,906 ounces (Griffis *et al.*, 2002) and was approximately 2,227,000 ounces in 2004 (Bermúdez-Lugo, 2004). The decline in production during this period was due to a variety of factors including: fallout from the BRE-X scandal that reduced capital investment in gold mining and exploration worldwide; a lower gold price; new prospects that underperformed when they went into production; and multiple geotechnical issues at established operations (Griffis *et al.*, 2002; Bermúdez-Lugo, 2004). This was followed by a steady increase in production to approximately 2,547,000 ounces in 2007 and 2,927,000 ounces in 2011, mainly due to upgrades and increased production throughputs and recoveries at established operations (Bermúdez-Lugo, 2011). The increase continued, with annual production estimates for 2012 and 2013 of 3,166,483 and 3,192,648 ounces respectively (Ghana Chamber of Mines, 2013; 2014). However, gold production fell to 3,167,755 ounces in 2014 due to a drop in production from some major producers caused by higher-than-average rainfall and other mining and processing challenges (Ghana Chamber of Mines, 2014). At the time of writing, the main gold producing prospects, in order of decreasing production during 2014, were: Gold Fields Ghana Tarkwa; Newmont Akyem; Newmont Ahafo; Kinross Chirano; Precious Minerals Marketing Company (PMMC) Gold, which sources gold from small-scale and artisanal mining; AngloGold Ashanti Obuasi; Perseus Mining Ashanti Belt Projects; Gold Fields Damang; AngloGold Ashanti Iduapriem; Golden Star Bogoso Prestea; Golden Star Wassa; and Adamus Resources (Ghana Chamber of Mines, 2014).

Regional geological setting of Ghana

The majority of Ghana is underlain by metamorphosed Palaeoproterozoic (2300-1900 Ma) rocks of the volcano-sedimentary Birimian Supergroup and the overlying clastic sedimentary Tarkwaian Group (Oberthür *et al.*, 1998; Griffis *et al.*, 2002) that make up the Man Shield (also known as the Leo Shield) of the West African Craton in Ghana (Griffis *et al.*, 2002) (Fig. 1). These units host the majority of the gold deposits in Ghana and are the focus of this section. However, numerous Palaeoproterozoic granitoids, which may host gold mineralisation (Oberthür *et al.*, 1995; Yao and Robb, 2000; Yao

et al., 2001), mafic intrusions as well as younger geological successions and intrusions, also occur and are briefly discussed. It is important to note that all the Birimian and Tarkwaian units in Ghana have been metamorphosed to lower greenschist facies, with local variations in the grade of metamorphism, especially around granitic intrusions, as well as in higher grade areas in parts of the northern belts (Griffis *et al.*, 2002). However, the preserved greenschist facies metamorphism could be a retrograde assemblage that was preceded by peak amphibolite facies metamorphism (John *et al.*, 1999; Yao and Robb, 2000). In addition, the Palaeoproterozoic granitoids have also been metamorphically overprinted with features such as foliation and mylonitisation (John *et al.*, 1999). The metamorphism of the Palaeoproterozoic units is discussed and reviewed by John *et al.* (1999) and Griffis *et al.* (2002) and will not be discussed in detail here.

West African Craton and the Man Shield

The West African Craton is Archean to Palaeoproterozoic in age and stretches from the Little Atlas mountains of Morocco in the north, to the Gulf of Guinea in the south. It is bound by younger mobile belts to the west and east, close to the northwestern coast of Africa, and along the northward extension of the border between Benin and Nigeria, respectively. It comprises three metamorphic and magmatic shields separated by two supracratonic sedimentary basins. The shields include: the Archean to Palaeoproterozoic Man Shield in the south; the Archean to Palaeoproterozoic Reguibat Shield in the north; and the Palaeoproterozoic Anti-Atlas Belt in the extreme north. The Taoudeni Basin occurs in the center and the Tindouf Basin in the north of the West African Craton (Ennih and Liégeois, 2008).

The Man Shield consists of an Archean nucleus to the west and Palaeoproterozoic Birimian units in the central and eastern parts (Griffis *et al.*, 2002; Ennih and Liégeois, 2008). The latter units comprise metasediments, metavolcanics and associated intrusive complexes that cover much of Ghana, Côte d'Ivoire, Burkina Faso, southern Mali, northern Guinea and the southwest corner of Niger (Griffis *et al.*, 2002).

Birimian Supergroup

The Birimian Supergroup was originally subdivided into the Lower Birimian comprising volcano-sedimentary units and the Upper Birimian comprising metavolcanics (Junner, 1935; 1940; Oberthür *et al.*, 1997; Griffis *et al.*, 2002). A more recent stratigraphic subdivision of the Birimian Supergroup proposed by Adadey *et al.* (2009) divides it into: the Sefwi Group composed of mica schists and metavolcanics; and the Kumasi Group composed of metasediments and intercalated andesitic beds (Perrouy *et al.*, 2012).

The volcanic belts (also termed greenstone belts) of the Birimian Supergroup strike in an approximately northeasterly direction for hundreds of kilometers through Ghana (Fig. 1), whilst the southern belts are thought to extend into southeastern Burkina Faso and southwestern Niger. The belts have widths of approximately 20 to 70 km, narrowing to 10 to 20 km in the north of Ghana (Griffis *et al.*, 2002). The belt units are dominantly tholeiitic lavas, but also contain ultramafic rocks and intercalations of dacitic and rhyodacitic lavas and pyroclastics of andesitic-dacitic and calc-alkaline character (Attoh *et al.*, 2006; Dampare *et al.*, 2008; Berge, 2011). As mentioned previously, Birimian Supergroup volcanic belts, from southeast to northwest of Ghana, include the: Kibi-Winneba Belt; Ashanti Belt;

Manso Nkwanta/Asankrangwa Belt; Sefwi Belt; Bui Belt; Bole-Navrongo Belt; Wa-Lawra Belt; and Julie Belt (Fig. 1).

The sedimentary units on the margins of the volcanic belts and in the broad intervening basins (Fig. 1) are metamorphosed and tightly folded (Fig. 3). The basins are approximately 60 to 70 km wide in southern Ghana and narrow to the north (Griffis *et al.*, 2002). Various lithofacies with their respective depositional environments have been identified marginal to the belts and in the basins: wacke, turbidite-related facies (lower slopes of volcanic ridges); volcanoclastic/argillite facies (proximal to volcanic ridges); argillite/volcanoclastic facies (distal to volcanic ridges); argillite facies (low energy environments in central parts of basins); and chemical sediment facies (transitional zones between volcanic belts and basins; Hirdes *et al.*, 1993; Griffis *et al.*, 2002). The Birimian Supergroup metasedimentary basins in Ghana include: the Cape Coast Basin in south-central Ghana; the Kumasi and Sunyani Basins in southwestern Ghana; and the Maluwe Basin in western Ghana (Fig. 1).

The formation of the Birimian volcanic belts has been interpreted to have occurred in an oceanic island arc setting (Sylvester and Attoh, 1992; Dampare *et al.*, 2008). However, Feybesse *et al.* (2006) implied a more complex model where plutonic activity and deposition on a continental margin, followed by juvenile basic intrusive and extrusive magmatism, and finally old continental and juvenile crust collision, formed the tectonic setting in which the volcanic belts formed. The Birimian Supergroup metasediments are generally considered to have been derived from the adjacent volcanic belts and deposited along the volcanic ridges and in adjacent basins (Griffis *et al.*, 2002).

Age constraints from zircons in the metavolcanics of the Birimian Supergroup vary between 2162 ± 6 Ma and 2266 ± 2 Ma, whereas detrital zircon grains from the metasediments yield ages of between 2180 and 2130 Ma (Davis *et al.*, 1994; Oberthür *et al.*, 1998; Griffis *et al.*, 2002; Adadey *et al.*, 2009; Loh *et al.*, 2009; Perrouy *et al.*, 2012).

Tarkwaian Group

The Tarkwaian Group and its equivalents consist of a variety of sandstones, conglomerates and argillites that are found within many of the volcanic belts in West Africa. In Ghana, the Tarkwaian Group is best developed within the Ashanti Belt (Fig. 1), where it attains a thickness of approximately 2,500 m, and the Bui Belt, where it attains a thickness of approximately 9,000 m. Occurrences of the Tarkwaian Group have also been found on the eastern margin of the Sefwi Belt, in the Kibi-Winneba belt and the northern Nangodi Belt (Griffis *et al.*, 2002).

The Tarkwaian Group in the Ashanti Belt formed in a long, narrow basin with the western fault-bounded contact forming a half-graben. It is subdivided into four major units, which are, from the base to the top: the Kawere Group; the Banket Series (also referred to as Banket Formation); the Tarkwa Phyllite; and the Huni Sandstone. The Kawere Group comprises conglomerates and sandstones and varies in thickness between 250 and 700 m. The overlying Banket Series (Fig. 4) comprises conglomerates, made up of Birimian quartz pebbles and volcanic clasts, with interbedded cross-bedded sandstones. The Banket Series hosts the Tarkwa Placer gold deposit (<100 m thick gold zone), attains an estimated maximum thickness of 600 m and grades upwards into the Tarkwa Phyllite, which is up to 400 m thick. The latter grades into the uppermost Huni Sandstone that comprises an approximately 1,400 m thick sequence of sandstones with

Figure 3: Northwest to southeast schematic cross section of a typical Ashanti-type, Birimian mesothermal quartz vein and quartz vein-associated sulphide gold deposit (adapted from Griffis *et al.*, 2002).

interbedded quartzites and phyllites, intruded by minor dolerite sills (Kesse, 1985; Strogon, 1991; Griffis *et al.*, 2002; Pigois *et al.*, 2003; Perrouy *et al.*, 2012).

In the Bui Belt (Fig. 1), the Tarkwaian Group consists of two sedimentary cycles within an elongate, overturned syncline in the center of the belt (Kiessling, 1997; Griffis *et al.*, 2002): the Bui cycle (~2,000 m thick) comprising the Nuapo, Kane and Mundale Formations; and the Sabiyi cycle (~7,000 m thick), comprising the Nyanchulo and Tombe Formations. The Bui cycle only occurs in the northern part of the basin, whereas the Sabiyi cycle occurs across the entire basin. Both cycles have quartzite at the base, coarsening upwards to conglomerates which are, in turn, overlain by upward fining quartzites. The predominantly siltstone Mundale Formation occurs at the top of the Bui cycle. The Tarkwaian conglomerates of the Bui Belt contain substantial concentrations of Palaeoplacer gold as mined in Tarkwa (Griffis *et al.*, 2002).

The depositional setting of the Tarkwaian Group units is very different to that of the underlying Birimian Supergroup sedimentary units. The conglomeratic units of the Tarkwaian Group are interpreted as having been deposited in alluvial fans and then reworked by braided stream channels (Sestini, 1973; Kiessling, 1997; Griffis *et al.*, 2002). The latter are thought to have concentrated fine particles of gold within the channel conglomerates.

The maximum age of deposition for the Tarkwaian Group is constrained to approximately 2133 to 2132 Ma based on detrital

zircon from the Kawere Group and Banket Series (Davis *et al.*, 1994; Hirdes and Nunoo, 1994; Pigois *et al.*, 2003; Perrouy *et al.*, 2012), although Perrouy *et al.* (2012) estimate, from all available concordant zircon data, that deposition could have started as late as 2107 Ma. From the intrusion of metagabbro sills (Adadey *et al.*, 2009) and granitoids (Oberthür *et al.*, 1998) respectively, the age of deposition for the Tarkwaian Group is also constrained to approximately 2102 to 2097 Ma (Perrouy *et al.*, 2012).

Palaeoproterozoic intrusions

Granitoid intrusions of Palaeoproterozoic age are common in Ghana, with two types distinguished: belt granitoids (traditionally called Dixcove-type); and basin granitoids (traditionally called Cape Coast-type; Yao *et al.*, 2001; Griffis *et al.*, 2002) (Fig. 1). The belt granitoids are small to medium in size, older than the basin granitoids (2145–2190 Ma), similar to I-type granitoids and generally associated with volcanic belts. The basin granitoids, in contrast, occur in large batholithic complexes, are younger than the belt granitoids (2090–2125 Ma), similar to S-type granitoids and generally intrude into sedimentary basins (Griffis *et al.*, 2002). These two types of granitoids also have further distinguishing characteristics with regards to mineralogy, geochemistry, contact metamorphism, alteration and textures, which are reviewed in more detail by Yao and Robb (1998) and Griffis *et al.* (2002). An economic classification also exists where

Figure 4: Northwest to southeast cross section of a typical Banket Formation-hosted Tarkwaian palaeoplacer gold deposit (adapted from Griffis *et al.*, 2002).

the granitoids are classified as mineralised and unmineralised (Yao and Robb, 1998; Yao *et al.*, 2001). The Palaeoproterozoic belt and basin granitoids have generally intruded both the Birimian volcanic belts and sedimentary basins across northern, western and southern Ghana (Yao and Robb, 2000).

Mafic intrusives, likely of Palaeoproterozoic age, also occur in the majority of volcanic belts of Ghana and are abundant in the Ashanti and Sefwi Belts (Griffis *et al.*, 2002). They generally appear to post-date belt granitoids but pre-date the metamorphism of the volcanic belts. It is thought that two compositional types are most common: sills and feeder dykes with tholeiitic basalt affinity in areas dominated by mafic flows; and later stage gabbro-dioritic intrusions. In the Ashanti belt they occur as extensive sills and minor dykes intruding the Tarkwaian clastic sediments, with airborne geophysical data suggesting similar mafic intrusions in the Birimian volcanics and volcanoclastics (Griffis, 1998; Griffis *et al.*, 2002). Another example of a larger complex hosting mafic intrusives is the Mpohor Intrusive Complex, located approximately 15 km northwest of Takoradi in southwestern Ghana, which hosts the Mpohor gold deposit. The Mpohor intrusions have granodioritic, dioritic and gabbroic compositions, mark the end of the Eoeburnean magmatic phase (Perrouy *et al.*, 2012; 2014) and have a possible link with the previously mentioned Ashanti Belt mafic sills (Griffis, 1998; Griffis *et al.*, 2002).

Geological units of younger age

The sedimentary rocks of the Volta Basin cover close to one half of Ghana's surface (Griffis *et al.*, 2002) and straddle the borders of Ghana, Togo, Benin, Burkina Faso and Niger (Porter *et al.*, 2004). The units have a gentle dip and were deposited on the Eburnean basement of the Man Shield (Nédélec *et al.*, 2007), marking a major Precambrian unconformity (Griffis *et al.*, 2002). The units, from the base upwards, are indicative of a cratonic, epicontinental basin (Bombouaka Supergroup; ~1,000 m thick) changing to a passive

margin (Oti or Penjari Supergroup; ~2,500 m thick) and then a foreland basin (Tamale Supergroup and overlying sandstones; ~500 m thick), which was formed during the Pan-African orogeny (Affaton *et al.*, 1991; Griffis *et al.*, 2002; Porter *et al.*, 2004). Ages for the sedimentary rocks of the Volta Basin include: approximately 993 Ma for clays from the lower Bombouaka Supergroup; approximately 660 Ma for clays (Griffis *et al.*, 2002) and a minimum age of 620 Ma for the Oti Supergroup (Nédélec *et al.*, 2007); and ranges of 500 to 360 Ma for the Tamale Supergroup (Affaton *et al.*, 1991; Griffis *et al.*, 2002).

In the southeastern corner of Ghana a series of northeast-trending units occur that are in fault contact with the Birimian Supergroup, Volta Basin and Eburnean granitoid units. The westernmost extension of the Togo Belt, known in Ghana as the narrow, elongate Buem Formation on the western margin, the adjacent Togo Series to the east, and the high grade Dahomeyan metamorphics on the eastern margin, occur in the southeastern corner of Ghana, along its border with Togo (Griffis *et al.*, 2002). The Togo Belt is a collisional belt related to the Pan-African orogeny and formed during the formation of Gondwana when West Africa was accreted onto the supercontinent at approximately 610 Ma (Hoffman, 1999; Griffis *et al.*, 2002).

Phanerozoic sediments also occur along the coast of Ghana and in numerous offshore basins. These are described in more detail by Kesse (1985), Wright *et al.* (1985), Petters (1991) and Griffis *et al.* (2002). Mesozoic dykes are common in southern Ghana and have been shown by airborne geophysical data to extend to the north (Griffis and Agezo, 2000; Griffis *et al.*, 2002).

Deformational history of the Birimian belts

Deformational structures, especially with regards to the mesothermal gold mineralisation, appear to be the dominant factor in controlling the distribution of gold mineralisation in Ghana's Birimian belts (Griffis *et al.*, 2002). The Birimian Supergroup and Tarkwaian Group, which host the majority of Ghana's gold resources, have

undergone multiple deformational events that can be linked to the Eburnean orogeny (~2130–1980 Ma; Feybesse *et al.*, 2006; Perrouty *et al.*, 2012). This is especially evident in the Ashanti region in southwestern Ghana where six deformational events (termed D1 to D6) have been identified. The deformational events are as follows (Perrouty *et al.*, 2012; 2015):

- The D1 event occurred before deposition of the Tarkwaian Group and is termed the Eoeburnean deformation event, which caused regional scale folding in the Sefwi Group metavolcanics through north-south compression. D1 synorogenic granitoids were also intruded between 2187 and 2158 Ma.
- The D2 event was an extensional phase that opened the Kumasi and Akyem basins into which the Kumasi Group was deposited. On the western side of the Ashanti Belt, the contact between the Sefwi and Kumasi Groups is marked by the Ashanti Fault.
- The D3, or Eburnean event, is characterised by large folds, formed through northwest-southeast compression within both the Birimian and Tarkwaian units.
- The D4 event is marked by small scale shear zones cross cutting D3 folds on the western Ashanti Belt. It also caused reactivation of splays of the Ashanti Fault. At Wassa gold mine a fold that is interpreted to be associated with the D4 event is observed. Both the D3 and D4 events are thought to have been contemporaneous with the Eburnean magmatic phase.
- The D5 event is characterised by small scale (1 cm to 5 m) symmetrical recumbent folds that are open to tight and defined by a subhorizontal crenulation cleavage.
- The D6 event formed open folds defined by a subvertical crenulation cleavage.

Although these deformational events are defined for the Ashanti Belt, other gold-bearing belts in Ghana show similar deformational events. For example, three deformational events (defined here as D_{W1} – D_{W3}) have been identified in the Wa-Lawra Belt in northwestern Ghana (Block *et al.*, 2015; Amponsah *et al.*, 2015a): the D_{W1} event, which was caused by north-south crustal compression; the D_{W2} event, which is characterised by north-south extension and exhumation of high grade terranes; and the D_{W3} event, which is characterised by steeply dipping northeast-, north- and northwest-trending shear zones. The Julie deposit, located in the Julie Belt in northwestern Ghana, also shows three deformational events (D_{J1} – D_{J3}), where D_{J1} and D_{J2} correspond to the D_{W1} and D_{W3} events in the Wa-Lawra Belt respectively (Amponsah *et al.*, 2015b). The D_{J3} event is characterised by northeast- to southwest-orientated brittle faulting (Amponsah *et al.*, 2015b).

The D_{W1} and D_{W2} events in the Wa-Lawra Belt and D_{J1} event in the Julie Belt likely correspond to the D1 and D2 events in the Ashanti Belt. The D_{W3} event in the Wa-Lawra and the D_{J2} event in the Julie Belts show similarities to the D3 and D4 events of the Ashanti Belt. The D_{J3} event could also possibly correspond to the D4 event of the Ashanti Belt. It therefore appears that at least the D1 to D4 events defined for the Ashanti Belt are representative of the gold-bearing Birimian belts of southwestern, western and northwestern Ghana.

Geological setting and description of main gold mineralisation types in Ghana

Studies of gold occurrences in West Africa have identified five

regional types of gold deposits (Griffis *et al.*, 2002). These are: tourmalinised turbidite-hosted deposits; disseminated gold-sulphide deposits; Tarkwaian palaeoplacers; mesothermal auriferous arsenopyrite and quartz vein mineralisation (from here on referred to as mesothermal quartz vein and quartz vein-associated sulphide type mineralisation); and mesothermal gold-quartz vein deposits. The mesothermal quartz vein and quartz vein-associated sulphide type mineralisation hosted in Birimian Supergroup units (Figs. 1 and 2) and the Tarkwaian palaeoplacer type hosted in Tarkwaian Group units (Figs. 1 and 3), are the most significant types of gold occurrences in Ghana. In the Ashanti Belt, Oberthür *et al.* (1995) have further subdivided the mesothermal quartz vein and quartz vein-associated sulphide type mineralisation into shear-zone hosted quartz vein types and quartz vein associated sulphide ore types. This subdivision is commonplace (e.g. Leube *et al.*, 1990; Oberthür *et al.*, 1998; Allibone *et al.*, 2002b; Kuma *et al.*, 2010; Fougrouse *et al.*, 2015). Oberthür *et al.* (1995) also added disseminations and stockwork hydrothermal gold mineralisation in basement-type granitoids as an additional mineralisation type. Therefore deposits belonging to the mesothermal quartz vein and quartz vein-associated sulphide, palaeoplacer and hydrothermal mineralisation in granitoid types, are the most commonly occurring in Ghana and will be the focus of this review. The other three regional type occurrences for West Africa are generally absent or insignificant in Ghana, although a genetic link has been suggested between the mesothermal quartz vein and quartz vein-associated sulphide type mineralisation and turbidite-hosted deposit types (Berge, 2011). Supergene modification of mesothermal vein gold mineralisation has also been documented in the Ashanti Region (Bowell, 1992).

Table 1 summarises the location, mineralisation types, average gold grades and resources of major gold occurrences in Ghana.

Mesothermal quartz vein and quartz vein-associated sulphide type mineralisation

Mesothermal quartz vein and quartz vein-associated sulphide type mineralisation (Fig. 3), sometimes referred to as Ashanti shear zone type mineralisation, is the most important gold mineralisation type in Ghana. Obuasi (also referred to as the Ashanti deposit), the largest gold mine in the region, is the type locality for this mineralisation type. Other deposits in Ghana (Fig. 1; Table 1) where this is an important mineralisation type include Bepkong, Bibiani, Bogosu, Damang, Konongo, Prestea, Wassa and the Yamfo district. This mineralisation type has been estimated to have a total gold inventory of approximately 1,100 t (~32 Moz) in Ghana (Milési *et al.*, 1991; Mumin *et al.*, 1994; Oberthür *et al.*, 1997; Yao *et al.*, 2001; Griffis *et al.*, 2002; Allibone *et al.*, 2002b; Pigois *et al.*, 2003; Tunks *et al.*, 2004; Amponsah *et al.*, 2015a; Fougrouse *et al.*, 2015; Parra-Avila *et al.*, 2015; Perrouty *et al.*, 2015).

Generally, mesothermal quartz vein and quartz vein-associated sulphide type mineralisation is confined to tectonic corridors of up to more than 50 km long and several kilometers wide (Milesi *et al.*, 1992; Griffis *et al.*, 2002) that trend north northeast to northeast and are concentrated along the margins of Ghana's Birimian belts (Griffis *et al.* 2002) (Fig. 1). Ghana's Birimian or 'greenstone' belts are made up of the metasediments and metavolcanics of the Birimian Supergroup along with younger Tarkwaian Group siliciclastics. The mineralisation appears to be strongly associated with regional structures such as shear zones and fault systems. At Obuasi, gold

Table 1: The location, type of gold mineralisation, average grade and estimated resources of known gold deposits in Ghana. The mesothermal vein type mineralisation listed in the table is short for the mesothermal quartz vein and quartz vein-associated sulphide type or Ashanti-type mineralisation.

Name of deposit	Location	Mineralisation types	Average grades	Total resource estimates (recent and/or past)	References
Atewa Range	Kibi-Winneba Belt Southeastern Ghana, near the town of Kibi	Mesothermal vein type	NA	NA	Griffis <i>et al.</i> (2002)
Winneba-Mumford Area	Southern extension of Kibi-Winneba Belt	Mesothermal vein type; Palaeoplacer type	~0.5-1.0 g/t	NA	Griffis <i>et al.</i> (2002)
Abosso	Ashanti Belt/Kumasi Basin Southern Ashanti Belt, ~20 km north-east of Tarkwa, south of Damang	Mesothermal vein type; Palaeoplacer type	~7 g/t	~0.6 Moz Au	Griffis <i>et al.</i> (2002)
Anwia	15 km northwest of Axim, 1 km north of Nkroful, Kumasi Basin	Mesothermal vein type	~1.3 g/t	~0.15 Moz	Griffis <i>et al.</i> (2002)
Ayanfuri	Central Ashanti Belt, 16 km west of Dunkwa-on-Ofin	Mesothermal vein type; Granitoid type	~1.5 g/t	0.2 Moz Au	Griffis <i>et al.</i> (2002)
Benso	Eastern limb of Ashanti Belt, ~38 km southwest of Wassa deposit	Mesothermal vein type	NA	NA	Parra-Avila <i>et al.</i> (2015)
Besease	7 km west of Nkawka, northeast cover of Ashanti Belt	Mesothermal vein type, alluvial	~4.7 g/t	~0.2 Moz	Griffis <i>et al.</i> (2002)
Bogosu	Southwestern Ghana, 60-90 km northeast of Atlantic coastline	Mesothermal vein type	~2.0-5.3 g/t	>2.5 Moz Au	Mumin <i>et al.</i> (1994); Oberthür <i>et al.</i> (1997); Griffis <i>et al.</i> (2002); Allibone <i>et al.</i> (2002)
Dabokrom	15 km northwest of Tokaradi	Mafic-hosted mineralisation	~3-15 g/t	~0.7 Moz	Griffis <i>et al.</i> (2002)
Damang	Southern Ashanti Belt, ~20 km northeast of Tarkwa.	Mesothermal vein type; Palaeoplacer type	~1.3-2.2 g/t	~5 Moz Au	Griffis <i>et al.</i> (2002); Pigois <i>et al.</i> (2003); Tunks <i>et al.</i> (2004)
Golden Ridge	130 km northwest of Accra, northeastern margin of Ashanti Belt	Mesothermal vein type	NA	NA	Griffis <i>et al.</i> (2002)
Iduapriem	Southern end of Tarkwa district, southern hill of Tarkwa syncline	Palaeoplacer type	~1.2-1.7 g/t	~2 Moz Au	Griffis <i>et al.</i> (2002)
Konongo	Northeastern extremity of Ashanti Belt, ~70 km northeast of Obuasi	Mesothermal vein type	~1.1-3.9 g/t	~0.9 Moz	Oberthür <i>et al.</i> (1997); Griffis <i>et al.</i> (2002)
Kubi	Western margin of Ashanti Belt, 6 km northeast of Dunkwa	Mesothermal vein type	~6g/t	~0.8 Moz	Griffis <i>et al.</i> (2002)
Mampon-Aboronye	20 km southwest of Dunkwa, western flank of Ashanti Belt	Mesothermal vein type	~5.5 g/t	~0.4 Moz	Griffis <i>et al.</i> (2002)
Nkran Hill	40 km west-northwest of Obuasi	Mesothermal vein type; Granitoid type	~2.2 g/t	>2.5 Moz Au	Griffis <i>et al.</i> (2002)
Nkroful	15 km northwest of Axim, west of Ashanti Belt, Kumasi Basin	Mesothermal vein type, alluvial	<4 g/t	NA	Griffis <i>et al.</i> (2002)
Obuasi	Ashanti Region, 60 km south of Kumasi, 160 km northwest of Accra	Mesothermal vein type; Granitoid type	~2.6-10.1 g/t	>60 Moz	Bowell <i>et al.</i> (1990); Oberthür <i>et al.</i> (1997); Osae <i>et al.</i> (1999); Yao and Robb (2000); Fougereuse <i>et al.</i> (2015)
Prestea	Southwestern Ghana, 60-90 km northeast of Atlantic coastline	Mesothermal vein type	~3.4 g/t	>7.2 Moz Au	Mumin <i>et al.</i> (1994); Oberthür <i>et al.</i> (1997)
Salman	15 km north of Axim, western boundary of Ashanti Belt	Mesothermal vein type	~1.6-2.3 g/t	~1.2 Moz	Griffis <i>et al.</i> (2002)

Table 1 contd...

Name of deposit	Location	Mineralisation types	Average grades	Total resource estimates (recent and/or past)	References
Tarkwa	Southwestern Ashanti Belt, from Bonsa River in south to Damang in north	Palaeoplacer type	~1.2-2.4 g/t	>40 Moz	Griffis <i>et al.</i> (2002); Pigois <i>et al.</i> (2003);
Teberebie	Western ridge of Tarkwa syncline	Palaeoplacer type	~2.0-2.4 g/t	~2 Moz Au	Griffis <i>et al.</i> (2002)
Wassa	Southern Ashanti Belt, ~40 km northeast of Tarkwa.	Mesothermal vein type	~2.4 g/t	~4 Moz Au (possibly up to 10 Moz)	Parra-Avila <i>et al.</i> (2015); Perrouty <i>et al.</i> (2015)
Abore North	Asankrangwa Belt 45 km southwest of Kumasi; Asankrangwa Belt	Mesothermal vein type; Granitoid type	~2 g/t	~0.3 Moz	Griffis <i>et al.</i> (2002)
Mpeasem	Western side of Ofin River, Asankrangwa Belt	Mesothermal vein type	~2.5 g/t	~0.8 Moz	Griffis <i>et al.</i> (2002)
Bibiani	Sefwi Belt Eastern margin of Sefwi Belt, 80 km west southwest of Bibiani	Mesothermal vein type	~2.6 g/t	~1.8 Moz Au	Griffis <i>et al.</i> (2002)
Chirano	90 km southwest of Kumasi, central western margin of Sefwi Belt	Mesothermal vein type; Granitoid type	~2.2 g/t	~1.4 Moz	Griffis <i>et al.</i> (2002)
Ntotoroso	30 km south of Sunyani, Sefwi Belt	Mesothermal vein type; Granitoid type	~2.3 g/t	~1.4 Moz	Griffis <i>et al.</i> (2002)
Yamfo-Kenyase	South of Sunyani, Sefwi Belt	Mesothermal vein type; Granitoid type	~3 g/t	~6.2 Moz	Griffis <i>et al.</i> (2002)
Brohani	Bui Belt Central western Ghana	Palaeoplacer type	>1 g/t	NA	Griffis <i>et al.</i> (2002)
Dokrupe	Bole-Navrongo Belt Southern margin of Bole-Navrongo Belt	Mesothermal vein type	~2.8 g/t	~0.18 Moz	Griffis <i>et al.</i> (2002)
Bepkong	Wa-Lawra Belt Northwestern Ghana, Wa-Lawra Belt	Mesothermal vein type	~1.8 g/t	~0.1 Moz	Amponsah <i>et al.</i> (2015a)
Julie	Julie Belt Northwestern Ghana, Julie Belt	Granitoid type	~1.5 g/t	~0.8 Moz	Amponsah <i>et al.</i> (2015b)

mineralisation is restricted to the northeast striking Ashanti fault zone where the Ashanti thrust fault is subdivided into mineralised splay faults that consist of graphitic shears (Fougerouse *et al.*, 2015) (Fig. 5A).

The first subtype of mesothermal quartz vein and quartz vein-associated sulphide type deposits, namely the quartz vein gold deposits, have multiple stage (e.g. three generations at Wassa; Perrouty *et al.*, 2015), extensive, steeply dipping (Fig. 5B) vein systems. The systems vary from thin (<2 m), discrete veins in parallel sets (e.g. at Prestea), to broad stockwork systems where the veins can be as thick as 20 m to 55 m. Generally the quartz vein-hosted gold mineralisation appears to be associated with the regional ductile to brittle D3 deformational event of northwest to southeast compression, as observed at Bepkong, Bogoso, Damang, Obuasi and Wassa. However, earlier quartz vein-hosted gold mineralisation associated with the D1 deformational event which caused folding of the Sefwi Group by

north-south compression has been observed at Wassa (Griffis *et al.*, 2002; Obuasi; Bibiani *et al.*, 2002; Allibone *et al.*, 2002b; Tunks *et al.*, 2004; Amponsah *et al.*, 2015a; Fougerouse *et al.*, 2015; Perrouty *et al.*, 2015).

Associated with the quartz vein systems is the second subtype of the Ashanti-type mineralisation, namely quartz vein-associated sulphide mineralisation which is characterised by wide disseminated sulphide zones in the host rocks that can extend up to 100 m (e.g. at Prestea) into the host rock. Gold mineralisation in the disseminated sulphide zones is generally subeconomic and/or refractory (Griffis *et al.*, 2002). However, at Obuasi it makes up more than 50% of the ore reserve (Fougerouse *et al.*, 2013). The zones appear to occur as variably sized pods and are generally cut by quartz vein systems (Figs. 3 and 5C), indicating an earlier gold mineralisation stage for the disseminated sulphides (Griffis *et al.*, 2002). The sulphide mineralisation appears to be associated with the regional extensional

D2 deformation event (Fougerouse *et al.*, 2013; 2015) but could also be coeval to the D3 event-associated quartz vein mineralisation (Oberthür *et al.*, 1997).

The host rocks for mesothermal quartz vein and quartz vein-associated sulphide type mineralisation include: metasediments usually in proximity to graphitic/carbonaceous, siliceous or manganiferous chemical sedimentary rocks; mafic volcanic rocks; and belt intrusions (Griffis *et al.*, 2002). These host rocks, excluding the belt intrusions, comprise the volcano-sedimentary Birimian Supergroup. For example, at Obuasi the gold mineralisation is hosted in the metasedimentary Kumasi Group lithologies (Fougerouse *et al.*, 2015) whereas at Wassa, gold mineralisation is hosted in the volcano-sedimentary Sefwi Group lithologies (Perrouy *et al.*, 2015). However, mesothermal gold mineralisation can also occur in Tarkwaian Group conglomerates, sandstones and phyllites, as has been observed at Damang Gold Mine (Tunks *et al.*, 2004).

Tarkwaian palaeoplacer mineralisation

Economic gold concentrations occur in the quartz pebble conglomerate of the Banket Series of the Tarkwaian Group (Fig. 4).

The mineralisation is generally considered to be of modified-palaeoplacer type. The type locality for this deposit type is the Tarkwa district, located in the southwestern extremity of the Ashanti Belt (Fig. 1). Deposits in Ghana (Fig. 1; Table 1) where this is an important mineralisation type include Abosso-Damang, Iduapriem, Tarkwa and Teberebie. This mineralisation type has been estimated to have a total gold inventory of approximately 550 t (~16 Moz) in Ghana (Pigois *et al.*, 2003; Tunks *et al.*, 2004; Klemd *et al.*, 1993; Griffis *et al.*, 2002; Milési *et al.*, 1991; Yao *et al.*, 2001).

The gold-bearing conglomerates of the Banket Series crop out in two areas in Ghana (Fig. 1): from the southwest of the country to the edge of the Volta Basin in the northeast, a region that is 250 km long and 16 km wide; and in west central Ghana over an area that is 140 km long and 0.8 km wide (Kesse, 1990). The Banket Series is marked by a number of well packed quartz pebble conglomerates (Fig. 6A) that were deposited from southeasterly to northwesterly flowing rivers (Oberthür *et al.*, 1995). The mature and clean nature of the conglomerates and interbedded sandstones suggest that reworking took place (Kesse, 1990). The conglomerates have been subjected to low grade metamorphism producing chlorite-sericite assemblages (Kesse, 1990).

Figure 5: Photographs illustrating some features of Birimian mesothermal gold mineralisation from gold deposits in Ghana. A) Quartz veins and mineralisation in graphitic sheared faults at Obuasi Mine (photograph courtesy of AngloGold-Ashanti). B) Wassa Mine's B ore shoot illustrating the narrow and steeply dipping nature of the mined out mineralisation (photograph courtesy of Stephane Perrouy). C) Arsenopyrite in the metasediments surrounding the quartz veins at Obuasi Mine (photograph courtesy of AngloGold-Ashanti). D) Visible gold occurring in fractures within a quartz vein at Obuasi Mine (photograph courtesy of AngloGold-Ashanti).

Gold occurs within four conglomeratic reefs in the Banket Series: the footwall Sub-basal reef; the Main (Basal) Reef; the West (Middle) Reef; and the hanging wall Breccia Reef (Fig. 4) (Klemd *et al.*, 1993). The best gold grades occur in the Main (Basal) Reef, although the overlying conglomerates contain significant gold and the interbedded cross-bedded quartzites (Fig. 6B) also contain some gold (Griffis *et al.*, 2002). The conglomeratic sequence varies in width in the Tarkwa syncline of the Ashanti belt from 30 to 45 m in the east to 60 to 75 m in the west. The conglomerate occurs as lenses, individually between 600 and 1,000 m long and 100 to 150 m wide (Griffis *et al.*, 2002).

Hydrothermal gold mineralisation in basement-type granitoids

Due to the revival in Ghana's gold industry in the 1980s, increased exploration led to the discovery of gold deposits hosted in

Figure 6: Photographs illustrating some features of Tarkwaian palaeoplacer gold mineralisation from gold deposits in Ghana. A) A well-packed quartz pebble conglomerate from the Banket Formation at Iduapriem Mine (photograph courtesy of AngloGold-Ashanti). B) Cross-bedded quartzite, with dark layers of haematite on bedding and cross bedded surfaces, interbedded with the conglomerates of the Banket Formation at Iduapriem Mine (photograph courtesy of AngloGold-Ashanti). C) Open folding in Tarkwaian sedimentary rocks caused by the D3 deformational event at Damang Mine (photograph courtesy of Stephane Perrouty).

Palaeoproterozoic Birimian belt and basin granitoids which occur across southwest, west and northwest Ghana. Gold deposits in Ghana where this mineralisation type occurs (Table 1; Fig. 1) include Ayanfuri, Chirano, Julie, Nkran Hill, Ntoroso, Obuasi and Yamfo. This mineralisation type has been estimated to have a total gold inventory of approximately 100 t (~2.9 Moz) in Ghana, but could be even higher with more recent discoveries such as the granitoid-hosted Julie gold deposit in northwestern Ghana (Yao and Robb, 2000; Yao *et al.*, 2001; Griffis *et al.*, 2002; Amponsah *et al.*, 2015b).

Mineralised granitoids are generally smaller than the unmineralised ones, are granodioritic to granitic in composition and occur as small, steeply dipping stockworks and sulphide disseminations that are concordant with the regional faults and shears that strike northeast and east (Oberthür *et al.*, 1995; Yao and Robb, 2000; Yao *et al.*, 2001; Amponsah *et al.*, 2015b). They have generally intruded Birimian metasediments (for example phyllites at Obuasi; Yao and Robb, 2000) and mineralisation occurs in both the granitoids and metasediments (Griffis *et al.*, 2002). The overall size and shape of the gold mineralised granitoid ore bodies in Ghana are generally poorly constrained. However, at the Julie deposit in northwestern Ghana, the granitoid-hosted ore deposit consists of two plunging lenticular shaped swarms of orientated veins within shear zones that vary in thickness between 20 m and 50 m, with a measured strike extent of up to 100 m (Amponsah *et al.*, 2015b). The gold mineralisation occurs within and around quartz veins and stockworks in altered zones that show two (Yao and Robb, 2000) to three (Amponsah *et al.*, 2015b) cross cutting generations of veining. Not all vein generations are necessarily associated with gold mineralisation. The veins fill extensional fractures and are deformed (Yao *et al.*, 2001).

Mineralogy of gold occurrences

Mesothermal quartz vein and quartz vein-associated sulphide type mineralisation

The mesothermal quartz vein gold ores typically border graphitic shear zones (Fig. 5A) and contain variable but high grades of visible gold in thick quartz veins (Fougerouse *et al.*, 2015). The visible gold occurs in micro-fractures that overprint the quartz veins (Fougerouse *et al.*, 2015) (Fig. 5D) and is generally intergrown with polymetallic sulphides (Oberthür *et al.*, 1995). The quartz is medium to dark grey in colour and may contain small amounts of ankerite and host rock fragments in unmineralised parts. Along with visible gold and polymetallic sulphides, muscovite occurs in the mineralised microfractures (Griffis *et al.*, 2002; Fougerouse *et al.*, 2015). Rare occurrences of aurostibite, bismuthotellurides and auriferous lollingite are also observed in quartz vein ores (Oberthür *et al.*, 1995).

The quartz vein-associated disseminated sulphide ores are dominated by arsenopyrite (~60-95%; Fig. 5C) and also contain pyrite, pyrrhotite, marcasite, chalcopyrite and rare native gold (Fougerouse *et al.*, 2015). Larger arsenopyrite grains can be zoned with gold-rich rims and gold-poor cores. The gold is locked in the sulphide lattice of mostly arsenopyrite but also pyrite (Oberthür *et al.*, 1994; Griffis *et al.*, 2002; Fougerouse *et al.*, 2015) and is generally refractory (i.e. cannot be recovered by cyanidation), although some deposits (e.g. Nkran Hill, Chirano, Ntoroso and Ayanfuri) contain significant native gold (Griffis *et al.*, 2002).

Alteration envelopes of variable sizes occur around the quartz vein systems. Alteration types include silicification, chlorite and carbonate alteration, sericitisation and albitisation. The disseminated sulphide zones surrounding the quartz vein systems are generally highly silicified and are therefore thought to form part of the alteration envelopes (Griffis *et al.*, 2002).

Tarkwaian palaeoplacer mineralisation

The conglomerates that host the gold mineralisation in the Banket Series are oligomictic, well-sorted and consist mostly of vein-quartz pebbles (>90%) and subordinate schist and quartzite pebbles (Kesse, 1985; 1990; Milési *et al.*, 1991; Klemd *et al.*, 1993) (Fig. 6A). The matrix is made up of quartz and heavy mineral sands with the latter comprising hematite with some ilmenite, magnetite and rutile. In the Main Reef, which has the highest gold contents, the gold is concentrated in the basal 20 cm and the highest gold contents are associated with well-packed hematite- and magnetite-rich horizons or payshoots, parallel to palaeochannels. The gold shows two modes of occurrence: as fine (10–60 µm) grains of free gold within the matrix of the conglomerate, associated with the heavy mineral sands; and as intergrowths, overgrowths and inclusions with authigenic ilmenite/rutile aggregates, magnetite and hematite (Kesse, 1990; Eisenlohr, 1992; Klemd *et al.*, 1993). The gold has a silver-depleted composition (Eisenlohr, 1992).

Quartz veins cross cut the mineralised conglomerates in places and can contain minor gold and pyrite mineralisation (Eisenlohr, 1992) and sulphidised haloes (Klemd *et al.*, 1993). In addition to commonly occurring close to quartz veins, sulphides can also occur in proximity to the faults and dykes cross cutting the conglomerates (Eisenlohr, 1992).

Hydrothermal gold mineralisation in basement-type granitoids

The ore mineral assemblage encountered in the quartz veins and associated alteration zones in granitoid-type gold mineralisation includes mainly pyrite and arsenopyrite, with minor chalcopyrite, sphalerite and galena. Pyrite is the most abundant sulphide and two generations, namely early coarse and late fine grains and aggregates occur. The gold mostly occurs as free gold micro-inclusions within pyrite and arsenopyrite but can also occur as larger grains within fractures or on the edges of pyrite. Minor solid solution or sub-microscopic gold also occurs in pyrite (Oberthür *et al.*, 1995; Yao and Robb, 2000; Amponsah *et al.*, 2015b).

Alteration zoning is present in the granitoids surrounding the quartz veins and decreases from the ore zones outwards. The strongest alteration within and directly surrounding mineralisation, comprises a mineral assemblage of sericite, quartz, ankerite, calcite, tourmaline, rutile, pyrite and arsenopyrite. The original textures of the granitoid are destroyed and the rocks have a bleached appearance due to carbonatisation. The size of the alteration halo is variable and, for example, is much larger at Julie (~50 m; Amponsah *et al.*, 2015b) than at Obuasi (~1 m; Yao and Robb, 2000). Further away from the mineralised zone the alteration assemblage is characterised by albite, sericite, calcite, chlorite, pyrite and rutile and then finally by chlorite, epidote and biotite. The latter assemblage is considered to be a greenschist facies metamorphic overprint (Yao and Robb, 2000; Amponsah *et al.*, 2015b).

Age of gold mineralisation

Mesothermal gold mineralisation in rocks of the Birimian Supergroup and granitoids

Detrital zircons from Birimian metasandstone at Obuasi (thought to be of the Kumasi Group) have been dated at a minimum age of 2155 ± 2 Ma (Oberthür *et al.*, 1998) and provide a maximum age for mesothermal gold mineralisation in the Birimian Supergroup metasediments. The age of gold mineralisation in belt granitoids at Sakpa Mine in the Bole-Navrongo belt, has been determined at between 2110 ± 32 Ma and 2133 ± 21 Ma, using uranium-lead (U-Pb) on hydrothermal rutile (Yao and Robb, 1999). For basin granitoids at the Obuasi and Ayanfuri mines, the age of gold mineralisation has been determined at between 2086 ± 4 and 2098 ± 7 Ma using Pb-Pb on hydrothermal rutile and galena (Oberthür *et al.*, 1998). These ages of mineralisation post-date the granitoid emplacement by approximately 5 to 30 Ma (Yao *et al.*, 2001). The similarity of the quartz vein-associated gold mineralisation in the granitoids and the Birimian metasediments, as well as their close geological association, therefore suggests that the age of mineralisation in the granitoids is close to the minimum age of mineralisation in the Birimian metasediments. In addition, Pb/Pb model ages of quartz vein-hosted galena, bournonite and gold at Ashanti Mine, gave a range of approximately 2120 to 2080 Ma (Höndorf *et al.*, 1994; Oberthür *et al.*, 1995). Mesothermal gold mineralisation in the Birimian metasediments therefore appears to be constrained between approximately 2155 Ma and 2080 Ma. This age range pre-dates and also overlaps the 2130 to 1980 Ma Eburnean orogeny (Feybesse *et al.*, 2006; Perrouty *et al.*, 2012), which is reconcilable with D2 (pre-Eburnean) disseminated sulphide- and D3 (Eburnean) quartz vein-associated mesothermal gold mineralisation.

However, at Wassa Mine the mesothermal gold mineralisation is hosted in the lower Sefwi Group and appears to be associated with the D1 Eoeburnean deformational event. As mentioned in an earlier section, D1 synorogenic granitoids intruded between 2187 and 2158 Ma (Perrouty *et al.*, 2012; 2015), implying that this is the age range for an earlier mesothermal gold mineralisation episode at Wassa.

Tarkwaian palaeoplacer mineralisation

The deposition of the Tarkwaian Group occurred between approximately 2133 Ma and 2097 Ma, which will also be the depositional age range for any palaeoplacer gold. With regards to the mesothermal quartz vein-associated gold mineralisation that overprinted the Tarkwaian palaeoplacer mineralisation, U-Pb ages on hydrothermal xenotime suggest that the mesothermal mineralisation occurred at 2063 ± 9 Ma (Pigois *et al.*, 2003). This is younger than the mineralisation age range for Birimian Supergroup-hosted mesothermal gold mineralisation discussed in the previous section (2155–2080 Ma), but still falls within the age range of the Eburnean orogeny (2130–1980 Ma).

Genetic models for gold mineralisation

Mesothermal quartz vein and quartz vein-associated sulphide type mineralisation

The association of Ashanti type mineralisation with deformational

fabrics and features indicates that more than one episode of gold mineralisation occurred in deposits hosted in the Birimian Supergroup of Ghana. The majority of deposits show evidence for the quartz-vein associated sulphide ores to have formed during the D2 extensional event and the quartz vein free gold ores to have formed during the Eburnean D3 compressional event (e.g. Allibone *et al.*, 2002b; Tunks *et al.*, 2004; Amponsah *et al.*, 2015a; Fougrouse *et al.*, 2015; Perrouty *et al.*, 2015). However, examples of quartz vein free gold ores associated with the Eoeburnean D1 compressional event are also encountered (Perrouty *et al.*, 2015). This deformational association, as well as the location of gold mineralisation close to major shear zones (Oberthür *et al.*, 1995) and fault systems (e.g. the Ashanti fault; Fougrouse *et al.*, 2015), termed “structural corridors” (Griffis *et al.*, 2002), also highlight the importance of structural controls on the development of gold mineralisation. Hydrothermal fluids were therefore most likely moved from a deeper crustal origin into sites of mineralisation along shear zones and faults in the granitoids and Birimian lithologies by Eoeburnean and Eburnean orogenic stress and strain cycling through seismic pumping, or a “fault valve” fluid flow model (Sibson *et al.*, 1975; 1988; reviewed by Robb, 2005).

Fluid inclusion studies indicate that the quartz vein-mineralising fluids were CO₂-dominated gas mixtures with N₂ and minor CH₄ (Oberthür *et al.*, 1995). Although H₂O is absent in the fluid inclusions, evidence from alteration mineral compositions (Mumin *et al.*, 1996; Manu *et al.*, 2013) and fluid inclusions in Birimian granitoid-hosted quartz vein gold mineralisation (Oberthür *et al.*, 1995; Yao and Robb, 2000) suggest that H₂O was also dominant in the fluids at least during some stages of fluid evolution. The fluids were deep-seated and of magmatic or metamorphic origin and the veins formed at a temperature of 400 ± 50°C and fluid pressures of 2 kbar to 5 kbar (Oberthür *et al.*, 1995). For Bogosu and Prestea, Mumin *et al.* (1996) proposed that the fluids were of metamorphic origin only. Temperatures derived from the ankerite-siderite composition geothermometer from carbonates occurring in mineralised rocks at Bogosu and Prestea, indicate that gold mineralisation occurred over a temperature range of 340°C to 140°C at crustal depths of 7 km to 11 km. The lack of chemical re-equilibration between the ore fluid and country rock also suggests that the fluid ascent from its deep source to the shallower mineralisation sites was rapid. Decrease in temperature, pressure and CO₂-H₂O immiscibility in the hydrothermal fluids, is thought to have caused the precipitation of the ore minerals (Mumin and Fleet, 1995; Mumin *et al.*, 1996; Manu *et al.*, 2013).

Tarkwaian palaeoplacer mineralisation

Observations and evidence in support of a sedimentological control (of detrital or palaeoplacer origin) for the gold in the Banket Series are as follows: the gold payshoots follow palaeochannels; economic gold concentrations are associated with other heavy mineral concentrations; gold occurrences are unrelated to quartz veins and sulphidisation (Klemd *et al.*, 1993; Oberthür *et al.*, 1995); and the gold is generally depleted in silver (Eisenlohr, 1992; Klemd *et al.*, 1993). Interpretations of the depositional environment include: alluvial fans on a piedmont surface with later braided river streams from the east dispersing the alluvial sediment (Sestini, 1973; Kiessling, 1997); and braided tributary channels originating from the east and joining up with a main trunk channel flowing to the north (Strogen, 1991).

The source of the placer gold in the Banket Series is a matter of debate. Where early authors considered the mesothermal quartz vein-

associated gold of the Birimian Supergroup as the source for Tarkwaian palaeoplacer gold (e.g. Junner *et al.*, 1942; Kesse, 1984), it was later determined that the D2 and D3 deformational events, with which the mesothermal gold mineralisation is associated, also overprinted the Banket Series (Milési *et al.*, 1991; Eisenlohr, 1992) (Fig. 6C). The detrital gold in the Banket Series was therefore already deposited when the D2 and D3 events helped concentrate mesothermal gold mineralisation in the metasediments of the Birimian Supergroup. The southeast to northwest palaeocurrent directions at Tarkwa also make it impossible for the Birimian gold mineralisation in the area to have been the gold source for the Banket Series in this region (Oberthür *et al.*, 1995). The occurrence of Eoeburnean (D1 deformational event) gold mineralisation in the Sefwi Group lithologies at Wassa, could be indicative of an older gold source for the paleoplacers (Perrouty *et al.*, 2015).

It is important to note that some gold mineralisation occurs within the quartz veins that cross cut the conglomerates, suggesting some gold remobilisation by fluids during deformation and metamorphism (Eisenlohr, 1992), similar to the modified placer mineralisation model for the Witwatersrand gold reefs of South Africa (e.g. Els, 1991; Robb *et al.*, 1997; Frimmel and Minter, 2002; Hayward *et al.*, 2005).

Hydrothermal gold mineralisation in basement-type granitoids

In addition to the geological setting, geochemistry, geochronology and mineral assemblages, quartz vein fluid inclusion studies have been important in constraining the genetic history of gold mineralisation in the granitoid bodies (e.g. Yao and Robb, 2000; Yao *et al.*, 2001; Amponsah *et al.*, 2015b). The composition of the granitoid-hosted fluid inclusions in the Ashanti Belt is comparable to those in mesothermal gold deposits in Ghana (Yao *et al.*, 2001), suggesting a genetic link between the two.

The mineralised Palaeoproterozoic belt and basin granitoids are considered to be good sites for gold mineralisation due to their brittle nature during deformation and would have provided good conduits for fluid flow (Yao *et al.*, 2001). For Obuasi, Yao and Robb (2000) proposed that the gold mineralisation in the granitoids was caused by a metamorphic, reduced, low-salinity H₂O-CO₂-NaCl fluid, in a brittle deformational regime during the waning stages of the Eburnean orogeny at approximately 2100 Ga. A low-salinity H₂O-CO₂ fluid was also proposed by Oberthür *et al.* (1995). Pressure and temperature conditions were likely 1 kbar to 3 kbar and 180°C to 350°C, respectively, and gold deposition was thought to have been induced by H₂O-CO₂ fluid immiscibility and/or sulphidisation during alteration. Fluids characterised by CO₂-N₂±CH₄ could also have been involved with gold mineralisation, as observed in fluid inclusions at Sansu mine (Yao *et al.*, 2001).

The genetic model proposed by Amponsah *et al.* (2015b) for the granitoid-hosted gold mineralisation at the Julie deposit in northwestern Ghana show some similarities and differences to those proposed for the Ashanti Belt (Yao and Robb, 2000; Yao *et al.*, 2001). A similar H₂O-CO₂-NaCl mineralising fluid of moderate to low salinity that underwent liquid immiscibility in a brittle to ductile deformational regime is also proposed for the Julie deposit. However the temperature and pressure of the fluid during immiscibility are estimated to have been 220°C and less than 1 kbar, respectively (Amponsah *et al.*, 2015b), towards the lower range of that proposed

for the Ashanti Belt. The most notable difference in the genetic models for the Ashanti and Julie Belts, is the timing of gold mineralisation. The mineralised veins at the Julie deposit are associated with the D_{J1} shear zone (Amponsah *et al.*, 2015b) that likely corresponds to the D1 event in the Ashanti Belt, suggesting that gold mineralisation occurred earlier in the tectonic history of the Julie Belt than it did in the Ashanti Belt.

Gold exploration in Ghana

The geographical situation of Ghana divides the country into a tropical rain forest belt in the south that transitions northwards into tropical savannah. Most of the country's gold production has come from the south, with only minor prospects discovered to date in the northwestern part of the country.

The wet tropical climate has resulted in deep chemical weathering of the bedrock in both the rain forest and the savannah areas, with very little fresh rock outcrop exposed. There is no record of how the famous and rich Ashanti and related gold deposits were discovered, but it can be assumed that the early gold prospectors simply dug pits and trenches into any gold showings found by chance at surface. If gold was struck, the exploration diggings turned into small artisanal mines and were worked until the ore ran out. Such artisanal prospecting and mining continue to this day in parts of Ghana.

With Western colonisation and the establishment of industrial-scale mining (discussed above) by companies such as Ashanti Goldfields Corporation and Tarkwa Goldfields Limited, more systematic exploration was carried out to increase ore resources near existing mining operations, and to discover new deposits. Early prospecting took the form of pitting and trenching "on trend" of existing deposits, followed by drilling, when gold assays of soil and rock samples showed positive results. This form of prospecting indirectly recognised that linear geological structures controlled some of the mineralisation.

Modern exploration methods, especially for completely hidden ore deposits, developed alongside the systematic study of the types of gold mineralisation, as reviewed in this paper. The physical and chemical characteristics of the ore deposits, together with the weathering regime, determine the optimum exploration techniques that will increase the chances of locating deeply buried deposits. With the advent of the space age, remote sensing techniques using satellite data have played an increasingly important role in regional exploration (Owusu *et al.*, 2006; Kwang *et al.*, 2014).

A modern exploration programme will be fully integrated, taking into account all available geoscientific data sets to focus targeting (Robert *et al.*, 2007; Kuma *et al.*, 2010; Magalhães and Filho, 2012). Geological, geophysical and geochemical information will be overlain, using geographic information systems (GIS) software, on topographic maps and satellite imagery, to tease out the features that may indicate the location of an ore deposit.

The importance of Ghana as a gold producing country is emphasised by the continued study and re-interpretations of the well-known deposits such as Obuasi and Tarkwa (Allibone *et al.*, 2002a; 2002b; Perrouy *et al.*, 2012; 2014; Fougereuse *et al.*, 2015). A full understanding of the types of mineralisation is the foundation for effective exploration.

A symposium was held in May 1990 in Accra, on gold exploration in the tropical rain forest belts of southern Ghana (Barning, 1990). Amongst others, papers were presented on geophysical prospecting

in the search for gold in the Ashanti area, and the use of geochemistry in the exploration for gold. Five lode gold case studies were presented, together with two on alluvial gold deposits. The interested reader will find Barning (1990) of use with regards to the conventional exploration techniques that are still important in modern exploration (Nude and Arhim, 2009; Arhim, 2013; Tisbaoh and Grant, 2009; Wemegah *et al.*, 2015).

The availability of powerful computers and the development of sophisticated GIS programmes have allowed the rapid merging of diverse geoscientific data sets that are being interpreted to focus mineral detection (Porwal and Carranza, 2015). One such attempt was carried out by Carranza *et al.* (2009) who mapped the prospectivity and estimated the number of undiscovered prospects for lode gold in the southwestern Ashanti Belt in Ghana (Fig. 7). They carried out mineral prospectivity mapping (MPM) and mineral resource assessment (MRA), two distinct predictive modelling methods for analysing geological and mineral occurrence data with a view to facilitating strategic mineral exploration over the study area. In combination, the two techniques predicted the occurrence of 37 to 40 undiscovered lode gold deposits in the southwestern Ashanti Belt (Carranza *et al.*, 2009).

Another modern technique that is being used for broad strategic exploration of the Ashanti Belt is 3D modelling, as reported by Perrouy *et al.* (2014). Building on 2D remapping and re-interpretation

Figure 7: Map of predicted mesothermal gold prospective areas along with the locations of spatially coherent and non-coherent prospects as well as old mines from the southwestern Ashanti Belt (adapted from Carranza *et al.*, 2009). Known gold deposits and prospects are used in training sets for the mineral prospectivity mapping. Spatially coherent deposits/prospects are those that show the best spatial correlation with the geological parameters (faults, lineaments) used in the analysis. The deposits/prospects that show poor correlation with the geological parameters are deemed spatially non-coherent. A detailed discussion is provided by Carranza *et al.* (2009).

of the Sefwi Group (Perrouy *et al.*, 2012), the authors used Geomodeller and Gocad software to build a 3D model of the Sefwi Group rocks. With the inclusion of 21 known gold occurrences in the model, it was noticed that 85% of the gold showings in the Sefwi Group occur within 1,500 m of the contact with the basaltic BV1 horizon. The authors thus infer that there is strong evidence for a lithostratigraphic control on the gold mineralisation in the Sefwi Group. They postulate that the BV1 unit could either have acted as a physical or chemical trap for gold-bearing hydrothermal fluids, or could have been the primary source of the gold (Perrouy *et al.*, 2014). The latter interpretation has been suggested by other researchers and reviewed by Nyame (2013). Similar mapping and 3D modelling of structural controls on the Chirano gold occurrences was carried out by Kenworthy *et al.* (2009), in order to better delineate resources and exploration targeting near existing mines.

Once a target has been identified, drilling needs to be undertaken to, firstly, prove the existence and continuity of the potential ore body at depth, and, secondly, to delineate the potential mineral resources and ore reserves. Drilling is generally acknowledged as the most expensive stage of an exploration programme, and hence the information obtained from drilling must be maximised, especially from diamond drill core. The hole can be geophysically surveyed using a down-hole probe, and optically scanned to obtain structural data. The core in the core trays can be digitally scanned for archiving, and spectroscopically scanned to reveal details of mineralogy and alteration that may be associated with gold mineralisation. Such geophysical and geochemical logs complement the traditional geological logging method and facilitate rapid decision making during exploration.

In conclusion, one has to bear in mind the old maxim often quoted by the late Professor DA Pretorius, the founding director of the Economic Geology Research Unit (EGRU) (now Institute - EGRI) at the University of the Witwatersrand, Johannesburg, South Africa: “to search for elephants, you have to be in elephant country”. When you explore for gold in Ghana (or elsewhere), you have to be in places that are favourable for gold mineralisation, otherwise you will be wasting time and money. Ghana is certainly elephant country, and it is a matter of time before some of the “undiscovered lode gold deposits” predicted by Carranza *et al.* (2009) are found.

Future potential for gold in Ghana

Industrial-scale mining

A comprehensive report released by the Ghana Chamber of Mines (GCM) and the International Council of Mining and Metals (ICMM) at the time of writing of this review (August 2015), emphasises the importance of gold mining to Ghana (GCM-ICMM, 2015). To quote: “The mining sector attracts more than half of all foreign direct investment, generates more than one-third of all export revenues, is the largest tax-paying sector and makes a significant contribution to GDP and employment.” The compilers of the report aimed to provide an independent and objective evidence base regarding mining’s past, present and possible future contributions to the Ghanaian economy and society. The annual gold production for 2013 for the seven largest gold producers, the latest data available at the time of writing, was also reported (Table 2).

The mining and fiscal statistics for seven of the largest gold mining operations in Ghana, which produced some 60% of the gold produced in 2013, are illustrated in graphs, and projections have been made to the year 2022. The compilers used data from 2010 to 2013 as a basis, and projected production out to 2022, averaging 1.896 million ounces per year for the 13 year period. Similar projections gave sales revenues of US\$ 2,517 million on average, with expenditures of US\$ 2,262 million. As with most projections, a number of assumptions had to be made, such as the future price of gold, working costs, etc. which impart a significant level of uncertainty to the statistics. Nevertheless the report is positive on the role that gold mining will be playing in Ghana’s economy in the near future.

The GCM-ICMM report does not list the current gold resources of the seven mining companies operating in Ghana that were studied. It is thus instructive to ascertain whether these projected production figures can be sustained to 2022 by summing the latest available gold resources reported by the seven mining companies (Table 2). It is evident that there are sufficient gold resources reported by the seven studied companies to sustain mining to the year 2022. The GCM-ICMM report thus paints an overall realistic picture about the future of large-scale gold mining in Ghana.

One aspect arising out of this brief look into the future is the

Table 2: Annual gold production for 2013 and total gold resources reported by the seven gold mining companies studied in the GCM-ICMM 2015 report. Other than the GCM-ICMM 2015 report, the gold resources statistics are taken from AngloGold-Ashanti (2014), Endeavour Mining (2015), Gold Fields Limited (2015), Golden Star Resources (2015), Kinross Gold Corporation (2015), Newmont (2015) and Perseus Mining Limited (2015).

Mining Company Name	Location in Ghana	Annual Output 2013 (ounces)	Total Resources (ounces)	Year Reported
Adamus Resources	Teluku-Bokazo and Nkrofu	105,215	1,901,000	2014
AngloGold Ashanti	Obuasi and Iduapriem	239,052	33,730,000	2013
Chirano Gold Mines	Chirano	274,683	2,271,000	2014
Gold Fields Ghana	Tarkwa and Damang	785,421	14,800,000	2014
Golden Star Resources	Prestea and Wassa	330,807	6,653,000	2014
Newmont Ghana	Ahafo and New Abirem	699,366	5,660,000	2014
Perseus Mining (Ghana)	Ayanfuri	198,608	3,280,000	2011
Total		2,633,152	68,295,000	

Notes: (1) Adamus Resources has being taken over by Endeavour Mining.

(2) Annual output for 2013 from the GCM-ICMM Report, 2015.

disparity between the production from the AngloGold Ashanti (AGA) mines and the reported mineral resources. This is due to the current suspension of mining operations and the re-configuration of the Obuasi mine by AGA. Obuasi alone accounts for 27.39 million ounces of the gold resource, and is expected to return to being a significant gold producer in the country by 2016. This is strengthened by the announcement on 16 September 2015 that AGA and Randgold Resources Limited (RRL) have entered into an agreement to form a joint venture (JV) to redevelop and operate the Obuasi gold mine (Anonymous, 2015). The JV has a high probability of being successful, as RRL has a good track record of profitable and efficient gold mining in West Africa.

Artisanal and small-scale mining

Artisanal and small-scale mining (ASM) was the only producer of gold in Ghana prior to the twentieth century (Griffis *et al.*, 2002). The GCM-ICMM report estimates that 36% (~1 Moz) of the total gold produced in Ghana in 2013 came from ASM, a significant amount. This type of mining activity provides a livelihood to many people in some poorly developed African countries, and is a significant job provider in Ghana. The estimated gold production of approximately 1 million ounces in 2013 from ASM is significantly higher than estimates in 2000 of approximately 146,000 ounces (Griffis *et al.*, 2002), indicating that this is a growing sector in Ghana's economy. The growing importance of the artisanal and small scale gold mining sector has also been illustrated by the shift of artisanal diamond miners to artisanal gold mining in recent years due to, among other reasons, decreasing industrial-scale diamond production in Ghana, the increasing cost of artisanal diamond mining due to stricter regulations on diamond production and export, as well as increasing gold prices from 2001 to 2011 (Nyame and Grant, 2012).

The socio-economic, legal and environmental impact of the artisanal and small scale gold miners in Ghana, have been significant. Socio-economic impacts include: the modest economic recovery of mining communities; the discovery of new gold deposits; the development of innovative ASM techniques; a net migration into mineral-rich regions; and increased security threats due to crime and police raids. The greatest legal impact has been attempts by Ghana's and other sub-Saharan African countries' governments, to formalise ASM (Nyame and Blocher, 2010). From an environmental point of view the increased use of mercury by artisanal miners for gold recovery is of great concern due to the associated environmental degradation (Nyame, 2010; Nyame and Grant, 2012; 2014).

Whether the recent level of informal production is sustainable is difficult to predict, but the fact that Ghana is richly endowed with many very small to world-class gold deposits strongly suggests that artisanal and small scale gold mining will form part of the Country's economy well into the future.

Acknowledgements

The Department of Geology at the University of Johannesburg, the Palaeoproterozoic Mineralisation Research Group (PPM) and the Department of Science and Technology (DST) and National Research Foundation (NRF) funded Centre of Excellence for Integrated Mineral and Energy Resource Analysis (CIMERA) are thanked for their funding and support. AngloGold-Ashanti, Stephane Perrouy and Nic Beukes are also thanked for providing photographs for this

contribution. Mike Robertson and Frank Nyame are thanked for their constructive reviews of this contribution.

References

- Adadey, K., Clarke, B., Théveniaut, H., Urien, P., Delor, C., Roig, J.Y. and Feybesse, J.L. (2009). Geological map explanation-Map sheet 0503 B (1:1 000 000), CGS/BRGM/Geoman. Geological Survey Department of Ghana (GSD), No MSSP/2005/GSD/5a.
- Addy, S.N. (1998). Ghana: revival of the mineral sector. *Resources Policy*, 24, 229-239.
- Affaton, P., Rahaman, M.A., Trompette, R. and Sougy, J. (1991). The Dahomeyide orogeny: tectonothermal evolution and relationships with the Volta Basin. In: Dallmeyer, R.D. and Lécroché, J.P. (Eds), *The West African Orogens and Circum-Atlantic Correlatives*, Springer-Verlag, New York, 107-122.
- Allibone, A.H., McCuaig, T.C., Harris, D., Etheridge, M.A., Munroe, S., Byrne, D., Amanor, J. and Gyapong, W. (2002a). Structural controls on gold mineralization at the Ashanti gold deposit, Obuasi, Ghana, *Society of Economic Geologists Special Publication* 9, 65-93.
- Allibone, A., Teasdale, J., Cameron, G., Etheridge, M., Uttley, P., Soboh, A., Appiah-Kubi, J., Adanu, A., Arthur, R., Mamphey, J., Odoo, B., Zuta, J., Tsikata, A., Pataye, F., Famiyeh, S. and Lamb, E. (2002b). Timing and structural controls on gold mineralization at the Bogoso Gold Mine, Ghana, West Africa. *Economic Geology*, 97, 949-969.
- Amponsah, P.O., Salvi, S., Béziat, D., Baratoux, L., Siebenaller, L., Nude, P.M., Nyarko, R.S. and Jessell, M.W. (2015a). The Bepkong gold deposit, Northwestern Ghana. *Ore Geology Reviews*, <http://dx.doi.org/10.1016/j.oregeorev.2015.06.022>.
- Amponsah, P.O., Salvi, S., Béziat, D., Siebenaller, L., Baratoux, L. and Jessell, M.W. (2015b). Geology and geochemistry of the shear-hosted Julie gold deposit, NW Ghana. *Journal of African Earth Sciences*, <http://dx.doi.org/10.1016/j.jafrearsci.2015.06.013>.
- AngloGold Ashanti (2014). Integrated Annual Report 2014. www.anglogoldashanti.com.
- Anonymous (2015). Groundbreaking partnership to revive Obuasi Gold Mine. <http://www.randgoldresources.com/groundbreaking-partnership-revive-obuasi-gold-mine>. Last accessed 20 October 2015.
- Arhin, E. (2013). Use of regolith geochemistry to delineate gold mineralization under cover: A case study in the Lawra Belt, NW Ghana. Unpublished PhD thesis, University of Leicester, 257pp.
- Aryee, B.N.A. (2001). Ghana's mining sector: its contribution to the national economy. *Resources Policy*, 27, 61-75.
- Attoh, K., Evans, M.J. and Bickford, M.E. (2006). Geochemistry of an ultramafic-rodignite rock association in the Paleoproterozoic Dixcove greenstone belt, southwestern Ghana. *Journal of African Earth Sciences*, 45, 333-346.
- Barning, K. (Ed) (1990). Symposium on gold exploration in tropical rain forest belts of Southern Ghana, Minerals Commission, Accra, 200pp.
- Berge, J. (2011). Paleoproterozoic, turbidite-hosted, gold deposits of the Ashanti gold belt (Ghana, West Africa): Comparative analysis of turbidite-hosted gold deposits and an updated genetic model. *Ore Geology Reviews*, 39, 91-100.
- Bermúdez-Lugo, O. (2004). The mineral industry of Ghana. In: U.S. Geological Survey Minerals Yearbook-2004, 20.1-20.5.
- Bermúdez-Lugo, O. (2011). The mineral industry of Ghana. In: U.S. Geological Survey Minerals Yearbook-2011, 20.1-20.6.

- Block, S., Ganne, J., Baratoux, L., Zeh, L., Parra-Avila, A., Jessell, M., Ailleres, L. and Siebenaller, L. (2015). Petrological and geochronological constraints on lower rocks crust exhumation during Paleoproterozoic (Eburnean) orogeny, NW Ghana, West African Craton. *Journal of Metamorphic Geology*, 33, 463-494.
- Bowell, R.J. (1992). Supergene gold mineralogy at Ashanti, Ghana: Implications for the supergene behaviour of gold. *Mineralogical Magazine*, 56, 545-560.
- Carranza, E.J.M., Owusu, E.A. and Hale, M. (2009). Mapping of prospectivity and estimation of number of undiscovered prospects for lode gold, southwestern Ashanti Belt, Ghana. *Mineralium Deposita*, 44, 915-938.
- Dampare, S.B., Shibata, T., Asiedu, D.K., Osa, S. and Banoeng-Yakubo, B. (2008). Geochemistry of Paleoproterozoic metavolcanic rocks from the southern Ashanti volcanic belt, Ghana: Petrogenetic and tectonic setting implications. *Precambrian Research*, 162, 403-423.
- Davis, D.W., Hirdes, W., Schaltegger, E. and Nunn, E.A. (1994). U-Pb age constraints on deposition and provenance of Birimian and gold-bearing Tarkwaian sediments in Ghana, West Africa. *Precambrian Research*, 67, 89-107.
- Eisenlohr, B.N. and Hirdes, W. (1992). Structural development of the early Proterozoic Birimian and Tarkwaian rocks of southwest Ghana, West Africa. *Journal of African Earth Sciences*, 14, 313-325.
- Ellis, A.B. (1893). *A History of the Gold Coast of West Africa*, Chapman and Hall, London, 400pp.
- Ghana Chamber of Mines (2013). Performance of the mining industry in 2013, 10pp. Available at ghanachamberofmines.org/media/publications.
- Els, B.G. (1991). Placer formation during progradational fluvial degradation: the late Archean Middelvllei gold placer, Witwatersrand, South Africa. *Economic Geology*, 86, 261-277.
- Endeavour Mining (2015). Website: <http://www.endeavourmining.com/s/Nzema.asp>. Last accessed 26 August 2015.
- Ennih, N. and Liégeois, J.-P. (2008). The boundaries of the West African craton, with special reference to the basement of the Moroccan metacratonic Anti-Atlas belt. In: Ennih, N. and Liégeois, J.-P. (Eds.), *The Boundaries of the West African Craton*, Geological Society, London, Special Publications, 297, 1-17.
- Feybesse, J.-L., Billa, M., Guerrot, C., Duguey, E., Lescuyer, J.-L., Milesi, J.-P. and Bouchot, V. (2006). The Paleoproterozoic Ghanaian province: Geodynamic model and ore controls, including regional stress modeling. *Precambrian Research*, 149, 149-196.
- Fougerouse, D., Micklethwaite, S., Miller, J., McCuaig, T.C. and Ulrich, S. (2013). Multistage mineralization of the giant Obuasi gold deposit, Ghana. In: *Mineral Deposit Research for a High-Tech World, 12th SGA Biennial Meeting 2013, Proceedings volume 3*, 1105-1108.
- Fougerouse, D., Micklethwaite, S., Miller, J., Ulrich, S. and McCuaig, T.C. (2015). The Obuasi gold deposit, Ghana: A West African giant. *Ore Geology Reviews*, <http://dx.doi.org/10.1016/j.oregeorev.2015.06.019>.
- Frimmel, H.E. and Minter, W.E.L. (2002). Recent developments concerning the geological history and genesis of the Witwatersrand gold deposits, South Africa. In: Goldfarb, R.J. and Nielsen, R.L. (Eds.), *Integrated Methods for Discovery: Global Exploration in the Twenty-First Century*, Society of Economic Geologists, Littleton, Special Publication vol. 9, 17-45.
- Ghana Chamber of Mines (2014). Report on the performance of the mining industry (2014), 22pp. Available at ghanachamberofmines.org/media/publications.
- Ghana Chamber of Mines (GCM) and the International Council on Mining & Metals (ICMM) (2015). Mining in Ghana – What future can we expect? Report published jointly by the GCM and ICMM, Accra and London, 70pp. Available from www.icmm.com.
- Gold Fields Limited (2015). Annual Report 2014. www.goldfields.co.za.
- Golden Star Resources (2015). Website: <http://www.gsr.com/operations/reserves-and-resources/default.aspx>. Last accessed 26 August 2015.
- Griffis, R.J. (1998). Explanatory notes – geological interpretation of geophysical data from southwestern Ghana, Minerals Commission, Accra, 51pp.
- Griffis, R.J. and Agezo, F.L. (2000). Mineral Occurrences and Exploration Potential of Northern Ghana, Minerals Commission Report, Accra, 132pp.
- Griffis, R.J., Barning, K., Agezo, F.L. and Akosah, F.K. (2002). Gold deposits of Ghana, Minerals Commission, Accra, 432pp.
- Hayward, C.L., Reimold, W.U., Gibson, R.L. and Robb, L.J. (2005). Gold mineralization within the Witwatersrand Basin, South Africa: evidence for a modified placer origin, and the role of the Vredefort impact event. In: McDonald, I., Boyce, A.J., Herrington, R.J. and Polya, D.A. (Eds.), *Mineral Deposits and Earth Evolution*, Geological Society, London, Special Publications, 248, 31-58.
- Hilson, G. (2002). Harvesting mineral riches: 1000 years of gold mining in Ghana. *Resources Policy*, 28, 13-26.
- Hirdes, W. and Nunoo, B. (1994). The Proterozoic paleoplacers at Tarkwa Gold Mine, SW Ghana: sedimentology, mineralogy, and precise age dating of the main reef and west reef, and bearing of the investigations on source area aspects. *Geologische Jahrbuch, Reihe D*, 100, 247-311.
- Hirdes, W., Davis, D.W. and Eisenlohr, B.N. (1992). Reassessment of Proterozoic granitoid ages in Ghana on the basis of U/Pb zircon and monazite dating. *Precambrian Research*, 56, 89-96.
- Hirdes, W., Senger, R., Adjei, J., Efa, E., Loh, G. and Tettey, A. (1993). Explanatory notes for the geological map of southwest Ghana – 1:100,000 (Wiawso, Asafo, Kukuom, Sunyani and Berekum sheets). *Geologische Jahrbuch, Reihe B*, 83, 139pp.
- Hoffman, P.F. (1999). The break-up of Rodinia, birth of Gondwana, true polar wander and the snowball Earth. *Journal of African Earth Sciences*, 28, 17-33.
- Höndorf, A., Oberthür, T., Gast, L., Vetter, D. and Schmidt Mumm, A. (1994). Lead isotope systematics of the mineralisation at the Ashanti gold mine, Obuasi, Ghana. *Geologische Jahrbuch, D100*, 155-166.
- Illife, J. (1995). *Africans – The History of a Continent*, Cambridge University Press, Cambridge, 323pp.
- John, T., Klemd, R., Hirdes, W. and Loh, G. (1999). The metamorphic evolution of the Paleoproterozoic (Birimian) volcanic Ashanti Belt (Ghana, West Africa). *Precambrian Research*, 98, 11-30.
- Junner, N.R. (1935). Gold in the Gold Coast, Gold Coast Geological Survey Memorandum no. 4, Accra, 67pp.
- Junner, N.R. (1940). Geology of the Gold Coast and Western Togoland with Revised Geological Map, Gold Coast Geological Survey Bulletin no. 11, Accra, 40pp.
- Junner, N.R., Hirst, T. and Service, H. (1942). The Tarkwa Goldfield. *Gold Coast Geological Survey Memoirs*, 4, 75pp.
- Kenworthy, S., Noormohamed, K., Stuart, H. and Hodkiewicz, P. (2000). Mapping and 3D modelling of structural controls in the Chorano gold deposits, Ghana: keys to better resource delineation and near-mine exploration targetting. *Proceedings of the Seventh International Mining Geology Conference 2009*, The Australian Institute of Mining and Metallurgy, Melbourne, 101-108.
- Kesse, G.O. (1984). The occurrence of gold in Ghana. In: Foster, R.P. (Ed), *Gold '82: The geology, geochemistry and genesis of*

- gold deposits, Balkema, Rotterdam, 645-659.
- Kesse, G.O. (1985). The Mineral and Rock Resources of Ghana, Balkema Publishers, Rotterdam, 610pp.
- Kesse, G.O. (1990). An overview of gold resources in Ghana. In: Barning, K. (Ed.), Symposium on gold exploration in tropical rain forest belts of southern Ghana, Minerals Commission, Accra, 3-11.
- Kiessling, R. (1997). Sedimentation and structure in the Tarkwaian Group of the Bui Basin in West-Ghana. In: Zitzmann (Ed), Geological, Geophysical and Geochemical Investigations in the Bui Belt Area in Ghana, Geologische Jahrbuch, Reihe B, 88, 269pp.
- Kinross Gold Corporation (2015). Website: <http://www.kinross.com/operations/operation-chirano-ghana.aspx>. Last accessed 26 August 2015.
- Klemd, R., Hirdes, W., Olesch, M. and Oberthür, T. (1993). Fluid inclusions in quartz-pebbles of the gold-bearing Tarkwaian conglomerates of Ghana as guides to their provenance area. *Mineralium Deposita*, 28, 334-343.
- Kuma, J.S., Kim, Y.U., Boamah, D. and Sakamoto, I. (2010). Gold potential of the Ashanti Belt of Ghana. *Journal of The School of Marine Science and Technology, Tokai University*, 8, 25-39.
- Kwang, C., Ossei, E.M. Jnr. and Duker, A.A. (2014). Application of remote sensing and geographic information systems for gold potential mapping in Birim North District of eastern region of Ghana. *International Journal of Remote Sensing Applications*, 4, 48-55.
- Leube, A., Hirdes, W., Mauer, R. and Kesse, G.O. (1990). The early Proterozoic Birimian Supergroup of Ghana and some aspects of its associated gold mineralization. *Precambrian Research*, 46, 139-165.
- Loh, G., Hirdes, W., Anani, C., Davis, D.W. and Vetter, U. (1999). Explanatory notes for the geological map of southwest Ghana 1:100,000. *Geologische Jahrbuch, Reihe B*, 93, 150pp.
- Magalhães, L.A. and Filho, C.R.S. (2012). Targeting of gold deposits in Amazonian exploration frontiers using knowledge- and data-driven spatial modeling of geophysical, geochemical and geological data. *Surveys in Geophysics*, 33, 211-241.
- Manu, J., Hayford, E.K., Anani, C., Sakyi, P.A., Kutu, J.M. and Armah, T.E.K. (2013). Aspects of the chemical composition of the Birimian gold fluid. *Journal of Earth Sciences and Geotechnical Engineering*, 3, 87-106.
- Milési, J.P., Ledru, P., Ankrah, P., Johan, V., Marcoux, E. and Vinchon, Ch. (1991). The metallogenic relationship between Birimian and Tarkwaian gold deposits in Ghana. *Mineralium Deposita*, 26, 228-238.
- Milési, J.P., Ledru, P., Feybesse, J.L., Dommange, A. and Marcoux, E. (1992). Early Proterozoic ore deposits and tectonics of the Birimian orogenic belt, West Africa. *Precambrian Research*, 58, 305-344.
- Mumin, A.H. and Fleet, M.E. (1995). Evolution of gold mineralization in the Ashanti Gold Belt, Ghana: evidence from carbonate compositions and parageneses. *Mineralogy and Petrology*, 55, 265-280.
- Mumin, A.H., Fleet, M.E. and Chrysosoulis, S.L. (1994). Gold mineralization in As-rich mesothermal gold ores of the Bogoso-Prestea mining district of the Ashanti Gold Belt, Ghana: remobilization of "invisible" gold. *Mineralium Deposita*, 29, 445-460.
- Mumin, A.H., Fleet, M.E. and Longstaffe, F.J. (1996). Evolution of hydrothermal fluids in the Ashanti Gold Belt, Ghana: Stable isotope geochemistry of carbonates, graphite, and quartz. *Economic Geology*, 91, 135-148.
- Nédélec, A., Affaton, P., Grance-Lanord, C., Charrière, A. and Alvaro, J. (2007). Sedimentology and chemostratigraphy of the Bwipé Neoproterozoic cap dolostones (Ghana, Volta Basin): A record of microbial activity in a peritidal environment. *C.R. Geoscience*, 339, 223-239.
- Newmont (2015). Newmont Reserves and Resources as of December 31, 2014. Downloaded from: www.newmont.com/files/doc_downloads/reserves_and_resources/Reserves-Resources-for-Posting_Final.pdf on 26 August 2015.
- Nude, P.M. and Arhin, E. (2009). Overbank sediments as appropriate geochemical sample media in regional stream sediment surveys for gold exploration in the savannah regions of northern Ghana. *Journal of Geochemical Exploration*, 103, 50-56.
- Nyame, F.K. (2010). Policy challenges on mercury use in Ghana's artisanal and small-scale mining sector. *International Journal of Environment and Pollution*, 41, 202-213.
- Nyame, F.K. (2013). Origins of Birimian (ca 2.2 Ga) mafic magmatism and the Paleoproterozoic 'greenstone belt' metallogeny: a review. *Island Arc*, 22, 538-548.
- Nyame, F.K. and Blocher, J. (2010). Influence of land tenure practices on artisanal mining activity in Ghana. *Resources Policy*, 35, 47-53.
- Nyame, F.K. and Grant, J.A. (2012). From carats to karats: explaining the shift from diamond to gold mining by artisanal miners in Ghana. *Journal of Cleaner Production*, 29-30, 163-172.
- Nyame, F.K. and Grant, J.A. (2014). The political economy of transitory mining in Ghana: Understanding the trajectories, triumphs, and tribulations of artisanal and small-scale operators. *The Extractive Industries and Society*, 1, 75-85.
- Oberthür, T., Vetter, U., Schmidt Mumm, A., Weiser, T., Amanor, J.A., Gyapong, W., Kumi, R. and Blenkinsop, T.G. (1994). The Ashanti gold mine at Obuasi, Ghana: Mineralogical, geochemical, stable isotope and fluid inclusion studies on the metallogenesis of the deposit. *Geologisches Jahrbuch D*, 100, 31-129.
- Oberthür, T., Hirdes, W., Höndorf, A., Schmidt Mumm, A., Vetter, U., Weiser, T., Davis, D.W., Blenkinsop, T.G., Amanor, J.A. and Loh, G. (1995). A review of gold mineralisation in the Ashanti Belt of Ghana and its relation to the crustal evolution of the terrane. *Communications of the Geological Survey of Namibia*, 10, 121-127.
- Oberthür, T., Weiser, T., Amanor, J.A. and Chrysosoulis, S.L. (1997). Mineralogical siting and distribution of gold in quartz veins and sulfide ores of the Ashanti mine and other deposits in the Ashanti belt of Ghana: genetic implications. *Mineralium Deposita*, 32, 2-15.
- Oberthür, T., Vetter, U., Davis, D.W. and Amanor, J.A. (1998). Age constraints on gold mineralization and Paleoproterozoic crustal evolution in the Ashanti belt of southern Ghana. *Precambrian Research*, 89, 129-143.
- Owusu, E.A., Woldai, T., Barritt, S., Carranza, E.J.M. and Hale, M. (2006). Spatial association of gold deposits with remotely-sensed faults, south Ashanti Belt, Ghana. Conference: 6th AARSE international conference on earth observation and geoinformation sciences in support of Africa's development. Volume: ISBN 1-920-01710-0. 8 p. Downloadable at: http://www.researchgate.net/profile/Tsehaie_Woldai/publication/233791624_Spatial_association_of_gold_deposits_with_remotely_sensed_faults_South_Ashanti_belt_Ghana/links/0deec5252acd158475000000.pdf.
- Parra-Avila, L.A., Bourassa, Y., Miller, J., Perrouy, S., Fiorentini, M.L. and McCuaig, T.C. (2015). Age constraints of the Wassa and Benso Mesothermal Gold Deposits, Ashanti Belt, Ghana, West Africa. *Journal of African Earth Sciences*, <http://dx.doi.org/10.1016/j.jafrearsci.2015.05.017>.

- Perrouy, S., Aillères, L., Jessell, M.W., Baratoux, L., Bourassa, Y. and Crawford, B. (2012). Revised Eburnean geodynamic evolution of the gold-rich southern Ashanti Belt, Ghana, with new field and geophysical evidence of pre-Tarkwaian deformations. *Precambrian Research*, 204-205, 12-39.
- Perrouy, S., Lindsay, M.D., Jessell, M.W., Aillères, L., Martin, R. and Bourassa, Y. (2014). 3D modeling of the Ashanti Belt, southwest Ghana: Evidence for a litho-stratigraphic control on gold occurrences within the Birimian Sefwi Group. *Ore Geology Reviews*, 63, 252-264.
- Perrouy, S., Jessell, M.W., Bourassa, Y., Miller, J., Apau, D., Siebenaller, L., Velásquez, G., Baratoux, L., Aillères, L., Béziat, D. and Salvi, S. (2015). The Wassa deposit: A poly-deformed orogenic gold system in southwest Ghana – Implications for regional exploration. *Journal of African Earth Sciences*, <http://dx.doi.org/10.1016/j.jafrearsci.2015.03.003>.
- Perseus Mining Limited (2015). Website: http://www.perseusmining.com.au/reserves_and_resources.66.html. Last accessed 26 August 2015.
- Petters, S.W. (1991). *Regional Geology of Africa*, Springer-Verlag, Berlin, 722pp.
- Pigois, J.-P., Groves, D.I., Fletcher, I.R., McNaughton, N.J. and Snee, L.W. (2003). Age constraints on Tarkwaian palaeoplacer and lode-gold formation in the Tarkwa-Damang district, SW Ghana. *Mineralium Deposita*, 38, 695-714.
- Porter, S.M., Knoll, A.H. and Affaton, P. (2004). Chemostratigraphy of Neoproterozoic cap carbonates from the Volta Basin, West Africa. *Precambrian Research*, 130, 99-112.
- Porwal, A. and Carannza, E.J.M. (2015). Introduction to the Special Issue: GIS-based mineral potential modelling and geological data analyses for mineral exploration. *Ore Geology Reviews*, 71, 477-483.
- Robb, L.J. (2005). *Introduction to Ore-forming Processes*, Blackwell, Malden, 373pp.
- Robb, L.J., Charlesworth, E.G., Drennan, G.R., Gibson, R.L. and Tongu, E.L. (1997). Tectono-metamorphic setting of the paragenetic sequence of the Au-U mineralisation in the Archaean Witwatersrand Basin, South Africa. *Australian Journal of Earth Sciences*, 44, 353-371.
- Robert, F., Brommecker, R., Bourne, B.T., Dobak, P.J., McEwan, C.J., Rowe, R.R. and Zhou, X. (2007). Models and explorations methods for major gold deposit types. In: Milkereit, B. (Ed), *Proceedings of Exploration 07: Fifth Decennial International Conference on Mineral Exploration, Decennial Mineral Exploration Conferences*, Toronto, 691-711.
- Sestini, G. (1973). Sedimentology of a paleoplacer: the gold bearing Tarkwaian of Ghana. In: Amstutz, G.C. and Bernard A.J. (Eds), *Ores in Sediments*, Springer-Verlag, Heidelberg, 275-303.
- Sibson, R.H., Moore, J. McM. and Rankin, A.H. (1975). Seismic pumping – a hydrothermal fluid transport mechanism. *Journal of the Geological Society of London*, 131, 653-659.
- Sibson, R.H., Robert, F. and Poulsen, K.H. (1988). High-angle reverse faults, fluid-pressure cycling, and mesothermal gold-quartz deposits. *Geology*, 16, 551-555.
- Stokes, R.S.G. (1908). *Mines and Minerals of the British Empire*, Edward Arnold, London, 403pp.
- Strogen, P. (1991). The sedimentology, stratigraphy and structure of the Tarkwaian, western region, and its relevance to gold exploration and development. In: Kesse, G.O. (Ed), *Proceedings of the International Conference on the Geology of Ghana*, Geological Society of Ghana, Accra, 3, R1-R39.
- Sylvester, P.J. and Attoh, K. (1992). Lithostratigraphy and composition of 2.1 Ga greenstone belts of the West African craton and their bearing on crustal evolution and Archean-Proterozoic boundary. *Journal of Geology*, 100, 377-393.
- Tsiboah, T. and Grant, T. (2009). Application of geophysics to gold explorations in Ghana: examples from Newmont projects. *ASEG Extended Abstracts*, 2001(1), 1-5. Full text doi:10.1071/ASEG2009 ab089.
- Tsikata, F.S. (1997). The vicissitudes of mineral policy in Ghana. *Resources Policy*, 1997, 9-14.
- Tunks, A.J., Selley, D., Rogers, J.R. and Brabham, G. (2004). Vein mineralization at the Damang Gold Mine, Ghana: controls on mineralization. *Journal of Structural Geology*, 26, 1257-1273.
- Ward, W.E.F. (1967). *A History of Ghana* (4th ed), George Allen and Unwin, London, 454pp.
- Wemegah, D.D., Preko, K., Noye, R.M., Boadi, B., Menyeh, A., Danuor, K. and Amenyoh, T. (2015). Geophysical interpretation of possible gold mineralization zones in Kyerano, south-western Ghana using aeromagnetic and radiometric datasets. *Journal of Geosciences and Environmental Protections*, 3, 67-82.
- Wright, J.B., Hastings, D.A. and Jones, W.B. (1985). *Geology and Mineral Resources of West Africa*, G. Allen and Unwin, London, 187pp.
- Yao, Y. and Robb, L.J. (1998). The Birimian granitoids of Ghana: A review. *Economic Geology Research Unit (EGRU)*, University of Witwatersrand, Information Circular 322, 46pp.
- Yao, Y. and Robb, L.J. (1999). Gold mineralization associated with Birimian granitoids of Ghana. Final report to Goldfields of South Africa (unpubl.), University of Witwatersrand, Johannesburg, 247pp.
- Yao, Y. and Robb, L.J. (2000). Gold mineralization in Paleoproterozoic granitoids at Obuasi, Ashanti region, Ghana: Ore geology, geochemistry and fluid characteristics. *South African Journal of Geology*, 103, 255-278.
- Yao, Y., Murphy, P.J. and Robb, L.J. (2001). Fluid characteristics of granitoid-hosted gold deposits in the Birimian Terrane of Ghana: A fluid inclusion microthermometric and Raman spectroscopic study. *Economic Geology*, 96, 1611-1643.

Bertus Smith is a senior lecturer in the Department of Geology at the University of Johannesburg where he has been teaching and researching full-time since 2008. He is also involved as a researcher and student supervisor with the PPM Research Group and the South African Department of Science and Technology – National Research Foundation's Centre of Excellence for Integrated Mineral and Energy Resources Analysis (DST-NRF CIMERA) at the University of Johannesburg. His main research interests are economic geology, early Earth surface paleoenvironments and process mineralogy.

Susan Frost-Killian is a senior research geologist with The MSA Group (Pty) Ltd in Johannesburg, South Africa. She has almost twenty years professional experience covering: commodity, geological, and country research; metallogenic and prospectivity mapping; GIS; mineral assessments; technical editing and providing assistance with the compilation and submission of Competent Persons Mineral Resource Estimates, Scoping and Pre-Feasibility technical reports and due diligence reviews. Her experience covers regional and country specific projects in Africa, collaborative projects with African geological surveys, India, the United States, and some countries within the European Union, and country reports (minerals, geology, etc.) for various countries (global).

George Henry is the Administrative Manager of the South African Department of Science and Technology – National Research Foundation's Centre of Excellence for Integrated Mineral and Energy Resources Analysis (DST-NRF CIMERA) hosted at the University of Johannesburg and co-hosted at the University of the Witwatersrand. He has had a varied career in both industry and academia, having worked for Randgold Resources after doctoral graduation, the Council for Geoscience, and the Council for Industrial and Scientific Research, amongst others. He is interested in economic and exploration geology, and the origin of mineral deposits.