The geology of the giant Nyankanga gold deposit, Geita Greenstone Belt, Tanzania

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Abstract

Nyankanga gold deposit is the largest gold deposit found in Geita Greenstone Belt of northern Tanzania Craton. The deposit is hosted within an Archean volcano-sedimentary package dominated by ironstones and intruded by a large diorite complex, the Nyankanga Intrusive Complex. The supracrustal package has been fragmented by the intrusion of diorite, and associated igneous rocks forming the Nyankanga Intrusive Complex, and is now included within the intrusive complex as roof pendants. The ironstone fragments contain evidence of multiple folding events that occurred prior to syn- intrusion of Nyankanga Intrusive Complex. The entire package is cut by a series of NE-SW trending, moderately NW dipping shear zones with a dominant reverse component of movement but showing multiple reactivation events with both oblique and normal movement components. One of these shear zones, the Nyankanga Shear Zone, developed mainly along the ironstone-diorite contacts and is mineralised over its entire length. The gold mineralization is hosted within the damage zone associated with Nyankanga Shear Zone by both diorite and ironstone with higher grades typically occurring in ironstone. The mineralization is associated with sulfidation fronts and replacement textures in ironstones and is mostly contained as disseminated sulphides in diorite. The close spatial relationship between gold mineralization and ironstones suggests that the reaction between the mineralising fluid and iron rich lithologies played an important role in precipitating gold. Intense fracturing and microveining, mainly in the footwall of Nyankanga Shear Zone indicates that the activity of the shear zone played an important role by increasing permeability and allowing the access of mineralising fluids. The entire package is cut by a series of NW trending strike slip faults and ~ E-W trending late normal faults which have reactivated Nyankanga Shear Zone and may have played a role in the mineralising event.

Keywords: gold deposits; Archean; Tanzania Craton; Nyankanga gold deposit; roof pendants

1. Introduction

Archean gold deposits are one of the most important sources of gold worldwide (e.g. Goldfarb et al., 2001). Important mining camps are found in the Yilgarn Craton of Western Australia, the Superior Province in Canada, the Quadrilatero Ferrifero in Brazil, the Dharwar Craton in India, and the Kaapvaal, Zimbabwe and Tanzania Cratons in Africa. Except for gold deposits linked to intra-cratonic basins of which the Witwatersrand gold deposits are by far the largest, the bulk of Archean gold deposits are hosted within, or adjacent to greenstone belts, and share a series of common features commonly linked with orogenic gold deposits (e.g. Grooves et al., 1998). Such common features include: strong structural controls and an association with shear zones within greenschist to lower-amphibolite facies terrains, a hydrothermal origin with low-sulphidation ore assemblages and associated quartz and carbonate alteration, with the main ore forming events being late-tectonic (e.g. Grooves et al., 1998; Goldfarb et al., 2001; Bateman and Bierlein, 2007). By grouping these deposits as orogenic gold deposits it is implicitly assumed that tectonic processes in the Archean were essentially the same as plate-tectonic settings seen today (e.g. Bierlein et al., 2009); a premise that remains contested (e.g. Dirks et al., 2013; Bedard et al., 2013; Gerya, 2014). These deposits are therefore also commonly described with the less generic term Archaean lode gold.

Any rock type can host Archaean lode gold deposits (e.g. Anhaesser et al., 1986; Laznika, 2014), but in general most large deposits are found within the volcano-sedimentary greenstone sequences as opposed to nearby granite and gneiss units (e.g. Goldfardb et al., 2001; Laznika, 2014). Large deposits such as Kalgoorlie camp in Australia (e.g. Weinberg and van der Borgh, 2008; Blewett et al., 2010), Timmins camp in Canada (e.g. Robert and Paulsen, 1997; Gray and Hutchinson, 2001), Kolar gold field in India (e.g. Mishra and Panigrahi, 1999) and Bulyanhulu in Tanzania (e.g. Chamberlain, 2003) are intimately associated with mafic metavolcanics. Although there are many Archean BIF (banded iron formation) hosted deposits around the world very few have produced or contain large gold deposits (Steadman et al., 2014).

The geological literature on the Geita area of North West Tanzania is extremely limited in spite of the fact that has been recognised to contain a high density of world class/giant BIF hosted gold deposits (e.g. Goldfarb et al., 2001). The Geita Greenstone Belt hosts at least 10 separate gold deposits with historical production and estimated reserves of over 0.5 million ounces each, but only the Geita Hill gold deposit has been described in the geological literature (Borg, 1994). This description was based on underground workings that were operated between 1935-65; i.e. before the re-opening and massive expansion of mining in the Lake Victoria gold field. The Geita Hill gold deposit was described as a shear-zone hosted lode gold deposit hosted in an ironstone dominated supracrustal package intruded by diorite dykes and sills (Borg, 1994).

By far the largest gold deposit within the Geita Greenstone Belt, the Nyankanga deposit, occurs 1.5km to the SW of the Geita Hill deposit (Fig. 2). The Nyankanga gold deposit was discovered in 1995 based on a weak soil anomaly, which was drilled in 1996. The deposit is located along the same 5km long, NE trending mineralised zone as the Lone Cone deposits. Reported reserves in 2002, at the start of mining, for the Nyankanga gold deposit included 6.3 Moz @ 5.42 g/t (open pit), and 1.04 Moz @ 8.12 g/t (underground) (Marjoribanks, 2003) with significant reserves added by further exploration and with open potential at depth. Although, various aspects of the geology of the deposit have been described and interpreted in a series of internal reports (e.g. Ryan and Speers, 2002; Porter, 2003; Skead et al., 2003; Marjoribanks, 2003; Painter, 2004; Krapez, 2008; Basson, 2010; Brayshaw, 2010; Kolling, 2010; Nugus and Brayshaw, 2010), a formal description of the deposit is missing from the geological literature. In this contribution we present a comprehensive description and interpretation of the main factors controlling the gold mineralization in the giant Nyankanga gold deposit.

2. Regional geology

The northern half of the Tanzanian Craton contains a series of roughly E-W trending, narrow segments of NeoArchean (e.g. Kabete et al., 2012; Sanislav et al., 2014) greenstone belts separated and surrounded by granitoid intrusions and gneiss terrains (Fig.1), that are intrusive or sheared contact with the greenstone sequences. The stratigraphy of the greenstone belts has been subdivided into two main units, namely the Nyanzian Supergroup and the Kavirondian supergroup (e.g. Quennel et al., 1956; Gabert, 1990). The Nyanzian Supergroup has been further subdivided into Lower Nyanzian and Upper Nyanzian Groups. The Lower Nyanzian is dominated by mafic volcanic units (amphibolite, pillow basalt, minor gabbro) and overlain by the Upper Nyanzian which is dominated by felsic volcanic and pyroclastic units inter-bedded with banded ironstone, volcaniclastic sequences and immature turbiditic sediment (Kuehn et al., 1990; Borg, 1992; Borg and Shackelton, 1997; Borg and Krogh, 1999; Krapez, 2008). The Nyanzian Supergroup is unconformably overlain by the Kavirondian Supergroup, which consists mainly of coarse grained conglomerate, grit and quartzite. Underlying the supracrustal greenstone units is the Dodoman Supergroup, which consists of high-grade mafic and felsic granulite with subordinate lower-grade schist and thin slivers of greenstone (Kabete et al., 2012).

The overall stratigraphy and structural complexity of the greenstone belts and intervening granite-gneiss has not been described in detail and is generally poorly understood. For example the Sukumaland Greenstone Belt (Fig. 1) has been described as an arcuate-shaped belt in which intrusions of syn- to post-tectonic granitoids divide the belt into an inner arc dominated by mafic volcanic rocks and an outer arc dominated by banded ironstone, felsic tuff and volcaniclastic sediment (Borg et al., 1990; Borg, 1994). This subdivision may be too simplistic as indicated by the occurrence of abundant mafic units in the outer arc and abundant sediment and felsic volcanic intercalations in the inner arc with age distributions that are inconsistent with the original stratigraphic interpretations (e.g. Cloutier et al., 2005; Manya and Maboko, 2008).

The Geita Greenstone Belt (GGB, Fig. 2) constitutes an E-W trending segment of greenstone units situated directly south of Lake Victoria and forming the central northern part of the outer arc of the Sukumaland greenstone belt as defined by Borg et al. (1990). The greenstone belt is bounded by undeformed 2660 and 2620 Ma granites to the north, east and west (Sanislav et al., 2014), and by gneiss to the south. The contact of the greenstone mafic metavolcanics and the gneiss occurs along a steeply dipping E-W trending shear zone. The geochemistry and whole rock Sm-Nd ages for mafic metavolcanics within the SW part of the Geita Greenstone Belt indicate a MORB-like affinity and model ages of ca. 2823 Ma (Manya and Maboko, 2008). Their geochemistry and model ages are similar to those of the mafic metavolcanic units occurring further south of GGB (Manya and Maboko, 2003) suggesting that the greenstone units in Sukumaland Greenstone Belt may form discontinuous remnants of a once much more widely distributed greenstone sequence, now separated by intrusive granite batholiths (Manya and Maboko, 2008). The remainder of the Geita Greenstone belt is dominated by banded ironstone intercalated and overlain by turbiditic metasedimentary units (ranging from mudstone to rare conglomerate) with volcaniclastic beds, and intruded by diorite dykes and sills, and late granitoids. Borg and Krogh (1999) dated a trachyandesite sub-parallel to bedding (and interpreted as an extrusive unit) from Geita Hill, at 2699±9 Ma providing an estimate for the depositional age of the sedimentary sequence in the area; although it must be noted that the unit they dated was probably a fine-grained dioritic sill and not an extrusive unit (Sanislav et al., 2015). NE-striking, Neoproterozoic dolerite dykes cross-cut the GGB.

3. Host rock types

3.1. Sedimentary Rocks

The Nyankanga gold deposit (Fig. 3) is contained within a magnetite-rich sedimentary package (the ‘ironstones’ Fig. 2) consisting of inter-bedded sandstone-siltstone units locally intercalated with laminated chert and conglomeratic sandstone beds and overlain by a thick succession of epiclastics turbidite. The sedimentary succession was intruded by various generations of diorite, lamprophyre, feldspar and quartz porphyry, and has been metamorphosed to low greenschist facies. The ironstones are magnetic and contain at least three texturally distinct generations of magnetite. Primary sedimentary magnetite occurs as fine laminations within shale or chloritic mudstone beds intercalated with chert or fine-grained siltstone. Primary magnetite banding is generally continuous along strike but locally occurs as lenses associated with flaser-like textures. The second generation of magnetite is hydrothermal and forms zones of magnetite enrichment near and along shear zones. Because many shear zones are sub-parallel to bedding (see below) this generation of magnetite may resemble sedimentary magnetite, but can be distinguished by locally crosscutting bedding at a low angle and by bifurcations. The third generation of magnetite is remobilised sedimentary or hydrothermal magnetite present along crosscutting veins and fractures.

The ironstones can be subdivided into three stratigraphic units or lithofacies with both lateral and stratigraphic transitions observed. The lower most ironstone unit is about 3 m thick and consists of intercalations of graphite-rich magnetic shales or siltstone and laminated chert (Fig. 5a). The middle unit consists of poorly bedded magnetite and chert intercalations. The unit is usually dark-grey in colour and the chert beds are typically translucent pale-grey (Fig. 5b). The upper ironstone unit consists of laminated intercalations of silty, chloritic clastic sedimentary rocks interbedded with chert (Fig. 5c). Magnetite is present along the contact between chert beds and the overlaying clastics beds. This unit is usually dark-green in colour with planar, thin laminations. In general the boundaries between each of these units are gradational. Banded magnetite-chert units may occur within laminated ironstone or laminated ironstone within banded chert-magnetite. These ironstone rich units are intercalated with tens of centimetre- up to few meter-thick beds of epiclastic siltstone and coarse grained pebbly sandstone to conglomerate. Similar epiclastic units are present above the ironstone-rich unit where the thickness of individual beds can be in the range of tens of meters. The dominant lithology consists of fine grained chloritic-feldspathic quartzo-feldspathic sandstone and locally conglomerate. Pebble size fragments are common within the sandstones and many beds may contain intraformational fragments of chert and mudstone. Coarse- to very-coarse grained sandstone is found as lenses within thicker beds. The sequence is commonly graded (Fig. 5d), can be massive or stratified and erosional bases and flame structures are commonly preserved. Some sandstone beds grade up to siltstone, shale or magnetic shale and chert. In these situations the magnetic-rich shale and chert represent tens of centimetre thick intervals that overlie the sedimentary sequence. The quartzo-feldspathic sandstone has a detrital matrix composed of rounded quartz, feldspar, and mafic minerals, and may contain cobble size fragments of chloritic-feldspathic sandstones and plagioclase rich porphyries.

3.2. Igneous rocks

The host lithologies to the Nyankanga gold deposit (Figs. 3 and 4) are volumetrically dominated by a suite of intrusive rocks that include diorite (Figs. 5e and 5f) intruded by several generations of feldspar (Fig. 5g) and/or quartz porphyry (Fig. 5h) and lamprophyre dykes (Fig. 5j). Based on mineralogy, two main types of diorite have been identified in the Nyankanga deposit. These are plagioclase-rich diorite (Fig. 5e) and hornblende-rich diorite (Fig. 5f). Both varieties can be equigranular, or porphyritic with a range of matrix grain-size. The two types can grade progressively into each other and zones of hornblende-rich diorite can be found within plagioclase-rich diorite and vice versa; suggesting that this mineralogical variation is the result of magmatic differentiation rather than indicating different timing relationships. Some of the porphyritic diorite may contain up to 20% potassic feldspar in the groundmass suggesting a transition into monzodiorite towards granodiorite. The lack of chilled margins, pepperite microstructures or any sign of soft sediment interaction suggest that the diorite intruded at depth.

The felsic porphyries are light to medium grey in colour with obvious feldspar and/or quartz phenocrysts. Their matrix is usually fine-grained and contains quartz, plagioclase and amphibole. They are present usually as dikes.

Lamprophyre dykes are only minor occurrences in Nyankanga deposit, occurring as ~ 1 m wide dykes. They are light to dark brown in colour and contain abundant biotite, hornblende and calcite in the matrix and as veins.

4. Structural setting and intrusive history of Nyankanga gold deposit

The geology of Nyankanga gold deposit and the surrounding geology is dominated by a large, composite dioritic intrusive complex (Nyankanga Intrusive Complex), which was intruded by a series of felsic dykes (Fig. 4). Within Nyankanga pit there are 10-100m scale fragments of ironstone generally trending ENE-WSW and dipping moderately to shallowly NNW; i.e conformable to the regional trend of the surrounding greenstones. These ironstone fragments are wedge/tabular shaped, surrounded and intruded by diorite, and represent large country rocks clasts within Nyankanga Intrusive Complex. Their general orientation is similar to that of the surrounding country rocks suggesting that these large ironstone fragments have maintained their original orientation. Most of these ironstone fragments are fault bounded and one particular fault zone (the Nyankanga Shear Zone) is spatially associated with the gold mineralization. The ironstone unit contains a complex folding history prior to the development of Nyankanga Fault Zone. In the following section we document the sequence of folding and faulting that defines the structural setting of Nyankanga gold deposit.

D1- Bedding parallel foliation and shear (S0 and S1)

Bedding in ironstone is defined by mm- to cm-scale intercalations of chert and mudstone/shales locally interbedded with siltstone and sandstone beds. A fine penetrative cleavage (S1) is commonly developed within the mudstone/shale layers in ironstone. This cleavage is layer parallel, has been refolded during subsequent deformation events and may contain oriented chlorite. In Nyankanga gold deposit bedding has a general NE-SW trend and dips moderately to gently NW (average of 346°/44°; Fig. 6a). The variation in bedding orientation is due to a combination of folding, intrusion and faulting. Locally, the bedding planes contain rootless, isoclinal intrafolial folds (D1) which may reflect an early bedding parallel shear event.

D2-First isoclinal folding event

The bedding and S1 foliation are affected by several generations of folds, the earliest of which are referred to as D2 folds (Fig. 7a). D2 folds are generally isoclinal, non-cylindrical and show a wide dispersion in fold axis orientations that plot consistently along a great circle similar in orientation to bedding (S0). Because they are generally isoclinal, D2 folds are most clearly exposed, or most recognisable within D3 hinge zones. It is possible that high strain associated with D3 has further compressed and disrupted F2 folds turning them into parallelism to bedding especially along the limbs. Their isoclinal geometry suggest that actually in many situations layering may be a composite S0,1,2 structure.

D3- Dominant folding event

D3 folds (Fig. 7a) are the most common type of folds observed within ironstone rafts in the Nyankanga deposit. They are commonly asymmetric, cm- to m-scale, plunging inclined folds, with moderately NNE dipping axial planes. Throughout Nyankanga deposit F3 folds have a consistent Z-like asymmetry. This suggests that Nyankanga deposit lies on the SW limb of a NW plunging synform closing to the NE. In outcrops where the rocks are less altered and silicified, a spaced cleavage axial planar to the D3 folds is preserved. The cleavage dips moderately to steeply NNE (Fig. 6b; average 012°/67°) suggesting that the limb of the fold that contains Nyankanga deposit may be structurally overturned. The fold axis calculated from the bedding-cleavage intersection plunges 37° towards 301° which is similar to the fold axis calculated from bedding planes (43° towards 325°) and to the average D3 fold axes measured within the deposit (Fig. 6c; average 39° towards 316°). The dispersion in fold axes cleavage orientation is partly due to later fold overprints (see below).

D4 – Open upright folding

D4 folds (Fig. 7b) are common throughout the deposit and are cm- to 50m-scale open to closed, upright folds with near vertical, axial planes (270°/88°) and fold axes that plunge north between 10- 50°. They refold D3 folds and are locally associated with a spaced fracture cleavage parallel to the fold axial plane. In outcrop D4 folds locally display centimetre scale crenulation like geometries.

D5- Open recumbent folding

D5 folds are gentle, rarely open, recumbent folds that have a spaced sub-horizontal (0° to <30°) axial planar fracture cleavage. They refold earlier fold structures (e.g. Fig. 7c), and are associated with small reverse movements along axial planar fracture cleavage planes.

D6- Brittle-ductile shear zones and the Nyankanga Shear Zone

Nyankanga gold deposit is cut by a number of moderately NW to N dipping D6 shear zones (Fig. 8a) with a dominantly reverse movement (Figs. 8b and 8c), one of which is a narrow (0.05-2m wide) semi-ductile shear zone with a strike-length of at least 1.5km spatially related to gold mineralization and referred to as the Nyankanga Shear zone (Fig. 4). In general, the major shear zones dip moderately NW (Fig. 6d; average 335°/34°). The Nyankanga Shear Zone consists of an anastomosed array of sharp discontinuities that form discrete slip surfaces, which occur together with complex vein arrays, foliation domains defined by orientated mica (mainly chlorite) and pressure solution seams. Narrow, steeper-dipping shear zones link the imbricate thrusts to form a complex, anastomosing network of shear zones that occur throughout the large open pit at Nyankanga. Only some of these D6 shear zones are associated with mineralisation.

Within the Nyankanga shear zone, duplex arrays of slip surfaces at 0.1-1m scale occur within an anastomosed system, with horses separated by shallow-dipping surfaces with reverse slip and the same dip-direction as the shear zone envelope. The shallow dipping slip planes within the shear zone are widely spaced, and usually connect the upper and lower boundaries of the shear zone, leading to internal segmentation of the Nyankanga Shear Zone. The shear domains between the discrete slip surfaces are mostly narrow (0.01-0.3m) and consist of a combination of foliated domains preserving S-C fabrics (Fig. 8b) and domains dominated by gouge of broken rock in a clay matrix. The S-C fabrics consistently show reverse movement (Fig. 8b) along the Nyankanga Shear Zone. Most of the discrete slip planes that separate or occur as discontinuities within the foliated domains, contain shallowly-pitching, quartz slicken-fibres (Figs. 6e and 8c; average 31° towards 309°), consistent with dip slip reverse-sinistral movement. Many slip planes display evidence of overprinting slicken-fibers indicative of oblique slip (Fig. 6e). These lineations are shallowly plunging WSW or NNE and may have both normal and reverse components associated with the oblique movement. Overprinting these oblique slip lineations is a third set of lineations and steps consistent with a normal component of movement (Fig. 8d).

The system of D6 shear zones is most clearly developed within diorite and along diorite-ironstone contacts. In general the shear zones widen in areas dominated by ironstone, with damage zones extending into the sediments over several meters. Inversely, shear zones narrow within diorite. There is an array of steep veins and hydrothermal breccias associate with Nyankanga Shear Zone that is best developed in diorite in the proximity of ironstones enclaves (Figs.8a and 8e). .

The complex fabric relationships encountered within the D6 shear zones and the presence of multiple shear sense directions indicate the multi-staged history of the D6 shear zones.

D7- Sinistral and dextral shear zones

The intrusive rocks and the ironstones are cut by a series of steeply dipping dextral and sinistral shear zones (Figs. 3, 8f and 9a) with a distinct NW trend (Fig. 6f) which is similar to the one observed from the regional geological map (Fig.2) suggesting that they may have a regional significance or are related to the major NW trending regional shear zones. Associated with these NW trending shear zones is a subset of moderately to shallowly NW dipping sets of faults (Fig. 6f). These NW dipping faults are very similar in orientation to the Nyankanga Shear Zone and D6 shear zones but they have a limited extend and no associated shear fabric (e.g. S-C fabrics). However, they may indicate that D6 shear zones are secondary structures associated with the regional D7, NW trending, shears that bound Nyankanga deposit (e.g. Ryan and Speers, 2003; Painter, 2004). Alternatively, they may be related to the reactivation of D6 structures by D7 deformation. To the west of Nyankanga deposits a regional NW trending dextral strike slip shear zone (Fig. 2; Iyoda Shear in mine terminology) cuts and displaces the entire ironstone package and was interpreted to have played an important role in the development of Nyankanga Shear Zone and gold mineralization (Porter, 2004). This major shear zone is poorly studied so its full potential in gold mineralization is yet to be established.

D8 – Normal faults

Throughout the deposit there is a set of well-developed steeply dipping, ~ E-W trending, faults (Fig. 9b) that have a consistent normal component of movement with maximum a few meters observed displacement (typically less than 1 meter). The individual faults are 1-2 cm wide but can form up to a few meters wide deformation zones. They have a clay dominated gauge and a set of carbonate, pyrite and carbonate-pyrite association of thin veins within the deformation zone. They reactivated and displaced (centimetres to maximum one meter) D6 and D7 structures.

4.1. Intrusive sequence in relation to deformation

The Nyankanga gold deposit is dominated by a complex diorite intrusion, which in turn was intruded by feldspar and quartz porphyry dykes (Figs 3, 4). The low volume of sedimentary rocks present in the deposit makes the timing relationship between the main diorite and deformation less clear. In general the diorite-ironstone contact (average 321°/44°) parallels the bedding orientation (average 336°/44°) (Figs. 6a and 6g). It is common for the main diorite to contain enclaves of folded ironstone (Figs. 4 and 9b) preserving F3 folds. In the

Nyankanga deposit there is no clear evidence of diorite dykes being folded during D3 which suggests that the main stage of diorite intrusion occurred syn- to post-D3.

In the nearby Geita Hill and Lone Cone deposits (Fig. 2) diorite dykes that form part of the Nyankanga Intrusive Complex are folded by F3 folds indicating that the emplacement of Nyankanga Intrusive complex started before the onset of D3 deformation. Figure 9a shows the timing relationships between a hornblende diorite, a lamprophyre, a plagioclase diorite and F3 folds in the northwestern side of the deposit. The hornblende diorite parallels the bedding and possibly intruded during D3. The lamprophyre dyke cuts across the bedding and F3 folds, and the plagioclase diorite cuts the lamprophyre dyke along a fracture with a reverse sense of movement. Although this particular relationship suggests that hornblende rich diorite is earlier than plagioclase rich diorite, there are many situations where zones of plagioclase rich diorite are intruded by small dykes of hornblende rich diorite (Fig. 4) and vice-versa suggesting that the intrusion of hornblende and plagioclase rich diorite varieties alternate. Figure 4 shows a hornblende rich diorite dyke that intruded into the main diorite and cuts across the ironstone fragments at a low angle.

The feldspar and quartz porphyry dykes trend NE-SW and dip at slightly steeper angles than the average orientation of the bedding (Figs. 6a and 6h). The quartz porphyries generally dip steeper than and cross-cut the feldspar porphyries. D6 thrusts appear to have played a role in the emplacement of feldspar and quartz porphyries in the sense of providing the structural discontinuities along which these dykes have been emplaced. This is particularly obvious in the case of feldspar porphyries which become shallower when intersecting the Nyankanga Fault Zone, run sub-parallel to the fault zone and sometimes within the fault zone, and then cut across. Feldspar porphyries within Nyankanga Shear Zone have sheared margins with a normal component which is similar to late phases of movement along the shear zone. Both feldspar and quartz porphyries are cut and displaced by D7 dextral and sinistral shears and by D8 normal faults (Fig. 9b) indicating that they have been emplaced between D6 and D7.

5. Alteration features

5.1. Alteration halo

The alteration in the Nyankanga deposit displays a systematic change in mineralogy with distance from the mineralisation, and can be subdivided into three main alteration zones: a distal zone, a transitional zone and a proximal zone. Distal alteration is characterised by the association chlorite-epidote-calcite±actinolite-pyrite±pyrrhotite and is best developed in diorite, where it can be seen to overprint primary igneous textures. In the diorite, chlorite replaces primary biotite and hornblende while epidote replaces mafic minerals and plagioclase. Calcite occurs both as disseminations and calcite-pyrite or calcite-chlorite±epidote-pyrite veins. In ironstone this alteration zone is less prominent, but it can be recognised by the presence of chlorite in shale, actinolite near magnetite bands and rare calcite-chlorite-pyrite±pyrhotite veinlets (Fig. 10a).

The transitional alteration zone is characterised by biotite-chlorite-calcite±pyrite association. The difference between the distal alteration zone and the transitional zone is the appearance of biotite and increased abundance of calcite. Thin veins of biotite and associated thin biotite haloes occur throughout this zone. Within diorite, the transitional zone is further characterised by the appearance of biotite which replaces primary hornblende. Calcite±quartz-biotite-chlorite-pyrite veins occur throughout this zone (Fig. 10b).

Within the proximal alteration zone the dominant mineral association is quartz-calcite-dolomite/ankerite-hematite-pyrite-biotite. In diorite, biotite replacement of mafic minerals is common, and is associated with fine-grained, disseminated magnetite. Increased alteration intensity within this zone has locally resulted in a complete overprint of primary igneous textures due to silicification, carbonation and/or sulfidation. This pervasive alteration is accompanied by an increased vein density and hydrothermal brecciation. Hematite is present up to moderate intensity (Fig. 10c) but is absent where the silica alteration is strongest. Carbonate minerals mainly consist of dolomite and ankerite with lesser amounts of calcite. In ironstone extensive replacement of magnetite beds/lamina by pyrite (Figs. 10d, 10e and 10f) occurs to the extent that the original sedimentary textures are destroyed. Hydrothermal breccias are a common feature in this alteration zone (Figs. 10d and 10e). Hydrothermal brecciation is most commonly developed at the contact between intrusive and sedimentary lithologies.

Late calcite±quartz±pyrite veins cross cut all alteration zones. A late hematite alteration overprint can be recognised in the barren feldspar and quartz porphyries with sericite commonly replacing feldspar phenocrysts.

5.2. Veins and breccia zones related to the alteration zones

Veins

Nyankanga gold deposit contains several generations and types of veins across a wide range of orientations (Fig. 6j) and compositions. In general vein thickness varies from microscopic to ~ 30 cm, but some veins are as thick as 1 m. Veins are typically lensoidal to irregular in shape, with incipient brecciation being common along their margins. The overprinting relationship between different vein types is difficult to establish (except locally) due to overall large variations in vein orientation and composition. However, some general overprinting relationships have been established for the main vein types (Fig. 11). The earliest set of veins are cherty in nature, constrained to the ironstone layers and may represent early diagenetic or D1, layer parallel deformation related features. They are overprinted by all other vein generations and are not directly related to gold mineralization. The earliest set of veins linked to the alteration halo consists of chlorite-calcite ±pyrite veins which are overprinted by biotite-hematite-pyrite±quartz veins. These two types of veins are common in the distal alteration zone and are not mineralised.

Within the intermediate alteration zone chlorite-calcite and biotite-hematite-pyrite veins are overprinted by calcite-quartz-biotite-chlorite±pyrite veins, which in turn are overprinted by biotite-dominated veins. These veins may contain low gold grades, but are mostly unmineralised. They have a low distribution density, at ~1-2 veins per meter, with each vein reaching a maximum thickness of 1 cm and being a few tens of centimetres long. More commonly they are a few millimetres wide and a few centimetres long.

Within the proximal alteration zone all previously mentioned veins are overprinted by pyrite-rich, calcite-quartz-dolomite-pyrite and quartz-dolomite-pyrite veins. These veins may contain good gold grades and are spatially associated with the highest grade zones, and may locally form a dense vein network. Late quartz-carbonate±pyrite veins overprint mineralization, the felsic porphyries and are barren.

Figure 6j shows a stereonet plot of poles to all vein measurements from Nyankanga gold deposit. Two main directions can be observed. That is a set of steeply SW dipping, NNW trending veins and a set of moderately to steeply NW dipping, NNE trending veins. A third set of moderately E dipping veins is less well-defined. In general, the steep NNW trending veins are quartz-carbonate-pyrite or pyrite-rich veins that cut across the diorite-ironstone contact. The quartz-rich variety is the most common vein type across the deposit and some of these veins can be traced for up to 150 meters length. Some appear to predate or be early syn-Nyankanga Fault Zone being displaced across the fault zone. The pyrite rich veins appear to be spatially associated to the Nyankanga Fault Zone. They are better developed in ironstone where they cut across bedding mainly at high angles with a sub-set cutting across bedding at a lower angle and thus being shallower (Figs. 12a and 12b). This steeply dipping, NW trending pyrite rich and quartz veins are may be associated with D3 fold hinge (Figs. 12a and 12b) zones and locally may appear to follow D3 folds axial planes but they are much steeper than the axial plane of D3 folds. The sub-horizontal quartz-carbonate veins (Figs. 12a and 12b) cut across all vein sets and geological boundaries. Figure 12c shows an example where a set of steeply dipping NNW trending quartz-carbonate veins are truncated by moderately dipping, NNE trending quartz-carbonate veins that developed along a set of fractures that cut across and displace the NNW trending veins. The NNE trending veins have a similar average orientation to Nyankanga Shear Zone and are much better developed in the footwall of the fault zone suggesting a genetic link between the movement of the fault and the formation of these veins. As a general rule NNW trending quartz-carbonate veins appear to predate the NNE trending quartz-carbonate veins. However, the timing relationships between vein sets with different orientation may be more complicated. Measurement of vein orientation within the immediate vicinity of the Nyankanga Fault Zone shows a large variation in orientation and many conflicting overprinting relationships.

Breccia zones

Hydrothermal breccia zones are common in both diorite and ironstone. The breccias are almost exclusively developed in footwall rocks to the Nyankanga Shear Zone (Figs. 8 and 12d). They commonly have a jigsaw texture with rock fragments being cemented mainly by massive quartz with important infill of sulphide and carbonate. The breccia zones are generally surrounded by zones of intense stockwork veining (Figs. 8 and 12d) suggesting timing and genetic relationships between breccia formation and veining. Within the breccia zones veins of similar composition but different orientations can be identified. The breccia zones are usually tabular shaped, forming 2 to 4 m and 0.5 to 2 m long zones developed at high angles to lithological contacts and the Nyankanga Shear Zone. In general the long axes of breccia zones appear to plunge shallow W to SW. A distinct breccia horizon that was modelled based on pit mapping and core logging has a tabular shape, about 100 meters long, 40 meters wide and 3 to 7 meters thick, dips ~35° NE and the long axis is ~ E-W plunging 15° towards 280°. The overall shape of breccia zones (Figs. 12d and 13) and their almost exclusive location in the footwall of Nyankanga Shear Zone are consistent with brecciation occurring when Nyankanga Fault Zone was reactivated as a normal fault.

6. Gold mineralization

6.1. General characteristics

In general the gold mineralization in the Nyankanga deposit occurs in close spatial proximity to the Nyankanga Shear Zone with the bulk of the mineralization being located in the footwall (Fig. 4). The ore envelope at a cut-off grade of 0.5 g/t is tabular with a shallow, ~22°, W to NW dip, i.e. ~10° shallower than dip of Nyankanga Shear Zone. However, steeper mineralised zones up to 10 m thick are common and have a shape resembling imbricate splays in the hanging wall. The mineralization is preferentially located along ironstone-diorite contacts with high grade zones normally hosted by mineralised ironstone enclaves. Within diorite, mineralisation is generally lower grade and more disseminated across dispersed, stockwork zones. As a general rule high grade ore zones usually occur below Nyankanga Shear Zone and have steeper dip than the overall mineralization and the shear zone, and a shallow plunge towards SW and WSW.

Gold mineralization is intimately associated with fine-grained pyrite growth and silicification. In the ironstone enclaves, pyrite mineralization occurs as disseminations and stringers preferentially overprinting magnetite bands and occurring along magnetite-chert bedding contacts. In diorite, pyrite occurs as fracture fill in quartz/calcite/dolomite-pyrite veinlets and stockworks. In areas of higher ore grades, pyrite is finely disseminated throughout the groundmass with pervasive silica replacement. Within the proximal alteration halo there is a good relationship between zones of high ore grade and zones of brecciated ironstone characterised by extensive quartz veining and a high degree of sulfidisation. Zones of mineralised brecciated ironstone dip in general 35° NE and plunge ~ 15°W. Breccia zones within the diorite are mineralised but generally at lower grades than the ironstone breccia zones, with a steeper dip and a plunge of ~ 10 SW. There is also a good relationship between high grade mineralised zones and undulations of the fault zone that have produced dilatational jogs that permitted higher fluid influx. Where the Nyankanga Fault Zone is steeper the high grade ore zones are thinner and shallower and where the fault zone is shallower the high grade ore zones become steeper and wider. Mineralised zones are characterised by very sharp upper and lower contacts that commonly display narrow quartz breccia zones and intense pyrite alteration.

Based on the local geology controlling the individual ore zones, a few different mineralisation styles can be distinguished. High grade ore shoots usually are related to disseminated ironstone hosted mineralisation and fault-bound breccia and quartz veins. The disseminated mineralisation style is characterised by sulphide altered silicified ironstones with quartz-magnetite-pyrite±hematite alteration. The fault-bound quartz veins and breccia mineralization style form distinct domains in footwall of Nyankanga Shear Zone usually with a steeper orientation than the fault surfaces. The ore mineralogy is dominated by pyrite bearing quartz±carbonate cemented breccia and veins. Medium grade ore zones are usually related to bedding parallel small shear zones overprinted by thin vein arrays and with the mineral association quartz-magnetite-pyrite±hematite. The low grade ore zone are usually dominated by planar sheeted veins developed mainly in the footwall of Nyankanga Shear Zone and a quartz-carbonate-pyrite-chlorite-biotite assemblage.

In the hanging wall to Nyankanga Fault Zone there are a series of discontinuous low grade mineralized zones associated with reactivated thrusts having a similar orientation and history to Nyankanga Shear Zone.

6.2. Timing of gold mineralization in relation to structure and intrusive rocks

Gold mineralization in Nyankanga gold deposit is spatially associated with Nyankanga Shear Zone and hosted by ironstone and diorite. The bulk of the mineralization sits in the footwall of Nyankanga Shear Zone but some occurrences of isolated and discontinuous zones of low grade mineralisation are found in the hangingwall associated with shear zones along ironstone-diorite contacts that have a similar orientation to Nyankanga Shear Zone. The ironstone units hosting the mineralisation are complexly folded with D3 folding events being the most pronounced. D6 structures and the Nyankanga Shear Zone cut across the ironstone fragments at a low angle while the mineralised envelope (≥ 0.5 ppm) also appears to cut across the ironstones contacts at a low angle. This suggests that the gold mineralization postdates the ductile deformation recorded within the ironstone fragments. Both plagioclase diorite and hornblende diorite host gold mineralisation thus the emplacement of diorite predates gold mineralisation. Feldspar porphyries within Nyankanga Shear Zone contain low grade mineralization indicating a syn to late mineralization emplacement or contamination during emplacement. Quartz porphyries are barren and interpreted to postdate mineralization. Both feldspar porphyries and quartz porphyries are crosscut and displaced by D7 and D8 structures. However, these structures are not mineralised outside the mineralised zone but may have played a role in reactivating Nyankanga Shear Zone thus the gold mineralization must have occurred somewhere between D6 and D8 deformation events.

6.3. Relationship between veins, breccia zones and mineralization

Quartz-carbonate-pyrite, carbonate-quartz-pyrite and pyrite rich veins within and near mineralised zones are the only vein types that are mineralised. Chlorite, biotite (small and low density veins) bearing veins are not mineralised. Some of the steeply dipping NNW trending quartz veins may contain up to 5 ppm Au or more even when sampled away from the mineralised zone. An analysis of vein density versus gold grade (Nugus and Brayshaw, 2010; the veins were counted for each meter and plotted against gold grades) reveals that although locally a correlation between gold and vein density exists this is not a rule thus gold mineralization can occur in zones with low vein density. Figure 14 shows the relationships between vein density and gold grades from two drill holes passing through the mineralised zone. Figure 14a shows that there is a good correlation between the mineralised zone and increased vein density, the gold content increases where the vein density increases. However, this correlation is valid only within the vicinity of Nyankanga Shear Zone. Figure 14b shows that although there are zones of good correlation between gold grades and vein density there are also zones of high vein density and low gold grades or zones of high gold grades and lower vein density. Figure 14c shows a selection of pyrite rich vein only versus gold grade from an area dominated by quartz veins. There is more consistent relationship between pyrite rich veins density and gold grades. The analyses also show that the relationship between vein density and gold grades is strengthened or exists only in the proximity of Nyankanga Shear Zone.

Breccia zones adjacent to Nyankanga Shear Zone are mineralised. However, there is no generic relationship between high grade and breccia zones. As a general rule breccia zones developed in ironstones are more prone to contain high grade than breccia zones developed in diorite but there is no direct correlation between high grade mineralization and the extent of breccia in either lithology. Figure 13 shows an example of breccia zones developed mainly in the footwall diorite and its relationship to mineralization. The breccia zone lies at a high angle to Nyankanga Fault Zone. The breccia zone adjacent to the Nyankanga Fault Zone contains mainly low grade mineralization, further away there is a zone of medium grade which sharply passes into unmineralised breccia. Near the ironstone contact there is a small sub vertical breccia zone that is transected by both a medium and a high grade envelope surrounded by unmineralised diorite and ironstone. The high grade zones in diorite are near the breccia contact, they transect Nyankanga Fault Zone and are mainly related to the disseminated mineralization style.

7. Discussion

Two factors appear to have been essential for gold deposition in Nyankanga gold deposit: the host rock type which acted as chemical traps and the geometry and location of Nyankanga Shear Zone which acted as structural trap and possibly fluid conduit.

7.1. The role of iron rich lithologies in gold deposition (chemical traps)

The gold mineralization in Nyankanga gold deposits is entirely hosted within sulfidised wallrock; that is diorite and ironstone. Depending on the dominant type of Au-complex, the mechanism of gold precipitation may involve one or more of the following mechanisms: increase or decrease in pH, change in O_2 and S_2 fugacity, change in the activity of O_2, Cl^- or H_2, change in pressure and/or temperature, fluid mixing and boiling. Assuming that gold was transported in solution as bisulfide complexes changes in temperature and pressure can be eliminated as the cause of gold precipitation. That is because gold solubility from bisulfide complexes changes very little with temperature (e.g. Hayashi and Ohmoto, 1991; Gilbert et al., 1998) and there is no clear evidence of PT changes at the scale of Nyankanga deposit; the proximal alteration assemblage is the same throughout the deposit and of similar grade with the surrounding country rocks. Sulfidation of the wall rock, as the main gold precipitating mechanism, implies change in oxygen and hydrogen fugacity at given PT and consistent water activity and sulphur fugacity (e.g. Candela and Piccoli, 2005; Zhu et al., 2011). The most effective way to precipitate gold is to decrease the activity of reduced sulphur (e.g. Seward, 1973; Likhoidov et al., 2007). This can be done by dilution, oxidation, boiling or by precipitation of sulphide minerals with Fe-rich wallrock. The intimate association of gold with sulphide minerals (gold in pyrite rather than free gold) and the strong spatial correlation between gold mineralization, sulfidation fronts and Fe-rich ironstones and diorite suggest that sulphide deposition by interaction of mineralizing fluid with the chemically reactive wall rocks was an important mechanism in the formation of Nyankanga gold deposit. However, other factors contributing to sulphide minerals deposition, such as boiling, should not be excluded given the presence of mineralized hydrothermal breccias in both diorite and ironstones.

7.2. The role of Nyankanga Shear Zone

The mineralization in Nyankanga gold deposit is spatially related to Nyankanga Shear Zone and hosted within the surrounding damage zone. This close spatial association between Nyankanga Shear Zone and the gold mineralization suggest a genetic link between the shear zone activity and gold deposition. However, Marjoribanks (2003) interpreted Nyankanga Shear Zone and the related shear structures to postdate gold mineralization, with gold mineralization occurring at the intersection of ironstone (and nearby diorite) with a series of sub-vertical NW trending quartz veins and fractures acting as feeders. These feeders exploited a series of closely spaced fractures formed during cooling of the main diorite body forming the Nyankanga Intrusive Complex. In this view Nyankanga Shear Zone postdates mineralization and displaces bedding, diorite contacts and the ore zone. Such a scenario does not explain the intimate association of Nyankanga Shear Zone and the mineralized envelope, the fact that Nyankanga Shear Zone is mineralised over its entire strike length with most of the mineralization found within its immediate vicinity and the fact that the ore zone is not fragmented by fault movement. Moreover, the steep NNW trending quartz veins are only locally mineralised and only within the vicinity of Nyankanga Shear Zone. Most models (Ryan and Speers, 2002; Skead et al., 2003; Painter, 2004; Brayshaw, 2010; Nugus and Brayshaw, 2010; Kolling, 2010) interpret Nyankanga Shear Zone as the mineralised structures playing an important role as a fluid conduit and as a structural trap for gold mineralization. Earlier models (Ryan and Speers, 2002; Skead et al., 2003; Painter, 2004) consider the mineralization in Nyankanga gold deposit to be related to the S-SSW directed thrusting that occurred along Nyankanga Shear Zone. Their interpretation is based on ore shoot plunges that are similar in orientation to the stretching lineations along Nyankanga Shear Zone. More recent models (Brayshaw, 2010; Nugus and Brayshaw, 2010) argue that gold deposition occurred during periods of extension when Nyankanga Shear Zone was reactivated as a normal fault, thus mineralization is late in relation to Nyankanga Shear Zone activity. This interpretation is based on kinematic indicators on slip surfaces showing normal movement that overprint earlier reverse kinematic indicators and on the orientation of breccia zones and veins in the footwall which are consistent with normal movement along Nyankanga Shear Zone. Kolling (2010) advanced the hypothesis that the ironstone units within Nyankanga Intrusive Complex are roof pendants and the competency contrast between the massive diorite and the polydeformed ironstone fragments played a vital role in localizing zones of deformation thus enhancing permeability and creating favourable structural and chemical traps along diorite-ironstone contacts. In this view Nyankanga Shear Zone does not represent a regional feature related to tectonic movement but rather a localized deformation zone due to competency contrast between massive diorite and ironstone. Such an idea is favoured by the preferential location of the shear zone along diorite ironstone contacts and by a lack of mappable displacement along Nyankanga Shear Zone over more than 10 years of open pit mining. Although there is some controversy about the particular role played by Nyankanga Shear Zone in gold deposition most authors agree that Nyankanga Shear Zone is the mineralised structure and most probably the fertile conduit structure. Late timing of gold mineralization relative to the activity of Nyankanga Shear Zone is supported by the complete lack of ore fragmentation which raises the question whether or not the gold mineralization postdates Nyankanga Shear Zone. For example feldspar porphyries, containing low grade gold mineralization, intruded along Nyankanga Shear Zone; they are not deformed but have their contacts sheared within Nyankanga Shear Zone and show an overall normal sense of movement. The close spatial association between feldspar and quartz porphyries with Nyankanga Shear Zone suggest that the shear zone acted as a favourable discontinuity for the emplacement of these dykes. The normal shear sense observed along the sheared contacts of undeformed feldspar porphyries is consistent with the kinematics of D8 structures which may also be responsible for the normal reactivation of Nyankanga Shear Zone. A relationship between gold deposition and D8 normal structures is tentative in this case but D8 structures are mineralised only within the mineralized zone, while Nyankanga Shear Zone is mineralised over its entire strike length. Most probably the reactivation of Nyankanga Shear Zone during later deformation events (D7 and D8), is responsible for the gold mineralization and Nyankanga Shear Zone acted as both fluid conduit and structural trap.

The close spatial relationship between gold mineralization and second or third order structures is a very well documented setting for many Archean gold deposits (e.g. Morey et al., 2007; Dirks et al., 2013). However, the exact timing of gold mineralization in relation to the associated structure is less clear (e.g. Blenkinsop et al., 2000; Tripp and Vearcombe, 2004; Weinberg and van der Borgh, 2008) and in many cases multiple stages of gold deposition have been demonstrated (e.g. Wilkinson, 2000; Harraz, 2002; Large et al., 2007; Thomas et al., 2011), with local re-mobilization and grade enhancement playing key roles in forming gold deposits. Although, there are no detailed studies documenting different periods of gold mineralization for Nyankanga, a scenario where gold was introduced during multiple mineralising events should not be excluded.

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Figures captions

Figure 1

Simplified geological map of the Northern half of Tanzania Craton showing the main geological and tectonic units. SU – Sukumalanad Greenstone Belt; NZ – Nzega Greenstone Belt; SM – Shynianga-Malita Greenstone Belt; IS – Iramba-Sekenke Greenstone Belt; KF – Kilimafedha Greenstone Belt; MM – Musoma-Mara Greenstone Belt. Super-terrane boundaries are as proposed by Kabete et al., 2012: ELVST – East Lake Victoria, MLEST- Mwanza Lake Eyasi, LNST- Lake Nyanza, MMST – Moyowosi-Manyoni, DBST – Dodoma Basement, MAST – Mbulu-Masai, NBT – Nyakahura-Burigi. Inset map of Africa showing the location of Archean blocks.

Figure 2

Geological map of Geita Greenstone belt showing the location of the gold deposits and the main geological units and structures.

Figure 3

General geological map of Nyankanga gold deposit.

Figure 4

Geological section through the middle of Nyankanga gold deposits showing the relationship between the main rock types, structures and gold mineralization.

Figure 5

Photographs showing the main lithological units found within Nyankanga gold deposit. a) lower-most ironstone unit consisting of intercalations of graphite, graphite-rich magnetic shales or siltstone and laminated chert; b) poorly bedded magnetite and chert intercalations; c) laminated intercalations of siltstone and chert; d) example of centimeters thick graded sandstone bed within a siltstone dominated unit; e) example of typical porphyritic plagioclase diorite forming the main intrusive body in Nyankanga Intrusive Complex; f) example of porphyritic hornblende diorite; g) plagioclase porphyry – note the lack of visible quartz grains; h) quartz porphyry - note the resorbed nature of quartz porphyries; j) coarse grained lamprophyre with intense carbonate alteration.

Figure 6

Stereoplots showing: a) poles to bedding measurements; b) poles to D3 axial planar foliation; c) measurements of D3 fold axes; d) poles to D6 shear zones and Nyankanga Shear Zone; e) measurements of lineations on slip surfaces that form the Nyankanga Shear Zone showing an initial dip slip component of movement which was overprinted by oblique slip movement - note that the latest movement recorded along the slip surfaces is consistent with normal reactivation of Nyankanga Shear Zone; f) poles to D7 shear surfaces showing the main NW-SE trend and the associated NE-SW trending shallower faults; g) poles to sediment-diorite contacts; h) poles to feldspar and quartz-porphyry contacts with the sediments; j) contoured plot of poles to vein measurements from Nyankanga gold deposit – see text for details.

Figure 7

Photographs showing the main overprinting relationships between different folding events. a) isoclinal D2 folds refolded by D3; b) example of open - subvertical D4 folds; c) example of D3 folds being overprinted by D5 folds having a sub-horizontal fracture cleavage.

Figure 8

Photographs showing different structural features within Nyankanga gold deposit. a) exposure of Nyankanga Shear Zone – note the preferential development of breccia and quartz veins in the footwall rocks; b) example of S-C fabrics along Nyankanga Shear Zone showing reverse movement; c) slips surface along Nyankanga Shear Zone showing steps consistent with reverse movement; d) slip surface along Nyankanga Shear Zone showing steps consistent with normal movement; e) example of brecciation in the footwall of Nyankanga Shear Zone; f) example of NW-SE trending, D7, sinistral strike slip shear zone showing an apparent normal displacement – note the beds dip away moderately thus giving an apparent normal sense of movement.

Figure 9

Detailed wall maps illustrating relative timing relationships between different intrusive rocks (a) and between different types of structures and intrusive rocks (b).

Figure 10

Photographs showing alteration features found in Nyankanga gold deposit. a) calcite rich vein with minor chlorite and pyrite – note an earlier magnetite rich vein; b) example of quartz-carbonate-biotite-pyrite vein with minor chlorite – note that fine grained biotite has replaced the hornblende in the matrix; c) biotite-chlorite-pyrite microveining and moderately to intense hematite alteration; d) silica alteration overprinting an earlier sulfide (pyrite alteration) and associated brecciation; e) quartz-pyrite alteration overprinting an earlier hematite-pyrite-quartz alteration; f) pyrite-carbonate alteration with bedding replacement.

Figure 11

Chart showing a simplified interpretation of the relative timing between the main vein types and alteration.

Figure 12

Photograph (a) and interpretation (b) showing the relationships between different vein types in an outcrop. c) wall map showing timing relationships between two vein sets in that part of the deposit. d) wall map showing the relationship between Nyankanga Shear Zone, breccia zones and veining.

Figure 13

Detailed wall map showing the relationship between Nyankanga Shear Zone, breccia zones and gold mineralization.

Figure 14

Series of charts showing the relationship between vein density and gold mineralization along two specific sections across the mineralized zone. Modified from Nugus and Brayshaw (2010). See text for details.