Lake Victoria Goldfields

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After a period of relative dormancy, the Lake Victoria Goldfields (LVG) in Tanzania, Kenya and Uganda have emerged as an important site for gold mining and exploration in Africa. The Neoarchaean greenstone belts of the LVG are composed mainly of "Nyanzian" meta-volcanic sequences overlain by younger "Kavirondian" clastic metasedimentary strata. Intermediate to felsic plutonic rocks include local, older syn-volcanic bodies and an extensive suite of late, circa 2650-2640 Ma potassic (K)-granitoids, which substantially invade and disrupt the greenstone belts. Gold deposits are widely distributed but particularly concentrated in three belts: Sukumaland, Musoma-Mara and Busia-Kakamega. Many deposits are simply composed of quartz veins in shear zones and fractures in the Nyanzian host rocks (e.g. Bulyanhulu, Buck Reef and Rosterman). Buzwagi and Nyabirama are composed of quartz vein arrays within intrusions. Several are hosted by folded banded iron-formation (Geita, Golden Ridge, Tulawaka, and Nyanzaga). Nyanzaga, however, is a discordant pipe shaped stockwork containing dolomite, silica and sulphides as open-space fill in high level veins. Gokona-Nyabigena at North Mara is closely associated with porphyritic volcanic and sub-volcanic intrusive rocks and is noted for stockwork-disseminated mineralisation and extreme K-feldspar alteration. Field evidence points to a relatively late, syn-orogenic timing for the majority of the deposits irrespective of style. Most deposits were discovered and exploited in colonial times but many have been expanded considerably by modern exploration. Improved geological knowledge has resulted from this private sector exploration using high-resolution aeromagnetic, electromagnetic and radiometric surveys, followed up by regolith and outcrop mapping and systematic drill testing of large areas (rotary air blast (RAB), reverse circulation (RC), aircore and diamond drill core). Lithogeochemistry and geochronological studies have been carried out by several companies in support of their regional exploration programmes. The LVG is now considered mature from an exploration point of view, so future developments will require the investigation of vein deposits to greater depth and/or the discovery of additional examples of the lower grade stockwork-disseminated styles which may have been overlooked during the early rounds of exploration.

Introduction

Little was known about the gold potential of East Africa when the British and German colonial powers took possession of what are now Uganda, Kenya and Tanzania. Unlike Egypt, West Africa and Southern Africa, where gold played an important role in the economies of highly developed Iron Age cultures and where gold had been systematically mined for centuries, it appears the pastoral societies of East Africa historically showed little interest in gold.This was in spite of the presence of prolific greenstone belts (Figure 1 and 2) of the LVG, where outcrops of gold bearing rocks were locally plentiful.

Apart from the 1922 alluvial gold rush to the Lupa Goldfield (Figure1) it was only in the mid-1930s, when the United States Gold Reserve Act of 1934 resulted in a steep increase in the gold price, that interest in the gold mining industry was revived with major companies entering the field. In the late-1930s three gold mines dominated gold production in the LVG, namely Kiabakari, Buhemba and Geita (Figure 2), all located in what was then called Tanganyika Territory. While there was a plethora of small scale mining operations in Kenya, only the Rosterman Mine had a significant output of more than 250,000 ounces during its life span (1935-1952). The Ugandan portion of the LVG has seen limited mining and it is estimated that not more than 30,000 to 45,000 ounces were produced in the Busia district from 1937 to 1952.

Annual production of gold from the LVG reached a peak of more than 150,000 ounces in 1941 but by the 1950s smaller gold mines became unprofitable and closed. Tanzanian independence in 1961 saw a change in policy as agriculture was seen as a preferred foundation for national economic growth. By 1970 Buhemba, the last of the major mines, closed its mill and in 1972 commercial gold mining in the country stopped officially. While unofficial artisanal mining still thrived it took a dramatic change in government's economic policies to attract international capital back into mining. By the 1980s a number of international companies had re-started exploration activities in Tanzania, but it was the 1998 Mining Act that created an environment conducive for exploration, mining and international investment. The Kenyan and Ugandan parts of the LVG, although relatively under explored and having demonstrated past production, were considered to be of little interest to mining investors. To this date only two small gold mines, Kilimapesa and Kerebe, are operational in Kenya. Tanzania, however, saw a major influx of
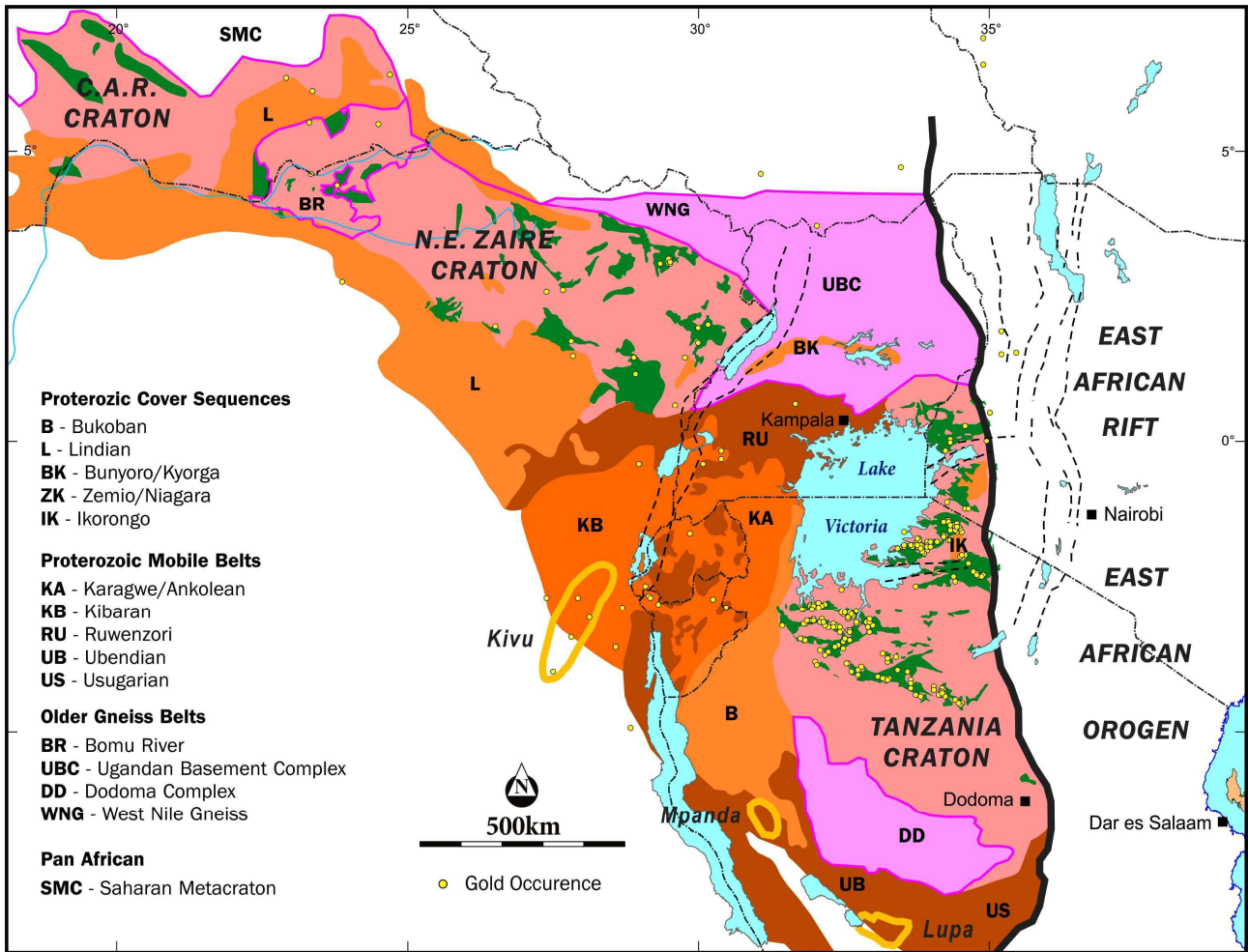
Figure 1: Geological setting of the Lake Victoria Goldfield within the eastern Congo Craton. The Proterozoic goldfields of Lupa, Mpanda and Kivu are identified but not discussed further in the text. Proterozoic cover sequences: B-Bukoban; L-Lindian; BK-Bunyoro/Kyorga; ZK-Zemio/Niagara; IK-Ikorongo. Proterozoic mobile belts: KA- Karagwe/Ankolean, KB-Kibaran; RU-Ruwenzori; UB-Ubendian; US: Usugarian. Older Gneissic belts: BR-Bomu River; UBC-Ugandan Basement Complex; DD: Dodoma Complex; WNG: West Nile Gneiss; Pan-African: SMC: Saharan Metacraton.

explorers and in 1999, Golden Pride was the first successful commercial mine to open in the post-colonial era. In quick succession another four mines came on stream, Geita (2000), Bulyanhulu (2001), North Mara (2002) and Tulawaka (2004). Buzwagi mine put its first ore through the mill in 2009. Gold production saw a dramatic rise from approximately 10,000 ounces in 1997 to a peak of 1.68 million ounces in 2005.

Discovery and Early History of the Mineral Field

The early phase of mining history of the LVG started with the colonial era and ended in 1970 when the last commercial mine closed in Tanzania.

In the former German East Africa, now Tanzania, systematic exploration started when the *Central Afrikanische Bergwerksgesellschaft* (CABG) was founded. Significant gold mineralisation was identified in 1906 at Sekenke within what is now known as the Sekenke-Iramba greenstone belt (Figure 2) and the first commercial gold mine in East Africa started production there in July

1909 (Figure 3). At the outbreak of World War I (WW I) a total of six mining companies were active in German East Africa (including Burundi and Rwanda) but Sekenke was the only significant producer. Total gold production at Sekenke from 1909 to 1915 was approximately 40,000 ounces at a grade of 34.6 g/t but ceased in 1915 due to war-time activities, at which time it represented more than 80% of the gold production of German East Africa. After WW I mining was largely artisanal and this only changed with the increase of the gold price in 1934 when there was a resumption of prospecting activities in East Africa. By the mid-1930s involvement of larger companies led to greater investment in underground mining. Exploration activities included stream sediment and outcrop sampling followed by trenching. Increasing use was made of diamond drilling techniques. Four major mines started operating during the inter-war period in the LVG, namely the Geita, Buhemba, Kiabakari and Rosterman (Figure 2).

The original discovery of gold in the Geita area was reportedly by a German prospector in 1898 (Cowley, 2001) and several narrow veins known as the Bismarck reef were mined until 1914 (Hester *et al.*, 1995). Intensive prospecting and sampling in the early 1930s (Doyle, 1934) led to several new discoveries and in 1936 the Geita
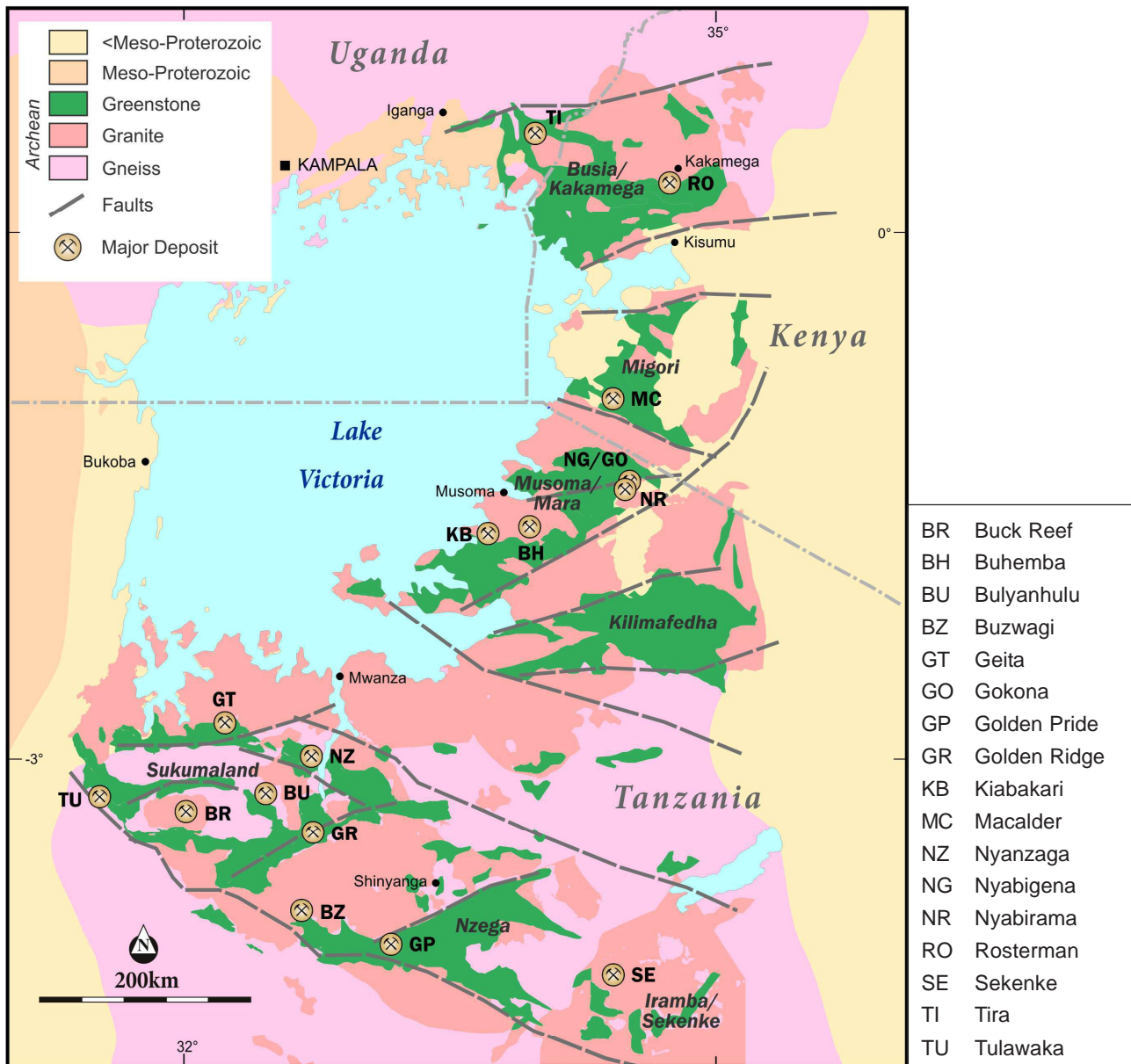
Figure 2: Nyanzian greenstone belts of the Lake Victoria Goldfields and locations of major gold deposits.

Mine (Geita Gold Mining Company Ltd) started production as the largest gold operation in East Africa. During its historic lifetime from 1936 to 1966 the mine produced more than 1 million ounces of gold at a grade of 5.3 g/t from five deposits: Geita Mine proper, Lone Cone, Prospect 30, Ridge 8 and Mawe Meru. Ore from Prospect 30 and Ridge 8 was transported over a distance of 15 kilometres via aerial cableway to the Geita mill. Mining methods were a combination of open pit and underground mining. The Geita mine closed in 1966 due to a combination of inadequate financing and the fixed gold price of $35 per ounce.

At Buhemba (South Nyanza Development Corporation), the second largest gold producer in the LVG prior to the advent of modern mining, full production began in the early 1930s, reaching a peak of more than 17,000 ounces in 1940. Mining continued until 1970 and by that time the mine had produced some 393,000 ounces of gold (Au) at an average grade of 11g/t and a recovery rate of 80%. The mine exploited the Buhemba and the Nyasanero Reefs, both

comprising quartz veins hosted by chloritic schists at lithological contacts.

Kiabakari was the third largest historical producer of the LVG but started only at a small scale in 1937. The main period of production began in 1959 by Tangold and, by the time the mine closed in 1966, approximately 283,300 ounces of gold at a grade of 6 g/t had been won. The mine was developed as an underground operation and a shaft was sunk to a depth of 490 metres. Mineralisation is of the disseminated type hosted by "adinol", a metamorphic rock comprising mainly quartz and albitic feldspar: mineralised portions are silicified and contain arsenopyrite.

The mineralisation at the Rosterman mine was hosted within an outcropping quartz vein and early mining extracted near surface ore to a depth of 5 metres at an average grade of approximately 50 g/t. Similar high grades have been reported from numerous other operations for shallow parts of the mineralised zones but a sharp drop in grade was often reported in fresh rock, evidence for significant

Figure 3: Sekenke gold mine (Photography by F. Schumacher, 1914)

surficial enrichment in the LVG. The Rosterman Mine (Rosterman Mines Ltd.) started operations in 1935. The ore was accessed via a vertical shaft that reached a depth of 588 metres and when operations ceased in 1952 some 259,000 ounces of gold at a grade of 12.3 g/t had been produced.

By 1938 over 70% of the total gold production from the LVG came from underground mining which was dominated by British and South African companies. By the early 1940s, gold was the most important exploited mineral in the region, its export value only exceeded by that of sisal. From 1934 to the early 1970s the gold price remained static at around $35 per ounce (Figure 4) and after World War II gold did not play a significant role in the international monetary system so there was little incentive for large companies to invest in the industry. Many of the smaller gold mines of the inter-war period in the LVG had closed by the late 1940s and only a few larger ones, such as the Rosterman, Buhemba, Kiabakari and Geita continued to operate. Geita mine, at that time the largest gold mine in East

Africa and employing around 2,200 miners, closed in 1966 as did Kiabakari, the third largest producer in Tanzania. Buhemba was the last significant mine to continue producing until it too ceased operating in 1970: at that point commercial gold mining declined rapidly from three tonnes per annum in the early 1960s to 10 kg in the early 1970s (Figure 4).

Commercial gold mining in East Africa ceased in 1972 when gold prices started to climb, reaching $154 per ounce in 1974 (Figure 4), at which time the State Mining Corporation (STAMICO) was formed in Tanzania to control gold production and to profit from the higher gold price. STAMICO took over the Buck Reef Mine in 1971 and reopened it in 1981, however eight years of production only yielded some 25,000 ounces of gold. The improved gold price did however result in an upsurge of artisanal mining activities which was not reflected in the official production figures. STAMICO was the official buyer of gold but only offered a fraction of the international gold price which encouraged smuggling. In 1990 the Bank of Tanzania was instructed by the government to buy the gold at parallel market prices to reduce the illicit gold trade. Due to this change in policy Tanzania suddenly emerged as an official gold exporter and gold became a major commodity which earned foreign exchange. The success of the exploration and eventual development of the gold mining industry in the 1990s was a classic example of junior exploration companies entering a new country first and then introducing the larger companies to develop the deposits. In Tanzania the first crop of juniors were TanCan, Pangea Minerals, Samax, Cluff and Sutton. From the early 1990s exploration activities picked up considerably and by 1998 exploration expenditures became amongst the highest in Africa with Anglo American, Ashanti Gold Fields, Randgold Resources, Rio Tinto, Sutton Resources, the Samax/Resolute Joint Venture and Afrika Mashariki Mines all being active. The resulting discoveries and mine development has led to a major increase in gold production in the LVG during the past 15 years (Figure 4).
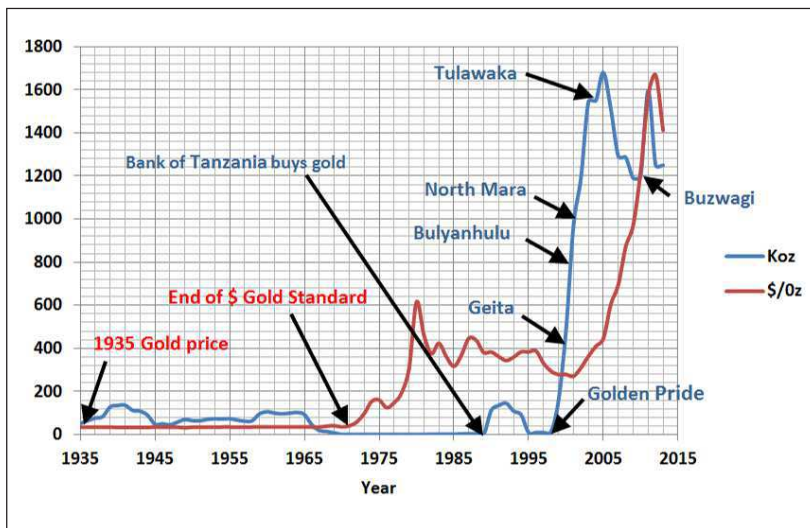

Figure 4: Gold price history (red) and LVG gold production (blue) from 1935 to 2013.

Regional geological setting

The Archaean greenstone belts of the Eastern Congo Craton occupy a WNW trending corridor more than 2000 kilometres long and between 350 and 550 kilometres wide (Figure 1). The corridor itself has been termed the "Ule-Nyanza granite-greenstone belt" (Cahen *et al.*, 1976) or the "Nyanza-Kibali granite-greenstone terrane" (Lavreau, 1984). The relative stability of the granite-greenstone belt from the Neoproterozoic to the present, however, is indicated by the presence of flat-lying Proterozoic cover sequences along its margins and locally in its interior (Figure 1), including the Lindian (Democratic Republic of Congo (DRC)) and the equivalent Bunyoro-Kyorga (Uganda), Bukoban (Tanzania) and Ikorongo (Tanzania). The Nyanza-Kibali terrane is naturally divided into three segments (Figure 1). The central segment has been termed the Upper-Zaire granitoid massif by Lavreau (1984) and is separated from the northwestern segment in the Central African Republic (CAR) by amphibolitic and charnokitic gneisses of the Bomu (a.k.a. Mbomo) River Gneissic Complex. The southeastern segment is separated from the central segment which underlies much of eastern DRC by a combination of the re-entrant Proterozoic mobile belts and the gneissic Uganda basement complex. Despite the two disruptions in their continuity, the greenstone belts within the Nyanza-Kibali terrane show predominant northwest-southeast structural trends, leading to the conclusion that they formed part of a single mass in Neoarchaean times (Cahen *et al.*, 1976). Nonetheless, many authors have distinguished the southeastern segment, (assigning it to the "Tanganyika Shield", "Tanzania Craton" or "Dodoman tectonic domain") from the central segment, which corresponds with the "northeastern Zaire Craton" (Foster and Piper, 1993; Borg and Shackleton, 1997).

The Tanzanian craton is flanked by younger mobile belts (Figure 1). The eastern margin of the craton is well defined by the East African Orogen (Mozambique belt) which is dominated by Neoproterozoic Pan-African deformation that overprints the West Nile Gneiss. The southwestern and southern contacts of the terrane are more complicated however, mainly marked by deformational fronts relating to Palaeoproterozoic (Ubendian-Usugaran and Ruwenzorian) and Mesoproterozoic (Karagwe-Ankolean, Kibaran) fold belts. The Ruwenzori and Karagwe-Ankolean re-entrant tends to isolate the Tanzanian and N.E. Zaire segments of the granite-greenstone terrane along a major structural corridor north of Lake Victoria (Figure 1). Inasmuch as this discontinuity is thought to involve Palaeoproterozoic, Mesoproterozoic and Pan African deformation and also coincides with the western arm of the much younger East African Rift system, it has been suggested to be a major crustal feature of Precambrian origin (McConnell, 1980).

The Lake Victoria Goldfields occupy the northern part of the Tanzanian Craton. The southern part is dominated by felsic Dodoma gneisses and granitoid rock and only local supracrustal Dodoma schist relicts (Kabete *et al*., 2012a). The northern part of the craton however, is hosted in a Neoarchaean granite-greenstone terrane which provides the host environment for the gold deposits (Figure 2).

Stratigraphy / Geological Setting

The systematic geological mapping of the entire LVG was conducted mainly by the colonial surveys in the 1930s and 1940s at the same time that many of the gold occurrences were discovered and exploited. As a matter of course, local names were applied to key

lithologic units but, with time it became evident that there are unifying themes applicable to the LVG as a whole. With this in mind, G.M. Stockley (1934) proposed the existence of three major chrono-stratigraphic "systems". The Basement System referred to the large areas of quartzo-feldspathic gneiss located mainly to the north, east and south of the LVG, whereas the Nyanzian and Kavirondian systems were defined to deal with the stratified metavolcanic and metasedimentary rocks of the greenstone belts within the goldfields. The terms relating to the last two are rooted in the geography of the region: Nyanza is the local name for Lake Victoria and its shoreline regions and Kavirondo denotes the gulf of the same name in the northeastern corner of the Lake and the adjoining lands to the north and south of it (Figures 2 and 6).

Closely related to the Nyanzian-Kavirondian subdivision is a corresponding nomenclature developed in the 1930s for granitoid rocks in the region. The original definitions of the granite types were presented by Grantham (1933) for Tanganyika but there is evidence that a similar system was adopted in Kenya (e.g. Shackleton, 1946). Grantham noted that his G.1 and G.2 granitoids do not as a general rule form kopjes or tors but commonly show flat pavement-like exposures. They were described as being commonly foliated, including gneiss and augen gneiss. Oligoclase-biotite G.3 granitoids also were described as foliated but to a lesser degree. Fine-grained grey G.4 granitoids and coarse-grained pink G.5 microline-granites were said to show little or no foliation, have abundant xenoliths at their margins and their occurrence in inselbergs and kopjes was considered typical. Although application of these distinctions over large areas is tenuous in a chronological sense, the overall implication is that there was a parallel evolution of the plutonic and supracrustal rocks and that the more deformed granitoids predate the Kavirondian (and supplied detritus) whereas the less deformed ones post-date the Kavirondian.

Many of the regional chronostratigraphic units of past workers are better converted to local lithostratigraphic groups and evaluated individually on their own merits. A critical aspect of a litho-stratigraphic approach, however, is to define depositional contacts and the relative "way-up" of key units, where possible using standard field observations in mafic volcanic flows, graded sandstones and mudstones and crossbedded sandstones: there is little evidence, including in the modern literature, that this has been done to any great extent in the LVG, even though these features are commonly exposed in several areas. The early workers relied on the dip of stratification to judge "way-up" but this is not always reliable. Part of their inference of relative age also relied on the perceived provenance of particular (older) clasts in conglomerate and this provided reasonable results in many cases but even in these cases supporting "way-up" observations are invaluable. A major advance in establishing a modern chronostratigraphic framework for the Goldfields, however, has been the application of the uranium (U)-lead (Pb) zircon method using Thermal Ionization Mass Spectrometry (TIMS) (Borg and Krogh, 1999), Ion Microprobe (Chamberlain and Tosdal, 2007; Kabete *et al.*, 2012b) and laser ablation (Wirth *et al.*, 2004), as analytical techniques at several localities throughout the goldfields. This data can be combined with knowledge of local lithostratigraphic sections where field evidence for "way-up" has been established to provide a provisional stratigraphic framework for the granite-greenstone terrane: in this context the historic stratigraphic terms regain some meaning and can be retained as informal chrono-stratigraphic units (Figure 5).
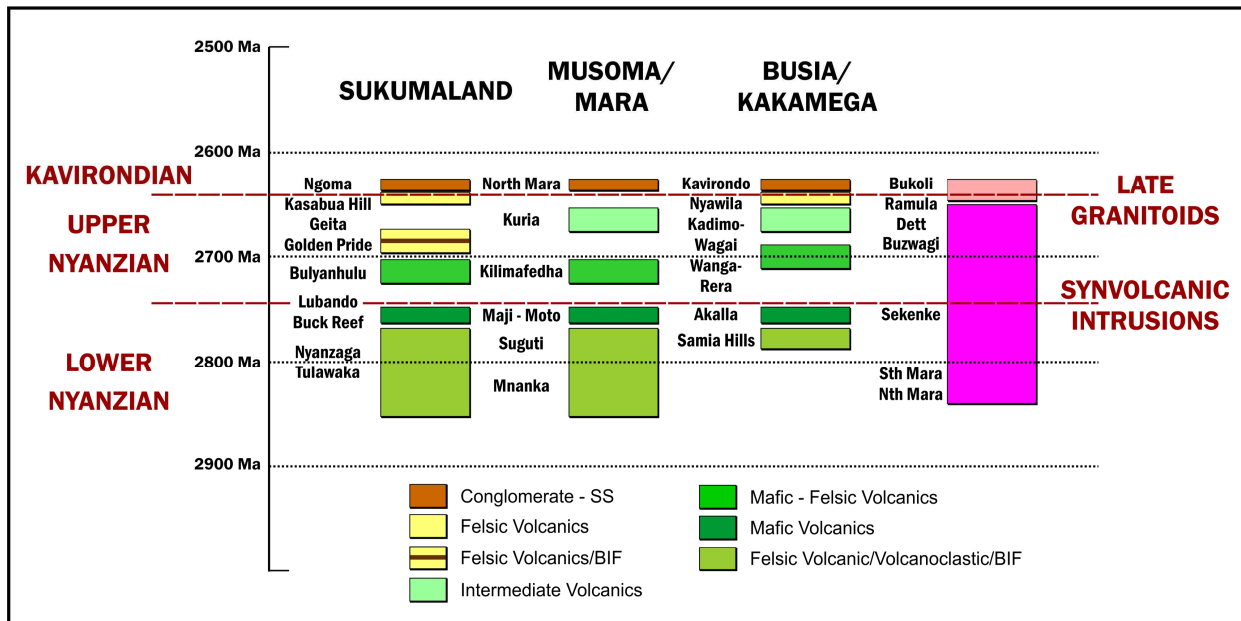
Figure 5: Chronostratigraphic column for the Lake Victoria Goldfields based on local lithostratigraphic sequences constrained by all available U-Pb geochronological data (see text for specific references).

The current data suggests reasonable chronostratigraphic comparisons can be made across the goldfields from Sukumaland in the south, northward into the Musoma-Mara and Busia-Kakamega domains (Figure 2). In each case, the oldest rocks are dominated by a sequence of felsic volcanic and volcaniclastic rocks intercalated with banded chert-oxide iron-formation and capped by a mafic volcanic sequence. Pre-2800 Ma (Mesoarchaean) crystallization ages for both rhyolite and syn-volcanic felsic intrusions have been established in the Tulawaka, Maji Moto and North Mara areas (Chamberlain and Tosdal, 2007). Somewhat younger Neoarchaean volcanic rocks are known from the Tinde Hills and Suguti and several *circa* 2750 Ma doleritic sills cut likely coeval mafic metavolcanic rocks at several locations in the Sukumaland belt. An apparent depositional gap is indicated at *circa* 2740 Ma (Chamberlain and Tosdal, 2007; Chamberlain *et al*., 2007) and this may ultimately provide a distinction between the upper and lower Nyanzian units. Younger volcanic and volcaniclastic units (*circa* 2720-2700 Ma) are widespread at Kilimafedha, Bulyanhulu, Kibiso Hills, Golden Pride and Geita and even younger intermediate to felsic volcanic units at *circa* 2675 are known in the North Mara district (Manya *et al*., 2006). The clastic sedimentary rocks which have been historically assigned to the Kavirondian, appear to have formed between 2660 and 2640 Ma based on detrital zircon populations in sandstone and ages of clasts from conglomerate (Chamberlain and Tosdal, 2007). The *circa* 2650 Ma rhyolite at Kasubuya Hill, south of Bulyanhulu notably formed within this interval (Borg and Krogh, 1999) emphasizing the fact that volcanic rocks make up part of the Kavirondian section as well.

The abundant granitoid rocks in the LVG provide the same spectrum of depositional ages as their volcanic counterparts (Chamberlain and Tosdal, 2007). Older granitoid rocks are not as abundant however, as the late, commonly potassium-rich, granitoid rocks which make up the many bodies of batholitic dimension surrounding the greenstone belts. The geochronological evidence suggests the majority of these intrusions crystallized between 2660 and 2640 Ma and a west-northwest striking steep foliation and accompanying shape lineations can commonly be observed in a variety of rocks including the Kavirondian strata, which span a similar age as the late granitoid rocks. This suggests that the deposition of the Kavirondian, the dynamothermal metamorphism which overprints it, and the contemporaneous late granitoid plutonism and accompanying contact metamorphism, all record the terminal orogenic deformation in this granite-greenstone terrane.

Major Districts, Mines and Ore Types

Previous reviews of many aspects of the geology of gold deposits in the LVG include Harris (1961), Pulfrey (1960), Stephenson (1981), Johnson (1983), Van Straaten (1983), Van Straaten (1984), Barth (1990), Gabert (1990), Kuehn *et al.* (1990), Foster and Piper (1993), Hester *et al.* (1995), Hester (2006), Ikingura *et al.* (2009) and Kabete *et al.* (2012a). The range of local geological settings of deposits and styles of mineralisation is described below drawing on the examples of the Bulyanhulu, Geita, Nyanzaga, Golden Ridge, Tulawaka, Buzwagi and Golden Pride mines in the Sukumaland and Nzega Belts, the Gokona-Nyabigena in the North Mara district and the Rosterman mine in Kakamega district (Figure 2).

Bulyanhulu

Bulyanhulu is a narrow-vein underground mine containing gold, silver and copper mineralisation associated with steeply-dipping reefs. Bulyanhulu commenced commercial production in 2001 and has produced over 3 million ounces of gold up to 2014. The current life of mine is estimated to be more than 25 years, based on its proven and probable gold reserves of 9.4 million ounces: the mine produces a gold-copper concentrate and doré bars.

The deposit is located in the Sukumaland greenstone belt (Figure 6), where repeated cycles of felsic and mafic volcanic rocks dominate the stratigraphy of the Bulyanhulu area (Figures 7a and b). The mine sequence occupies the western limb of a syncline (Figure 7b) and is
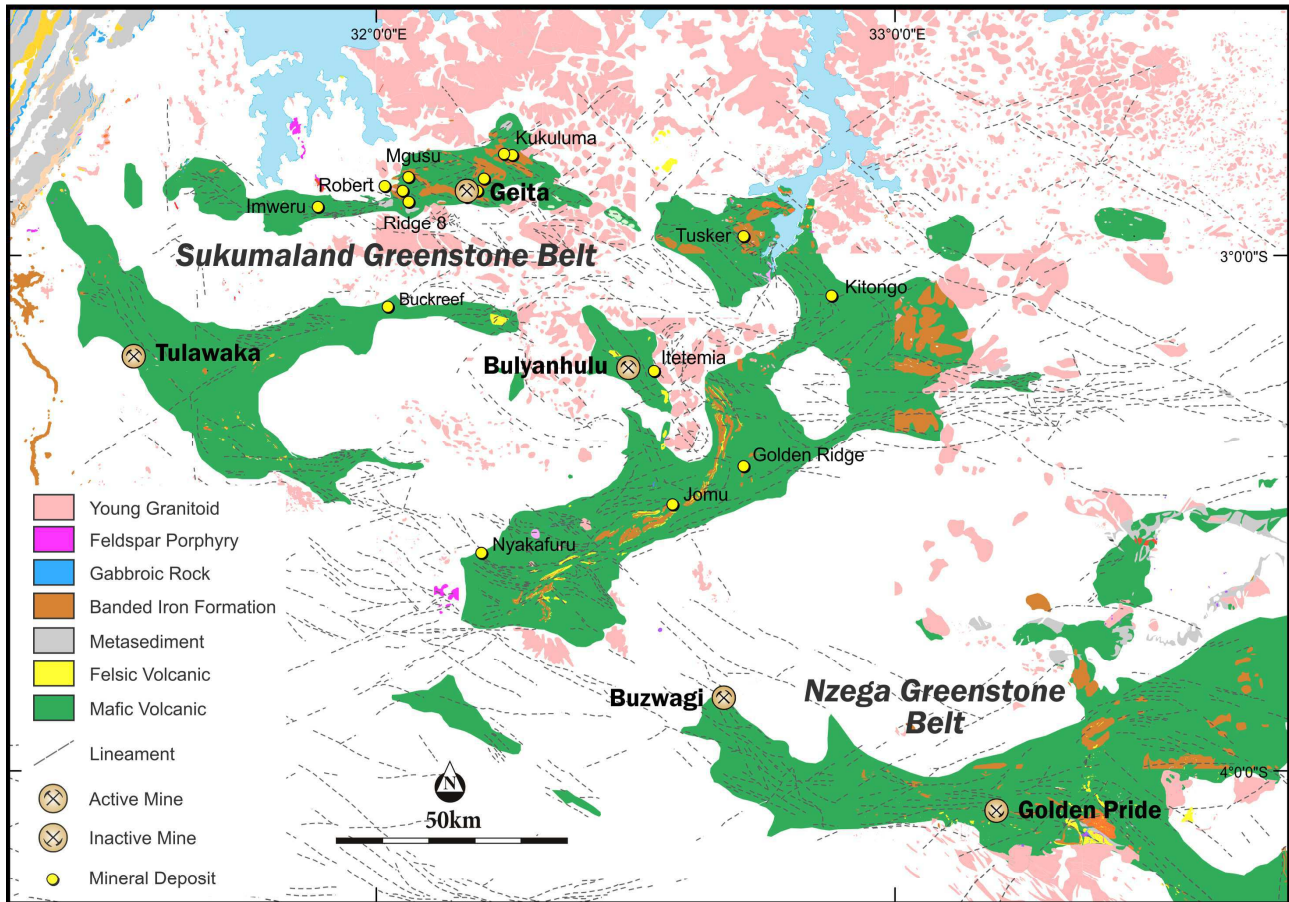
Figure 6: Geology of the Sukumaland and Nzega Greenstone Belts (compilation by J. Dobe, 2009).

composed of steeply dipping metavolcanic rocks of andesitic to rhyodacitic composition (Kapusta, 2001) and calc-alkaline chemical affinity. The felsic volcanic rocks (Kakola felsic unit) are best described as hyaloclastic flows formed by fracturing and disintegrations of quenched lavas, usually in a shallow subaqueous environment (Chamberlain, 2003). Mafic as well as felsic volcanic lithologies have been intruded by a series of quartz feldspar porphyries in the form of dykes and sills. These porphyries are chemically continuous with the calc-alkaline felsic volcanic rocks.The crosscutting relationships with regards to mineralisation clearly indicate that these porphyries pre-predate the mineralisation (Chamberlain, 2003). Mafic volcanic rocks are dominant in both the footwall and hanging wall of the mine sequence and are compositionally high iron tholeiitic basalts. The basalts are organized into massive and pillowed flows (Kapusta, 2001) and this allows establishment of the "way-up" of the sequence as a whole (Figure 7b). A series of intercalated sedimentary units, deposited during repeated breaks in volcanic activities (interflow sediments), are encountered in the volcanic sequence. The most prominent unit, termed the Kisii Shale, occurs at the boundary between the footwall mafic volcanics and the Kakola felsic unit and is host to the Reef 1 vein type mineralisation (Figure 7c). The upper portion of the Kisii shale, overlying carbon rich interflow argillite, is termed the Pyrite Zone due to abundant stringers and nodules of syngenetic pyrite (Figure 7d). Mineralisation at Bulyanhulu is restricted to quartz carbonate veins (Figure 7e) and narrow, peripheral alteration zones. In addition to Reef 1, a number of sub-parallel, less continuous

veins, the so-called Reef 2, are hosted by interflow sedimentary rocks in the mafic hanging wall volcanic rocks. The veins display the same style of mineralisation as Reef 1 but lack the syngenetic pyrite.

Although the Reef 1 mineralisation is clearly strata bound, it is also in a zone of strong foliation (graphitic phyllonite) in the metasedimentary rocks and this supports the idea that it is structurally in a shear zone as well. The vein is postulated to have formed as an extensional structure within the northwest-southeast striking Bulyanhulu Shear, a high angle reverse shear-zone active during inferred crustal shortening (Chamberlain, 2003). The mechanically weak argillites took up the majority of strain developed during shearing and acted as a conduit for the hydrothermal fluids wherever the Bulyanhulu Shear is hosted by the argillite. It can also be assumed that the pyritiferous argillites constituted chemically favourable host rocks for mineralisation. The central high grade core of the ore body, the Main Zone, forms a steep, northwesterly plunging zone of argillite-hosted quartz veins and lenses. The southeastern part of the orebody (East Zone) comprises sub-parallel quartz veins and stringers localised in the footwall and hanging wall contacts of the host sediments. Towards the northwest, in the direction that the thickened sediments pitch, the vein occurs as a single tabular body (West Zone). A number of sub-economic veins, such as the Shambani Reef and the Blue Reef are developed in the footwall of Reef 1 and these are similar to zones which are exploited at artisanal sites near Nyangarata and Nyangomanga to the west (Figure 7a).

Bulyanhulu is a truly remarkable orebody, not only because of
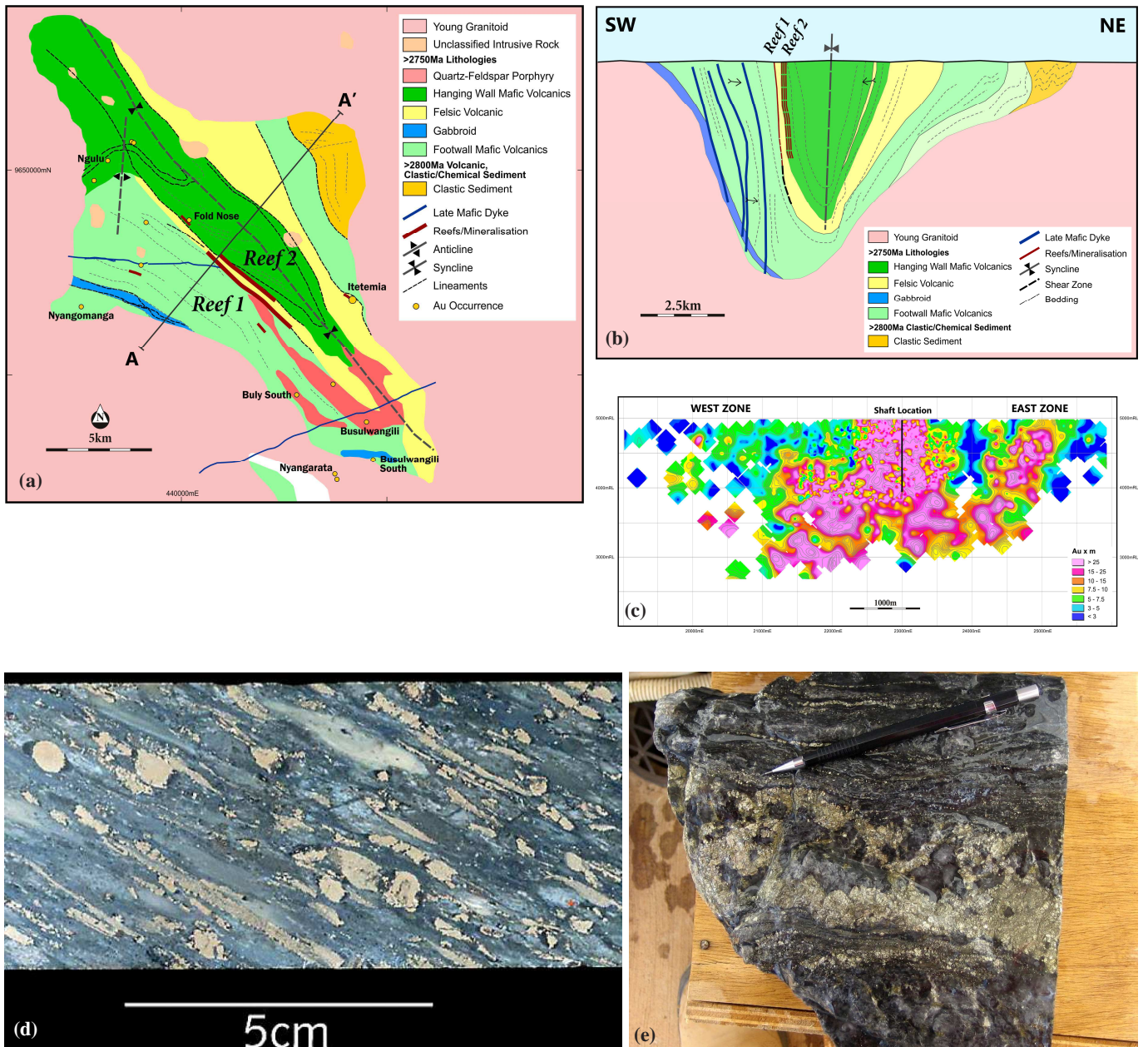
Figure 7: (a) Geological map of the Bulyanhulu area, illustrating the principal geological units and mineralised structures (Dobe, 2009);
(b) Simplified cross-section through the Bulyanhulu district showing the main mineralised structure (Dobe, 2009) – see figure 7a for
location of section. The arrows indicate "way-up" in mafic volcanic units; (c) Reef 1 grade x thickness (metre g/t Au) contour plot in a
vertical longitudinal section, Bulyanhulu deposit. The Cu content largely mimicks the gold distribution; (d) drill core specimen of sulphidic
volcaniclastic rock that constitutes the gold-poor "pyrite zone" at Bulyanhulu (photo from Kapusta, 2001); (e) Black quartz-sulphide vein
in foliated graphitic argillite, Bulyanhulu mine – note the shapes of terminations of the large crystals of vein quartz in contact with the
sulphide minerals.

the combination of high grade with high tonnage, but also because of
the rather unique style of mineralisation, which is best described as
a failed Volcanogenic Massive Sulphide (VMS) system that was
subsequently overprinted by typical shear zone hosted, orogenic
mineralisation. Since the gold is spatially associated with the so-called
"Pyrite Zone", which has many characteristics of a VMS deposit (e.g.
abundant syn-volcanic sulphides, barite inclusions in pyrite), an earlier
genetic model (Thiboutot, 1991) postulated a VMS origin for the ore
body. Subsequent studies (Chamberlain, 2003) showed however, that
the gold mineralisation is structurally controlled and later than the

VMS event. Chamberlain (2003) documented the mineralogical
paragenesis of Reef 1 and Reef 2 ores to show separate later stages
of vein formation and mineralisation and clearly demonstrated that
the early syn-volcanic pyrite is not associated with gold: the gold,
together with chalcopyrite was introduced later.

The Bulyanhulu mineralisation has an average copper resource
grade of approximately 0.5% and its distribution correlates well with
the gold. Extensive fluid inclusion and sulphur, carbon and oxygen
isotope studies by Chamberlain (2003), classified the mineralisation
to be of typical orogenic style. It is the strong association of gold

with copper that sets Bulyanhulu apart from most other Archaean orogenic gold deposits.

The East Zone shows a distinct 60° plunge to the west on a (metre g/t Au) contour plot of Reef 1 (Figure 7c). Grade shows some correlation with argillite thickness, i.e. where the argillite is widening the grade appears to drop and vice versa. This implies that the overall gold budget along strike remains fairly constant. The low grade zone between the Main and East Zone is intruded by porphyritic dykes.

Based on petrographic studies, two styles of alteration have been identified at Bulyanhulu (Mbuya *et al.*, 2002; Chamberlain, 2003). Pervasive alteration relating to regional metamorphism and seafloor spilitisation are ubiquitously developed. Shear related deformation and associated infiltration by hydrothermal fluids is reflected by intense alteration that progresses from distal carbonate to intermediate carbonate sericite alteration. Sericite, carbonate, quartz alteration is encountered proximal to the mineralisation. Adjacent to the mineralised zone the volcanics show progressive alteration and intense deformation resulting in a penetrative fabric. The geochemical alteration characteristics are consistent with those of Archaean lode gold deposits: notable, however, is the high copper and elevated molybdenum associated with gold, possibly pointing to a magmatic link.

Geita

The Geita Mine, owned by AngloGold Ashanti, is a multiple open pit operation with the potential for underground development. Six distinct gold deposits namely Nyankanga, Lone Cone, Geita Hill (Geita Trend) and Matandani, Kukuluma and Area 3 West (Kukuluma Trend), within two mineralised trends, make up the Geita Mining District (Figure 6).

The gold deposits of the Geita district are located in a synclinorial sequence of clastic and chemical sedimentary rocks which are flanked to the south by older, dominantly mafic volcanic rocks that contain the Samena Hill massive pyrite deposit, hosted by a thin felsic unit (Chamberlain and Tosdal, 2007). The stratified rocks in the Geita district comprise a magnetite-rich sedimentary package (ironstones) consisting of inter-bedded volcaniclastic sandstone-mudstone units locally intercalated with laminated chert and conglomeratic sandstone beds and overlain by turbiditic sandstone and mudstone. Although Chamberlain and Tosdal (2007) regarded these rocks to be epiclastic, they showed them to contain a relatively homogenous population of zircons which crystallized between 2687 and 2702 Ma, consistent with single cycle detritus from the same source terrane. Semi-concordant bodies of intermediate, feldspar-phyric rock which has been described variously as intrusive diorite or extrusive trachyandesite (Borg, 1994), occur locally within the volcaniclastic sequence. Borg and Krogh (1999), as well as Chamberlain and Tosdal (2007), reported a similar range of ages for the feldspar porphyry as for the surrounding stratified rocks so it is a moot point whether this rock is intrusive or extrusive. A younger body of barren hornblende-rich diorite (Figure 8a) clearly cuts the sequence south and west of the Nyankanga orebody (Cowley, 2001). The stratified volcaniclastic rocks are intercalated with chert-magnetite iron-formation (Figure 8a and b) which, at the Geita Mine, forms a unit ranging from 30 to 90 metres thick (Hester *et al.*, 1995). The iron-formations underlie the many hills in the district and also offer a good magnetic response so aeromagnetic anomalies provide additional evidence for the overall structural configuration of the folded strata. Minor intrusive dykes

ranging from lamprophyre to quartz-feldspar porphyry are common and some of the older ones have returned radiometric ages which are consistent with that of their hosts (Chamberlain *et al.*, 2007) but one lamprophyre dyke at Geita Mine is significantly younger with a maximum age of *circa* 2644 Ma (Borg and Krogh, 1999). Cowley (2001) argued that the felsic dykes at Nyankanga are also of at least two generations: an early altered variety parallel to the ore structure and a younger, post-mineral alteration set which crosscut and displace all other rock types and mineralisation. The rocks and orebodies in the Geita district have been oxidized to depths of 30 to 100 metres and show evidence of an *in-situ* lateritic weathering profile (Figure 8c). Some 5 to 15 metres of transported laterite covered the Nyankanga deposit (Cowley, 2001).

The stratified rocks and intermediate porphyry are deformed by mesoscopic, second generation (F2), reclined folds which plunge moderately north-northwest along northwest dipping axial planes (Borg, 1994). They overprint larger F1 folds and, at Geita Hill, are reportedly overprinted by smaller F3 folds with east-west axial planes. The relationships portrayed on mine maps and cross-sections suggest some of the younger dykes may also be folded, whereas others cut the folded strata. Some dykes appear to be coincident with a northward dipping shear zone along the Geita trend. Numerous northwest striking late faults transect the district dividing it into several discrete blocks (Figure 6).

At Geita Hill (Figure 8a and b) the mineralisation is controlled by a northwest dipping (~50°) and northeast-trending shear and as at Nyankanga, this shear is sub-parallel to the layering of the sedimentary package, cutting local, pre-mineralisation folds and lithological contacts. Mineralisation extends over a strike length of 2.3 kilometres. Four distinct, lithologically controlled, high grade, north plunging, shoots are encountered (Geita Hill, North East Extension, the Gap and Geita West) with grades reaching 8 g/t over a thickness of 40 metres (Bansah *et al.*, 2000). A series of pre-mineralisation northwest trending faults have resulted in changes of lithologies along strike of the mineralisation controlling shear. Shoots are encountered where favourable lithologies coincide with the channelways of the mineralising fluids. Geita West mineralisation is similar to that at Nyankanga (interbedded ironstones and diorite). At the Gap deposit, ironstones are interbedded with tuffs whereas the Geita Main and Northeast Extension deposits are ironstone dominated.

Nyankanga is the largest gold deposit within the Geita Greenstone Belt, located some 2 kilometres southwest of Geita Hill (Figure 8a) on the southwestern limit of the 5 kilometre long Geita Trend. The deposit is hosted by a northwesterly-dipping, ironstone dominated volcano-sedimentary package, intruded by diorite, which in turn has been intruded by lamprophyre, feldspar and quartz porphyries. The ironstones show a complex pre-intrusion folding pattern. The intrusive rocks have fragmented the sedimentary package resulting in intrusive hosted sediment rafts up to tens of metres in size. The rafts still show the orientation of the surrounding sediments. The mineralisation forms a roof pendant of the Nyankanga diorite intrusive complex (Sanislav *et al.*, 2015 in press). The intrusive complex is cut by a number of northwest-southeast striking shear zones dipping at 20-30° to the northwest. The shear zones primarily show reverse movement and their dip is sub-parallel to the stratigraphy. The Nyankanga shear zone is associated with the majority of the mineralisation; shearing occurs preferentially at diorite-ironstone contacts. High grade mineralisation sits in the footwall of the Nyankanga Shear Zone, has a steeper dip

than the overall mineralisation and a shallow plunge towards the southwest and west-southwest (Sanislav *et al.*, 2015, *in press*).

Within the Geita trend, orebodies are located along a clearly defined east-northeast curviplanar shear zone which dips moderately to shallowly to the north-northwest. Mineralisation is dominantly of veinlet-disseminated sulphide style and overprints virtually all of the host rock types. Zones of fracturing and metasomatic sulphidation of oxide iron-formation constitute many of the mineralised lenses along the trend such that there is a general correlation between gold and sulphide content (Borg, 1994). Gold and sulphides are unevenly distributed along the northward-dipping structure and tend to plunge to the northwest, sub-parallel to minor fold axes in the host iron-formation (Borg, 1994; Hester *et al.*, 1995; Mike Skead, *pers. comm.*, 2003). Most gold occurs as fine grained inclusions and fracture fill in the pyrite (Schandl, 1999).

At Nyankanga, gold is associated with zones of silicification and fine-grained pyrite in the iron-formation and with biotite-carbonate-sulphide veinlets, containing pyrite with local chalcopyrite, galena,
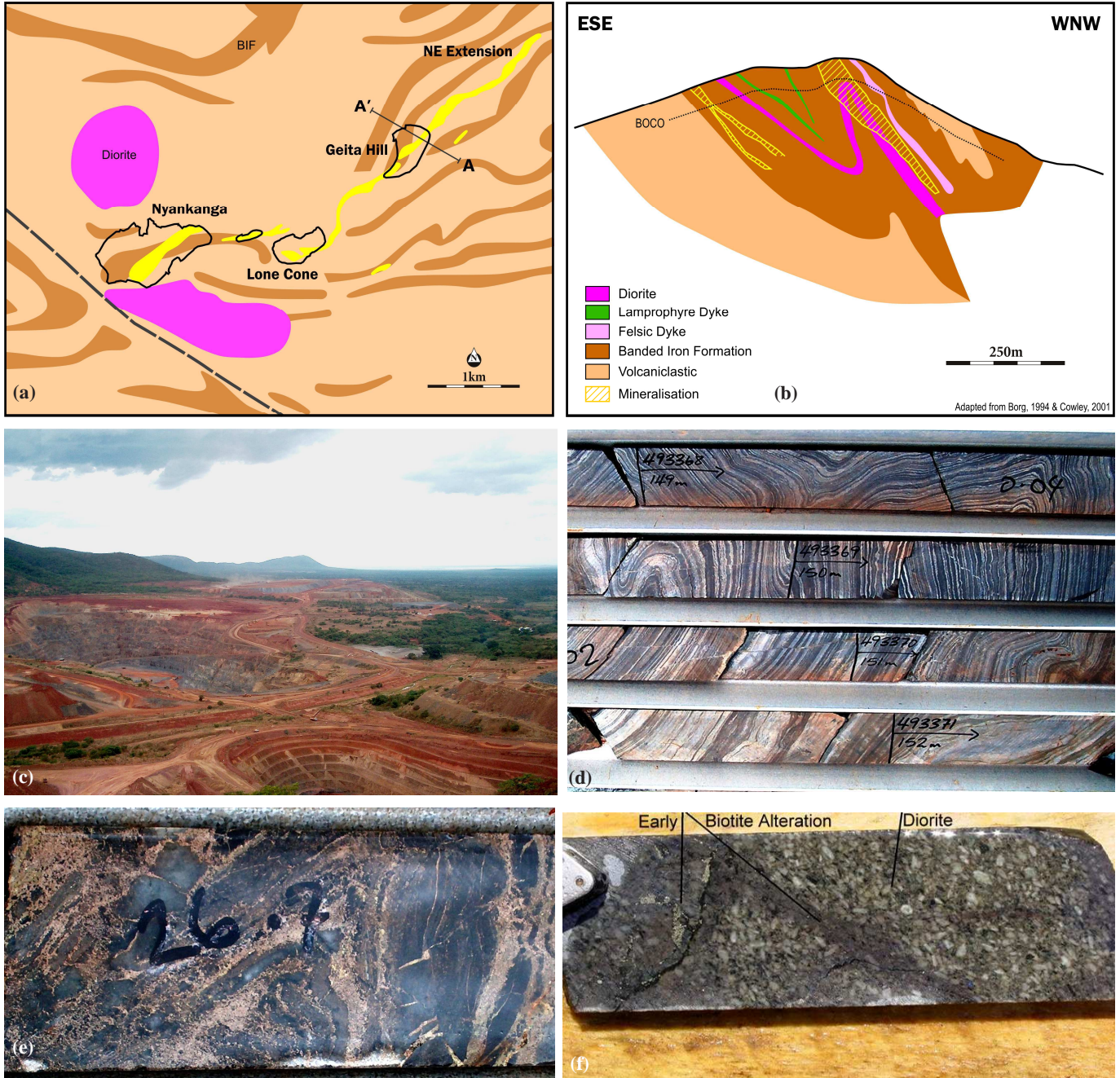

Figure 8: (a) Geology of the Geita Gold Trend: Legend: beige-volcaniclastic sandstone and mudstone; brown-iron formation; magenta – intermediate intrusions; pink-felsic intrusions; yellow – gold zones and deposits. (adapted from Borg, 1994; Cowley, 2001; Doyle, 1934; Sanislav et al., 2015 and information provided by AngloGold Ashanti); (b) Cross-Section through Geita Hill (see section line through Geita Hill on figure 8a); (c) view westward from Lone Cone hill toward Nyankanga pit; (d) Folded banded chert-magnetite iron formation in drill core, Geita trend; (e) sulphide-rich iron-formation in drill core carrying high grades of gold; (f) veinlet-style biotite alteration in porphyritic diorite (photo provided by M. Skead, 2003).

and sphalerite in diorite, with the better gold grades generally encountered in sulphidised ironstones. Although much of the gold in the Geita Trend is of veinlet-disseminated style, mineralisation, at the Northeast Extension deposit is associated with a persistent sulphide-poor quartz reef and quartz stringers which are enveloped by sulphidised iron-formation (Harris, 1961). In the Kukuluma block, the Matandani-Kukuluma and Area 3 zones are thought to be controlled by east northeast folds in the iron-formation which plunge shallowly to the east-southeast. The near-surface mineralisation in the iron-formation and diorite is highly oxidized but deeper sulphide zones containing pyrite, pyrrhotite and arsenopyrite are refractory and gold recovery is poor (approximately 60%).

The Mgusu trend includes Prospect 30 and the Nyamulilima trend the original Star and Comet discovery. Both are distinguished by the fact that gold mineralisation is controlled by a series of left-stepping *en echelon* north-northwest to northwest trending fault zones (Sanislav *et al.*, 2014). Although many of the deposits conform to the pattern of being associated with iron-formation, some are more distinctively associated with felsic intrusions, especially near their contacts, and have been described as being predominantly quartz reefs (Doyle, 1934). At the Ridge 8 deposit, west of Geita Hill, much of the gold is located in areas of overlap between *en echelon* veins (Hester *et al.*, 1995). The principal orebodies are located along the contacts between a 60 metre unit of banded iron-formation and adjacent volcaniclastic rocks. The ore was particularly sulphide-rich, ranging from 10% to massive sulphide (Harris, 1961) and contained arsenopyrite as well as pyrite and pyrrhotite. The Roberts deposit is noteworthy because it is controlled by northwest-striking faults cutting a large body of hypabyssal quartz-feldspar porphyry.

Apart from the sulphidation of the iron-formation, the effects of hydrothermal alteration at Geita are clearest in the diorite. Weak distal alteration 30 to 50 metres from ore is represented by the assemblage chlorite-epidote-calcite, with or without actinolite,

pyrite and pyrrhotite. In the intermediate alteration zone biotite appears and calcite shows an increased abundance. In the proximal alteration zone the dominant mineral association is quartz-calcite-dolomite/ankerite-hematite-pyrite-biotite, locally resulting in destruction of the igneous texture of the diorite due to silicification, carbonation and/or sulphidation, accompanied by brecciation, preferentially developed at diorite – ironstone contacts, and increased vein density (Sanislav *et al.*, 2015 *in press*). Borg (1994) showed that the geochemical expression of alteration at Geita Hill is the introduction of magnesium, calcium and potassium with their trace element counterparts barium, strontium and rubidium.

Nyanzaga

The Acacia Mining-owned Nyanzaga deposit is the most recent significant exploration project in the Sukumaland greenstone belt: it is also the largest undeveloped gold resource in the LVG. The deposit comprises two mineralised zones, Tusker Hill and the much smaller Kilimani oxide body, with a combined resource of more than 4.5 million ounces of gold at 1.42 g/t. The deposit is hosted by a folded sequence of chemical and clastic sediments (chert-ironstones sandstone/siltstone) and volcanic rocks of Nyanzian age (Figure 9a). Zircon age dating on a felsic volcanic breccia gave an age of 2779 ± 13 Ma (Chamberlain and Tosdal, 2007). A sequence of three mappable units has been recognised and these are, in upward stratigraphic order: the Tusker lower volcanic formation, mine sedimentary formation and the Tusker upper volcanic formation. These three units form the northwest plunging reclined Tusker anticline (Figure 9a). Within the Kilimani deposit three additional units have been recognized in drill core and outcrop and these are, in stratigraphic order: the Kilimani volcanic formation, Kilimani mudstone-sandstone formation and the Kilimani iron formation.
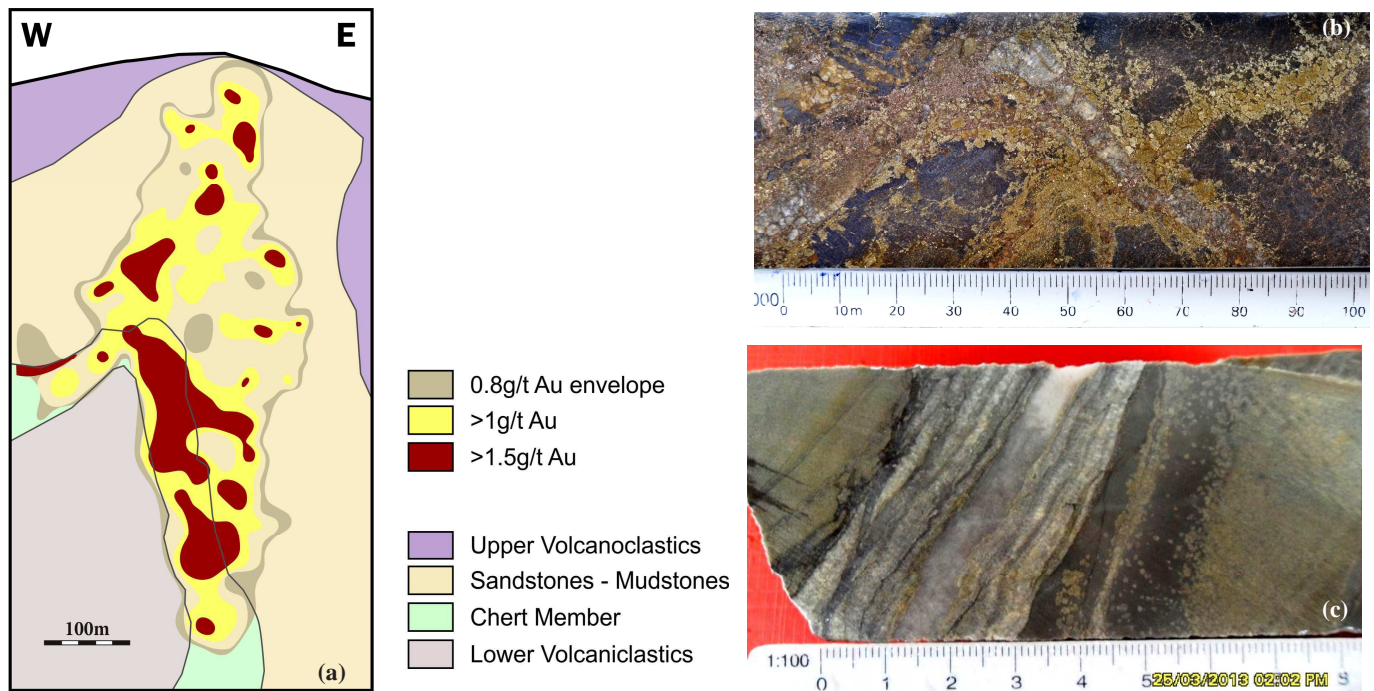
Figure 9: Nyanzaga deposit. (a) cross-section through the Tusker ore body showing lithologies and grade envelopes. Note the strong lithological control on gold mineralisation which favours ferruginous hosts; (b) Quartz-sulphide (pyrite, pyrrhotite) stockwork hosted by iron-rich sediment; (c) crustiform quartz-carbonate vein.

The main mineralisation at Tusker is hosted by an extensive, sub-vertical stockwork which occurs in an asymmetric pipe-like shape (600 metres x 300 metres in plan) and cuts across the stratigraphy within the Tusker anticline (Figure 9a). Deformation associated with the veins at the Tusker deposit is entirely brittle with mineralisation being stockwork and volcanic breccia hosted. The brittle deformation style allows the mineralisation to be classified as epizonal (Figure 9 b and c). Faults and shear zones are virtually absent in the deposit. Structural measurements on core reveal a set of conjugate pairs of fractures consistent with a vertical maximum compressive stress. There is a distinct lithological control on gold grade: the majority of the gold is hosted by relatively brittle, iron-rich sediments (particularly iron-rich mudstones and banded cherts), in the form of an extensive stockwork of crustiform carbonate veins (Figure 9c), quartz veins and quartz-carbonate breccias (Figure 9b).

Tusker shows an atypical metal association for orogenic gold deposits. There is a pronounced molybdenum–gold and to a lesser degree antimony-gold association and the ore shows an overall gold to silver ratio of approximately 1 which is unusually low for orogenic deposits. Interaction of ore forming hydrothermal fluids with crustal material is postulated. Barite is observed in some of the lithologies which can be explained by the reworking of older exhalative barite layers.

Golden Ridge and Tuluwaka

Golden Ridge and Tuluwaka are two deposits which share some similarities with Geita but, like Nyanzaga, differ in the stratigraphic position of the iron-formation host, which is in the Lower rather than the Upper Nyanzian sequence.

The Golden Ridge deposit is dominated geologically by a thick sequence of sediments, felsic volcanics, and lesser amounts of banded iron formation (BIF). The subdued topography of this region is transected by low hills, commonly consisting of erosion-resistant BIFs and associated cherts. The Golden Ridge, a sinuous BIF-supported ridge, is of this type. Substantial structural complexity marked by multi-stage folding, thrust duplexing, and faulting, is characteristic of the region's greenstone belts which are surrounded by extensive granitic plutons. Mineralisation at Golden Ridge is hosted in the thrusted lower portion of a BIF-chert package, close to a lithological contact with greywackes.

The Tuluwaka area straddles the presumed contact between the Rwamazaga and the Geita greenstone belts, which are part of the Nyanzian rocks forming the Sukumaland Greenstone Belt. The gold-quartz vein mineralisation is found in a shallow plunging shoot within a package of amphibolite facies sedimentary rocks including a garnet-amphibole iron formation, cut by feldspar porphyry dykes and a local granite pegmatite. The quartz vein is located within a thrust plane that cuts folded sedimentary rocks but is parallel to dykes (Cloutier *et al.*, 2005) and sulphidation of the iron-formation is common. The Tuluwaka mine operated from 2005 through to 2013, initially as an extremely rich open pit operation (average grade around 10 g/t Au) and in 2008 the transition was made to an underground mine. Significant eluvial enrichment shortened the payback period significantly. The mine, which was operated by Pangea Minerals, a wholly owned subsidiary of Acacia Mining, produced almost 1 million ounces of gold, nearly double the original feasibility study estimate. In 2014 African Barrick Gold (now Acacia Mining) transferred ownership of the mine to the State Mining Corporation (STAMICO).

Buzwagi

The Buzwagi mine is a low grade bulk deposit with a single large open pit, producing both doré bars and a copper-gold concentrate. The mine has so far produced over 900,000 ounces of gold and the processing plant is designed with a throughput capacity of 4.4 million tonnes of ore per year. In 2013 the mine produced approximately 180,000 ounces of gold at a head grade of 1.5 g/t. The current life of mine is estimated by Acacia Mining to be 5 years, with 3 years of mining and 2 years of processing stockpiles, based on proven and probable gold reserves of 1.1 million ounces (2013).

The deposit (originally known as Chocolate Reef) is located in the Nzega Belt (Figure 2) which is composed of Nyanzian basalts and intermediate volcanic rocks, as well as upper Nyanzian BIF, chert and felsic pyroclastic rocks. Locally, the Nyanzian rocks are overlain by Kavirondian epiclastic rocks. The greenstone and volcano-sedimentary units are variably folded and faulted but have historically been considered, on the macro scale, to represent a conformable, outward facing, homoclinal sequence. The deposit is hosted mainly within a composite granite-tonalite body which has intruded Nyanzian mafic volcanics, rather than having the more common mafic volcanic association observed elsewhere in the Sukumaland belt (Figure 6). The enveloping metavolcanic sequence only hosts minor mineralisation. The host granite-tonalite has intruded Nyanzian mafic volcanics. U-Pb (SHRIMP) dates of 2680 ± 9 Ma and 2765 ± 25 Ma have been obtained from the granite and tonalite respectively (Chamberlain and Tosdal, 2007): both ages are consistent with a syn-volcanic timing of the host intrusion at a regional scale which is definitively not related to the much younger late- to post-kinematic intrusions elsewhere in the belt (Figure 5).

Golden Pride

Golden Pride is centrally located in the Nzega Belt along the Bulangamirwa shear zone (Figure 2). The deposit is shear hosted with the two types of ore being "silica ore" and "chlorite ore". The Golden Pride mine is owned by Resolute Mining and commenced commercial production in 1998. It had produced 2.2 million ounces of gold by mid-2014 at the time of its closure.

The deposit is hosted by a variably foliated and sheared sequence of clastic sediments and minor intercalated chemical meta-sediments. This sequence is intruded by a number of felsic to mafic intrusive rocks, which include quartz feldspar porphyries, granodiorites and lamprophyres. These intrusions occur at, or close to, the Golden Pride Shear (GPSZ) and associated shears. Host rocks are metamorphosed from lower-to-middle greenschist facies. The deposit is located in the immediate hanging-wall of the regional, ~150 kilometres long, steeply south-dipping Bulangamirwa Shear Zone within intensely deformed and altered meta-sedimentary rocks of the Nyanzian System. Locally, at the mine scale, the Bulangamirwa Shear Zone is known as the GPSZ, and occurs as a 5 to 20 metre wide zone of moderate to intense deformation (Vos *et al.*, 2007). Foliation trends sub-parallel to the bounding faults and dips steeply southward. Stratigraphic units strike at a low angle to the boundaries of the fault block.

The "Chlorite ore" comprises pyrrhotite and pyrite-bearing chlorite biotite quartz calcite shear veins in siltstones and fine grained sandstones. The "Silica ore" comprises smoky grey, recrystallized quartz with minor pyrrhotite, arsenopyrite and visible

gold (often in late fractures) in silica flooded coarse grained sandstones. Silica ore generally shows higher gold grades when compared to chlorite ore.

North Mara

The North Mara Mines, currently operated by Acacia Mining, comprise the Nyabirama, Gokona and Nyabigena deposits (Figure 10a). By the end of 2014 these three deposits had produced a total of 2.87 million ounces of gold and had a combined reserve of 2.05 million ounces at 2.69 g/t Au and resources of 1.66 million ounces at 2.87 g/t Au. They lie within the northwestern portion of the Mara Musoma Greenstone Belt, in which three main time stratigraphic series have been documented, namely the gneissic Dodoman Basement, the Nyanzian volcanics and sediments, and the Kavirondian sediments (Stockley, 1934; Allibone *et al*., 2000; Tripp *et al*., 2007). East trending regional scale faults separate thrusted and folded segments of stratigraphy. These faults have been reactivated in places as normal faults during extension related to the East African Rifting, producing

prominent escarpments. Granitoid rocks have extensively intruded the greenstone belt at several stages throughout its development. Locally, Proterozoic sedimentary rocks and rift related Tertiary phonolitic lava flows cover the Archaean rocks.

The Gokona and Nyabigena orebodies lie immediately north of the Nyarwana Fault and are both of similar size, 500-600 metres in strike length and 150-200 metres wide, extending to depths of more than 300 metres. They are hosted by a sequence of Nyanzian age south dipping and south-facing intermediate fine-grained and distinctively feldspar-phyric volcanics and intrusives. Tertiary aged phonolite lavas cover much of the area. Mineralisation within the two deposits occurs as a series of moderate to steep southwesterly dipping, stacked tabular lenses, approximately conformable with the contacts of the local stratigraphy (Figure 10b). Individual lodes pinch, swell, and bifurcate, but are typically 30 metres to 60 metres in width. The system has undergone early ductile deformation (isoclinal folding and transposition) resulting in a consistent penetrative cleavage which parallels bedding. North-northeast striking brittle faults have been mapped offsetting the local stratigraphy and mineralised systems
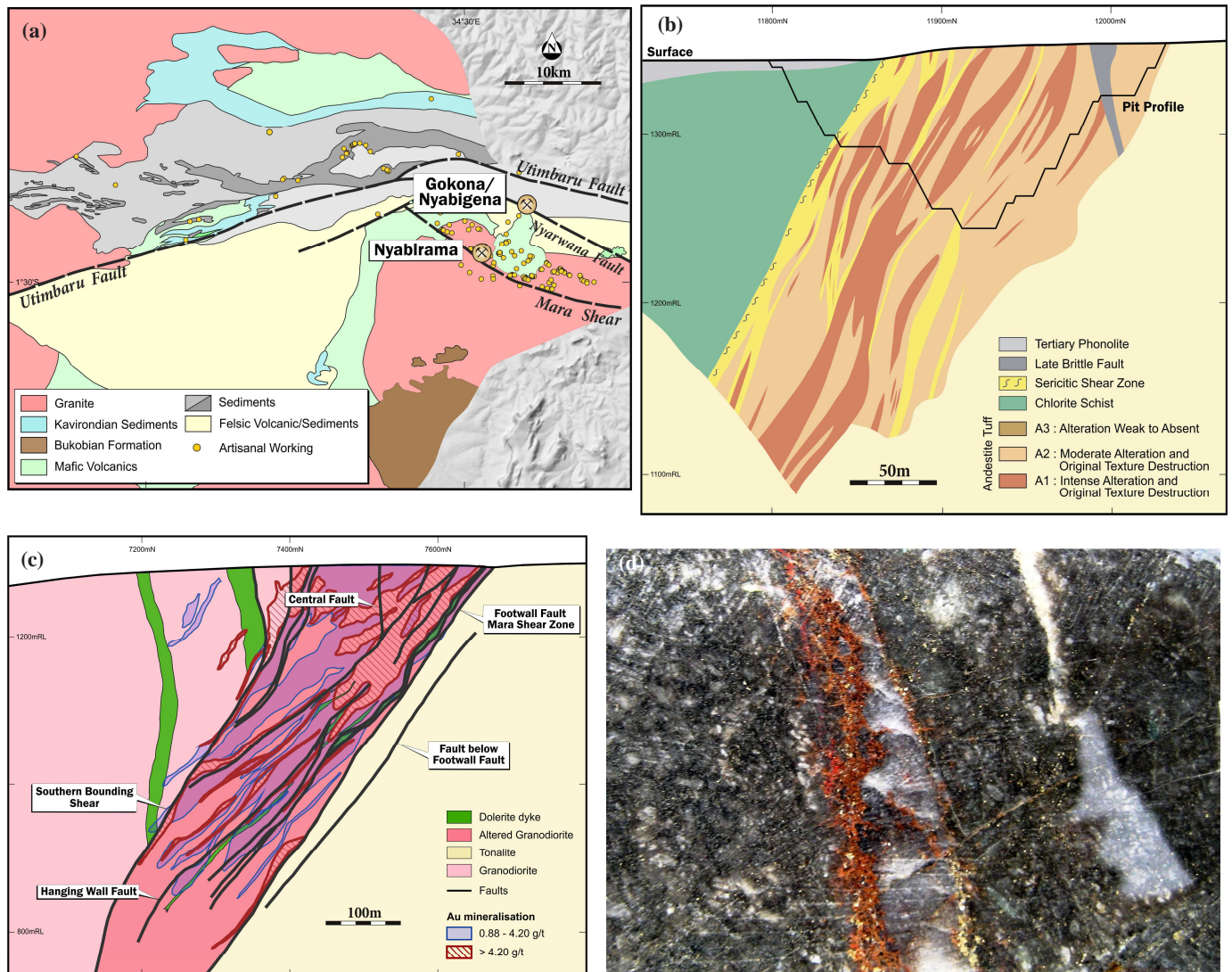

Figure 10. (a) Regional Geology of the North Mara area with location of mines and prospects; (b) Nyabigena deposit cross-section; (c) Nyabirama cross-section; (d) Sphalerite and pyrite selvages to a quartz vein within a feldspar-phyric volcanic rock from Gokona. The feldspar phenocrysts are obscured by silica and K-feldspar alteration.

by up to several hundred metres. Two types of veins have been documented as carrying gold; steeply dipping grey quartz veinlets and sulphidic stockwork stringer veins (e.g. Stewart *et al.*, 2001; Smith and Anderson, 2003; Tripp *et al.*, 2007). The higher gold grades are associated with the steeply dipping quartz veinlets which commonly contain coarse visible gold. Increased vein density also results in higher gold grades. Pyrrhotite is associated with grey quartz veins whereas arsenopyrite and pyrite are associated with stringer veins. K-feldspar, silica and sericite alteration has destroyed the texture of the volcanic host rock to varying degrees (Figure 10d).

The Nyabirama orebody is located 7 kilometres southwest of the Gokona and Nyabigena deposits along the Mara Shear, which tracks the northerly dipping contact between tonalite and granodiorite bodies (Figure 10c). The contrasting rheology of these units is thought to be responsible for the formation of a set of splays with intervening link structures that formed a dilatant zone amenable to trapping mineralised hydrothermal fluids. Major ore shoots at Nyabirama are consistently located in right-hand dilational jogs along the structures. Flatter segments of the main shears and intervening link structures also host ore shoots. Faults sub-parallel to the Mara Shear are common throughout the mineralised sequence and delineate the hanging wall of the deposit. Crosscutting west and northwest trending faults are also present. Gold occurs within the disseminated pyrite, silica gangue and quartz veinlets. The disseminated style of mineralisation accounts for the vast majority of the mineable deposit. The gold bearing quartz veins have widths that range from a few millimetres to several metres. K-feldspar, silica, albite, sericite and pyrite alteration associated with gold mineralisation, increases in intensity towards the centre of the deposit. Minor amounts of arsenopyrite, leucoxene, chlorite and calcite consistently occur within the albitic alteration assemblage. Significant silver and weakly anomalous antimony and molybdenum are associated with gold mineralisation.

Busia – Kakamega Greenstone Belt

The Busia-Kakamega Greenstone Belt lies on the northern edge of Lake Victoria extending northwest from Kakamega in Kenya, into Uganda (Figure 2). Mapping by the majority of workers (e.g. Pulfrey 1946; Huddleston 1954; Mason 2010) defined three broad stratigraphic divisions: gneissic basement, Nyanzian volcanic and sedimentary rocks and Kavirondian sedimentary rocks. Fault zones separate thrusted and folded segments of the stratigraphy. The sinuous nature of the belt toward the Uganda border suggests folding on a regional scale. Granitoid rocks have extensively intruded the greenstone belt throughout its development. The bulk of the Kenyan section of the belt has recently been mapped in detail by Acacia Mining and this is now one of the most intensively mapped areas of greenstone in East Africa. A detailed stratigraphy has been recognized in the area through geochronological work and field relationships. Lower Nyanzian volcaniclastics/BIFs and mafic volcanics are overlain by an Upper Nyanzian package of ultramafic, mafic to felsic volcanics. Younger Kavirondian polymictic conglomerates and sediments unconformably overlie the Nyanzian rocks (Figure 11).

The Rosterman was the largest gold mine in the Busia-Kakamega Belt and to date is the most productive in Kenya, having yielded 259,000 ounces of gold from 600,000 tonnes of ore at an average
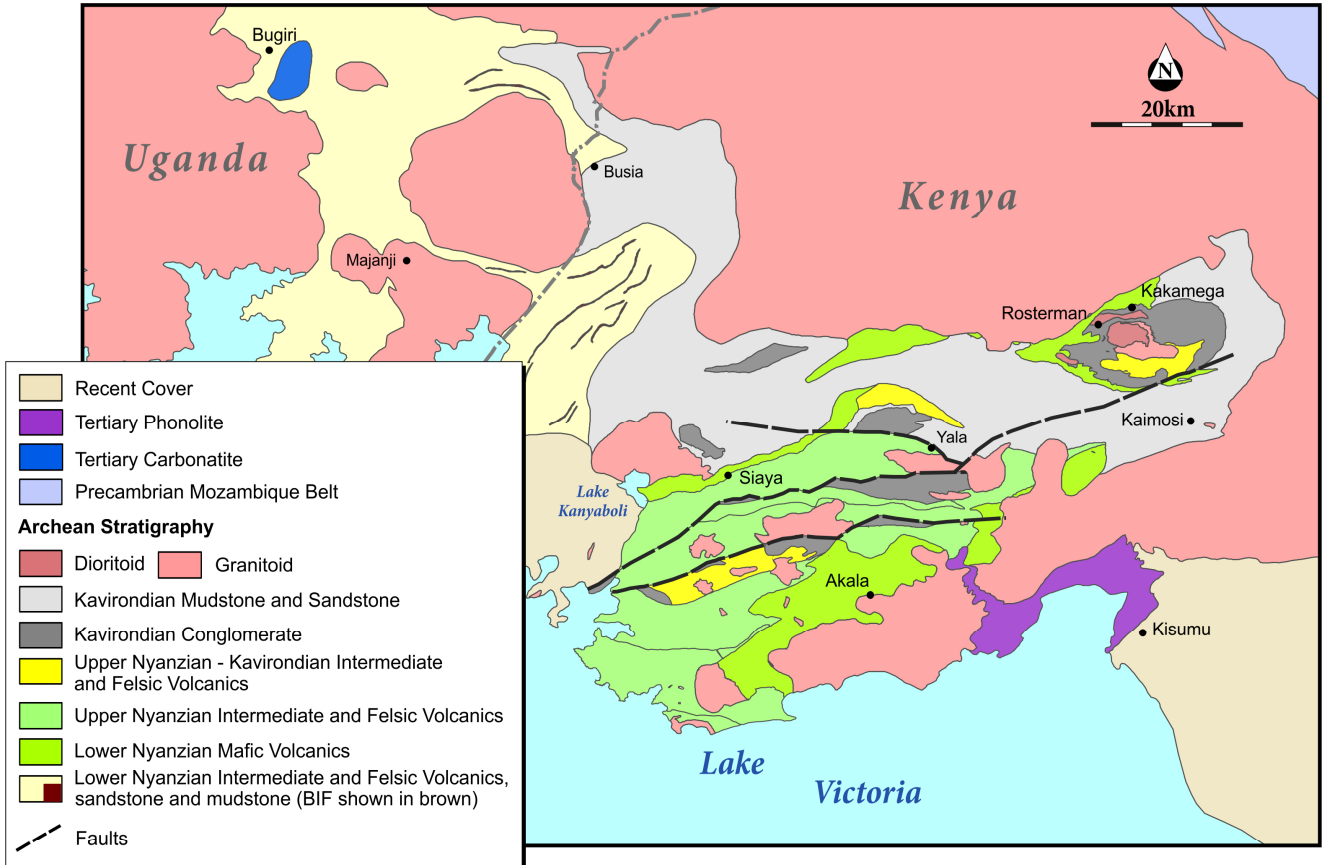

Figure 11: Geology of the Busia-Kakamega Greenstone Belt, western Kenya.

grade of 12.35 g/t between 1935 and 1952. The quartz lodes were mined to a depth of 600 metres.

A stacked quartz vein system is well developed in a quartz diorite body, which in places contains abundant microdiorite xenoliths. The veins extend into the surrounding intermediate volcanic breccias and polymictic conglomerates.

Mineralisation is contained in a series of sigmoidal stacked quartz vein reefs dipping 35° to the northwest and attached to a subvertical shear zone. The quartz veins strike parallel to the axis of the diorite body. Maximum dimensions of the veins are in the order of 250 metres long by 3.5 metres thick. The lodes consist of resinous white to smoky quartz. Chalcopyrite, pyrite and pyrrhotite occur rarely in the veins. Chlorite, tourmaline and sulphides (pyrite, pyrrhotite and chalcopyrite) are present on the quartz vein selvages. Minor pervasive alteration consists of hematite, sericite and carbonate (calcite, dolomite); with calcite stringer veins being common.

Origins of the mineralisation

Diverse styles of gold mineralisation are present in the LVG and these in part reflect the wide range of types of host rocks and structures that are found to be mineralised. Early descriptions (e.g. Harris, 1961) made a distinction between quartz vein and "impregnation" (disseminated sulphide) deposits. Many deposits are simply composed of quartz veins in shear zones and extensional fractures in their hosts (e.g. Bulyanhulu, Buck Reef, Rosterman). The Bulyanhulu veins are characterized by distinctive, pyrite-pyrrhotite-chalcopyrite-rich, lustrous black quartz, likely reflecting the hosting black argillite. Buzwagi and Nyabirama are composed of quartz vein arrays within intrusions. All of these variations are easily accommodated by the orogenic model of gold deposits in general (Groves et al., 1998; Hagemann and Cassidy, 2000). Although Chamberlain (2003) noted that Bulyanhulu shares many characteristics with quartz lodes elsewhere, quartz veins in a brittle-ductile setting, carbonate alteration, low salinity carbonic fluids and gold-silver-arsenic-bismuth metal signature, she also argued for a relatively involved genetic history. Most important perhaps is the clear evidence that Bulyanhulu is the site of a fossil syn-volcanic hydrothermal system that generated a barren massive sulphide deposit (the Pyrite Zone) and inherently the reducing pyritic, graphitic mudstones of the host Kisii shale unit. Volcanic-associated massive sulphides are known in other parts of the LVG as well, at Samena Hill near Geita and Macalder and Bumbo in Kenya but, although they do locally contain small zones of gold enrichment, their overall gold contents are well within the range of Archaean base metal massive sulphide deposits elsewhere. Chamberlain (2003) also documented a generation of early, high-temperature fluids associated with the emplacement of porphyritic intrusions, mainly in the footwall of the deposit but again there is no evidence that these fluids account for the exceptional concentration of gold at Bulyanhulu.

Several deposits in the LVG are hosted by folded banded iron-formation (Geita, Golden Ridge, Tulawaka and Nyanzaga) and their origins have proven more contentious, especially for the Nyankanga-Lone Cone-Geita Hill deposit, where a range of explanations have been proposed. Van Straaten (1984), following concepts espoused elsewhere at that time, suggested that the Geita gold mineralisation was essentially syn-volcanic and syngenetic with respect to the iron-formation. Others have noted, however, that the iron-formation at Geita was intruded by diorite which also is carbonatized and mineralised. Modifications of the syngenetic model therefore have been proposed to include an initial syngenetic accumulation of gold followed by later remobilization during either emplacement of crosscutting dykes (Kuehn et al., 1990), or regional metamorphism (Gabert, 1990). Borg et al. (1994) argued strongly against both the syngenetic and lateral secretion models in favour of syn- to late-orogenic fluids of magmatic origin which particularly interacted with the iron-formation that they regarded only as the preferred physiochemical trap. Part of the issue of interpreting the origin of these deposits is the different perceptions of the timing of gold introduction with respect to other geological events. One of the lines of evidence for syngenetic gold mineralisation was the observation of pyritic layers in the form of folds that were interpreted as being syn-sedimentary slumps (Van Straaten, 1984). A more likely explanation, however, is that late sulphidation of folded magnetite layers has overprinted syntectonic folds which share the same axial planes as regional folds elsewhere. Kabete et al. (2012) observed that gold mineralisation and the peak of regional deformation in the Geita camp can be bracketed between 2662 and 2673 Ma. The difficulty with this interpretation is that this age range logically predates the deposition of the Kavirondian sedimentary units (Tosdal et al., 1997; Chamberlain et al., in prep.), which share the same dynamo-thermal metamorphic fabrics as other stratified rocks in the region, including the hosts at Geita. The most consistent geochronological constraint, from a regional context, for timing of gold mineralisation at Geita is a U-Pb zircon age of 2644 ± 3 Ma reported for a pre-mineralisation lamprophyre dyke (Borg and Krogh, 1999).

Apart from Bulyanhulu and Geita, two deposits stand out from the rest in displaying significant deviation from the standard orogenic model. Although the Nyanzaga deposit is also hosted by folded iron-formation, the deposit is a discordant pipe-like body which cuts the axial planes of folds and into which a stockwork of dolomite, silica and sulphide veins have been introduced, showing evidence for high-level open-space filling of a type normally found in epithermal deposits. If related to the other orogenic vein deposits in the region, Nyanzaga at the very least must be regarded as an epizonal orogenic deposit (Groves et al., 1998) with exceptionally late timing. The Gokona-Nyabigena deposit in the North Mara district lacks obvious structural control and significant carbonate alteration but is strongly associated with a distinctive suite of porphyritic volcanic and sub-volcanic intrusive rocks in a dominantly clastic sedimentary setting. The deposit is noted for a stockwork-disseminated style of mineralisation and the close association of gold and extreme potassic-feldspar alteration and has the characteristics of what Robert et al. (2007) term "atypical" deposits which may be ultimately related to the emplacement of hypabyssal intrusions.

In summary, there is little evidence of the absolute age of gold mineralisation in the LVG but the overall inference is one of relatively late timing with respect to the circa 150 million year evolution of the terrane as a whole and an overall coincidence with the circa 2700-2650 Ma metallogenic epoch for many gold belts globally. There is a reasonably good fit, the local variations notwithstanding, with the orogenic model for greenstone gold deposits in general (Groves et al., 1998; Hagemann and Cassidy, 2000). By comparison with the Abitibi Goldfields of Canada and the Eastern Goldfields of Australia (Robert et al., 2005) however, the LVG lacks clear indications of major through-going faults and shear zones which coincide with strong linear trends in the distribution of the deposits. It is possible these

have been obscured by the emplacement of the exceptionally abundant late- to post-orogenic granitoid rocks.

Exploration Methods Leading to Discovery

The mines of the colonial era had been discovered by conventional prospecting whereas the exploration boom beginning in the 1990s relied on more sophisticated techniques including geophysics, remote sensing, radiometric and soil geochemical surveys. Geochemical surveys were by far the most efficient discovery tool.

Countrywide low resolution airborne geophysical surveys comprising gravity, magnetics, radiometric and electromagnetic methods were conducted from the 1970s (Darracott *et al.*, 1972; Batterham *et al.*, 1983). The UNDP conducted geochemical and geophysical exploration in the Geita area in 1985. Follow up work consisted of diamond drilling financed by the UN but work halted in 1994. Subsequent exploration focused largely on former mining areas. In 1994 Cluff Resources (British) acquired two prospecting licences covering much of the Geita area including the old Geita Mine.

In early 1996 Cluff Resources was taken over by Ashanti Goldfields (Ghana) and at that time the resource at Geita stood at about 400,000 ounces of gold. Following the award of the Geita Hill licence, underground channel sampling commenced at the old Geita Hill Mine followed by resource drilling. A soil geochemical survey over ferricrete covered terrain, west of the Lone Cone deposit, identified a >200 ppb gold soil anomaly. Subsequent rotary air blast drilling led to the discovery of Nyankanga, where high grade BIF hosted mineralisation was delineated. Nyankanga is now the main ore body at Geita Mine. An aggressive exploration programme had increased the Geita resource to about 3 million ounces by 1998. Work by SAMAX Gold Inc. started in 1995 and resulted in the identification of the Matandani deposit. Ashanti Goldfields acquired Samax in 1998 thereby increasing the Geita resource base to about 6 million ounces. Geita Gold Mine (GGM) commenced modern production in 2000 with an annual production target of 400,000 ounces, initially as a joint venture between AngloGold Ltd and Ashanti, before the two companies merged in 2004 and became AngloGold Ashanti. At the end of 2013 Geita had a probable reserve of 3.9 million ounces at a grade of 3.28 g/t Au. Indicated and inferred resources stood at 6.77 million ounces at 2.88 g/t Au.

Gold mineralisation at Buzwagi was allegedly first recognised by John Williamson (of Williamson Diamond Mine fame) in the 1950s. Exploration activities (1996-1999) commenced as a joint venture between Pangea Goldfields, a wholly owned subsidiary of Pangea Minerals (Canadian) and Anmercosa, the Tanzanian exploration arm of Anglo American Corporation (South African). Regolith and geological mapping, soil sampling, airborne and ground geophysical surveys were carried out. A somewhat diffuse soil anomaly was identified and followed up by trenching, RAB, RC and diamond drilling. Anmercosa ceased exploration in 1999 and decided in 2000 not to pursue the project and the project reverted to Pangea Minerals. In 2000 Barrick Gold (Canadian) acquired Pangea Minerals Ltd. and continued exploring the deposit. By the end of 2005 more than 300 diamond drill holes, totalling in excess of 110,000 metres had been drilled for resource delineation purposes. The estimated resource was 2.64 million ounces at 2 g/t Au. By 2007 the resource had been converted to Proven and Probable Reserves of 2.6 million ounces at 1.8 g/t Au and 0.131% copper.

The area around Bulyanhulu is covered by ferricrete, has only minor relief and did not attract any interest by explorationists or artisanal miners until gold was discovered in 1975, reputedly by a herdsman who observed gold bearing quartz in the roots of a fallen tree. Over the next two decades there was extensive movement into the area by artisanal miners. It is estimated that up to 30,000 artisanals worked the ground at Bulyanhulu. Government geologists conducted limited drilling work in the late 1970s. STAMICO continued with exploratory drilling between 1980 and 1982. Between 1983 and 1985 STAMICO entered into a joint venture with Outokumpu and Kone Corporation of Finland to carry out further drilling work. In December 1989 Placer Dome (Canadian) acquired the property, conducting exploration work until 1992 when they relinquished their property rights to Bulyanhulu. In August 1994 the government granted a prospecting licence to Kahama Mining Corporation Ltd, a subsidiary of Sutton Resources, a Vancouver based company. Sutton drilled some 387 holes on the property and estimated a resource of 9.2 million ounces by the end of 1998. Barrick Gold Corporation acquired Sutton Resources in March 1999 and finalized 430,000 metres of additional diamond drilling by 2001. A resource upgrade released at the end of 2001 increased the resource by 14.6 million ounces totalling 23.8 million ounces of gold in the ground. Barrick conducted extensive geophysical surveys such as aeromagnetics, induced polarisation (IP) and electromagnetics(EM) which were useful in unravelling the stratigraphy of the area. The "Pyrite Zone" argillite and other argillites occurring within the stratigraphic section at Bulyanhulu are easily traced by IP and EM surveys.

In 1996 Pangea Minerals became interested in the Tulawaka area after the interpretation of Landsat imagery and a Government of Tanzania aeromagnetic survey. As a result, a regional 1 kilometre by 100 metre, Bulk Leach Extractable Gold (BLEG) soil sampling program was initiated revealing several significant gold-in-soil anomalies. Two large virgin gold-in-soil geochemical anomalies were found at Matabe and Tulawaka. Matabe (also known as Kakindu), the larger of the two anomalies was overrun by thousands of artisanal miners who were evicted after 18 months, only after having depleted a rich eluvial gold cap rendering the deposit uneconomical for further development. Infill soil sampling was followed by RAB, RC and limited diamond drilling. In 2000 Barrick Gold acquired the project through its takeover of Pangea Minerals. The Tulawaka East Zone was identified as the main target. Based on a total metreage of 64,000 metres of drilling in 755 holes, a resource of 0.771 million ounces at a grade of 11.11 g/t Au was estimated: the resource was converted to Proven and Probable Reserves of 0.546 million ounces at 12.19 g/t Au.

Small scale underground mining in the North Mara area was active between the 1930s and 1970s (e.g. Mara Mine, Nyabirama, Komerera and Golden Glory). Local artisanal mining was ongoing through the 1980s. In 1987 a substantial artisanal gold rush occurred at Nyabigena following a discovery by a shepherd. It is estimated that approximately 3 tonnes of gold were recovered by these operations (Stewart *et al.*, 2001). In 1993 Afrika Mashariki Gold Mines (AMGM) recognised the lack of previous modern exploration conducted in the North Mara area and applied for 500 square kilometres of exploration tenements. Drilling beneath artisanal workings commenced in 1993 resulting in discoveries at Nyabirama and Nyabigena. By June 1996 gold resources of one million ounces had been defined. Ongoing exploration

continued to add resource and reserve ounces and by the end of 2001 resources had increased to 3.8 million ounces and reserves to 1.9 million ounces. Gokona lies beneath 6 to 40 metres of Tertiary lava approximately 600 metres west along strike from the Nyabigena deposit. It was discovered by an IP survey followed up by reconnaissance reverse circulation drilling. The IP technique was used due to the significant silicification (potassic feldspar/silica) and sulphidation (pyrite/arsenopyrite) observed in association with the gold mineralisation at the Nyabigena deposit. An initial resource of some 700,000 ounces grading 5.4 g/t Au was defined in December 2002, just over 12 months after the discovery hole. By December 2002 identified gold resources of approximately 4.4 million ounces and 3 million ounces of reserves had been delineated within three open-cut deposits (Nyabirama, Nyabigena and Gokona).

The exploration history of the Golden Pride project goes back to 1989 when Samax Resources was granted a prospecting license. At that time there were already artisanal miners exploiting shallow portions of the mineralisation. In 1994, Samax entered a joint venture with BHP Billiton to develop the mine but, in 1996, BHP decided not to progress with the project. Resolute then took over from BHP and subsequently acquired Samax's interests, as well. In September 1997, Resolute completed a feasibility study for the project with reported Proven and Probable Reserves of 1.39 million ounces grading 3.2 g/t gold.

The exploration history of Nyanzaga dates back to the colonial period when, in 1937, a gossan outcrop was identified on Tusker Hill. Modern exploration work at Nyanzaga was initiated in 1996 using soil sampling, rock chip (grab and trench) sampling, airborne magnetic and IP surveys. A strong gold in soil anomaly was identified at Tusker and Kilimani. Drilling at Nyanzaga started in 1997 for a total of 216,000 metres using a combination of diamond, RC and RAB/AC methods. In April 2012 African Barrick Gold (now Acacia Mining) announced a Mineral Resource estimate for the Nyanzaga Project of 4.6 million ounces Au, with 3.75 million ounces at 1.42 g/t Au in the Indicated and 0.85 million ounces at 1.81 g/t Au in the Inferred category. The estimates were made using a 0.45 g/t cut-off, a gold price of $1,400 per ounce and an estimated recovery of 86%.

Gold mineralisation at Golden Ridge was discovered in 1992 during a technical cooperation project between the German Federal Institute for Geosciences and Natural Resources (BGR) and the Geological Survey of Tanzania (MADINI).The deposit was detected by panning gully samples in the drainages derived from Golden Ridge. Follow-up bedrock sampling also returned anomalous results. Alerted by this activity, artisanal miners moved into the area and completed the discovery. The initial prospecting license was granted to TGG Mining Company Ltd in 1993. Pangea Minerals, through Pangea Goldfields Inc., a wholly owned subsidiary, optioned the property from TGG in 1994. Pangea mapped the licence and conducted limited soil geochemistry, trenching, ground magnetic, and IP programs followed up by drilling. Randgold Resources exercised an option agreement with Pangea Goldfields in 1995 and assumed management control of the property. Randgold completed a scoping study in 1996 reporting a (non-compliant) resource of 10.22 million tonnes at 2.44 g/t Au containing 0.8 million ounces Au to a depth of 100 metres. Barrick Gold Corporation purchased Randgold Resources' Tanzanian interests (Golden Ridge Exploration Pty. Ltd.) in 1999 and Pangea Minerals in early 2000 and continued exploration with systematic soil sampling, trenching, RC and diamond drilling. In 2011

a Mineral Resource of 677,000 ounces at 2.84 g/t Au Indicated and 93,000 ounces at 2.37 g/t Au Inferred was estimated. No further development has taken place on the property.

Future of the mineral field and exploration potential

For several years the LVG was seen as highly attractive for mining and exploration companies, with exploration expenditures in the year 1998 being the highest of any African country. However, the increased investment in exploration in the next decade did not lead to any large mines coming on stream after 2009. While a number of discoveries have been made, such as Golden Ridge and Nyanzaga, a higher gold price will be required to bring these deposits into production. The maturity of the LVG also requires new exploration ideas and technologies. The fact that many Archaean greenstone gold deposits worldwide have been shown to extend to depths of two kilometres or more suggests that one avenue is deeper exploration around existing deposits which possess high gold grades. Lower-grade, near surface deposits of the type exploited to date by open pit mining will be increasingly difficult to discover but the stockwork-disseminated deposits of similar setting and style to Gokona-Nyabigena may have been overlooked by prospectors and artisanal miners who have tended to focus on the more common quartz vein deposits.

Conclusions

The LVG is similar in most respects to Neoarchaean greenstone gold belts elsewhere in Africa, as well as globally. In specific terms, there are many geological parallels with the setting of deposits in the Zimbabwe Craton (Blenkinsop et al., 1997; Foster and Piper, 1993). These include a pre-2800 Ma greenstone sequence followed by a circa 2700 Ma upper volcanic unit (Upper Bulawayan) and ultimately by the circa 2650 Ma Shamvaian conglomeratic units which were considered analogues for the Kavirondian of the LVG by the colonial geologists. The Zimbabwe and Tanzanian Cratons share the remarkably similar dome-and-basin configuration (Blenkinsop et al., 1997) of cuspate greenstone segments in extensive bodies of granitoid rocks. Most important, however, both terranes are noted for the fact that the major portion of the gold production has been derived from structurally controlled veins, shear zones and sulphidic replacement zones in iron-formation (Herrington, 1995). Similar comparisons of settings and styles of mineralisation can also be found in the Superior and Yilgarn Cratons (Robert et al., 2005) and globally, the LVG represents an important contribution to the "Late Archaean Bonanza" (Barley et al., 1998) which saw a major introduction of gold to the Earth's crust in a relatively short period of time. One of the geological differences between the LVG and the other examples, however, is that it is a comparatively felsic terrane in terms of its igneous rocks. Although komatiitic rocks have been recognized locally by the authors in western Kenya, ultramafic rocks in general are rare whereas felsic volcanic, volcaniclastic and granitic rocks are dominant in much of the LVG.

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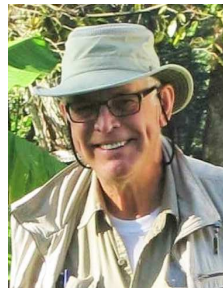
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