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

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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 main 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 Super group-hosted quartz vein gold mineralisation, but with a larger \( \text{H}_2\text{O} \) 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
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
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 2016).
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 northwest 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 Birimian Supergroup is discussed and reviewed by John et al. (1999) and Griffis et al. (2002). A more recent stratigraphic subdivision of the Birimian Supergroup proposed by Adadey et al. (2002) divides it into: the Sefwi Group composed of mica schists and metavolcanics; and the Kumasi Group composed of metasediments 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 (Perroux 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 dactitic and rhydodacitic 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); volcanioclastic/argillite facies (proximal to volcanic ridges); argillite/volcaniclastic 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 Sunnyari 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; Perroux 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
interbedded quartzites and phyllites, intruded by minor dolerite sills (Kesse, 1985; Strogen, 1991; Griffis et al., 2002; Pigois et al., 2003; Perrouty 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 predominately 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 zircons from the Kawere Group and Banket Series (Davis et al., 1994; Hirdes and Nunoo, 1994; Pigois et al., 2003; Perrouty et al., 2012), although Perrouty 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 (Perrouty 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
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 volcanioclastics (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 (Perroud 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 Super group; 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 Eoeburnean, 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 Eoeburnean 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 D91, D92, D93) have been identified in the Wa-Lawra Belt in northwestern Ghana (Block et al., 2015; Amponsah et al., 2015a): the D91 event, which was caused by north-south crustal compression; the D92 event, which is characterised by north-south extension and exhumation of high grade terranes; and the D93 event, which is characterised by steeply dipping northeast-, north- and northwest-trending shear zones. The July deposit, located in the July Belt in northwestern Ghana, also shows three deformational events (D11-D13), where D11 and D12 correspond to the D91 and D92 events in the Wa-Lawra Belt respectively (Amponsah et al., 2015b). The D13 event is characterised by northeast- to southwest-orientated brittle faulting (Amponsah et al., 2015b).

The D91 and D92 events in the Wa-Lawra Belt and D11 event in the July Belt likely correspond to the D1 and D2 events in the Ashanti Belt. The D93 event in the Wa-Lawra and the D12 event in the July Belts show similarities to the D3 and D4 events of the Ashanti Belt. The D13 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 palaeplacer 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., 2002; Kuma et al., 2010; Fougerouse 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 common 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, Bogoso, 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; Fougerouse 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 (Milési 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

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*June 2016*
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 Total resource | References |
|-----------------|----------|----------------------|------------------------|------------|
|                 |          |                      | grades estimates (recent and/or past) |            |
| Atewa Range     | Kibi-Winneba Belt | Southeastern Ghana, near the town of Kibi | Mesothermal vein type | NA | NA | Griffiths et al. (2002) |
|                 | Winneba-Mumford Area | Southern extension of Kibi-Winneba Belt | Mesothermal vein type; Palaeoplacer type | ~0.5-1.0 g/t | NA | Griffiths et al. (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 | Griffiths et al. (2002) |
|                 | Anwia     | Southern Ashanti Belt, ~15 km north-west of Accra, 1.5 km north of Nkroful, Kumasi Basin | Mesothermal vein type | ~1.3 g/t | ~0.15 Moz | Griffiths et al. (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 | Griffiths et al. (2002) |
|                 | Benso     | Eastern limb of Ashanti Belt, ~38 km southwest of Wassa deposit | Mesothermal vein type | NA | NA | Parra-Avila et al. (2015) |
|                 | Besease   | 7 km west of Nkawkaw, northeast cover of Ashanti Belt | Mesothermal vein type, alluvial | ~4.7 g/t | ~0.2 Moz | Griffiths et al. (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 et al. (1994); Oberthür et al. (1997); Griffiths et al. (2002); Allibone et al. (2002) |
|                 | Dabokrom  | 15 km northwest of Tokaradi | Mafic-hosted mineralisation | ~3-15 g/t | ~0.7 Moz | Griffiths et al. (2002) |
|                 | Damang    | Southern Ashanti Belt, ~20 km northeast of Tarkwa. | Mesothermal vein type; Palaeoplacer type | ~1.3-2.2 g/t | ~5 Moz Au | Griffiths et al. (2002); Pigois et al. (2003); Tunks et al. (2004) |
|                 | Golden Ridge | 130 km northwest of Accra, northeastern margin of Ashanti Belt | Mesothermal vein type | NA | NA | Griffiths et al. (2002) |
|                 | Iduapriem | Southern end of Tarkwa district, southern hill of Tarkwa syncline | Palaeoplacer type | ~1.2-1.7 g/t | ~2 Moz Au | Griffiths et al. (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 et al. (1997); Griffiths et al. (2002) |
|                 | Kubi      | Western margin of Ashanti Belt, 6 km northeast of Dunkwa | Mesothermal vein type | ~6g/t | ~0.8 Moz | Griffiths et al. (2002) |
|                 | Mampon-Aboronye | 20 km southwest of Dunkwa, western flank of Ashanti Belt | Mesothermal vein type | ~5.5 g/t | ~0.4 Moz | Griffiths et al. (2002) |
|                 | Nkran Hill | 40 km west-northwest of Obuasi | Mesothermal vein type; Granitoid type | ~2.2 g/t | >2.5 Moz Au | Griffiths et al. (2002) |
|                 | Nkroful   | 15 km northwest of Axim, west of Ashanti Belt, Kumasi Basin | Mesothermal vein type, alluvial | <4 g/t | NA | Griffiths et al. (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 et al. (1990); Oberthür et al. (1997); Osae et al. (1999); Yao and Robb (2000); Fougerousse et al. (2015) |
|                 | Prestea   | Southwestern Ghana, 60-90 km northeast of Atlantic coastline | Mesothermal vein type | ~3.4 g/t | >7.2 Moz Au | Mumin et al. (1994); Oberthür et al. (1997) |
|                 | Salman    | 15 km north of Axim, western boundary of Ashanti Belt | Mesothermal vein type | ~1.6-2.3 g/t | ~1.2 Moz | Griffiths et al. (2002) |
Table 1 contd...

| Name of deposit | Location | Mineralisation types | Average grades estimates (recent and/or past) total resource | 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 et al. (2002); Pigois et al. (2003); |
| Teberbie        | Western ridge of Tarkwa syncline | Palaeoplacer type | ~2.0-2.4 g/t ~2 Moz Au | Griffis et al. (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 et al. (2015); Perrouty et al. (2015) |
| Abore North     | Asankrangwa Belt 45 km southwest of Kumasi; Asankrangwa Belt | Mesothermal vein type; Granitoid type | ~2 g/t ~0.3 Moz | Griffis et al. (2002) |
| Mpeasem         | Western side of Ofin River, Asankrangwa Belt | Mesothermal vein type | ~2.5 g/t ~0.8 Moz | Griffis et al. (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 et al. (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 et al. (2002) |
| Ntotoroso       | 30 km south of Sunyani, Sefwi Belt | Mesothermal vein type; Granitoid type | ~2.3 g/t ~1.4 Moz | Griffis et al. (2002) |
| Yamfo-Kenyase    | South of Sunyani, Sefwi Belt | Mesothermal vein type; Granitoid type | ~3 g/t ~6.2 Moz | Griffis et al. (2002) |
| Brohani         | Bui Belt Central western Ghana | Palaeoplacer type | >1 g/t NA | Griffis et al. (2002) |
| Dokrupe         | Bole-Navrongo Belt Southern margin of Bole-Navrongo Belt | Mesothermal vein type | ~2.8 g/t ~0.18 Moz | Griffis et al. (2002) |
| Bepkong         | Wa-Lawra Belt Northwestern Ghana, Wa-Lawra Belt | Mesothermal vein type | ~1.8 g/t ~0.1 Moz | Amponsah et al. (2015a) |
| Julie           | Julie Belt Northwestern Ghana, Julie Belt | Granitoid type | ~1.5 g/t ~0.8 Moz | Amponsah et al. (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 Wass; 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 Wass. 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 Wass (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; Griffiths 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).](image-url)
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 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, Ntoro, 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 discordant 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).

**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).**

**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, 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 payhosts, 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 submicroscopic 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 Ga 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 (Höhndorf 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; Perrouy et al., 2012), which is reconcilable with D2 (pre-Eburneans) disseminated sulphide- and D3 (Eburneans) 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 (Perrouy 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; Fougerouse et al., 2015; Perroux et al., 2015). However, examples of quartz vein free gold ores associated with the Eoeburnean D1 compressional event are also encountered (Perroux 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; Fougerouse 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 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 suggest 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 palaeocontact 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 palaeoplacers (Perroux 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 Ma. 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
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 northern 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; Perroux et al., 2012; 2014; Fougerousse 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 (Porwol 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 Perroux et al. (2014). Building on 2D remapping and re-interpretation
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 present and possible future contributions to the Ghanaian economy and society.

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**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.**

| 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 Idiapriem | 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 been taken over by Endeavour Mining.
(2) Annual output for 2013 from the GCM-ICMM Report, 2015.

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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 Blobcher, 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.

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