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## Short Wavelength Infrared Spectral Characterization of the Mineralogy of Gokona and Nyabigena Andesite-Hosted Gold Deposits in North Mara, Tanzania

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### Abstract

The mineralogy of Gokona and Nyabigena gold deposits in Tanzania have been studied using Short Wavelength Infrared (SWIR) Spectrometry technique with an aim to fingerprint hydrothermal system responsible for the formation of the deposits and establish pertinent mineralogical signatures for gold deposition. Gokona and Nyabigena deposits are hosted in porphyritic andesite to basaltic andesite that contains plagioclase phenocrysts, pyroxene, hornblende and Fe-Ti oxides as primary minerals. Other minerals are actinolite, chlorite, epidote, albite and hematite, which indicate metamorphism of the rock under greenschist facies conditions. Hydrothermal alteration of the rock produced chlorite, sericite, carbonates (ankerite, siderite and calcite), pyrite and quartz, which is consistent with formation of the minerals in mid-crustal levels (< 5 km). Depth of absorption features of SWIR spectra for chlorite and sericite from borehole samples revealed intense formation of the minerals in the deposits. Sericite is proximal to ore zones, less crystalline and mainly muscovitic to phengitic in composition, whereas chlorite occurs distal to the ore zones, and is mainly intermediate (Fe-Mg) to Fe-rich in composition. These phyllosilicates indicate both pH and temperature control during hydrothermal alteration and provide signatures that can be targeted in exploration to extend mine lifespan.

**Keywords:** Hydrothermal alteration; Short Wavelength Infrared Spectrometry; Gold exploration; Musoma-Mara Greenstone Belt; North Mara mines

### Introduction

Gokona and Nyabigena deposits of the North Mara Gold Mine are among the large gold deposits in Tanzania, from which more than 2 million ounces of gold has been produced (Henckel et al. 2016, Ikingura et al. 2010). The deposits are located in the north-eastern Tanzania within Mara region, close to the Tanzanian-Kenyan border and within the Musoma-Mara Greenstone Belt (Figure 1). This belt has a long history of gold mining, whereby in most cases gold mineralisation is controlled by regional structures such as the Mara shear zone in North Mara mines.

Several gold prospects and deposits have been discovered in the shear zone, among them being Nyabirama, Komalera and Old Mara. Gokona and Nyabigena deposits are found along the Nyarwana fault adjacent to the Mara shear zone. These geologic structures still hold great potential for occurrence of significant gold mineralisation.

Despite of the potentiality, large part of the structures is covered by soil and young volcanic rocks, which add difficulty in uncovering hidden gold mineralisation. Available core samples from Gokona and Nyabigena deposits provide part of the

exposed gold footprint for hydrothermal system in the area. This study aims to use the core samples to characterize hydrothermal alteration mineralogy in Gokona and Nyabigena deposits using SWIR spectrometry together with petrography and X-ray diffraction techniques, and establish pertinent mineralogical signatures for areas of intensive gold deposition along the structures. The mineralogical signatures presented in this work can be used in planning new exploration drill holes in a more cost effective manner along the Nyarwana fault or Mara shear zones or within the region.

### **Regional Geology**

Gokona and Nyabigena deposits are found in the North Mara area within the Musoma-Mara Greenstone Belt (MMGB, Figure 1), which is one of the six greenstone belts making the Lake Victoria Goldfield (Borg and Shackleton 1997, Henckel et al. 2016). The goldfield is found to the south and east of the Lake Victoria northern Tanzania extending northwards to south-western Kenya and further toward south-eastern Uganda around Lake Victoria (Barth 1990). The MMGB form part of the eastern Tanzania Craton that is composed of amphibolites, trochilitic to granodioritic gneisses and migmatitic gneisses, which are thought to be the oldest in the belt (Pre-Nyanzian, Grey and MacDonald 1965). Other rocks include the Neoproterozoic meta-igneous rocks belonging to the Nyanzian Supergroup, granitoids, K-rich granite, gabbro and supracrustal rocks. The supracrustal rocks are metasedimentary and metavolcanic rocks including meta-basalts, meta-andesite, metadacite, rhyolite, ferruginous siltstones, chert and sandstone (Manya 2009, Manya et al. 2006, Mshiu and Maboko 2012, Mtoro et al. 2009).

The supracrustal rocks in the East Mara area are thought to have formed in a short time interval of about 30 Ma during the Neoproterozoic Era (2680 – 2650 Ma) within a magmatic arc (Manya et al. 2006, 2007).

Nyanzian Supergroup rocks are overlain with clastic sedimentary rocks belonging to the Kavirondian Supergroup, which include mainly polymict conglomerate, sandstone and siltstone (Figure 1, Grey and MacDonald 1965). The North Mara area has a long history of gold mining, whereby in most cases gold mineralisation is controlled by regional structures such as the Mara shear in the North Mara mines (Henckel et al. 2016). Adjacent to the Mara shear zone, the Nyarwana fault occurs, in which Gokona and Nyabigena deposits are found. Other deposits are Nyabirama and Komalera which occur along the Mara shear zone. The structures are exploited by numerous artisanal mine workings, and they still hold great potential for occurrence of a new significant gold deposit. To the north in the North Mara occurs another fault, which is known as the Utimbaru fault, visible as E – W escarpment in the area (Figure 2).

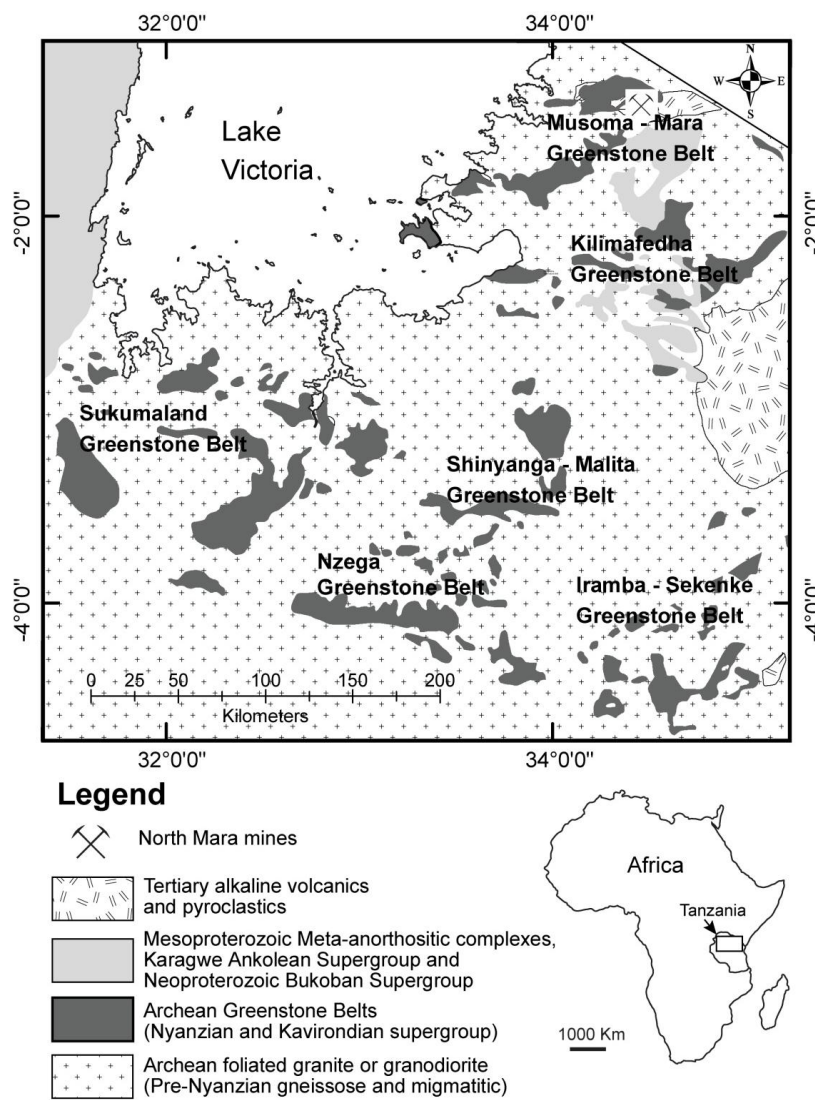
### **Local geology mineralisation and wall rock alteration in North Mara Mines**

The Gokona and Nyabigena gold deposits are found to the south of the Utimbaru fault and to the north of the Nyarwana fault (Figure 2). The deposits occur adjacent to each other and are of similar size, about 600 metres long and 200 metres wide (Henckel et al. 2016, Ikingura et al. 2010). The Gokona and Nyabigena deposits together with the Nyabirama deposit produced about 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 (Henckel et al. 2016). These deposits contain sub-greenschist to greenschist facies metamorphosed supracrustal rocks, mainly chloritic metasedimentary rock (mafic schist), sandstone, siltstone and porphyritic andesite to basaltic andesite, in which mineralisation is restricted within the andesite (Figure 3) (Kazimoto and Ikingura 2014). Other rocks include different generations of dolerite dykes that crosscut other rocks. The Gokona and Nyabigena deposits are thought to be

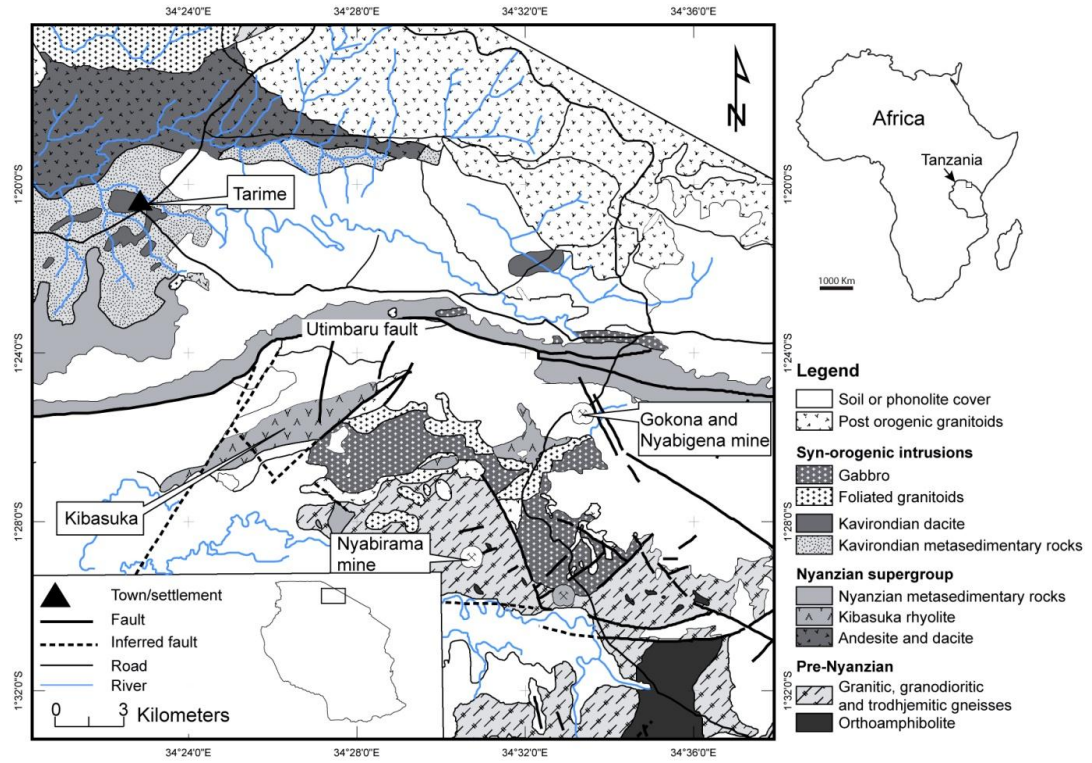
controlled by angular fault or joint or unconformity associated with the Nyarwana fault that cuts through metavolcanic and metasedimentary rocks (Allibone et al. 2000).

Host rocks in the deposits have been weakly to strongly hydrothermal altered in different parts by silicification, sericite, chlorite, carbonate and sulphide alterations (Figure 4). The gold mineralisation within the

two deposits occurs as stacked tabular lenses that are moderately to steeply dipping in south-westerly direction. Mineralised zones are intensely altered and are about 30 - 60 metres thick indicating pinch and swell patterns (Figure 3). Gold is found as disseminations or nuggets within quartz veins or veinlets, which are associated with pyrite, pyrrhotite and arsenopyrite.



**Figure 1:** Geological map showing Archean greenstone belts of the Lake Victoria Gold Field of Tanzania (modified from Kazimoto and Ikingura 2014).



**Figure 2:** Geological map of the Mara region showing geology of northern and eastern Mara and locations of the Gokona, Nyabigena and Nyabirama mines (modified from Kazimoto and Ikingura 2014).

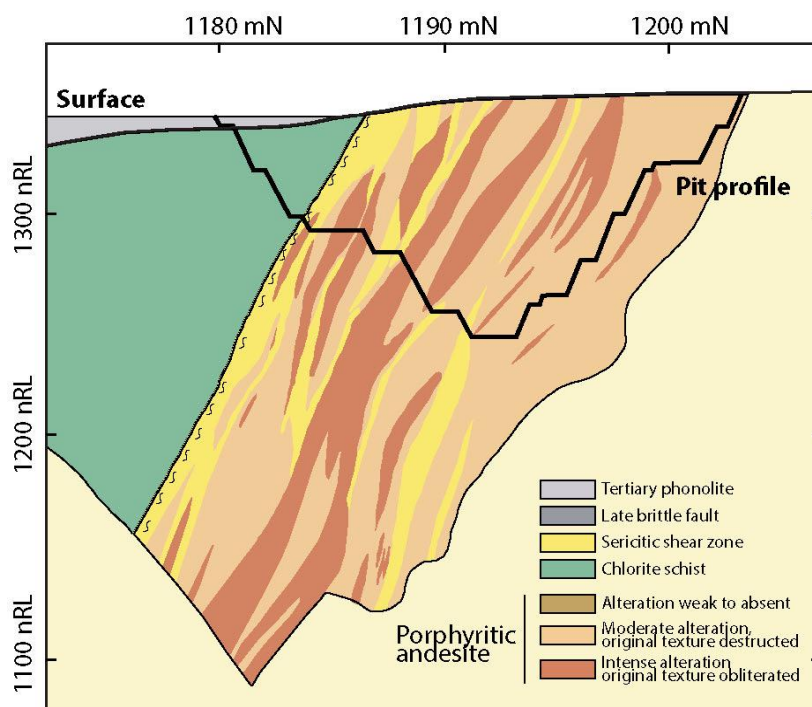


Figure 3: Cross-section of the Nyabigena deposit (modified from Henckel et al. 2016).



Figure 4: Gokona and Nyabigena andesite (a) Unaltered or weakly altered andesite with clearly visible feldspar phenocrysts, (b and c) strongly altered and mineralised andesite, and (c) decreased amount of feldspar phenocryst in strongly altered andesite and presence of visible gold.

#### Petrography and geochemistry of Gokona-Nyabigena andesite

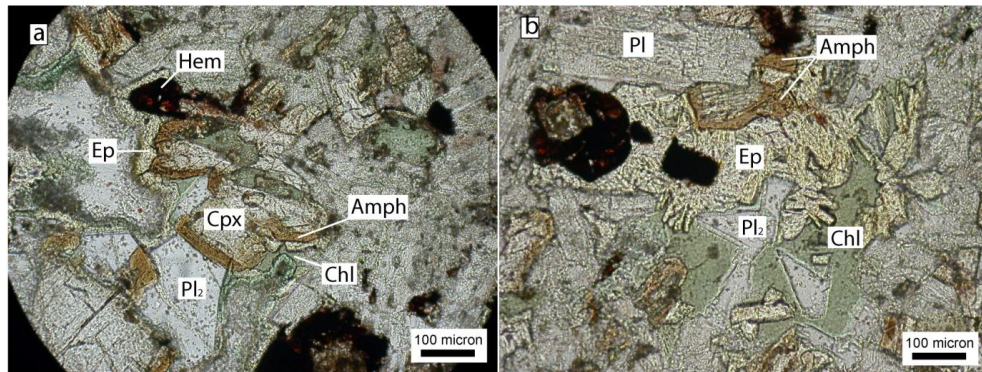
Unaltered or weakly altered Gokona-Nyabigena andesite contains pyroxenes, plagioclase, hornblende, and Fe-Ti oxides as primary minerals in areas that have remained unmetamorphosed (Kazimoto and Ikingura 2014). Other parts of the rock have chlorite,

epidote, amphibole, plagioclase and hematite, which formed at the expense of primary minerals (Figure 5). Hydrothermal alteration minerals include opaque (pyrite), sericite, quartz and carbonates (Kazimoto 2008). The Gokona-Nyabigena andesite classifies as basaltic andesite to andesite using trace element ratios Zr/Ti versus Nb/Y, which is



K-rich ( $K_2O/Na_2O = 2.9$ ) and has low Mg# (mean = 18) (Kazimoto and Ikingura 2014). For simplicity, the andesite and basaltic

andesite rock suite is referred to as andesite in the following text.



**Figure 5:** Micropetrographic plates of Gokona-Nyabigena andesite: (a) and (b) showing texture of unaltered Gokona-Nyabigena andesite containing mainly greenschist facies and some primary minerals: Hem-hematite, Ep-epidote, Cpx-clinopyroxene,  $Pl_{1,2}$ -plagioclase, Chl-chlorite, and Amph-amphibole.

## Materials and Methods

### Sampling and analytical methods

Core logging, sampling and SWIR analyses were done in the North Mara Gold Mine between June and July 2006. Portable Infrared Spectrometer (PIMA) was used to establish pertinent mineralogical fingerprints in the rocks of Gokona and Nyabigena deposits. Sampling was done at five metres intervals along drill core length such that more than 20,000 1 – 2 cm wide unweathered chip samples from different lithologies were scanned. Spectral data acquisition was achieved in 20 – 60 seconds, where by data saving was done with the aid computer connected to a PIMA spectrometer with PIMA Acquisition Module © 98 Version 2.2. Portable Infrared Mineral Analyser was internally calibrated after every 10 scans against a built-in wavelength standard. Spectra interpretation was done with the aid of automatic interpretation software, The Spectral Geologist (TSG) software. However, some complex spectra were further checked visually. Selected rock samples were either analysed by X-Ray Diffraction (XRD) or petrographically studied using polarising

microscope to compliment mineralogical interpretation of SWIR spectral data.

### Characterization of alteration mineralogy in gold deposits using SWIR

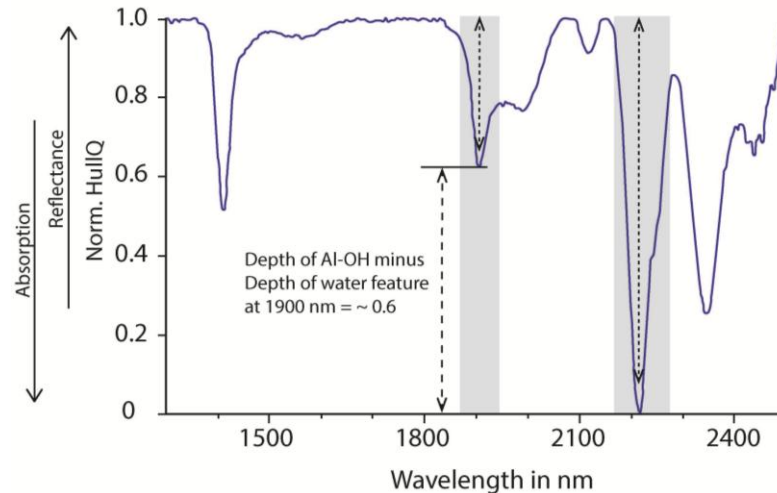
Hydrothermal alteration in gold deposits reflects hydrothermal fluid – host rock interaction. Several factors are known to control variations of alteration mineralogy associated with gold deposits. These include temperature, pressure, fluid to rock ratio, composition and conditions of hydrothermal fluids (Eh, pH, salinity and activities of H, K, Na, S,  $H_2O$  and  $CO_2$ ). Dominant alteration minerals can be assorted as quartz, carbonates, sulphides, mica and amphiboles. The resulted alteration minerals reflect nature of host rocks and auriferous hydrothermal fluids, which the latter may include combination of the following components:  $CO_2$ ,  $H_2O$ ,  $CH_4$ ,  $K^+$ ,  $Na^+$ ,  $Ca^{2+}$  and  $N_2$ , S (Groves et al. 2003). Different wall-rock alteration assemblages would develop at different crustal levels that hydrothermal alteration has occurred. Close to the earth's surface commonly sericite-carbonate-pyrite-clays bearing assemblage would

develop. Biotite-carbonate-pyrite or biotite-amphibole-pyrrhotite bearing assemblages form at deeper crustal levels (Groves et al. 2003, Mikucki and Ridley 1993, Ridley and Diamond 2000). Of these minerals, mica, carbonates, chlorite, clays and amphiboles are infrared active, so can be identified and characterised using Short Wavelength Infrared Spectrometry methods.

White mica has diversity in proportion of octahedral aluminium (Al) in the mineral structure that influences position of SWIR Al-OH absorption feature (Herrmann et al. 2001, Sun et al. 2001, Thompson et al. 1999, Yang et al. 2005). Usually, in SWIR spectrometry, paragonite has shorter SWIR Al-OH (< 2195 nm), while phengite exhibits long SWIR Al-OH absorption wavelength (2216 nm – 2228 nm) and normal muscovite has SWIR Al-OH absorption wavelength between 2200 nm and 2208 nm (Yang et al. 2001). Chlorite has characteristic SWIR absorption features centred between 2250 nm and 2350 nm related to Fe-OH and Mg-OH bonds in chlorite. Iron (Fe) and magnesium (Mg) contents ( $Fe\# = Fe/Fe + Mg$ ) in chlorite influence these absorption features. For example, Fe-rich chlorite has longer SWIR Fe-OH and Mg-OH absorption wavelengths compared to Mg-rich chlorite. Intermediate (Fe-Mg) chlorite has intermediate SWIR Fe-OH and Mg-OH absorption wavelength between that of Fe-rich and Mg-rich chlorite. The ranges for SWIR Fe-OH and Mg-OH absorption wavelength are 2235 nm – 2255 nm and 2320 nm to 2360 nm, respectively (Herrmann et al. 2001). Carbonates have same diagnostic SWIR absorption feature of Mg-OH bond as chlorite, between 2300 – 2350 nm, thus, carbonates and chlorite may interfere each other on Mg-OH absorption feature. For this study, Fe-OH absorption feature was used in determining the presence

of chlorite and chlorite composition in the samples.

The depth of SWIR Al-OH and SWIR Fe-OH absorption features or indices relates to the intensity of absorption of particular SWIR wavelength energy by the sample's Al-OH and Fe-OH bonds. The SWIR indices can be used to quantify or reflect on the relative quantity of white mica or clay minerals and chlorite, respectively in the rock sample. The depth of Al-OH absorption feature that has normalized hull quotient values > 0.4 indicates high white mica or clay abundance. Whereas, the depth of Fe-OH absorption feature that has normalized hull quotient values > 0.5 indicates high chlorite abundance. For white mica, the SWIR Al-OH absorption feature centred at 2200 nm and a SWIR H<sub>2</sub>O absorption feature centred at 1900 nm can be used to reflect on crystallinity of white mica. The difference between depth of Al-OH absorption features that measure relative proportion of white mica in the sample and the depth of the H<sub>2</sub>O absorption feature that measure intensity of H<sub>2</sub>O in the crystal structure of white mica inform about degree of crystallinity of white mica (Figure 6) (Howard and Halley 2006). At high temperature (>300 °C), the structure of mica is close to that of its stoichiometric composition. However, in low temperature (<300 °C) white mica loses tetrahedral Al and interlayer K for one tetrahedral Si (Cathelineau 1988, Jones et al. 2005). This causes white mica structure to have 2 atoms less per formula unit, in which the un-bonded H<sub>2</sub>O molecule often compensates for the gap. Thus, the difference in depth of Al-OH from depth of H<sub>2</sub>O can be used as a measure of white mica crystallinity, which is important in delineating temperature gradient in extinct hydrothermal systems. Thematic ranges and the corresponding degree of white mica crystallinity are shown in Table 1.



**Figure 6:** Selected white mica SWIR spectra showing height differences in normalized hull-quotient or depth of SWIR Al-OH feature at 2200 nm and H<sub>2</sub>O absorption feature at 1900 nm used as a measure of white mica crystallinity.

**Table 1:** Thematic ranges, corresponding degree of white mica crystallinity and potential causes for the crystallinity values (mineralogical or others).

Range	Mica crystallinity index	Phyllosilicate	Other causes
0.8 to 1.0	High	White mica	
0.7 to 0.8	Moderate		
0.5 to 0.7	Moderate		
0.2 to 0.5	Low	Illite	Water interference
0.0 to 0.2	Low	Illite or smectite	Water interference
-1.0 to 0.0	Very low	Smectite	Water interference

## Results

### *Detection of minerals by PIMA versus depth to the deposits*

The mineralogical composition of analysed samples by PIMA (in percentage) is presented in Table 2. At shallow depth (~10 m) seemingly unweathered samples from host rocks mainly contained muscovite and Fe-rich chlorite together with sporadic phengite, intermediate Mg-Fe, and Mg-bearing chlorite (Figure 7). Other minerals include the ones that are insensitive to PIMA (spectral, e.g. quartz, feldspars or Fe-sulphides), whereas, few samples contained clay minerals like halloysite, kaolinite, illite, dickite and montmorillonite. About 10 to 50 metres of depth in the deposits, muscovite and intermediate Fe-Mg chlorite were

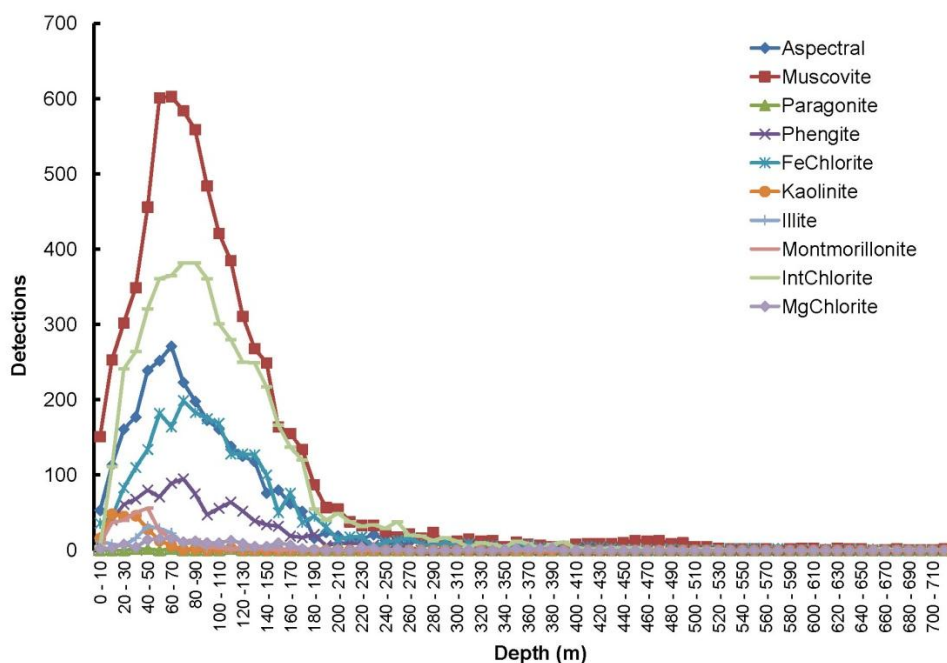
increasing in the samples. Intermediate chlorite was frequently detected in the rocks compared to Mg- or Fe-bearing chlorite (Figure 7). Other minerals that were detected include Fe-chlorite, actinolite and clay minerals (montmorillonite, kaolinite and illite). Below 50 metres depth to about 90 metres, the frequency of detection of muscovite further increased to reach its peak detection. Intermediate (Fe-Mg) chlorite was important type of chlorite as compared to Fe bearing chlorite, and spectrally insensitive (spectral) minerals and phengite increased (Figure 7). Other minerals detected in the rocks include pyrophyllite, alunite and clay minerals (montmorillonite, kaolinite and illite). Biotite, phlogopite, actinolite, hornblende, and carbonate minerals including



calcite, ankerite and siderite were also picked. Beyond 90 metres depth to 700 metres, detection of muscovite, intermediate chlorite, Fe bearing chlorite, phengite and aspectral minerals reached the peak detection frequency and started to decrease as the depth of sampling increased (Figure 7). Few clay minerals were detected in selected samples including mainly montmorillonite, kaolinite, illite and halloysite. Different zones of hydrothermally altered andesite (Figure 4) associated with gold contained mainly phengitic muscovite, phlogopite and Fe-chlorite. Other minerals are ankerite, siderite, intermediate Fe-Mg chlorite and calcite. Contrary to this zone, unmineralised sericitized zones (Figure 3) contained muscovite and intermediate Fe-Mg chlorite.

**Table 2:** Minerals as detected by PIMA in the samples from Gokona and Nyabigena deposits

Minerals	Detections (%)
Muscovite	33.5
Int-chlorite	23.7
Aspectral (quartz, feldsapr, pyrite)	13.7
Fe-chlorite	11.4
Phengite	4.9
Clay minerals	4.7
Mg-chlorite	0.8
Pyrophyllite	0.6
Hornblende	0.4
Calcite	0.4
Epidote	0.4
Actinolite	0.3
Phlogopite	0.4
Biotite	0.2
Siderite	0.2
NH_Alunite	0.1
Ankerite	0.1
Zoisite	0.1



**Figure 7:** Detection frequencies of different minerals by PIMA in rock chip samples as depth increased from the surface to sub-surface.

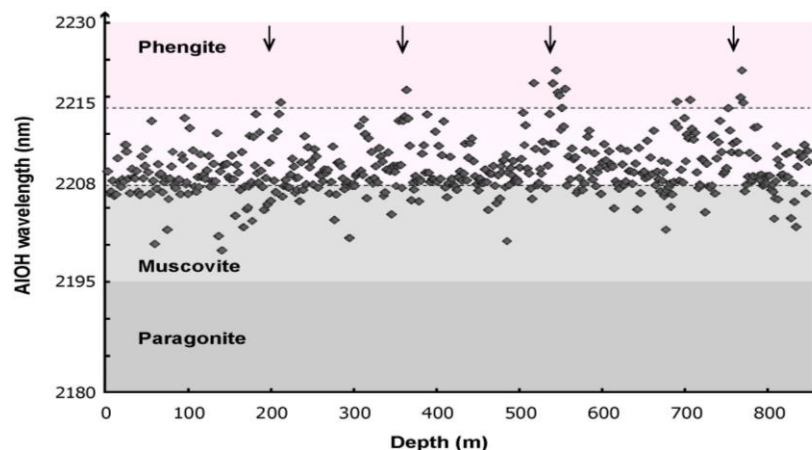
### *Depth of Al-OH and Fe-OH absorption features*

The depth of SWIR Al-OH absorption features in the Gokona and Nyabigena andesite ranged between 0.0 and 0.6, which reflected a low to moderate white mica abundance in the andesite at different zones of the gold deposit. Mineralised areas within the andesite had low values of depth of SWIR Al-OH absorption (0.1 and < 0.1) that reflected low white mica/sericite abundance in the ore zones. Contrary, unmineralised and least mineralised host rocks around the ore zones showed relative higher depth of Al-OH absorption between 0 and 0.5. The depth of Fe-OH absorption ranged between 0.0 and 0.8, which indicate variable (low to high) contents of chlorite in the rocks. Generally, chlorite was a common mineral detected in the Gokona and Nyabigena deposits. Mafic rocks or rocks affected by chlorite alteration were found to have a relative higher depth of Fe-OH absorption. The depth of absorption features in the mafic schist ranged between 0.2 and 0.3, whereas in sandstone and siltstone the range was 0 to 0.3. Mineralised and hydrothermally altered andesite affected by silicification and K-feldspar alteration showed a very low depth of Fe-OH

absorption (0 – 0.1) compared to unmineralised and least altered andesite surrounding the ore zone.

### *Al-OH absorption responses and white mica composition*

The andesite in Gokona and Nyabigena deposits showed Al-OH absorption wavelength range between 2184.2 and 2229.7 nm. The Al-OH absorption wavelength varied with variation in alteration intensity of the andesite and mineralisation. Strong hydrothermally altered andesite in the ore zones yielded Al-OH absorption wavelength between 2203.9 nm and 2228.7 nm. Moderately mineralised and strongly altered andesite had Al-OH absorption wavelength between 2186.4 nm and 2227.8 nm, whereas moderately to weakly altered and mineralised andesite had Al-OH absorption wavelength between 2210.5 and 2229.7 nm. Detailed inspection of individual boreholes and log sections of both Gokona and Nyabigena deposits indicated that hydrothermally altered and mineralised andesite is associated with a shift of mica composition toward muscovite to phengitic muscovite composition (Figure 8).



**Figure 8:** Al-OH absorption wavelengths of samples from Gokona-Nyabigena andesite showing Al-OH absorption wavelengths by sericite suggesting muscovitic to phengitic sericite composition. Arrows show subtle changes in sericite.

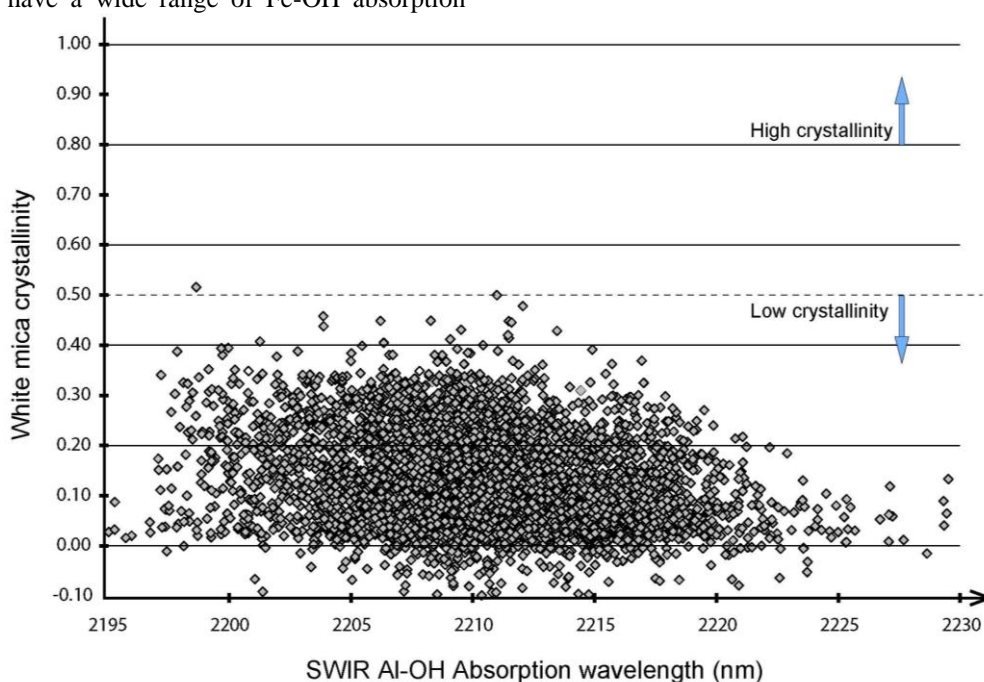
**Fe-OH absorption response and chlorite composition**

The Fe-OH absorption response from dolerites within Gokona and Nyabigena is characterised by Fe-OH absorption wavelengths range between 2246.7 and 2264.1 nm, which encompasses a wide range of chlorite composition (Mg-rich, intermediate and Fe-rich chlorite). Mafic schist and sandstone are characterized by intermediate (Fe-Mg) to Mg-rich chlorite with Fe-OH absorption wavelength range of 2245.9 – 2257 nm and 2249.2 – 2255.8 nm, respectively. Andesite and siltstone have a wide range of Fe-OH absorption wavelengths, 2240 – 2267 nm, indicating a diverse chlorite composition in the rocks. Ore zones and altered lithologies were also found to have a wide range of Fe-OH absorption

wavelengths. Mineralised andesite has range of Fe-OH absorption between 2240 and 2267 nm.

**White mica crystallinity**

The minimum and maximum values of mica crystallinity ranged between 0 and 0.6. Most samples contained white mica with very low crystallinity values between 0.1 and 0.2. White mica crystallinity was observed preferentially to associate with muscovite or phengitic muscovite (Figure 9). Other samples have relative high white mica crystallinity values (> 0.3). On the plan map, distribution of the SWIR white mica crystallinity increases toward mineralised areas and decreases towards the surroundings (Kazimoto 2008).



**Figure 9:** Plot of Al-OH absorption wavelength versus white mica crystallinity showing high mica crystallinity is more associated with muscovite or phengitic muscovite.

**Mineralogical composition of host rocks by X-ray Diffraction (XRD) technique**

To supplement mineralogical studies by both petrographical and SWIR spectrometry

techniques, selected sample from Gokona and Nyabigena deposits were analysed using XRD spectrometer. The XRD detected plagioclase feldspar and quartz in samples

from all the rocks in the deposits. In addition to these minerals, mafic schist contained clinocllore, while siltstone and sandstone contained ferroan-clinocllore and vanadian barian muscovite (sericite). Moreover, hydrothermally altered and mineralised andesite contained quartz, albite, microcline, muscovite, calcite, clinocllore and biotite.

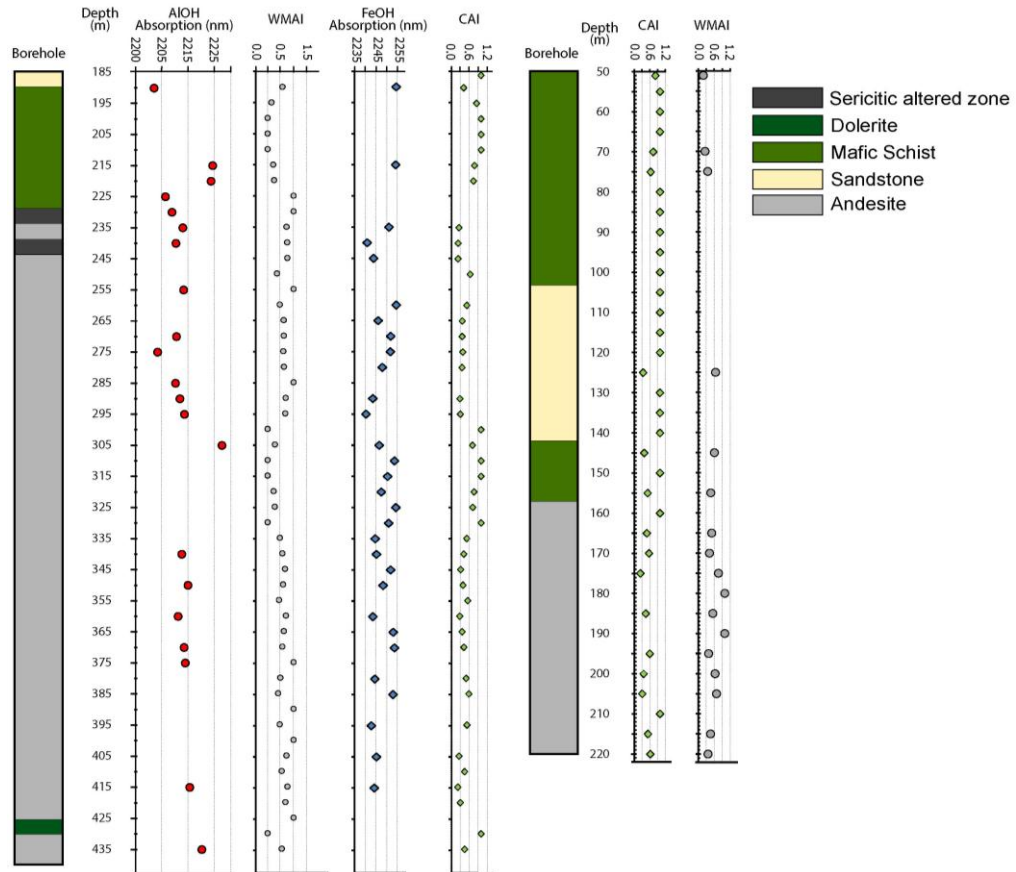
### Discussion

#### *Hydrothermal alteration mineralogical assemblage and constraints on conditions*

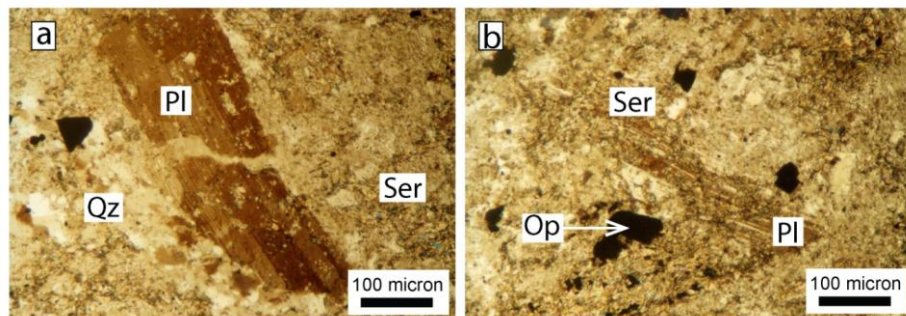
The host rocks in Gokona and Nyabigena deposits contain an assemblage of pyroxene, hornblende and Fe-Ti oxides (Kazimoto and Ikingura 2014). This assemblage is magmatic (primary) and is recognised in areas that are both weakly metamorphosed and hydrothermally unaltered. Parts of the andesite that are metamorphosed contain chlorite, actinolite, plagioclase feldspars, epidote, zoisite and hematite (Figure 5), which indicate greenschist facies metamorphism of the rock. Hydrothermally altered andesite contains sericite, chlorite (clinocllore), quartz, pyrite, K-feldspar, albite and carbonate minerals (calcite, ankerite and siderite) as main hydrothermal products (Table 2). Other minor minerals include phlogopite, biotite, pyrophyllite, K-alunite, and epidote. The assemblage of sericite-ankerite or/and biotite-ankerite has been noted to be associated with hydrothermal systems under temperatures between 250 °C and 420 °C, as it was in

mafic rocks hosted gold deposits of the Yilgarn Craton (Mikucki and Ridley 1993). Therefore, giving an indication of the hydrothermal alteration of the Gokona and Nyabigena andesite at shallow crustal depths (epizonal < 5 km depth), which is dominated by greenschist facies conditions (Groves et al. 2003, 1998).

White mica and chlorite alteration indices (WMAI and CAI, van Ruitenbeek et al. 2005, Huston et al. 1999) calculated as  $D_{\text{Al-OH}} / (D_{\text{Al-OH}} + D_{\text{Fe-OH}})$  and  $D_{\text{Al-OH}} / D_{\text{Fe-OH}}$ , respectively, whereby  $D_{\text{Al-OH}}$  is depth of Al-OH absorption feature and  $D_{\text{Fe-OH}}$  is depth of Fe-OH absorption feature, indicates that the andesite have been affected by the sericite alteration (Figure 10). The indices also revealed chlorite alteration of mafic schist and sandstone (Figure 10). Intense sericitization of Gokona and Nyabigena andesite that is associated with destruction of feldspar in the rock and high depth of Al-OH absorptions (Figure 10 and 11), reflects prevailing low pH (acidic) conditions during alteration and gold deposition. Hydrolysis of feldspar to form sericite requires low pH conditions, from which the pH of the reacting fluids would increase. Formation of pyrophyllite and K-alunite in the deposits further provides support for acidic condition in addition to oxidizing conditions. Contrary to the intense sericite alteration in andesite, chlorite alteration appears to be significant in sandstone and mafic schist (Figure 10).



**Figure 10:** Down-hole logs of boreholes at Gokona deposit showing variation Al-OH and Fe-OH absorption wavelengths with depth from different lithologies into the boreholes, and white mica and chlorite alteration indices (WMAI and CAI).



**Figure 11:** Micropetrographic plates of hydrothermally altered Gokona-Nyabigena andesite: (a) and (b) showing texture of deformed and sericitized plagioclase (Pl), sericite (Ser) associated with opaque (Op) minerals (pyrite?) and quartz (Qz).



**Sericite composition and crystallinity**

Petrographical studies of Gokona-Nyabigena andesite revealed that sericite formed at the expense of plagioclase (Figure 11). Detection counts of white mica and the values of the depth of Al-OH absorption indicate the andesite has been strongly sericitized, and sericite is a common hydrothermal alteration product in the rock (Figure 7 and 11). The composition of sericite as revealed by Al-OH absorption wavelengths of the rocks is mainly phengitic (Fe-Mg), however, with a subtle compositional variation in different zones or parts of rocks in the deposits (Figure 8). Although, such variation is invisible on core or hand samples, it has been found that adjacent to the ore zone sericite is mainly phengitic muscovite with mean Al-OH of 2214 nm, but increases or decreases as one moves away from the ore zones. The variation in sericite composition from K-bearing (normal muscovite) to Fe-Mg bearing (phengitic muscovite) reflects changes in octahedral Al<sup>vi</sup> content within white mica (Tschermark substitution) related to prevailing physicochemical conditions of the fluids during sericite formation (Duke 1994, Jones et al. 2005, Velde 1967).

According to Wang et al. (2017), the prevalence of phengitic muscovite over normal K-rich muscovite within or adjacent to ore zones within the Archean Kanowna Belle gold deposit is a result of pH and redox conditions that prevailed during gold deposition. By applying modelling and considering mineralogy of the deposit, they predicted pH between 3.4 and 4.6 and oxidising conditions for the white mica composition characteristics at the Kanowna Belle gold deposit (Wang et al. 2017). Similarly, the predominance of phengitic muscovite in the Gokona and Nyabigena deposits can be suggested as a result of similar pH conditions (~3 – 4.5) that prevailed during gold deposition. Moreover, an assemblage of sericite, ankerite with or

without albite in the rocks, may indicate acidic to near neutral pH conditions.

It has also been noted that samples in the deposits have sericite that is less crystalline in terms of depths of Al-OH and H<sub>2</sub>O features (Figure 9). However, if compared to the surroundings of the deposits, the index for white mica crystallinity decreases away from the deposit or ore zones (Kazimoto 2008). Thus the change in white mica crystallinity indicates hydrothermal temperature gradient from high temperature areas within the ore zone that experienced strong interaction with hot hydrothermal fluids to low temperature areas that have little interaction with the hydrothermal fluids.

**Chlorite composition and Fe-OH absorption responses**

The host rocks in the Gokona and Nyabigena deposits show variations in the Fe-OH absorption wavelengths due to the type of chlorite present in the rocks. The Fe-OH absorption wavelengths in mafic schist are 2245 to 2257 nm, while sandstone and andesite have ranges of 2249 – 2256 nm and 2240 – 2267 nm, respectively. Such wide ranges indicate different chlorite compositions (Fe-, Mg- and Fe-Mg bearing, Fe-number) in the rocks.

The X-Ray diffraction analysis revealed that the sandstone contains ferroan clinocllore, whereas the andesite and mafic schist contain clinocllore. This study did not find a clear variation in chlorite composition within lithologies that may be linked to hydrothermal alteration or gold mineralisation. However, widespread chlorite in the rocks reflects the crustal depth and conditions by which hydrothermal alteration occurred (epizonal, greenschist facies). Chlorite composition is controlled by temperature at which hydrothermal alteration occurs. Normally, at high temperature conditions Mg-rich chlorite is stable and common if compared to Fe-rich chlorite (de Caritat et al. 1993). Concentrations of Fe<sup>2+</sup> and Mg<sup>2+</sup> in the hydrothermal fluid may also

control compositions of hydrothermal chlorite and carbonate minerals (e.g. ankerite). Moreover, subtle differences on chlorite compositions between different rocks, sandstone versus andesite, indicate lithological control on chlorite composition. All these are considered to have played a big role in controlling chlorite composition in the deposits. Lithological control of chlorite composition has also been noted in different andesite hosted hydrothermal deposits or geothermal systems, for example in Wairakei, New Zealand; base metal sulphide deposits at Rosebery and Western Tharsis, Tasmania, and Highway-Reward, Queensland (Herrmann et al. 2001, Yang et al. 2000).

#### **Summary and Conclusions**

Short Wavelength Infrared Spectroscopy (SWIR) together with petrography and X-ray diffraction (XRD) in the present study has enabled recognition of the mineral assemblage developed within the host rocks of Gokona and Nyabigena gold deposits of the North Mara mines. The least altered Gokona and Nyabigena andesite contains actinolite, chlorite, epidote and zoisite, plagioclase feldspar (albite), quartz, which indicates greenschist facies metamorphism of the rock. Hydrothermally altered andesite contains an assemblage of sericite, chlorite (clinochlore), quartz, albite, K-feldspar, pyrite, biotite, calcite and ankerite. Chloritic schist contains clinochlore, plagioclase feldspar, sericite and quartz, whereas sandstone contains ferroan clinochlore and sericite (vanadian barian muscovite). These mineral assemblages give an indication of their formation in mid-crustal levels (< 5 km depth, epizonal), in which assemblages of sericite-ankerite or biotite-ankerite are usually stable. Sericite and chlorite are important hydrothermal alteration minerals in the host rocks of the Gokona and Nyabigena deposits. Intense sericite formation in the rock which was associated with silicification and sulphide alteration of the rocks, is responsible for destruction of primary

porphyritic texture of the andesite, and reflects low pH conditions of the mineralising fluids. SWIR analyses using PIMA enabled determination of sericite composition in the rock, adjacent to the ore zones to be mainly phengitic (Fe, Mg, Si) with an average Al-OH absorption wavelength of 2214 nm. Subtle variations in Al-OH absorption wavelength are attributed by changes in sericite composition in different parts of the deposits related to pH variations. Sericitized zones in the rock contain K-rich sericite (muscovite) showing higher degrees of crystallinity. SWIR Fe-OH absorption analysis complemented with XRD investigation enabled recognition of chlorite composition in the rocks hosting gold mineralisation in the North Mara Mines. The chlorite is Fe-Mg (intermediate-type), ranging from ferroan-clinochlore to clinochlore. The compositional variation is thought to be controlled largely by lithological composition, temperature, and composition of hydrothermal fluids. The mineralogical signatures obtained in this study can be used to generate gold mineralisation targets in the North Mara Mines but also in other areas of the MMGB. In addition, the approach may be extended in areas with similar style of gold mineralisation elsewhere.

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