



Faculty of Sciences

Department of Earth and Environmental Sciences

**PETROGRAPHIC AND GEOCHEMICAL CHARACTERISATION OF
SELEBI-NORTH COPPER-NICKEL (CU-NI) DEPOSITS, SELEBI
PHIKWE, NORTH-EASTERN BOTSWANA**

by

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Abstract

The Selebi-Phikwe copper-nickel deposit, located in north-eastern Botswana, is hosted by the Phikwe Complex. The Phikwe Complex is within the Central Zone of the Limpopo Mobile Belt which has been subjected to two episodes of regional metamorphism. The Phikwe Complex consists of various types of gneisses such as granite gneiss, hornblende gneiss, biotite gneiss, pelitic schist, amphibolite and meta-sedimentary rocks. It is generally accepted that Ni-Cu mineralisation is hosted in metamorphosed gabbro-norites, pyroxenites and peridotites.

Previous studies investigated Ni-Cu mineralisation in the Selebi-Phikwe ores from geological, mineralogical and geochemical aspects to discuss petrogenesis of these ores and host rocks, including the Ni-Cu mineralisation. Apart from (Wakefield 1976), relationship between sulphide mineralisation and metamorphism on the Selebi-North sulphides has been rarely investigated. Therefore, the aim of this study is to discuss the formation process of sulphide ores, taking into consideration the effect of metamorphism on the Selebi-North sulphide deposits. The objectives are i) to identify and study the textural relationship between ore and rock-forming minerals, ii) to determine the geochemical composition of host rock and Ni-Cu mineralisation and iii) to determine the pressure-temperature conditions at the Selebi-North area.

After collecting samples from the Selebi-North underground mine, petrographic, geochemical, and mineralogical works were conducted using a petrographic microscope, an Inductively Coupled Plasma-Optical Emission Spectrometer and Electron Probe Micro-Analyzer.

The collected and identified samples were mica-free amphibolite, mica-rich amphibolite, biotite schist and Ni-Cu ore.

Petrographic investigations revealed that minerals present in mica-free amphibolite are amphibole, plagioclase, quartz and disseminated sulphides and oxides. Mica-rich amphibolite is composed of amphibole, plagioclase, biotite, quartz, oxides and disseminated sulphides. Furthermore, biotite schist is primarily composed of biotite, plagioclase, quartz, disseminated sulphides and oxides. Sulphide minerals present in all types of ores consist of pyrrhotite, pentlandite, chalcopyrite and pyrite. Silicate minerals and magnetite are also observed in these ores. Based on the amount of ore minerals, ore is classified into disseminated, semi-massive and massive.

Disseminated to semi-massive ores often show sulphides along the foliation and schistose plane, implying that the ore and host rock were subjected to metamorphism. Three different occurrences of mineralisation were observed in the ores i) sulphides along the gneissic fabric, ii) sulphide veinlets cutting across the gneissic fabric and iii) mineralisation associated with sericite and biotite alteration.

Pyrrhotite is the predominant sulphide in massive ores and often contain lamellae of pentlandite. Pentlandite occurs dominantly associated with the pyrrhotite grain as lamellae and loop textures and along the grain boundaries of pyrrhotite (Figure 12 F and G). Chalcopyrite commonly occurs in relatively higher abundance in close proximity to amphibolite silicates in semi-massive ore and at the margins of pyrrhotite in massive ore (Figure 12A-close proximity with silicates and G chalcopyrite exsolved from sulphides). Furthermore, chalcopyrite has been observed to infill cracks and cleavage planes along silicate minerals. Minor pyrite occurs predominantly in sheared areas. Magnetite occurs mainly as subhedral and euhedral and sometimes with sulphide inclusions, indicating that sulphur was saturated during magnetite crystallization in the magma.

Whole rock geochemical analysis shows that the host rocks of the Ni-Cu mineralisation are characterised by slight enrichment of the LREE and displays a negative Eu anomaly.

On the basis of the trace element data, it indicates that ores and rocks in Selebi-North were formed in island arc basalt, a subduction setting.

The Selebi-Phikwe deposits has been documented to be subjected to two episodes of metamorphism that occurred at 2.7-2.6 and 2.0Ga. The pressure-temperature conditions prevailing at Selebi-North were determined to be 706-711 °C and 6.2-7.3 kbar. During these metamorphic conditions, pentlandite is postulated to have been not been melted.

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1.0 Introduction

1.1 Background of magmatic Ni-Cu (PGE) deposits

1.1.1 Formation of Ni-Cu-PGE sulphides in magmatic system

Magmatic ore deposits form when mafic to ultramafic magmas crystallize, and an immiscible sulfide liquid segregates and collects the chalcophile elements (Naldrett, 1989a). These magmas melt in regions of the mantle that are hotter than usual, and they ascend towards the crust because their density is typically lower than that of the surrounding mantle rocks (Arndt et al., 2005). They may stop in magma chambers at density discontinuities when they reach the crust and crystallise as intrusive materials, or they may pass through the chambers and erupt as lava flows at the surface. The resultant formed rocks typically contain mostly silicate minerals and only trace amounts of oxides and other auxiliary minerals. The accumulation of economically abundant ore metals does occur occasionally, though, as a result of minute variations in the mantle source's composition, the mode or degree of partial melting, the timing and mechanisms of emplacement and crystallisation, or the compositions of assimilated crustal materials (Arndt et al., 2005).

The production of magmatic Fe-Ni-Cu platinum-group element (PGE) sulphide deposits goes through four crucial stages. 1) The partial melting of the mantle results in the formation of a metal-bearing, mafic or ultramafic parental magma, which separates from the solid residue and ascends via the asthenospheric and lithospheric mantles before intruding onto the crust or erupting on the surface. 2) The magma interacts with the minerals that constitute its wall, losing heat, creating a hybrid or contaminated magma, and frequently adding crustal S. These interactions cause an immiscible sulphide melt to form or segregate (Naldrett, 1989a).

The tenors of ore metals are increased as a result of the sulphide melt's dynamic interaction with a significantly greater body of silicate magma, especially for strongly chalcophile elements. Ultimately, enough of the metal-rich sulphide liquid accumulates to create an economically viable deposit (Naldrett, 1989a,b, 2004).

1.1.2. Magma generation and emplacement

Magmas are frequently classified as primary or derivative by petrologists. Derivative magmas have undergone some kind of differentiation or contamination, whereas primary magmas are those that are most similar to their source rocks. Tholeiitic and alkali basalts are the main products of partial melting of a garnet peridotite mantle, according to experimental work by Yoder and Tilley (1962), with tholeiites developing closer to the surface than alkali basalts. According to Green and Ringwood (1967), tholeiitic and alkali basalts are both primary but differ due to the extent of pyrolite mantle partial melting, with alkali basalts having a greater percentage melt. There are numerous variants on these models. Every magma generation model will take into account the type of source rock, original depth, partial melting level, pressure-temperature environment, and physical process of magma separation. However because basalts are so common in both space and time along with having a very consistent composition, most models consider basalts to be the closest thing to primary magmas and as a result suggest a relatively homogeneous global layer in the mantle (Peterfreund, 1981).

Melting is the first step in the creation of magma and can be triggered by any one of the following: 1) a rise in temperature, 2) a release of pressure, 3) an influx of volatiles, or 4) a combination of these factors. Melt, solids, and volatiles are the three components that make

up lava and magma. The melt consists of ions from liquid mineral materials (Peterfreund, 1981).

Crystallized minerals floating in the liquid melt make up the solids. These minerals might already be cool. Volatiles are gaseous substances that are dissolved in the magma and include gaseous water vapour, carbon dioxide, sulphur, and chlorine. These three substances, have an impact on the magma's physical behaviour (Wallace, 2005).

1.1.3 Sulfide saturation and separation of immiscible sulfide liquid

Important prerequisites for the formation of magmatic Ni-Cu-PGE deposits include the sulphide saturation of a magma, the separation of immiscible sulphide liquid, and the presence of an appropriate physical environment for the accumulation and concentration of the metal-rich sulphide liquid. Experimental studies on the solubility of sulphur in mafic magmas have demonstrated that a variety of processes can lead to sulphur saturation in mafic magma (Mavrogenes and O'Neill, (1999); Holzheid and Grove (2002); O'Neill and Mavrogenes (2002); Clemente et al. (2004); Jugo et al. (2005); Scaillet and Macdonald (2008); Moune et al. (2009)).

Mafic magmas that are emplaced at relatively shallow depths are unlikely to be sulphide saturated, according to Mavrogenes and O'Neill (1999), who demonstrated that the solubility of sulphide in a mafic magma increases with decreasing pressure. They stated that either substantial fractional crystallisation or the addition of external sulphur must take place for sulphide saturation to be attained in the low-pressure environment.

While Seat et al. (2009) present evidence from the Nebo-Babel deposit that mantle S can be adequate to support ore development, Keays and Lightfoot (2010) claim that crustal S must be added to mantle-derived magmas in order to achieve S adequacy.

Fractional crystallisation is the sole method for achieving sulphide saturation in a mafic magma that does not involve mixing the magmas or interacting in any way with the surrounding rocks. As minerals like olivine, pyroxene, feldspar crystallise and raise the melt's S concentration, it might result in the separation of "cotectic" quantities of sulphide liquid (Ripley & Li, 2013). According to Miller (1999) and Park et al., (2004), sulfide-poor but PGE-enriched strata like those in the Sonju Lake intrusion are assumed to be the product of fractional crystallisation of a tholeiitic melt. In the Jinbaoshan intrusion in China, Tao et al., (2007) hypothesised that olivine and chromite crystallisation in the magma produced PGE-enriched dispersed sulphide zones, which led to the sulphide saturation.

The majority, but possibly not all, of the planet's massive Cu-Ni-(PGE) deposits show evidence of mixing processes during their evolution, either involving a crustal contamination or a magma with a different composition from the mantle. Chemical mixing of magmas has been proposed by Godel et al., (2011) as a crucial process in the generation of the Nebo-Babel deposits.

The production of high-grade PGE deposits, like those of the Merensky Reef in the Bushveld Complex and the JM Reef in the Stillwater Complex, had previously been thought to involve chemical mixing of magmas (Cawthorn et al., 2002). Ripley & Li (2009) showed that combining two magmas might cause the combined magma to saturate in sulphur. The quantity of liquid sulphur that may develop will typically be small, and the end-member magmas' sulphur contents play a crucial role in determining the degree of sulphide saturation.

It is unknown if big tonnage, sulfide-poor Cu-Ni-(PGE) deposits might form, while PGE-rich deposits could. A distinct kind of mixing is made up of mafic magmas and the partial melt created by absorbed, siliceous wall rocks (Huppert et al., 1985).

According to Irvine (1975), a mafic magma's sulphide solubility could be reduced by the addition of SiO_2 while the formation of an immiscible sulphide liquid was promoted. A mechanism to cause sulphide saturation in mafic magmas has been proposed using magma silicification or felsification.

There is little doubt that in deposits where S isotope values are strongly anomalous, crustal S has contributed significantly to the ore genesis. Keays and Lightfoot (2010) concluded that crustal S is crucial for the development of magmatic Ni-Cu deposits.

1.2 Significance of Copper (Cu) and Nickel (Ni)

Copper and nickel play an important role in development, Cu is utilized for manufacturing, transmission, distribution of power, transportation and building (Figure 1) while Ni mainly serves as a key metal in the production of stainless steel and electric vehicle batteries (Figure 2). Although the consumption of Cu and Ni is observed to be stabilizing in developed countries, primary production of Cu and Ni is still increasing and is postulated to increase exponentially by 2100 (US Geological Survey, 2017a).

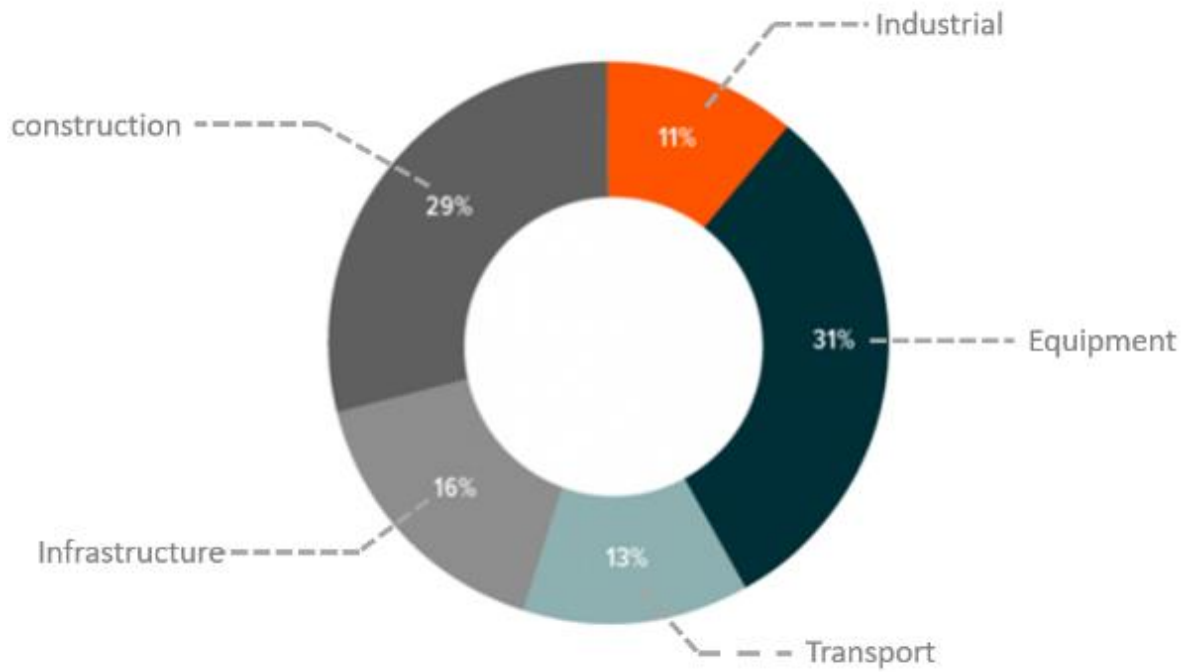


Figure 1: Main industrial use of Copper and Nickel (International Copper study Group, 2016).

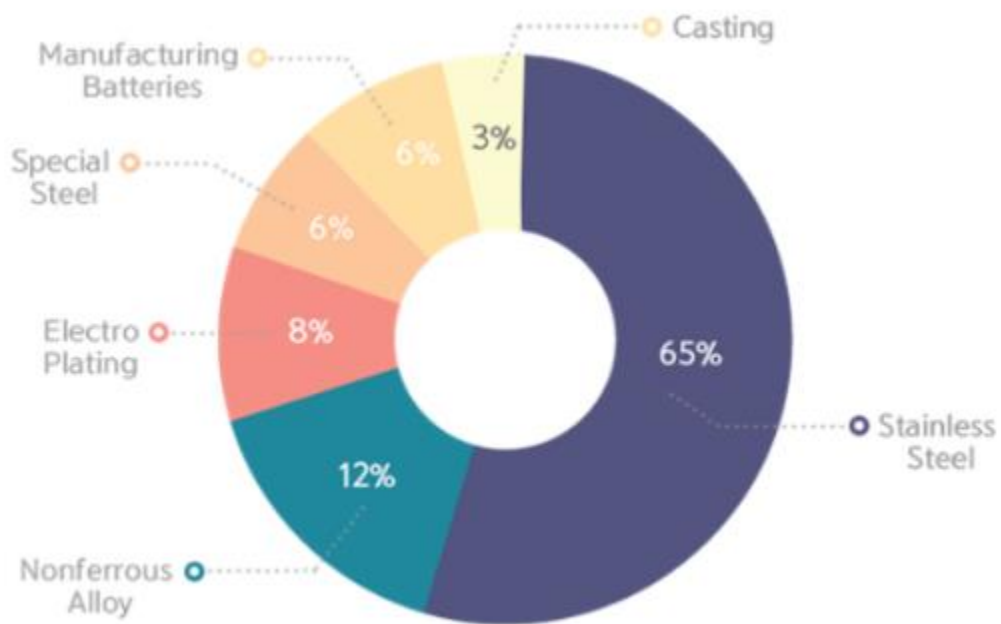


Figure 2: Main Industrial uses of Nickel (U.S Geological Survey, 2017).

1.3 Location of the study area

The Selebi-North underground mine is located within the Selebi-Phikwe town in the Central District of Botswana (Figure 3). The town is approximately 400km north of Gaborone and 150km south of Francistown. Selebi Phikwe can be accessed through the A1 Road, with a 56km turn off at the Serule junction. Bamangwato Concession Limited (BCL), prior to liquidation, extracted Ni-Cu ores in Phikwe, Selebi, Southeast extension and Selebi-North mines. The head office of BCL mine is adjacent to the Phikwe open shaft mine. The Selebi, Southeast Extension and Selebi-North zones are 17km, ~1km and 14km away from the main offices, respectively.



Figure 3: Map of Botswana showing location of the study area (Modified after Kooganne, 2018)

1.4 Exploration and Production History of Selebi-Phikwe

The concession agreement between Mineral Separation Limited, the government of Botswana and Roan Selection Trust (RST) to commence the mining of Cu and Ni in Selebi area in 1963 was made on the 2nd of June 1959. The shares of agreement made consisted of Botswana government (7.5%), Lion Ore Mining International group (6%) Botswana RST (85%) and 1.5% owned by other companies.

Prospecting the area began in 1959, which covered an area of about 67,600 square kilometres.

During the prospecting soil sampling technique was used, which were guided by in-depth aerial photography. This prospecting spun for approximately 3 years and led to the discovery of the Selebi Ni-Cu ore in 1963. Further exploration unveiled other ore occurrences with similar characteristics to the Selebi ore, including the most significant, Phikwe ore.

In order to obtain the characteristics of the ore, the properties of the host rock material including bulk metallurgical testing, underground exploration was necessary and began in 1967, followed by plant construction and sinking of Phikwe No.1, No.2 and Selebi shafts. The Selebi shaft was temporarily halted in favour of an open pit in Phikwe, which was to be operated in conjunction with underground mining technique.

The surface plant was commissioned in November 1973, and the first matte was produced. In 1980, the smelter ran at an annual production rate of 50 000 tonnes of matte per year. Two types of finished mattes were produced containing Cu, Ni, Co and PGE (such as platinum-Pt, palladium-Pd and gold-Au). The two mattes differ in accordance with the refinery specifications. In 2015, BCL achieved 30,954 tonnes of matte containing Cu, Ni and Co.

Production was low in 2015 due to a scheduled smelter renovation outage. Total 2016 output (including BCL and toll partners) was 60,110 tons, with BCL contributing 23,812 tons. In October 2016, BCL mine was placed under provisional liquidation (BCL, 2016).

1.5 Previous research in Selebi Phikwe mine

A study on the structural and metamorphic evolution of the Phikwe Ni-Cu sulphide deposit of Selebi-Phikwe was carried out by Wakefield (1976). Wakefield (1976) discussed the origin of Phikwe deposit. Sulphide blebs in olivine and spinel imply that the Ni-Cu mineralisation was of magmatic origin and they were captured in these minerals as immiscible sulphides.

The coarse grain size of the igneous assemblages indicates that the original magma was intrusive rather than extrusive sulphide/silicate magma. The amphibolite (host rock) is in the same stratigraphic position in Selebi, Selebi-North and Phikwe deposits. This, therefore, suggests that, combined with rock chemistry, the sulphides are to be linked to an extensive troctolitic stratabound intrusion.

A study on the composition of magmatic Ni–Cu–(PGE) sulphide deposits in the Tati and Selebi-Phikwe belts of eastern Botswana was executed by Maier et al. (2008). Most of the intrusions in NE Botswana (Selkirk and Tekwane intrusions and Selebi-Phikwe mafic–ultramafic intrusions) are of gabbro noritic composition. Troctolite, pyroxenites, and peridotites are less common. The Tati intrusions lie in a 2.6–2.7 Ga greenstone band. As a result of severe tectonism, the age and paleotectonic environment of the Selebi-Phikwe intrusions are less clear but could be comparable to Tati. According to Maier et al. (2008) lithophile trace element data suggest their origin in an oceanic island arc setting and the magmas did not assimilate much of the upper crust during emplacement. The Selebi Phikwe intrusions

specifically Dikoloti generally contain a higher crustal component compared to the Tati intrusions, as shown by higher Th/Y, Ta/Yb, and La/Sm ratios. This could be caused by the introduction of country rock fragments, giving rise to the possibility that Selebi-Phikwe magma emplacement is of an island arc setting. Orogenic belts are more likely to host Ni deposits than previously thought (Maier et al., 2008).

The Tati and Selebi-Phikwe deposits have systematically differing metal concentrations, suggesting they are not co-genetic. The Cu/Ni and Pd/Ir ratios of Tati and Selebi Phikwe deposits range between 0.1-1 500, which is typical for sulphides formed in basaltic magmas.

According to Maier et al., (2008) the Tati sulfide is made up of the phoenix and selkirk which have a Cu/Ni ratio of 0.41 and 0.87. The Cu/Ni ratio does, indeed vary through the deposit, from disseminated to massive, the content of Cu decreases while Ni increases. The grade of phoenix and selkirk are 0.85% Cu and 2.05% Ni at 4.50×10^6 tonnage and 0.81%Cu and 0.93%Ni at 3.30×10^6 tonnage The Tati sulphide mineralisation is Ni and PGE rich, with a high Pd/Ir ($\gg 100$), suggesting crystallisation from rations, and Pd/Ir ratios (100), indicating equilibration of less differentiated basalt with sulphides before emplacement (Maier et al., 2008).

An investigation on the multiple sulphur and iron isotope composition of magmatic Ni-Cu-(PGE) sulphide mineralisation from eastern Botswana was carried out by Fiorentini et al. (2012). Fiorentini et al. (2012) used multiple sulphur isotope data to discuss the sulphur source of magmatic Ni-Cu-(PGE) deposits in the Tati and Selebi-Phikwe Belts of eastern Botswana. Sulphur isotope data for mineralised samples of the Selebi-Phikwe Greenstone Belt are quite different from the Tati Greenstone Belt. The small range of $\delta^{34}\text{S}$ values from -3.1 to $+0.3\text{‰}$, can be explained by mass dependent processes affecting mantle-derived S,

sulphides from the Selebi-Phikwe greenstone belt shows a significant negative $\Delta 33S$ anomaly, which reflects possible input (refers to positive accumulation of sulphur) from a crustal reservoir. The negative $\Delta 33S$ anomaly in the Selebi-Phikwe deposits show that sulphur may have been assimilated from massive sulphide lenses, either barren or mineralised, related with felsic rocks or black shales with early diagenetic pyrite nodules. Sulphur in deposits that are along the Tati Greenstone Belt in Botswana may largely be derived from the mantle. Thus, incorporation of crustal S may not have been an important mechanism in triggering sulphide saturation in these magmas. Rather, other processes such as fractional crystallization, assimilation of silicates, and pressure and temperature changes may contribute to the mineralisation process to form PGE-rich deposits. Even though the specific source of S in the Selebi-Phikwe greenstone belt remains unknown, Fiorentini et al. (2012) proposes that $\Delta 33S$ measurements, even in S-poor terranes hosting mineralisation, may reveal the significant contributions of crustal sulphur that were essential to saturate the magma.

1.6 Aim and objectives of the study

Several studies have been conducted on the crustal architecture of Archaean terranes of Botswana side of the Central Zone of the Limpopo Mobile Belt, including the structural and metamorphic evolution of the Phikwe Complex, Along with Mineralogical and Geochemical Characteristics of the Selebi-Phikwe Magmatic Ni-Cu Deposit (McCourt et al., 2004; Wakefield, 1976; Kooganne 2018) and the geochemical and sulphur isotopic characteristics of the Phikwe Ni-Cu sulphide deposits (Maier et al., 2008; Fiorentini et al., 2012). However, investigation of the relationship between sulphide mineralisation and the metamorphic effect on the Selebi-North sulphides remain poorly understood.

Therefore, the aim of this research is to discuss the formation process of sulphide ores with consideration of the effect of metamorphism on the Selebi-North mine. The objectives of the study are i) identifying the textural relationship between ore and rock-forming minerals, ii) analysing the geochemical composition of host rocks and country rock in Selebi-North area and iii) investigating the mineral chemistry of both silicates and sulphides to discuss the pressure-temperature condition at the study area.

This study will contribute new sights on Ni-Cu mineralisation to the already existing knowledge of Selebi Phikwe mine.

1.7 Scope of the study

This research will examine the mineralogy and geochemistry of Selebi-North ore and host rock. Because the deposit and host rock are in a metamorphosed terrain, the influence of metamorphism on the ore deposit will also be studied.

2.0 Geology and Tectonic Setting

2.1 Setting of the Limpopo Mobile Belt

The 600km long and 250km broad Limpopo Complex in Southern Africa is a Neoarchean orogenic belt situated between the Zimbabwe Craton and the Kaapvaal Craton (Ranganani et al., 2002).

The Limpopo Belt, which is divided into Northern Marginal Zone (NMZ), Central Zone (CZ) and Southern Marginal Zone (SMZ) (Figure 4), was formed by collision of the Zimbabwe and Kaapvaal Cratons based on photogeological methods, composition, and structure (e.g., Carney et al., 1994; Khoza et al., 2013). The NMZ is mostly composed of granite-greenstone and is found along the side of the Zimbabwe Craton. The South-dipping North Limpopo Thrust Zone separates the NMZ from the Zimbabwe Craton. The south-dipping Triangle Shear Zone marks the NMZ's southern and northern limits (Khoza et al., 2013).

The Central Zone lithological assemblage is made up of predominately metasediments, S-type granitoids, and supracrustal rocks. Two metamorphic events during 2.7-2.6 Ga affected the CZ, resulting in the observable complicated fold structure (Smith et al., 2011). The U-Pb zircon age dating data obtained from granitoids gneiss from the CZ reported by Bagi et al., (2002) range from 2.73 to 2.64 Ga. The Palala-Tshipise Shear Zone divides the CZ from the Southern Marginal Zone in South Africa.

The suture zone for the collision of the two Cratons is indicated by mylonitic characteristics. There was just one metamorphic event in the SMZ, during 2.72-2.65 Ga, which deformed the enderbitic gneisses.

The SMZ is separated from the Kaapvaal Craton by the north-dipping Hout-River Shear Zone (HRSZ) (Smith et al., 2011, Khoza et al., 2012).

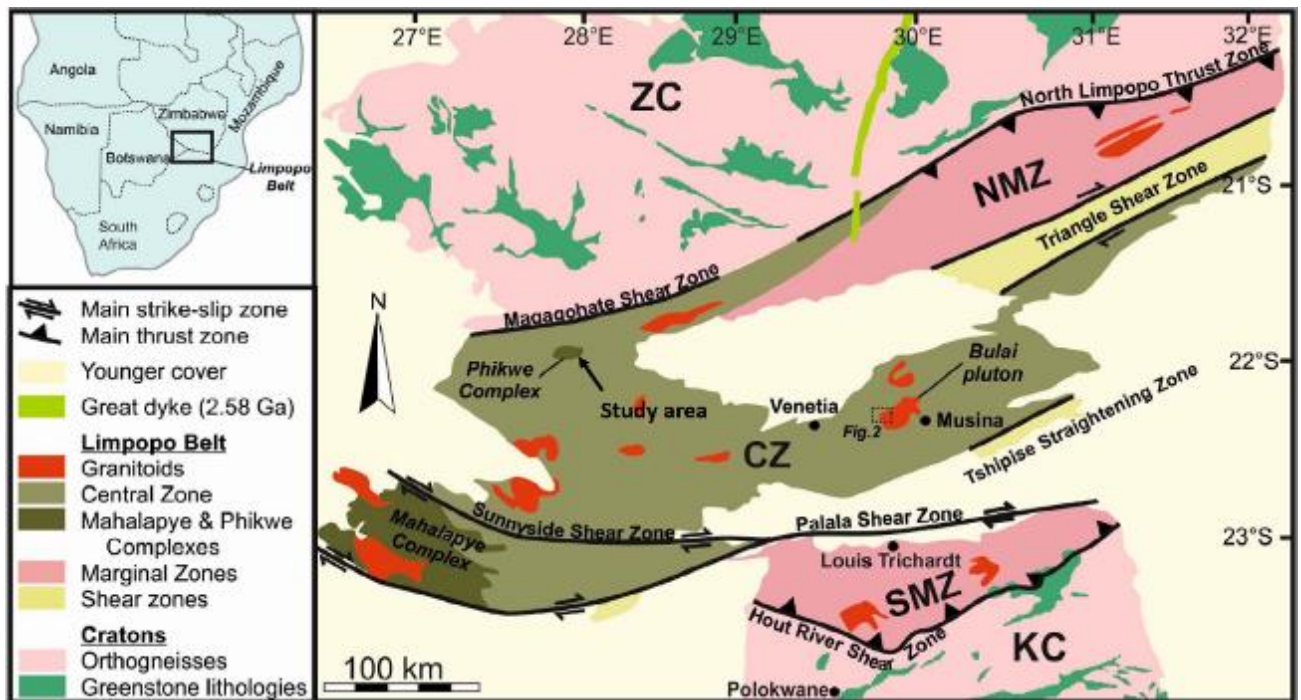


Figure 4: Overview map of the Limpopo Belt showing major subdivisions into Northern Marginal Zone (NMZ), Central Zone (CZ) and Southern Marginal Zone (SMZ), major shear zones and major shear zones and the adjacent Kaapvaal (KC) and Zimbabwe Cratons (ZC)

2.2 Geology of Phikwe Complex

The Phikwe Complex, including the study area, is situated at the northern part of CZ of the Limpopo Mobile Belt (figure 5). Phikwe, Selebi, and Selebi-North Ni-Cu sulphide deposits exist in high grade metamorphosed Archean gneisses (Carney et al., 1994; Maier et al., 2008).

The Phikwe Complex is composed of undifferentiated para- and orthogneisses, anorthositic gneisses, granitic gneisses, and ultramafic rocks. The Phikwe Complex gneisses are divided into two types: banded gneisses and granitic gneisses. The banded gneisses are hornblende, quartzo-feldspathic, and anorthositic. The orebodies occur as conformable stratabound associated with amphibolites hosted within a sequence of gneisses (Carney et al., 1994).

Ores and host rocks underwent two episodes of deformation that seem to have affected the Central Zone of the mobile belt (Hoffman, 2001). Geochronological research revealed an Archean age (>2600 Ma) for the host rocks (Brown, 1988). Deformation thins, folds, and attenuates orebodies in the NNE-SSW direction. The N is structurally governed by two macro-structures. The synformal basin at Selebi and the antiform at Phikwe to the north of Selebi represent these features (Dirks, 2005).

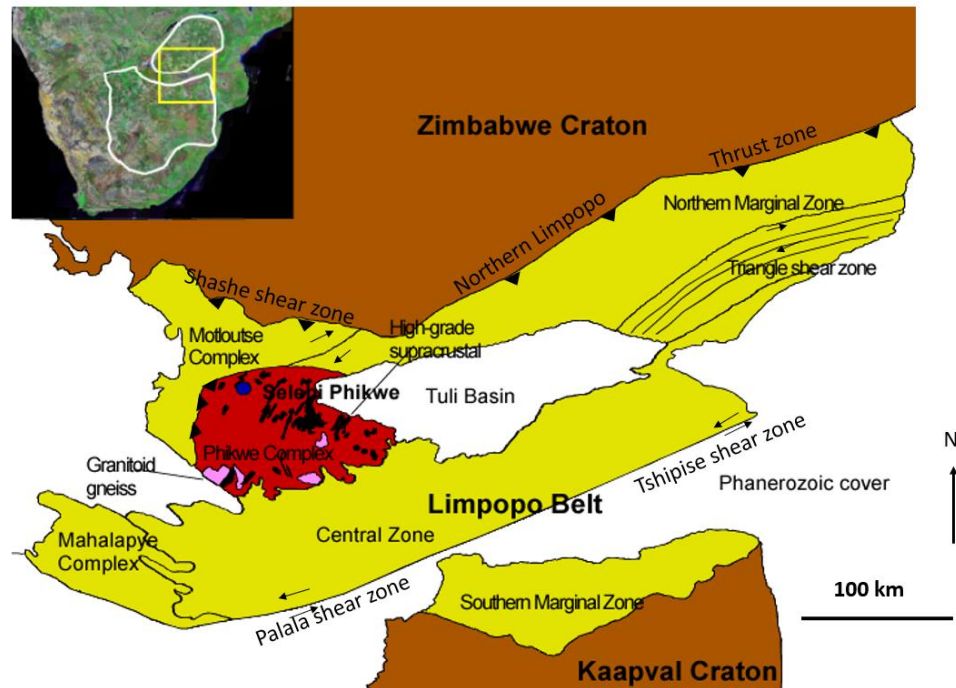


Figure 5: Location map of the Phikwe Complex within the CZ of the Limpopo Mobile Belt (Modified from Rajesh et al., 2020 & Maier et al., 2008)

2.3 Local geology of the study area

According to Wintley (unpublished) the Selebi North Ni-Cu orebody is an anticline with a sulphide-rich amphibolite layer plunging 45 degrees west (Figure 6). The ore body is segmented into; the South Limb (SL), North 1 (N1) Limb, North 2 (N2) Limb and North 3 (N3) Limb. All limbs share a geological horizon that connects the ore bodies. The primary structure is a 45-degree isoclinal F2 fold.

Mineralisation and structural tendencies follow the F2 axis. The amphibolite thickens towards in the hinge. Description of the following sections are based on (Wintley unpublished).

The South Limb

The South limb is 0.1-15.0m in width and dips 40-80 to the degrees south. At 516 meter level (ml), the strike length is measured to be approximately 450m while its depth was determined

to be 200m at 800 ml. The South limb is divided into four segments: SL1 through SL4. Each section has its unique geologic character which plays a crucial role when converting resource to reserve. The ore body is characterised by mineralised amphibolite layer with massive sulphide ore on the hanging wall and lower grade disseminated amphibolite on the footwall. Pods and lenses predominately occur in the disseminated zone. Quartzo-feldspathic pegmatoid veins are observed, which invade the Ni-Cu ore body.

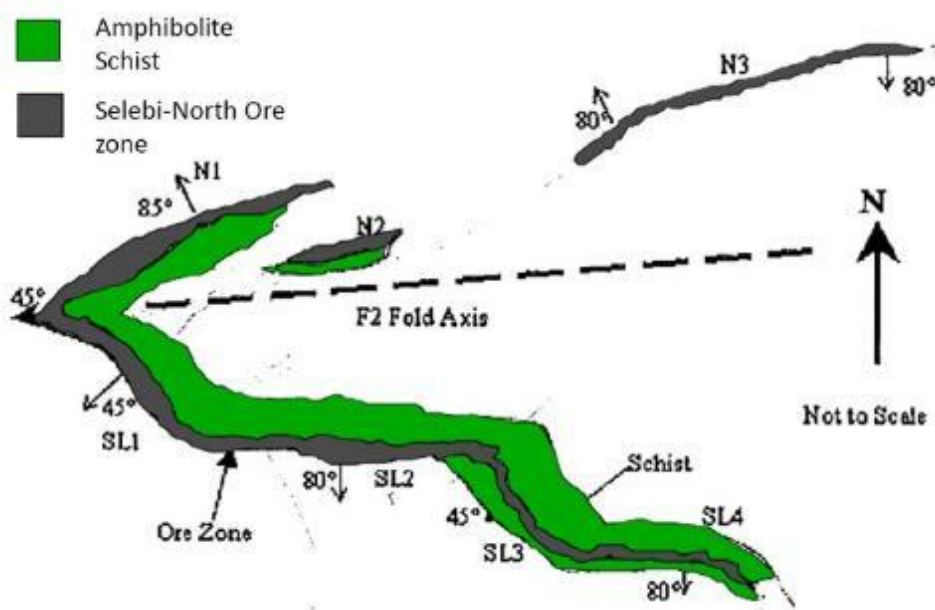


Figure 6: Distribution map of the Selebi-North ore body at 504 ml (Witley, unpublished)

The footwall is regarded as the contact between crystalline amphibolite and biotite schistose amphibolite, which grades into hornblende-phlogopite-plagioclase schist. This schist contains minor amounts of disseminated sulphides and lenses of massive sulphides are rarely observed. The schistose layer is not economically viable. The ore body hanging wall is usually a grey quartzo-feldspathic gneiss containing minute amphibole and biotite.

Towards the eastern extremity, a barren schist grading into altered hornblende gneiss the hornblende gneiss is mostly barren with occasional massive sulphide injections.

The North 1 Limb

The N1 Limb is 0.1-18.0m broad and dips 80-90 degrees to the north. At 516 ml the length of the strike of the N1 Limb is 150m. The footwall is hornblende-phlogopite-plagioclase schist and has a tight synform sloping 45 degrees west on an F2 trend. Sulphides and Biotite schist often occur along with fold. Numerous fold gneiss inclusions may be noticed on the hanging wall.

The North 2 Limb

The synform's southern limb continues to the North 1 Limb East area. The N2 limb has a 50m strike length which is said to be economic. The ore shoot slants 45° to the west. Schist-gneiss-mineralised amphibolite is widespread with a dip that terminates rapidly and mineralisation becomes discontinuous. The hanging wall is characterised as quartzo-feldspathic gneiss while the footwall is altered micaceous schist, which is similar to that in the N1 limb. The amphibolite layer shears off and discontinues east of the economic zone.

The North 3 Limb

The N3 limb is a narrow sub vertical sulphide orebody, which has a strike length of 330m on 385ml. On the eastern extremity, the orebody is characterised by amphibolite with low concentration of Ni and Cu, increase in orebody parallel shearing and orebody splitting. The western side of the N3 becomes uneconomic due to its narrowing and shearing out. The thin ore shears out and meets the N2 limb.

The hanging wall and footwall consist of gneisses. The amphibolite content relative to the ore increases towards the east of N3 (Wintley, unpublished). The Ni/Cu ratio of Selebi North is

0.89, it increases towards the massive portion of the ore because of a surge in Ni and decreases moving away attributed to an increase in chalcopyrite. During the fractionation of komatiitic and basaltic magmas, Ni and Ir act in a compatible manner, but Cu and Pd is incompatible in the absence of sulphides (e.g Barnes and Maier 1999; Crocket 2002). As a result, the Ni/Cu and Ir/Pd ratios of the sulphides that segregate from fractionating magmas tend to decrease (Barnes and Maier 1999; Crocket 2002).

3.0 METHODOLOGY

In order to achieve the aim and objectives of this study, field work was conducted, which included underground rock sampling from the Selebi-North zone in BCL. Laboratory works composed of microscope observations, Induced Coupled Plasma Optical Emission Spectrometer and Electron Probe Micro Analyzer.

3.1 FIELD WORK

Field investigations were carried out at Selebi North underground mine. Reconnaissance core logging was done to understand the relationship between host rock and mineralised zone. Underground lithological samples were collected at 450, 570 and 810ml. The collected samples were mineralised disseminated, semi massive and massive ore, and barren rocks (amphibolite and biotite schist). Most of the samples were the least altered representative units.

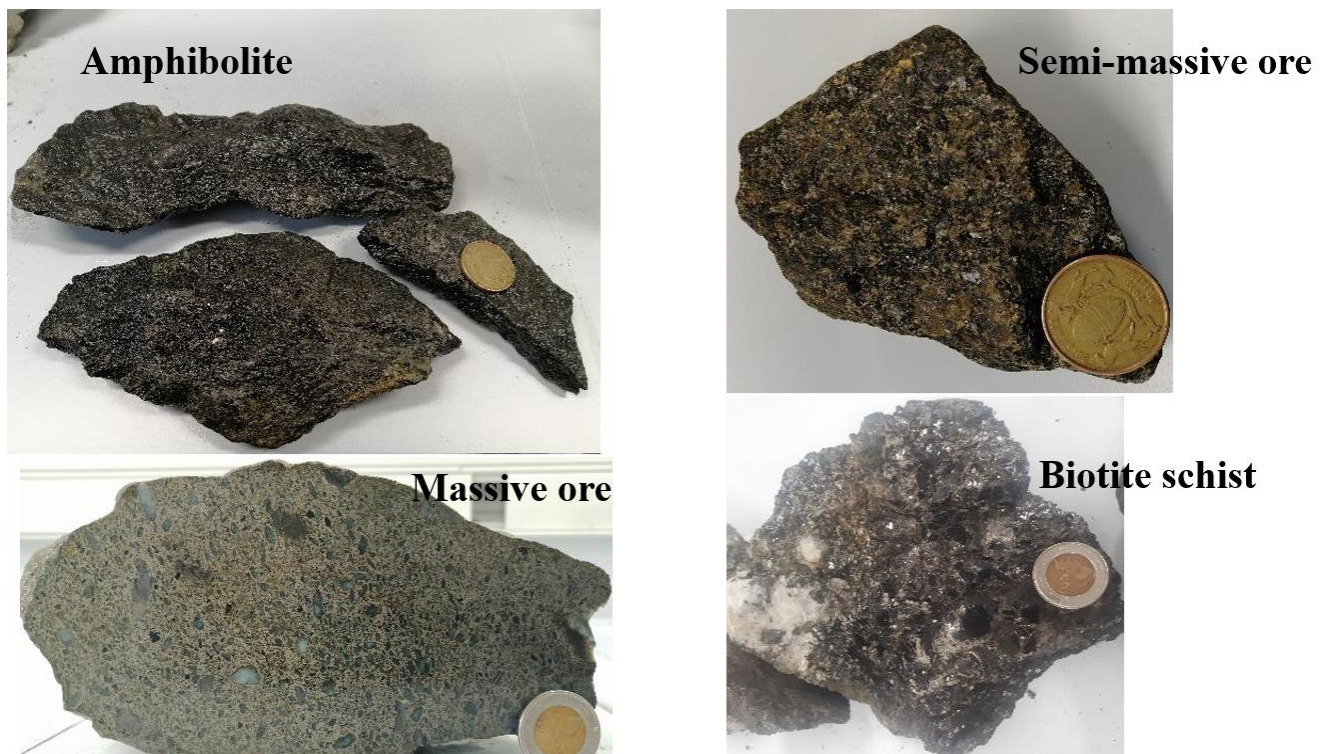


Figure 7: representative lithology of Selebi-North underground mine

3.2 PETROGRAPHY

POLISHED SECTIONS

Polished sections were made in the mineral dressing room at the Earth and Environmental Sciences Department (EESD) in Botswana International University of Science and Technology (BIUST). The representative sulphide rock chips were cut to 2.5cm length, 1.5cm width and 2cm thickness. After drying, the samples were manually grinded with #150, #320, #800, #1000, #2000, and #3000 mesh powders on matching plates. After the grinding, samples were polished by using 3 μm and 1 μm diamond polishers. The polished surface was inspected under reflected light to identify opaque minerals.

POLISHED THIN SECTIONS

After collecting rock and ore samples, thin sections were made to study the petrography of both the main and minor phases and the textural relationships between ore minerals and rock-forming minerals. Polished thin sections were also made in the same laboratory where polished sections were made.

The rock samples were initially cut into 2cm by 2cm slabs using a main diamond blade floor saw. They were then heated overnight at 90°C on an oven hotplate to eliminate moisture from the representative rock slabs. The samples were mounted on the glass slides using either 1:10 Petropoxy 154 or E-bod. Petropoxy 154-bonded samples were dried overnight at 90°C on a hotplate. Clips were employed to keep the slides in place and remove air bubbles that formed during installation. The mounted samples were dried overnight to harden the adhesive. The mounted samples were trimmed to 1mm using a secondary cutter. The thick pieces were subsequently ground to 30 microns using prepalap machine (#600 mesh powder).

After each mesh powder, a 10-minute ultrasonic bath was utilized to grind down the thick areas. The polished thin parts were next polished with 3m and 1m diamonds for around 15 minutes a piece. The thin slices were viewed using an optical microscope with both reflected and transmitted light.

3.3 Induced Coupled Plasma Optical Emission Spectrometer (ICP-OES)

After being ground into a powder and dried overnight at 110°C, solid samples were weighed into a Teflon Hot Block vessel at a rate of 0.200 g per sample.

The Hot Block digested solid materials using the Briggs digestion process (Hylander et al., 2009), which utilised perchloric acid (HClO₄), Hydrochloric acid (HCl), Hydrofluoric acid (HF) and Nitric acid (HNO₃). The operation took two days and required a perchloric-acid fume hood.

The sample containers were cleaned with distilled water prior to adding chemicals. There were 3 mL of HCl, 2 mL of HNO₃, 1 mL of HClO₄, and 2 mL of HF in the original reagent combination. In an HClO₄ fume hood, the samples were heated on the Hot Block at 110°C until they were completely dry. After that, the samples were chilled to the touch. 1 mL of HClO₄ and 2 mL of distilled water were added to each sample, and the mixture was then heated to dryness at 160 °C. The samples were once more refrigerated before each receiving 1 mL of aqua regia (3 parts HCl to 1 part HNO₃) and 15 minutes to react. Each sample received 9 mL of 1% HNO₃ before being sealed, heated for an hour at 95°C in a drying oven, and then chilled. The materials were washed into 50-mL graduated centrifuge tubes if there were no solid particles left in the container. The samples were kept in these tubes as well. In order to prepare the samples for ICP-OES, they were first digested.

Prior to analysis, the following solutions were prepared; a sample probe rinse solution of 1% ultrapure HNO₃, an internal standard solution of 10 ppm Sc in 1% ultrapure HNO₃, a calibration blank and calibration standards for three-point calibration, and a calibration check blank solution. Once the calibration was complete, the samples were loaded into the ICP-OES for analysis. All the analysis were done in the EESD in BIUST.

3.4 Electron Probe Micro Analyzer (EPMA)

Polished thin sections were quantitatively analysed utilizing a JOEL JXA-8230 Electron Probe Micro-analyser in the EESD at BIUST.

The conditions for the analysis of sulphides were as follows: accelerating voltage, 15kV; beam current, 20 nA, electron beam diameter, 5µm and background counting duration 5-20 sec. Iron (metal Fe, K α), sulphur (Fe.S₂, K α), copper (metal Cu, K α), nickel (metal Ni, K α), cobalt (metal Co, K α), chromium (metal chromium, K α), arsenic (GaAs, L α), and tellurium (metal Te, L α) were employed as standard material. The accelerating voltage of 15kV; beam current of 20nA; probe diameter of 1 µm and background counting duration of 0-20 sec were used. Standard materials for silicate analysis were Sodium (Jadeite, K α), Magnesium (Diopside, K α), Aluminium (Almandine, K α), Silicon (Diopside, K α), Fluorine (Diopside, K α), Chromium (metal Cr, K α), Barium (Barite, K α), Potassium (Orthoclase, K α), Calcium (Diopside, K α), Titanium (Rutile, K α), Manganese (Rhodonite, K α), Iron (Almandine, K α), Caesium (Pollucite, L α) and Chloride (Tugtupite, K α) supplied by EESD.

4.0 PETROGRAPHY OF COUNTRY ROCK, HOST ROCK AND MINERALISED ZONE

Studied rocks are composed of biotite schist (country rock) and amphibolite (host rock).

Furthermore, nickel-copper mineralization is investigated in collected samples.

4.1 Biotite Schist

Silicate minerals in biotite schist is composed of quartz (66%), biotite (28%), plagioclase (4%) amphibole (1%) and minor opaque minerals (pyrrhotite, chalcopyrite, pentlandite, magnetite and pyrite) (1%). Figure 8 shows mineral occurrences of the biotite schist. The dominant mineral, quartz has a diameter of 800 μ m, followed by plagioclase (680 μ m), biotite (600 μ m) and amphibole(550 μ m). Quartz grains are typically relatively coarser and some of them are >1 mm in diameter (Figures 8a and b). Furthermore, the quartz grains often show undulose extinction (Figures 8b and d), indicating that biotite schist was deformed. Biotite grains generally show elongated shape and oriented into a schistose fabric (Figures 8a to d). Biotite shows a close association with amphibole, where possible biotite alteration could have affected amphibole (Figures 8a and b). Opaque minerals are comprised of sulphides (major amount of pyrrhotite and minor chalcopyrite) are interstitial to silicate minerals (Figures 8a to d).

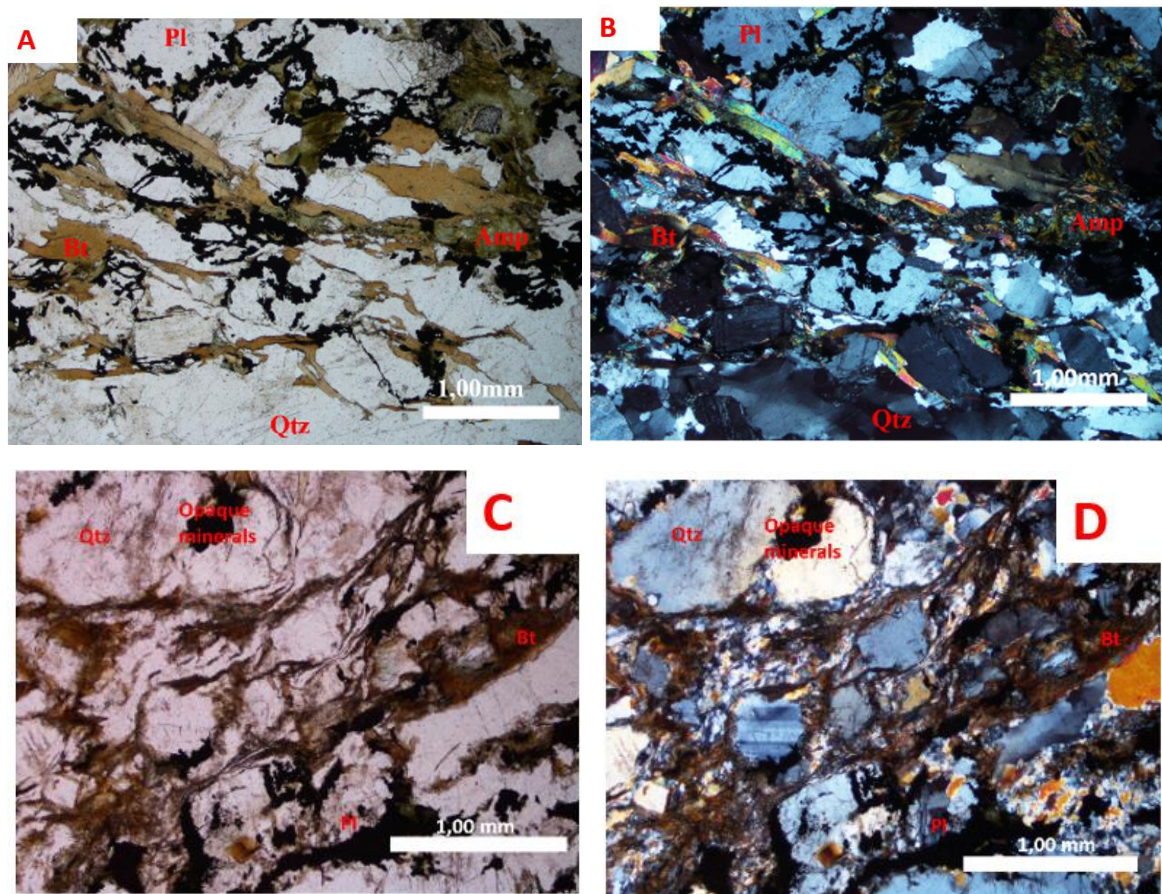


Figure 8: Photomicrographs of the studied biotite schist. Abbreviations are biotite (Bt), quartz (Qtz), plagioclase (Pl) and amphibole (Amp). Opaque minerals (pyrrhotite, pentlandite, chalcopyrite and pyrite) are observed as black color. A: biotite schist with foliated biotite (PPL), B: same part of A under XPL with Undulose extinction, C and D quartz-dominant portion of the biotite schist (C:PPL, D:XPL)

4.2 Amphibolite

Amphibolite is subdivided into mica-rich and mica-free amphibolite. Mica-rich amphibolite consists of predominantly amphibole (59%), quartz (21%), biotite (17%) and plagioclase (3%) while Mica-free Amphibolite is made up of majority amphibole (67%), quartz (29%) and minor amount of plagioclase (4%) (Figure 9). Amphibole grains show subhedral to anhedral shape (figure 9) and a 60-120° cleavage plan (Figures 9e and 9f). Amphibole grains largely show a straight-line boundary with silicates but in figure 9a and 9b the silicate grain is showing an irregular grain boundary with quartz. Quartz occurs as subhedral shape and plagioclase shows an anhedral shape (figure 9d and 9e).

Both amphibolites show alignment of amphibole (800µm in diameter) and biotite (550µm) grains in a foliation fabric, as an effect of metamorphism in Selebi-North. Plagioclase (350µm) and quartz (850µm) show albite twining and undulose extinction respectively. The opaque minerals occur interstitial to the silicates consist of predominately of pyrite (70%), chalcopyrite (20%) and pentlandite (10%).

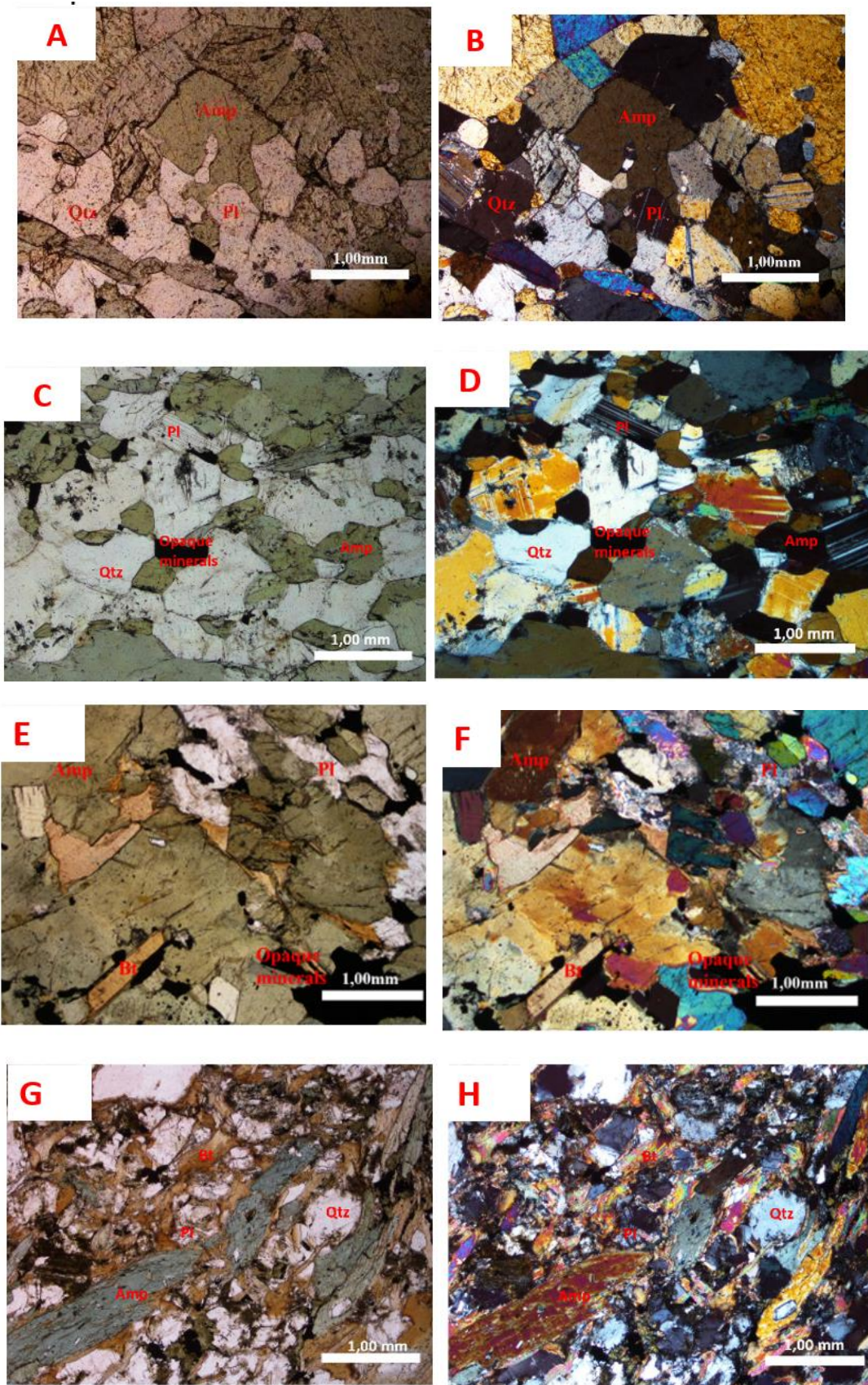


Figure 9: Photomicrographs of the studied amphibolite (A-D: mica-free amphibolite). Abbreviations are same as Fig 8. A: irregular shape of amphibole (PPL), B: same view as A (XPL), C: relatively felsic mineral rich part (PPL), D: same part of C (XPL)

4.3 Ni-Cu mineralisation

Fe-Ni-Cu sulphide mineralization is observed in mica-rich amphibolite and mica-free amphibolite. Furthermore, biotite schist also contains sulphide mineralization as minor to trace amount. The mineralised zone is classified into disseminated, semi-massive and massive based on the amount of sulphides.

The modal proportions of disseminated sulphides contains 90% barren rock and 10% ore, within the 10%, 85% is pyrite 12% chalcopyrite and 3% pentlandite. Semi-massive sulphides are composed of 51% ore material and 37% barren rock, the 51% ore is made up of 34% pyrrhotite, 29% pentlandite, 27% chalcopyrite and 10% pyrite. Lastly the massive sulphide ore has 83% ore and 17% barren rock, the 83% ore is made up of 38% pyrrhotite, 35% pentlandite, 26% chalcopyrite and 1% magnetite. The modal proportions affirm a sulphide zonation pattern, where shallower disseminated sulphides contain predominantly pyrite and chalcopyrite, semi-massive- chalcopyrite and pyrrhotite and massives-mainly pyrrhotite and pentlandite.

Figure 10 shows sulphide minerals and their texture in disseminated ores. Disseminated sulphides are observed in both amphibolites (Figures 10a to d) and biotite schist (Figures 10e and f). These sulphides are made up of pyrrhotite (650µm in diameter), pentlandite (400µm in diameter) and pyrite (250 µm in diameter) often observed along with foliation and schistose fabric (Figures 10a, 10b, 10e and 10f).

Sulphide veinlet, composed of pyrite, is recognized, cutting across the foliation fabric of mica-rich amphibolite (Figure 10c and 10d), indicating it postdate the formation of sulphide minerals (Figure 10c and 10d).

Apart from the mineralization along the schistose fabric, sulphides in biotite schist, have a twofold mode of occurrence. Firstly, pyrrhotite occurs within biotite cleavage planes, possibly indicating that mineralization occurred after biotite had crystalized (Figures. 11a and b). Secondly, sulphide minerals mainly chalcopyrite was observed in fractures of quartz mineral (Figures. 11c and 11d). The evidence of fractures infiltrated by chalcopyrite is a clear indication of the effect of metamorphism and deformation affecting Selebi-North.

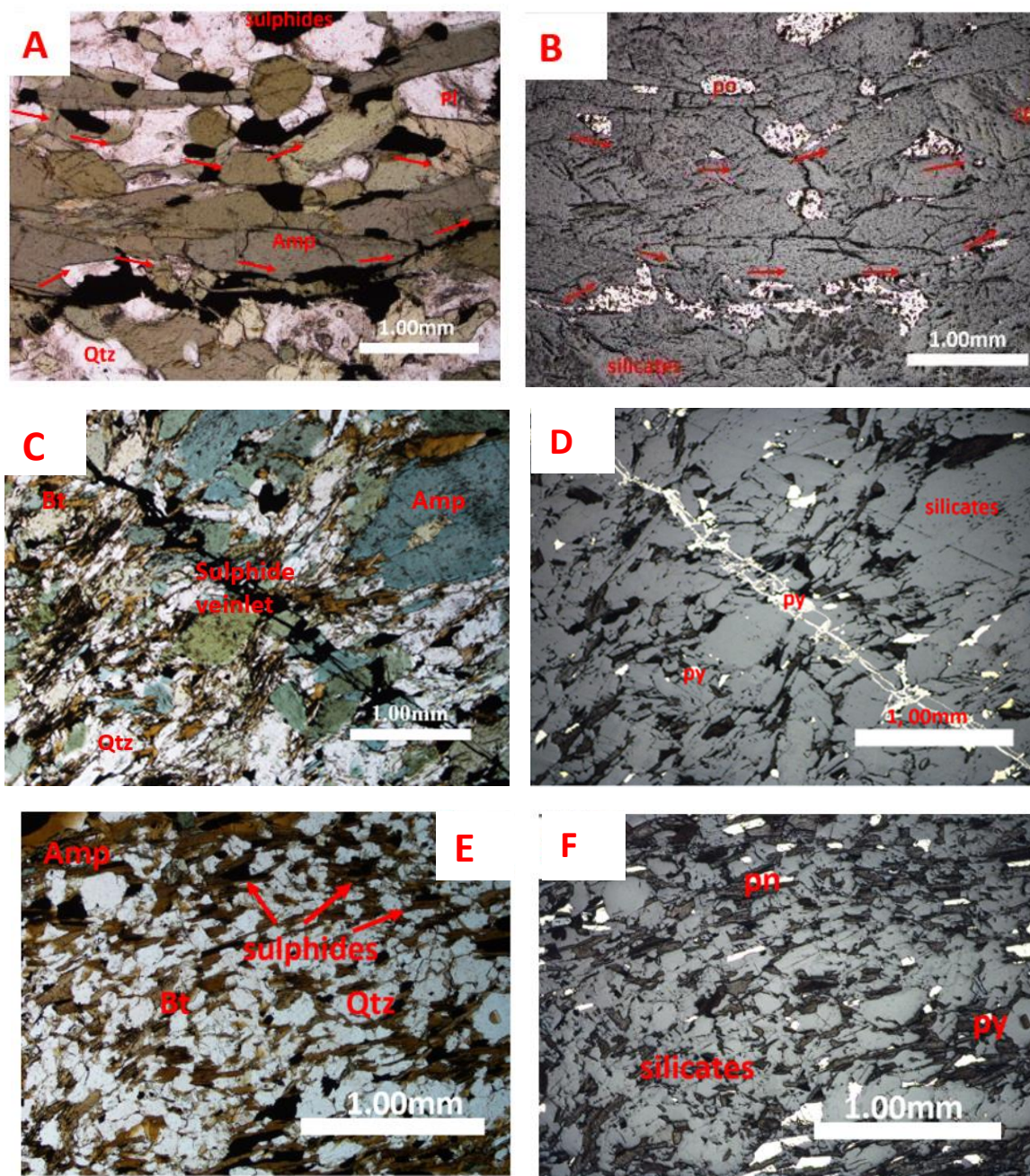


Figure 10: Figure 10: Photomicrographs of the disseminated ores. (A, B: mica-free amphibolite, C, D: mica-rich amphibolite, E, F: biotite schist). Abbreviations are as follows: po: pyrrhotite, py: pyrite and pn: pentlandite. Abbreviations for silicate minerals are same as Figure 8. A: silicates and sulphides along the foliation plane in amphibolite (PPL), B: same views as of A (Reflected light), C: silicates and sulphides in amphibolite with pyrite veinlet (PPL), D: same part of C (Reflected light), E: In biotite schist (PPL), F: same part of E (Reflected light). Sulphide minerals are composed of pyrrhotite, pentlandite, chalcopyrite and minor pyrite. All three types of ore, disseminated, semi-massive and massive ores, include pyrrhotite, pentlandite and chalcopyrite. Pyrite is observed mainly in disseminated ore.

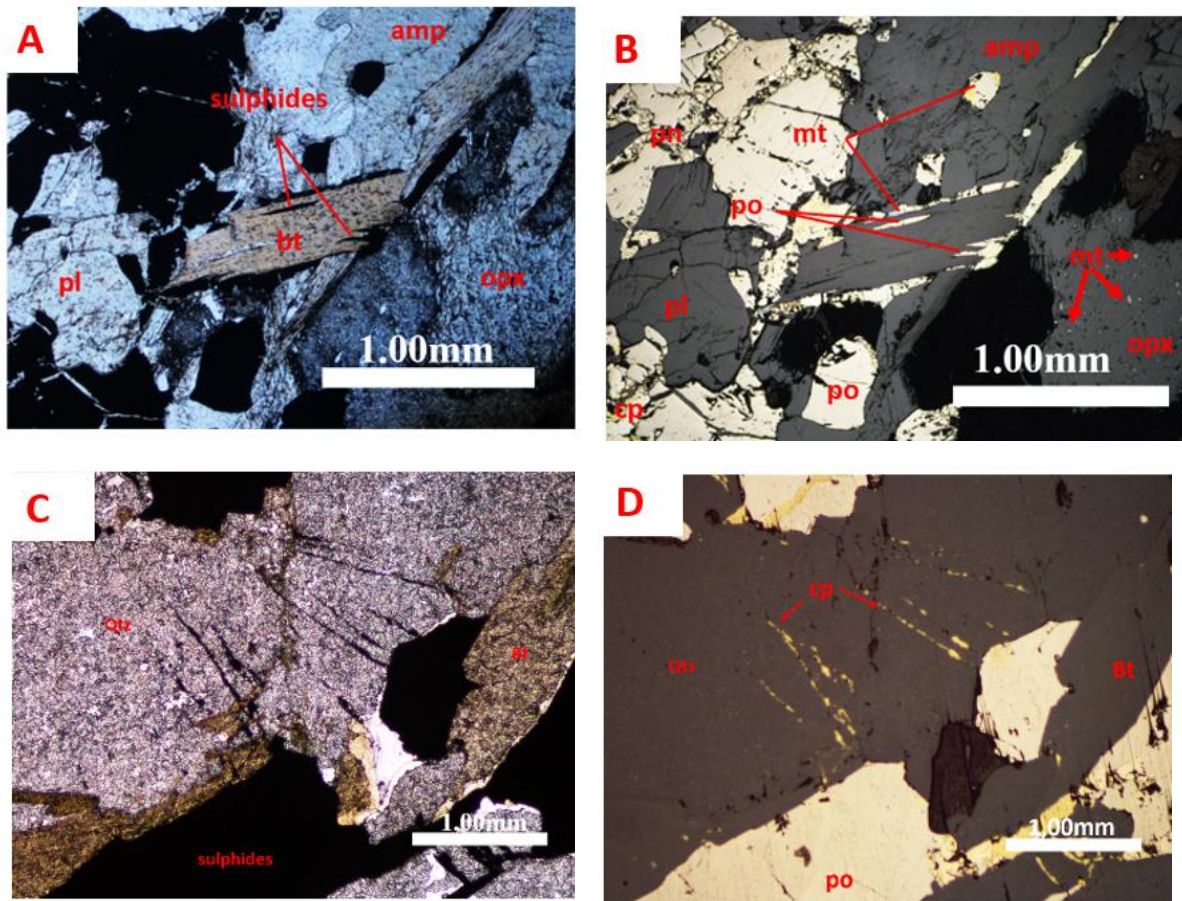


Figure 11: Photomicrographs of sulphide minerals in biotite schist. Abbreviations are as follows: cp: chalcopyrite and mt: magnetite. Other abbreviations are same as Figure 8 and 10. A: pyrrhotite occurrence within a biotite cleavage plane (XPL), B: same part of A (Reflected light), C: chalcopyrite filling microfracture in quartz (XPL), D: same part of C (Reflected light).

Figure 12 shows sulphide minerals and magnetite in semi-massive and massive ores. Pyrrhotite (34%) is the major component of semi-massive ore, followed by pentlandite-(32%) chalcopyrite (24%) and pyrite (6%) and magnetite (4%). Shapes of sulphide in semi-massive ore are typically irregular and often have straight-lined boundary with silicates (Figure 12a and 12b). In the relatively sulphide-rich part, larger grains of sulphides have silicate inclusions (Figure 12b). Pyrrhotite is predominant in the massive ore, as well as in semi-massive ore. Pentlandite and chalcopyrite are also observed but less than pyrrhotite. Compared with semi-massive ore, massive ore contains relatively higher amount of magnetite.

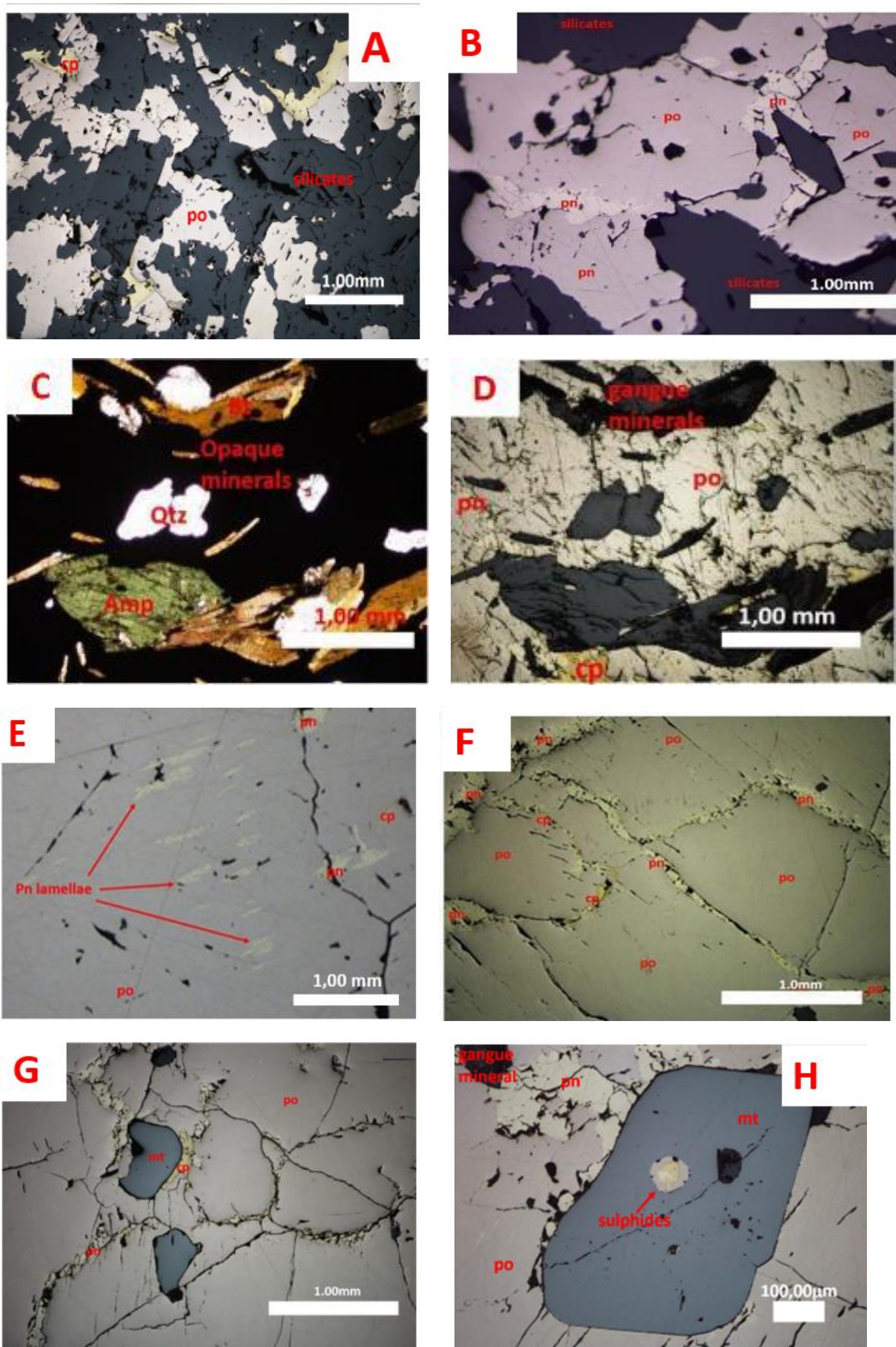


Figure 12: Photomicrographs of sulphide minerals in semi-massive (A and B) and massive (C to H) ores. Abbreviations are same as Figures 8, 10 and 11. A, B: irregular and often have straight-lined boundary with silicates), C, D: larger grain sulphide includes much smaller size of silicates, E: Pyrrhotite grains include pentlandite lamellae, D, B: continuous pentlandite "loop pentlandite" along the grain margin of pyrrhotite, G, H: magnetite grain anhedral to subhedral include sulphide.

Large sulphides enclose silicate minerals such as quartz and biotite (Figure 12c and 12d). Pyrrhotite often includes pentlandite lamellae (Figure 12e). Narrow and continuous pentlandite occurrences were observed (Figure 12b and 12f) similar to “loop pentlandite” in Mukwakwami et al. (2014). Magnetite grains are frequently enclosed by sulphide aggregate(s) shown in (Figure 12g and 12h). Grain size of magnetite varies from 100µm to 1.7mm and its shape is typically euhedral to subhedral. Furthermore, a magnetite grain (1.7mm in diameter) has sulphides and silicate as inclusion (Figure 12h).

The Ni/Cu ratio of disseminated mica free/rich amphibolite is 0.93-0.94, for Biotite schist is 1.05, semi-massive id 1.10 and massive sulphide is 1.14. The variance in Ni/Cu ratio between lithologies is too narrow to be able to draw substantive conclusions from.

5.0 MINERAL CHEMISTRY

Mineral chemistry of several silicates and sulphides were analysed using EPMA in order to clarify their compositions and to infer the P-T conditions of the host rock.

5.1 Silicate minerals

Table 1 shows representative chemistry of amphibole in mica-rich and mica-free amphibolite. Amounts of SiO₂ 11.401-46.125 wt%, Al₂O₃ 8.647-16.132 wt%, CaO 0.001-12.991 wt%, TiO₂ 0.290-1.422 wt% and MnO 0.085-19.799 wt% components are similar in two-types of amphibolite and biotite schist. Figure 13 illustrates the compositions of the amphibole, showing that chemical compositions of these amphiboles fall in actinolite composition. Furthermore, this figure shows that amphiboles in mica-free amphibolite contain higher Fe-component than those in mica-bearing amphibolite.

Chemical compositions of biotite in Mica-rich amphibolite are shown in Table 2, the major elements are SiO₂ (37.02-39.67 wt%), Al₂O₃ (15.35-16.47 wt%), MgO (29.63-30.18 wt%) and K₂O (9.01-10.65 wt%). While that of Biotite schist is SiO₂ (36.21-37.52wt%), Al₂O₃ (15.39-16.47 wt%), MgO (28.01-30.75 wt%) and K₂O (9.01-10.65 wt%).The compositions of biotite from biotite schist and mica-rich amphibolite are both classified as phlogopite (Figure 14).

Mineral chemical composition of plagioclase is provided Table 3. Mica-rich amphibolite is predominately composed of SiO₂ (45.32-46.95 wt%), Al₂O₃ (31.57-32.57 wt%), CaO (15.51-16.89 wt%), Na₂O (1.83-2.51 wt%) and K₂O (0.04-1.79 wt%). Mica-free amphibolite SiO₂ (57.09-58.26 wt%), Al₂O₃ (26.05-27.31 wt%), CaO (9.51-11.03 wt%), Na₂O (3.28-4.59 wt%) and K₂O (0.02-0.08 wt%).

Lastly Biotite schist is made up of SiO₂ (66.48-67.80 wt%), Al₂O₃ (15.64-16.78 wt%), CaO (0.00-0.04 wt%), Na₂O (10.67-11.16 wt%) and K₂O (0.53-0.72 wt%). Chemical compositions of plagioclase from the biotite schist plot in the albite field (Figure 15). On the other hand, some of plagioclase are classified as albite, while others are classified as labradorite and bytownite.

Table 1: Representative chemical compositions of amphibole.

Major oxides (wt.%)	Amphibole (Mica-rich Amphibolite)	Amphibole (Mica-rich Amphibolite)	Amphibole (Mica-rich Amphibolite)	Amphibole (mica-free Amphibolite)	Amphibole (mica-free Amphibolite)	Amphibole (mica-free Amphibolite)
SiO ₂	44.10	45.70	43.40	42.20	40.30	41.60
TiO ₂	0.42	0.41	0.38	0.31	0.46	0.36
Al ₂ O ₃	9.84	9.99	9.86	10.54	10.33	9.22
Cr ₂ O ₃	0.10	0.12	0.11	0.12	0.19	0.12
Fe ₂ O ₃	4.84	4.77	4.39	21.69	17.95	17.62
MnO	0.31	0.31	0.32	0.50	0.34	0.37
MgO	22.77	22.66	22.76	9.00	9.31	9.74
CaO	12.14	12.20	12.09	11.39	11.78	11.85
Na ₂ O	1.08	1.03	1.08	1.47	1.16	1.01
K ₂ O	0.51	0.51	0.50	0.01	0.57	0.46
Total	96.10	97.68	94.89	97.22	92.39	92.35
Mg ₇ Si ₈ O ₂₂ (OH) ₂	50	53	54	48	49	50
Fe ₇ Si ₈ O ₂₂ (OH) ₂	23	21	23	27	25	26
Ca ₇ Si ₈ O ₂₂ (OH) ₂	27	26	23	25	26	24

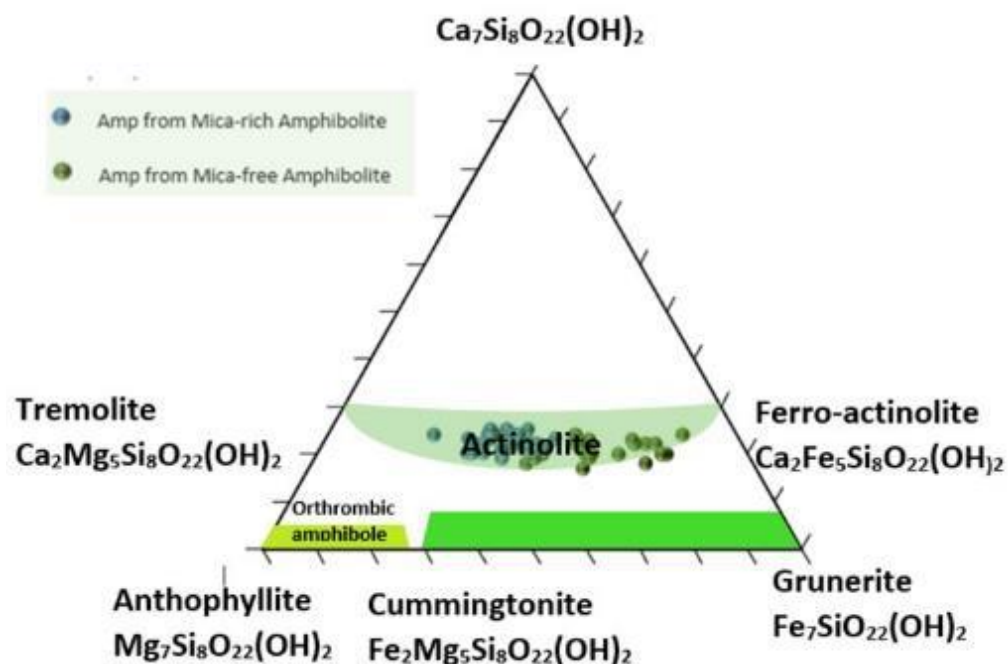


Figure 13: Quadrilateral compositions of amphibole from Selebi-North amphibolite (Leaker et al., 1997)

Table 2: Representative chemical compositions of biotite obtained from mica-rich amphibolite and biotite schist.

Major oxides (wt.%)	Biotite (Mica-rich Amphibolite)	Biotite (Mica-rich Amphibolite)	Biotite (Mica-rich Amphibolite)	Biotite (Mica-rich Amphibolite)	Biotite (Biotite Schist)	Biotite (Biotite Schist)	Biotite (Biotite Schist)	Biotite (Biotite Schist)
SiO ₂	37.37	37.36	37.17	37.02	36.51	37.16	36.52	36.43
TiO ₂	1.35	1.38	1.39	1.30	1.29	1.29	1.55	1.49
Al ₂ O ₃	16.04	16.13	15.97	15.83	15.98	16.05	15.98	16.00
Cr ₂ O ₃	0.12	0.12	0.10	0.09	0.10	0.07	0.07	0.08
Fe ₂ O ₃	0.66	0.51	0.76	0.65	0.92	1.07	0.77	0.90
MnO	0.11	0.12	0.09	0.12	0.12	0.11	0.09	0.09
MgO	29.89	29.80	29.87	29.81	29.98	29.88	29.58	29.51
CaO	0.00	0.01	0.02	0.08	0.06	0.04	0.00	0.00
Na ₂ O	0.26	0.25	0.23	0.33	0.24	0.21	0.25	0.24
K ₂ O	10.30	10.24	10.28	9.98	9.77	10.02	10.20	10.33
F	0.06	0.10	0.17	0.21	0.11	0.16	0.18	0.05
Cl	0.07	0.06	0.07	0.07	0.07	0.07	0.07	0.07
Total	96.23	96.08	96.12	95.48	95.14	96.14	95.25	95.21
Mg	78	81	79	80	90	96	79	92
Al ^{VI} +Fe ³⁺ +Ti	15	13	14	12	5	2	13	7
Fe ²⁺ +Mn	7	6	7	8	5	2	8	1

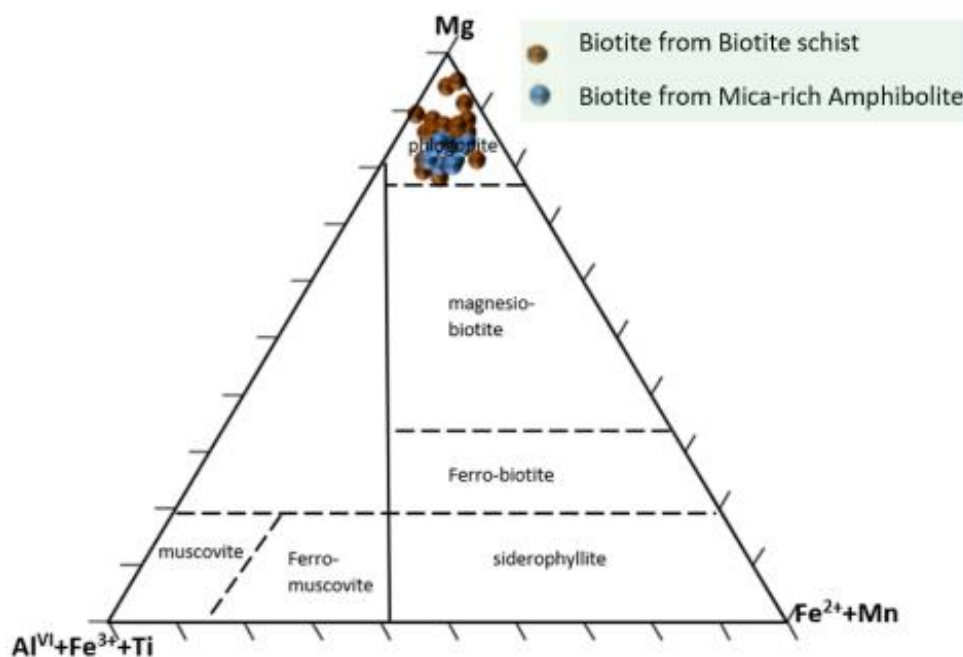


Figure 14: Classification diagram for biotite obtained from mica-rich amphibolite and biotite schist (Foster, 1960)

Table 3: Chemical compositions of plagioclase from biotite schist and amphibolite.

Major oxides (wt.%)	Plagioclase (Mica-rich Amphibolite)	Plagioclase (Mica-rich Amphibolite)	Plagioclase (Mica-free Amphibolite)	Plagioclase (Mica-free Amphibolite)	Plagioclase (Biotite schist)	Plagioclase (Biotite schist)
SiO ₂	46.82	46.79	57.14	58.26	67.37	67.50
TiO ₂	0.01	0.00	0.02	0.01	1.39	1.41
Al ₂ O ₃	32.40	32.33	26.07	26.61	16.71	16.07
Cr ₂ O ₃	0.00	0.00	0.00	0.02	0.05	0.05
Fe ₂ O ₃	0.14	0.12	0.08	0.11	0.79	0.83
MnO	0.00	0.00	0.02	0.00	0.23	0.21
MgO	0.00	0.00	0.00	0.01	0.25	0.89
CaO	16.48	16.87	10.61	11.00	0.00	0.00
Na ₂ O	2.09	2.51	4.59	3.41	11.13	11.16
K ₂ O	1.79	0.05	0.08	0.07	0.66	0.19
Total	99.72	98.67	98.60	99.49	98.58	98.32
An	67	78	71	65	3	5
Ab	18	12	16	20	90	92
Or	15	10	13	15	7	3

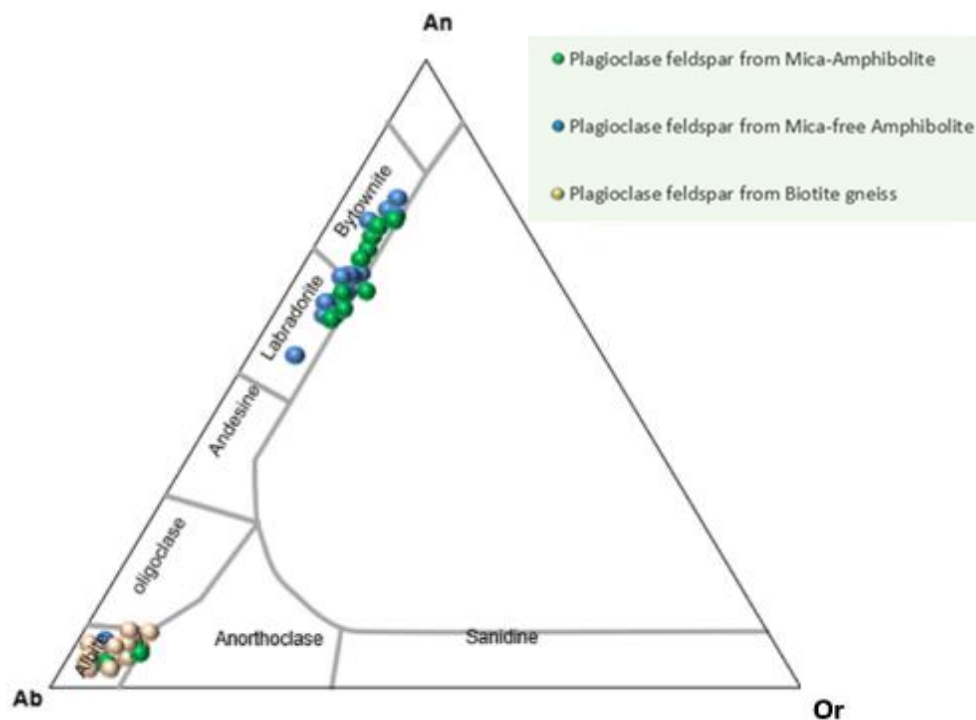


Figure 15: Ternary classification diagram (Deer et al., 1992) for plagioclase feldspar from Selebi-North amphibolite and Biotite schist.

5.2 Sulphide minerals

As described in Chapter 4.0, sulphide minerals are composed of pyrrhotite, pentlandite, chalcopyrite and pyrite. In this section, chemical compositions of pyrrhotite and pentlandite were analysed. Tables 4 and 5 shows representative chemical compositions of pyrrhotite and pentlandite, respectively. The Fe and S content in pyrrhotite of disseminated sulphide is (43.9-45.7 wt%) & (52.1-53.3 wt%) semi-massive sulphide (46.0-47.1 wt%) & (53.1-54.3 wt%) and massive sulphide (46.0-47.4 wt%) & (51.0-53.4 wt%). In terms of pentlandite, the Fe, S, Ni and Co content of disseminated sulphide are (23.7-25.0 wt%), (48.3-51.1 wt%) (23.7-25.0 wt%) and (0.7-1.2 wt%), in Semi-massive sulphide (24.4-25.7 wt%), (47.5-47.7 wt%), (24.4-25.7 wt%) and (1.1-1.3 wt%). Lastly massive sulphide (23.8-29.6 wt%), (32.6-47.5 wt%), (27.0-35.3 wt%) and (1.5-2.1 wt%).

Pyrrhotite grains contain < 1.0 wt% Ni, Co and Cu. Cobalt content in pentlandite ranges 1.1-2.1 wt%.

Table 4: Representative chemistry of pyrrhotite.

Elements wt%	Po (Disseminated sulphide)	Po (Disseminated sulphide)	Po (Semi- massive sulphides)	Po (Semi- massive sulphides)	Po(massive sulphide)	Po(massive sulphide)	Po(massive sulphide)	Po(massive sulphide)
Fe	45,3	44,3	46,4	47,1	46,4	46,3	46,1	46,0
Ni	0,2	0,4	0,3	0,0	0,3	0,4	0,2	0,4
Co	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
Cu	0,0	0,0	0,0	0,0	0,0	0,0	0,1	0,0
S	53,2	53,3	53,2	53,4	53,2	52,0	53,4	51,1
TOTAL (wt%)	98,8	98,0	100,0	100,6	100,0	98,7	99,9	98,6
Fe/S	0,9	0,8	0,9	0,9	0,9	0,9	0,9	0,9

Table 5: Representative chemistry of pentlandite.

Elements wt%	Pn (Disseminated sulphide)	Pn (Disseminated sulphide)	Pn (Semi massive)	Pn (Semi massive)	Pn (Semi massive)	Pn (Massive)	Pn (Massive)	Pn (Massive)
Fe	25,0	23,7	25,0	25,7	24,4	29,5	23,8	29,6
Ni	22,8	25,6	26,1	25,6	26,8	35,3	27,0	34,6
Co	1,1	1,2	1,1	1,1	1,3	1,8	1,6	2,1
Cu	0,0	0,0	0,0	0,0	0,0	0,0	0,2	0,0
S	51,1	49,4	47,7	47,6	47,5	33,4	47,4	32,6
TOTAL (wt%)	100,0	100,0	99,5	100,0	100,0	100,0	100,0	98,8
Fe/Ni	1,1	0,9	1,0	1,0	0,9	0,8	0,9	0,9

Fe/S atomic ratio of pyrrhotite (Figure 16) and Fe/Ni ratio of pentlandite (Figure 17) range 0.83-0.90 and 0.84-1.10, respectively. No notable difference has been observed between the ratios of disseminated, semi-massive and massive ore.

Figure 16 implies that although some of the pyrrhotite lack iron (or excess of sulphur)

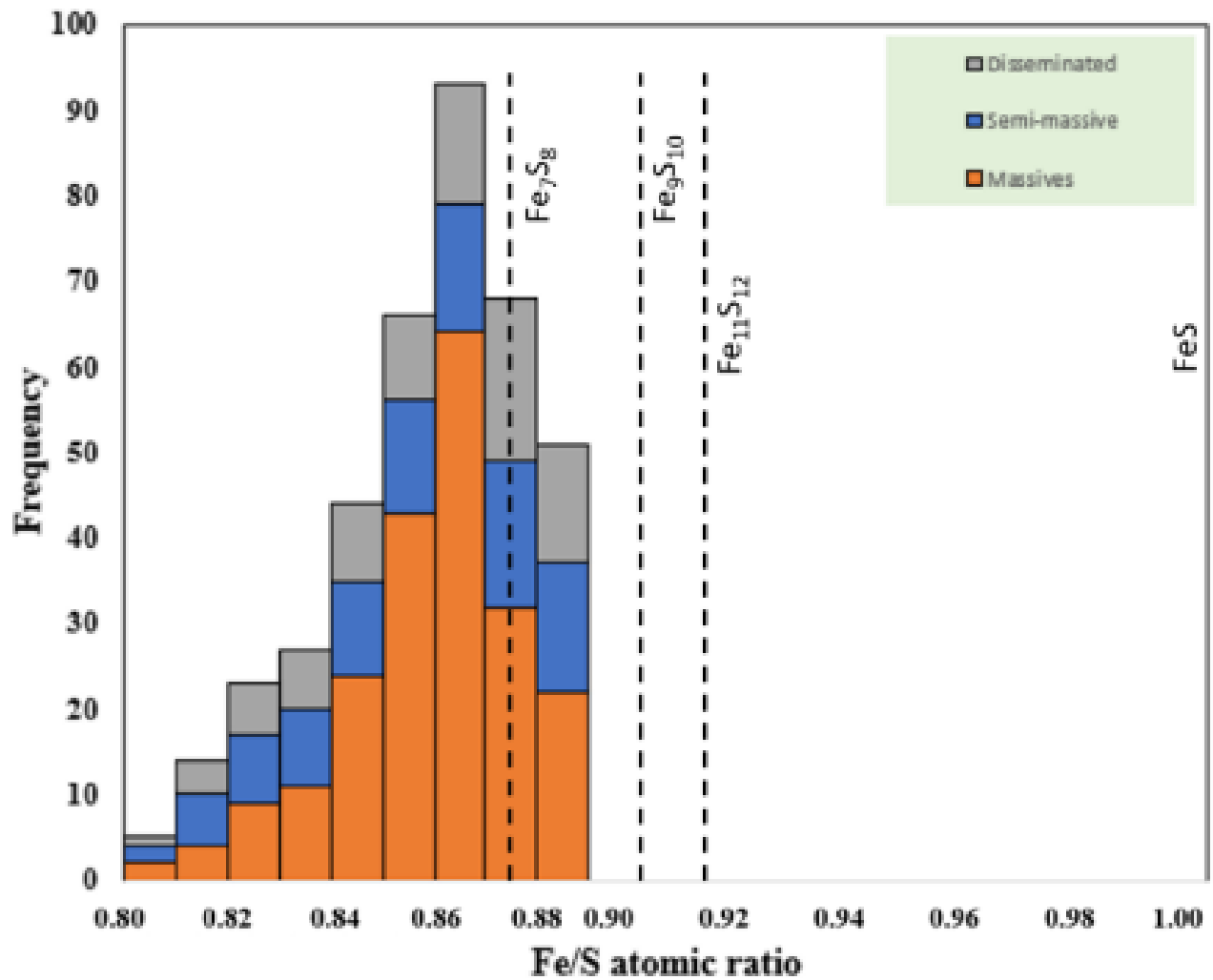


Figure 16: Pyrrhotite histogram.

compared with the ideal composition, most of the pyrrhotite can be considered as Fe_7S_8 composition (monoclinic pyrrhotite).

Chemical compositions of pentlandite, shown in Figure 17, indicate that pentlandite grains in all types of ore in Selebi-North are relatively Ni-rich.

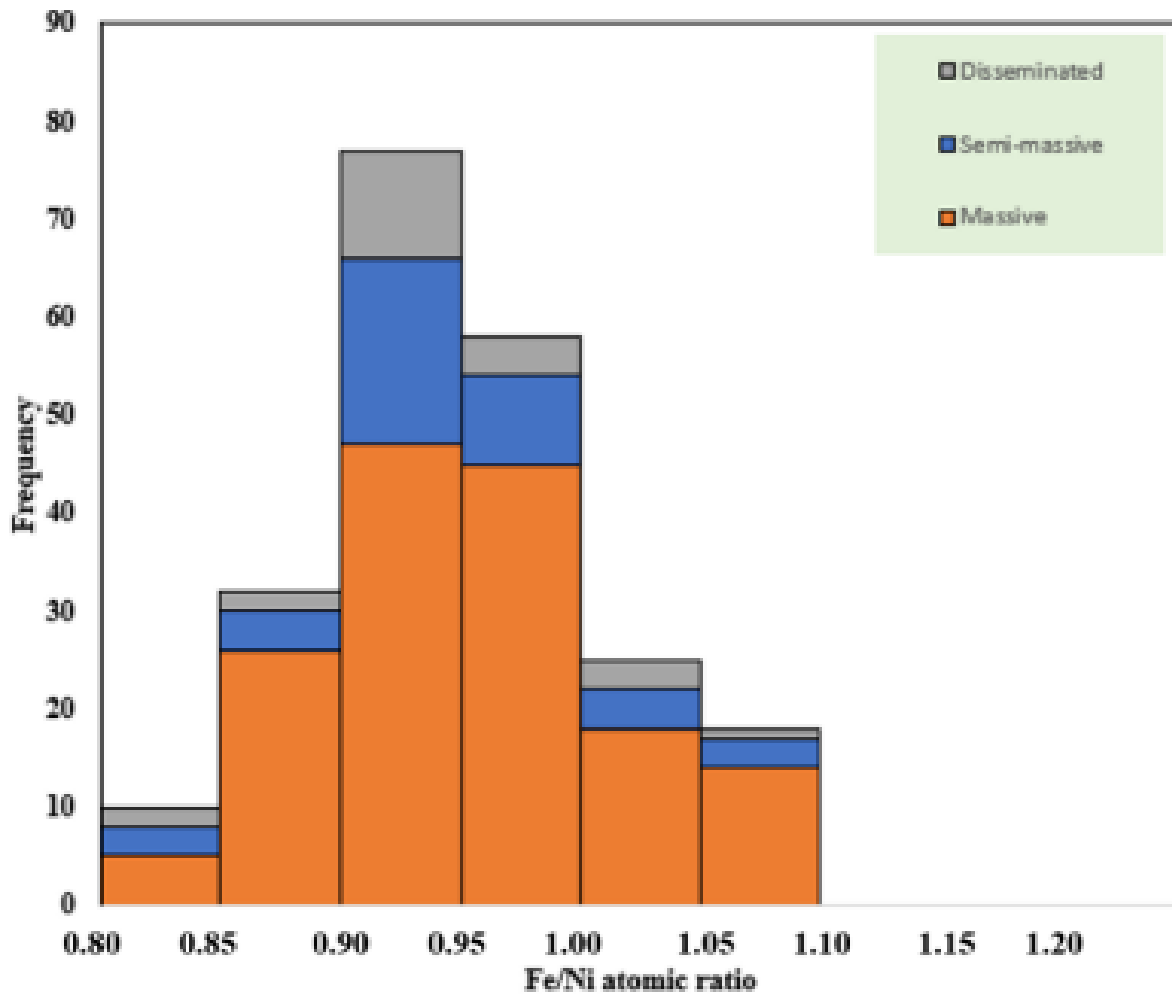


Figure 17: Pentlandite histogram.

The Co/Ni ratio of pyrite ranges between 5-34 with an average of 7.5-8.5, thus based on this ratio, Selebi-North ore could be considered as volcanogenic in origin (Arnold, 1973).

Consideration that the Selebi-North ore has been subjected to high grade metamorphism which could affect the Co/Ni ratios Arnold, (1973).

The Ni/Cu ratio of disseminated mica free/rich amphibolite is 0.93-0.94, for Biotite schist is 1.05, semi-massive is 1.10 and massive sulphide is 1.14. According to Maier et al., (2007) the Selebi-North tenor is 1.24 wt%, which is consistent with crystallization from a basaltic magma.

6.0 WHOLE ROCK GEOCHEMISTRY

Major and trace elements of amphibolite and biotite schist were analyzed by ICP-OES. In amphibolite, the dominant oxide components (Table 6) are Al_2O_3 13.0-19.4 wt%, Fe_2O_3 10.4-21.7 wt% and MgO 7.2-16.9 wt%. In case of biotite schist, K_2O 4.72-9.81 wt% is relatively higher than MgO 6.26-7.42 wt%. In terms of amount of trace elements, Ba 47-563 ppm, Zr 14-274 ppm, Ce 27.6-41.3 ppm and Nb 2.9-9.4 ppm in mica-rich amphibolite are more concentrated than those in mica-free amphibolite and biotite schist.

6.1 Major elements

Mica-rich Amphibolite consists of SiO_2 44.0-47.0 wt%, Al_2O_3 17.5-19.4 wt%, Fe_2O_3 8.9-11.7 wt%, CaO 3.6 wt%, MgO 10.3-12.7 wt%, Na_2O 1.3-5.8 wt%, K_2O 0.7-5.4 wt%, Cr_2O 0.0-0.07 wt%, TiO_2 0.02-0.54 wt%, MnO 0.01-0.18 wt%, P_2O_5 <0.00 wt%, Sr 0.01-0.04 wt% and BaO 0.01-0.08 wt%. Loss on ignition (LOI) at 1.05- wt%.

Mica-free Amphibolite includes SiO_2 42.1-46.3 wt%, Al_2O_3 12.6-14.7 wt%, Fe_2O_3 13.1-14.9 wt%, CaO 3.6-8.7 wt%, Mg 10.3-12.7 wt%, Na_2O 1.3-5.8 wt%, K_2O 0.7-5.4 wt%, Cr_2O 0.00-0.09 wt%, TiO_2 0.14-0.25 wt%, MnO 0.02-0.24 wt%, P_2O_5 0.01-0.09 wt%, Sr <0.01 wt% and BaO 0.01-0.03 wt%. LOI at 0.72-2.24 wt%.

Biotite schist composes of SiO_2 40.1-43.9 wt%, Al_2O_3 15.5-17.7 wt%, Fe_2O_3 20.41-21.94 wt%, CaO 0.01-0.05 wt%, MgO 6.25-7.42 wt%, Na_2O 2.14-4.50 wt%, K_2O 4.72-9.81 wt%, Cr_2O 0.04-0.08 wt%, TiO_2 0.01-0.31 wt%, MnO 0.11-0.40 wt%, P_2O_5 0.01-0.02 wt%, SrO <0.01 and BaO <0.01. LOI at 0.39-1.23 wt%.

Table 6: Representative major elements of the studied amphibolite and biotite schist.

Major oxides (wt.%)	Mica-rich Amphibolite	Mica-rich Amphibolite	Mica-free Amphibolite	Mica-free Amphibolite	Biotite schist	Biotite schist
SiO ₂	44.1	45.7	43.4	42.2	40.3	41.6
TiO ₂	0.3	0.4	0.2	0.2	0.3	0.0
Al ₂ O ₃	19.4	19.0	13.0	13.9	17.7	17.6
Fe ₂ O ₃	10.4	10.6	13.7	13.4	21.3	21.7
Cr ₂ O ₃	0.1	0.0	0.0	0.1	0.1	0.1
CaO	5.5	4.2	7.7	8.1	0.0	0.0
MgO	12.4	11.7	16.7	16.9	6.3	7.2
MnO	0.2	0.2	0.1	0.1	0.1	0.3
Na ₂ O	4.7	4.5	2.7	2,9	3.9	4.1
K ₂ O	0.9	2.8	0.7	0,7	8.8	5.7
P ₂ O ₅	0.3	0.1	0.0	0.1	0.0	0.2
LOI	1.2	1.3	1.0	1.1	1.0	1.3
TOTAL	99.2	100.4	99.5	100.4	99.8	99.6

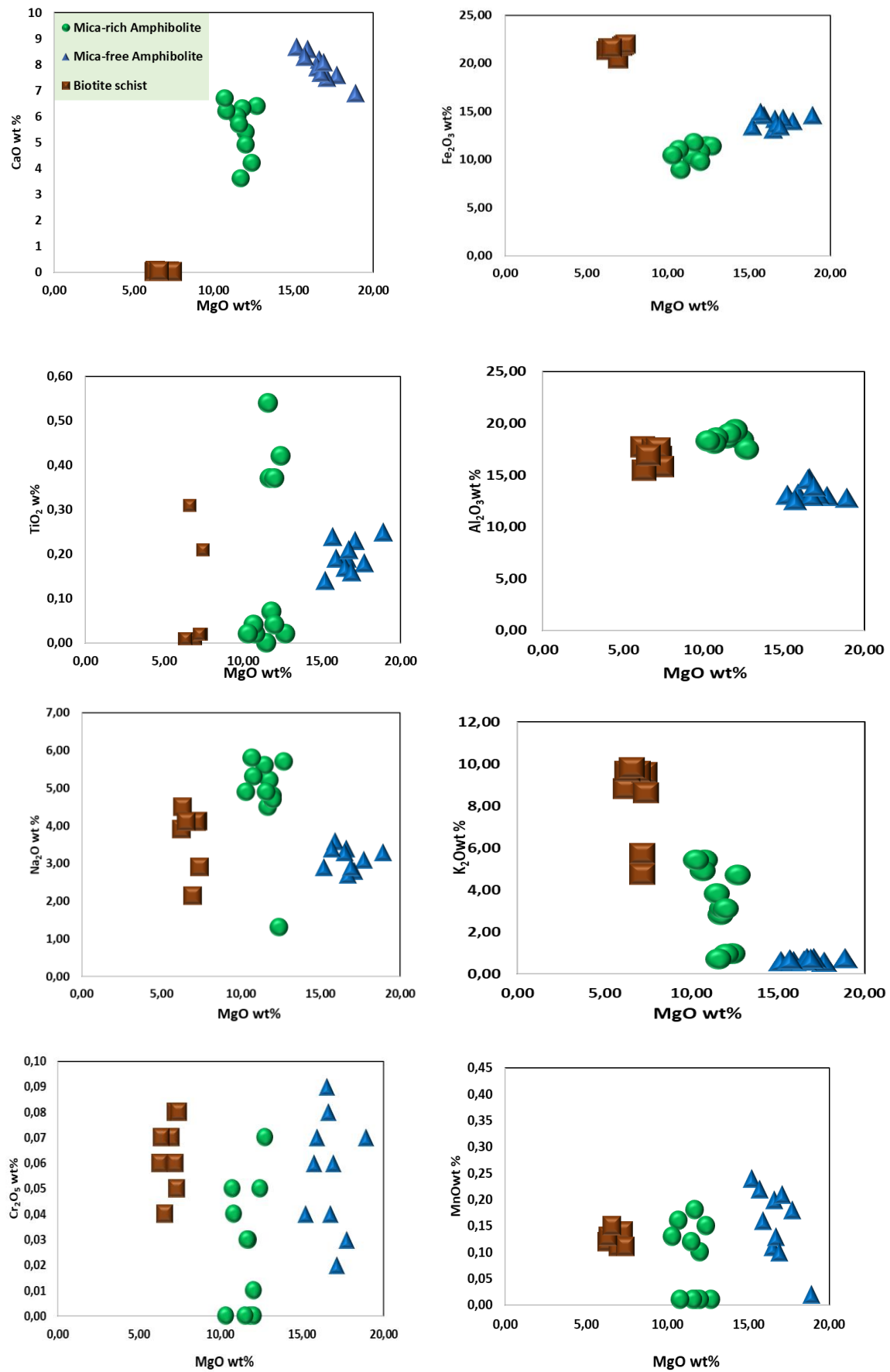


Figure 18: Major element bivariate (hacker) plots for the host rocks from Selebi-Phikwe.

The Selebi North rocks exhibit compositional variation in the major element bivariate plots; as MgO content increases, K₂O, TiO₂, Al₂O₃, and Na₂O content decreases while Fe₂O₃ content increases (Figure 18), indicating that the chemical variation was primarily influenced by crystallisation of mafic mineral phases. The feldspar and biotite contents are reflected in the mica-rich amphibolites greater Al₂O₃ and K₂O compositions.

6.2 Trace elements

Mica-rich amphibole (Table 7) depicts values of Ba and Sr at 47-563 ppm and 59.4-94.9 ppm that are significantly higher in comparison to Mica-free Amphibolite and Biotite schist which range 12-351 ppm and 17.6-18.3 ppm respectively. Mica-free Amphibolite and Biotite Schist have similar values of Zr but Mica-rich Amphibolite has significantly higher Zr at 88-147 ppm.

The primitive-mantle normalized (Sun & McDonough 1989) trace elements patterns are presented in Figure 19. There is a certain enrichment of rare earth elements such as, Nd 2-47ppm, Ce 4-73ppm and Gd 2-27ppm. All the rock samples show a negative Eu anomaly.

Figure 19 shows the spider diagram of these rocks investigated in this study. Several data from previous research are also included in the figure for comparison. This diagram shows that amounts of normalized trace elements of the studied rocks gradually decrease from

Table 7: Trace elements of the investigated amphibolite and biotite schist.

Trace elements (ppm)	Mica-rich Amphibolite	Mica-rich Amphibolite	Mica-free Amphibolite	Mica-free Amphibolite	Biotite Schist	Biotite Schist
Rb	36	35	28	28	13	13
Ba	519	517	238	229	12	58
Th	6	6	127	124	14	11
U	3.1	2	2	11	4	3
Nb	45	41	9	9	5	5
Ta	22	34	15	17	17	19
La	7	11	23	15	11	9
Ce	62	59	7	34	10	23
Pr	8	8	1	1	1	1
Nd	34	30	3	3	5	5
Zr	134	128	6	16	22	22
Hf	7.3	0.3	3	4	11	6
Sm	23	4.3	1	10	9	5
Eu	1	1	3	1	3	1
Gd	28	21	19	15	7	5
Sr	43.8	94.9	17	10.4	14	14.37
Dy	19.7	4.2	17	6	11	7
Ho	3.8	7	3	28	6	14
Er	12	37	9	21	4	1
Yb	3	8	1	10	1	2
Y	61	25	6	15	7	6
Cs	12	29	29	38	8	24

left to right of these elements and negative Eu anomalies are observed except data of Kooganne (2018) which shows positive Eu anomaly for Selebi mica-bearing amphibolite (red-colored line in Figure 19).

Data of the concentration of the trace elements were also used to assume the tectonic setting of the study area. Figure 20 shows the diagrams to infer the tectonic setting of basaltic rock. Calculation formulas of DF1 and DF2 for each figure in Figure 20 are described in Table 8.

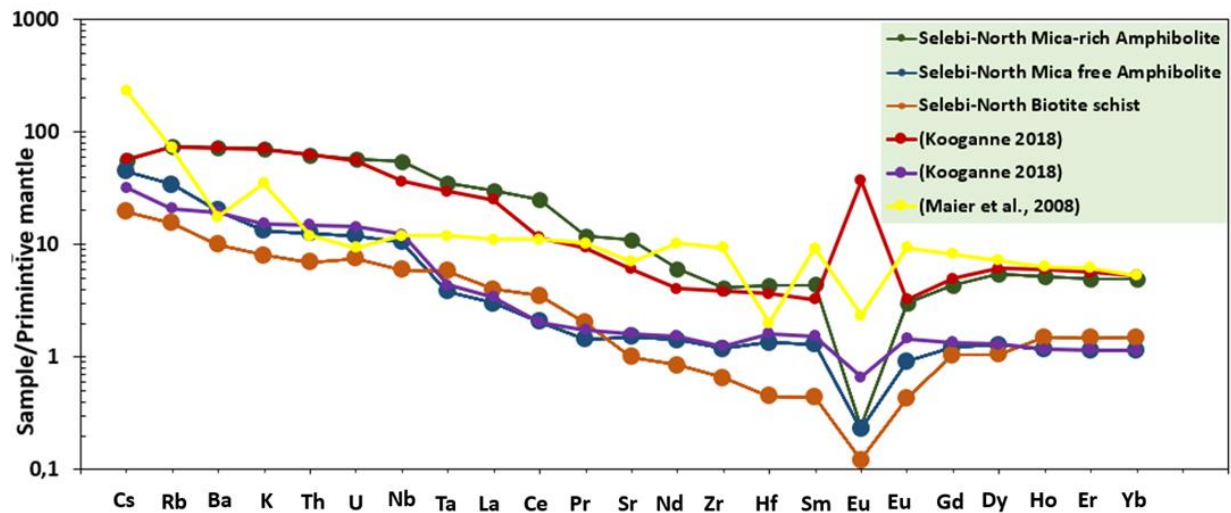


Figure 19: Primitive mantle-normalised rare earth element plots for the representative host rocks (of 29 data sets) from Selebi-North, Selebi(Kooganne, 2018) and Phikwe (Maier et al., 2008). Normalizing factors adopted from Sun & Donough (1989).

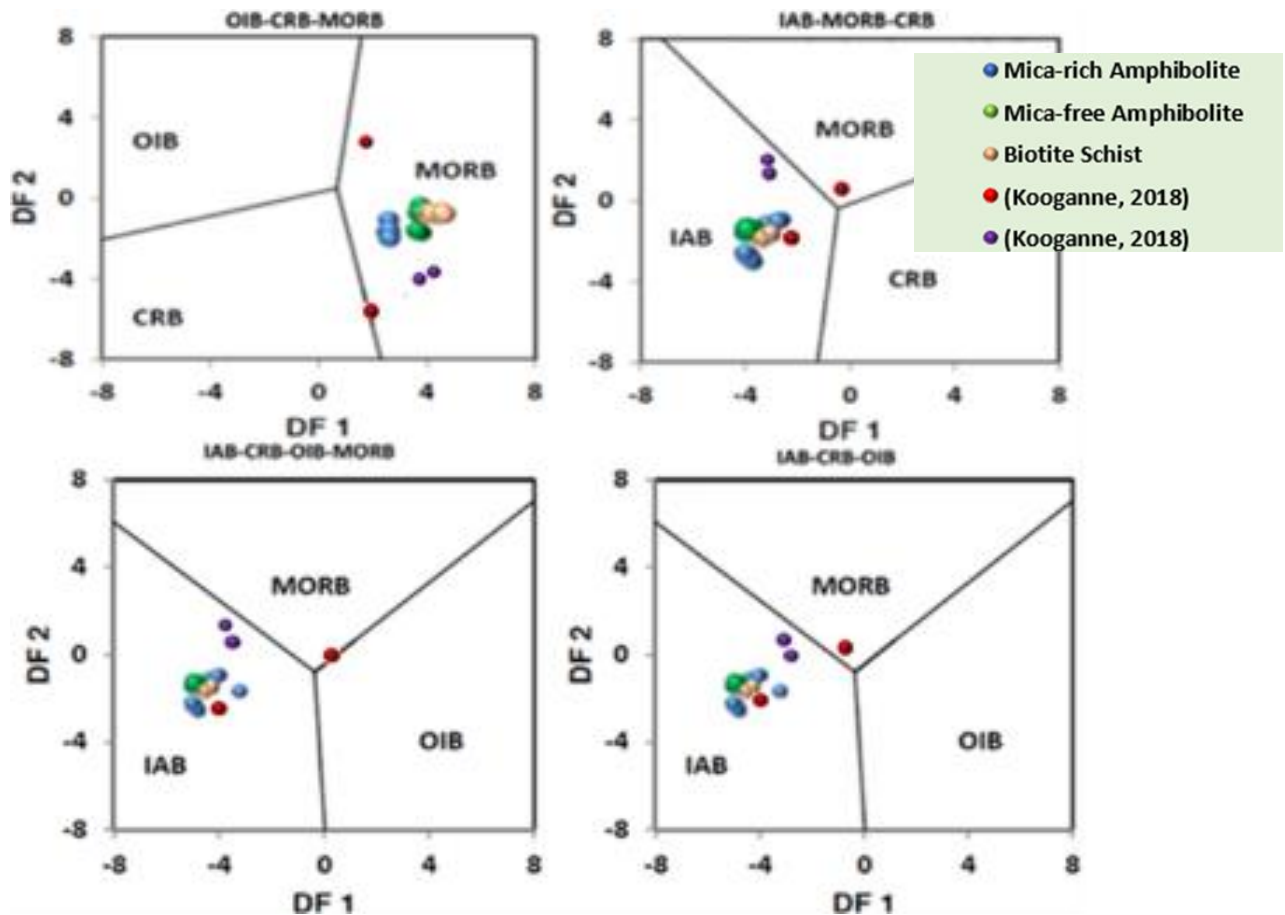


Figure 20: Tectonic setting of rocks of Selebi-North and Selebi (Kooganne, 2018) ore deposits, OIB- ocean island basalts, IAB- island arc basalts, MORB-mid-ocean ridge basalts, CRB- continental rift basalts (Agrawal et al., 2008).

Table 8: Calculation formulas for implicating tectonic setting based on some trace elements.

	Calculation formula
OIB-CRB-MORB	$DF1 = -0.5558 \log_e (La/Th) - 1.9508 \log_e (Sm/Th) + 2.2935 \log_e (Yb/Th) - 0.6890 \log_e (Nb/Th) + 4.1422$ $DF2 = -0.9207 \log_e (La/Th) + 3.6520 \log_e (Sm/Th) - 1.9866 \log_e (Yb/Th) + 1.0574 \log_e (Nb/Th) - 4.4283$
IAB-MORB-CRB	$DF1 = 0.3305 \log_e (La/Th) + 0.3484 \log_e (Sm/Th) - 0.9562 \log_e (Yb/Th) + 2.0777 \log_e (Nb/Th) - 4.5628$ $DF2 = -0.1928 \log_e (La/Th) - 1.1989 \log_e (Sm/Th) + 1.7531 \log_e (Yb/Th) + 0.6607 \log_e (Nb/Th) - 0.4384$
IAB-CRB-OIB-MORB	$DF1 = 0.3518 \log_e (La/Th) + 0.6013 \log_e (Sm/Th) - 1.3450 \log_e (Yb/Th) + 2.1056 \log_e (Nb/Th) - 5.4763$ $DF2 = -0.3050 \log_e (La/Th) - 1.1801 \log_e (Sm/Th) + 1.6189 \log_e (Yb/Th) + 1.2260 \log_e (Nb/Th) - 0.9944$
IAB-CRB-OIB	$DF1 = 1.7517 \log_e (Sm/Th) - 1.9508 \log_e (Yb/Th) + 1.9573 \log_e (Nb/Th) - 5.0928$ $DF2 = -2.2412 \log_e (Sm/Th) + 2.2060 \log_e (Yb/Th) + 1.2481 \log_e (Nb/Th) - 0.8243$

7.0 DISCUSSION

7.1 Petrographic textures

From petrographic observations, Ni-Cu mineralisation in Selebi North ore zone is hosted in amphibolite (Figure 9 a-h) and minor amounts of ore in biotite schist (Figure 8 a-d). The disseminated sulphide samples show occurrences of sulphides in a randomly dispersed manner within the host rock matrix (Figure 9 e&f). Some amphibolites and biotite schists samples show ore minerals aligned to the foliation fabric (Figure 10 a&b) and schistose fabric (Figure 8 a & b)), indicating that the sulphides were subjected to the metamorphism and deformation that occurred in the area.

Sulphide veinlet, composed of pyrite, is observed, cutting across the gneissic fabric of mica-rich amphibolite (Figure 10 c & d) indicating that some mineralization is post metamorphism.

Pyrrhotite occurs within biotite cleavage planes, possibly indicating that mineralization was mobilized along the weak cleavage planes of the biotite grain (Figure 11 a & b). Secondly, sulphide minerals mainly chalcopyrite was observed in fractures of quartz (Figure 11 c & d). The prevalence of chalcopyrite within fractures is clear evidence for the effect of metamorphism and deformation on the Selebi-North ore.

In massive sulphides, pyrrhotite forms large (approximately 1.5mm in diameter) grains with interstitial rim pentlandite surrounding the pyrrhotite grain. This type of texture is referred to as pegmatoid sulphides by Wakefield (1976). Wakefield (1976) elaborates that the pegmatoid texture is suggestive of crystallization under hydrostatic pressure. This pressure might be related to the deformation and metamorphism in the area.

Craig and Kullerud (1969) outlined that above 600°C sulphides are typically represented in a monosulphide solid solution (Mss) state. The temperature at which chalcopyrite begins to exsolve from Mss is approximated between 600 and 450°C, and for pentlandite, below 400°C. In the Selebi North samples, pentlandite is observed exsolving from pyrrhotite as fine grained lamellae (Figure 12 e). Conventionally, pentlandite exsolves from intermediate solid solution (Iss) at 400°C (as previously stated) but Craig and Kullerud (1969) mention that pentlandite is unstable in high temperature Iss. Thus, only minute amounts exsolve as fine grained lamellae at <650°C. As temperatures cool, some of these fine grained lamellae coarsens up by diffusion of Ni and other trace elements such as cobalt to form the pentlandite grain (Dare et al., 2014). Figure 12 f shows some finer and more coarser pentlandite that can attest to these.

Within the pyrrhotite grain, chalcopyrite can be seen exsolving from Mss as fine grained lamellae (Figure 12 d). Chalcopyrite is also observed with interstitial rim pentlandite (Figure 12 f).

Magnetite is observed as subhedral to anhedral (Figure 12 g & h). Naldrett, (1969) considers magnetite primary, as it directly crystallised from the sulphide melt. In (Figure 12 h), An inclusion of sulphides is observed within the magnetite grain. An interpretation can be given that during the magnetite grain's formation, some of the sulphide melt got trapped within the grain. As the sulphide melt cooled, chalcopyrite and pentlandite exsolved in that order and formed a circular zonation of pyrrhotite-chalcopyrite and pentlandite.

7.2 Mineral Chemistry and Geochemistry.

Based on these plots shown in Figure 20, protolith of the amphibolite and biotite schist investigated in this study was formed in IAB-related tectonic setting, that is, subduction-related setting. This is good correlated with the assumption by Kooganne (2018) who studied Selebi Phikwe samples.

Ba and Sr form part of the alkaline earth metals that were formed in the early earth (U.S Geological Survey, 2002). The enrichment of Ba and Sr can be attributed to the accumulation from country rocks as the mafic-ultramafic belt intruded the pre-existing rocks. Thus, an interpretation can be made that sulfide saturation might be triggered by assimilation of S from country rock.

In overall the Ni/Cu ratio appears to have not been changed by metamorphism.

There is a recent yet underreported observation of the lack of Cu-rich sulphides and dominance of pyrrhotite and dominance of pyrrhotite, pentlandite bodies such as in the Munali deposits in Zambia (Holwell et al., 2017). This is not the case for Selebi-North deposits, Cu-rich sulphides, specifically chalcopyrite is prominent in semi-massive and massive sulphides. Chalcopyrite is observed as lamellae in pyrrhotite and along the pentlandite loops and chalcopyrite inclusions are observed in magnetite (see Figure 12 e-h).

Kooganne (2018) described that cobalt in pyrite is mainly less than <0.1 wt%. Therefore, it may indicate that pentlandite is the major source of cobalt in Selebi North Ni-Cu ore.

7.3 Pressure - temperature condition of host rock

Mineral compositions of silicate minerals in the host rock were analysed in order to estimate pressure (P) - temperature (T) condition of the metamorphism. By using amphibole-plagioclase geothermobarometry (Sayari, 2016), where mineral chemistry data from adjacent plagioclase and amphibole was recalculated to atom per formula unit. The values were then fed to the program. Resulting in P-T condition of the amphibolite which is host rock of the Ni-Cu mineralisation in Selebi-North ranges ~706-711 °C and 6.2-7.3 kbar (Figure 21). Millonig (2009) estimated the P-T condition of the garnet-bearing amphibolite in the Phikwe Complex and calculated that the average peak P-T condition of the amphibole is ~750-820 °C and 7.0-7.5 kbar. Furthermore, Hickman and Wakefield (1975) suggested an Archean peak P-T conditions, ~740-760 °C and ~7.3-7.6 kbar. Therefore, it can indicate that P-T condition of amphibolite which is the host rock of Ni-Cu mineralisation in the Selebi-North zone is lower than that estimated by Millonig (2009).

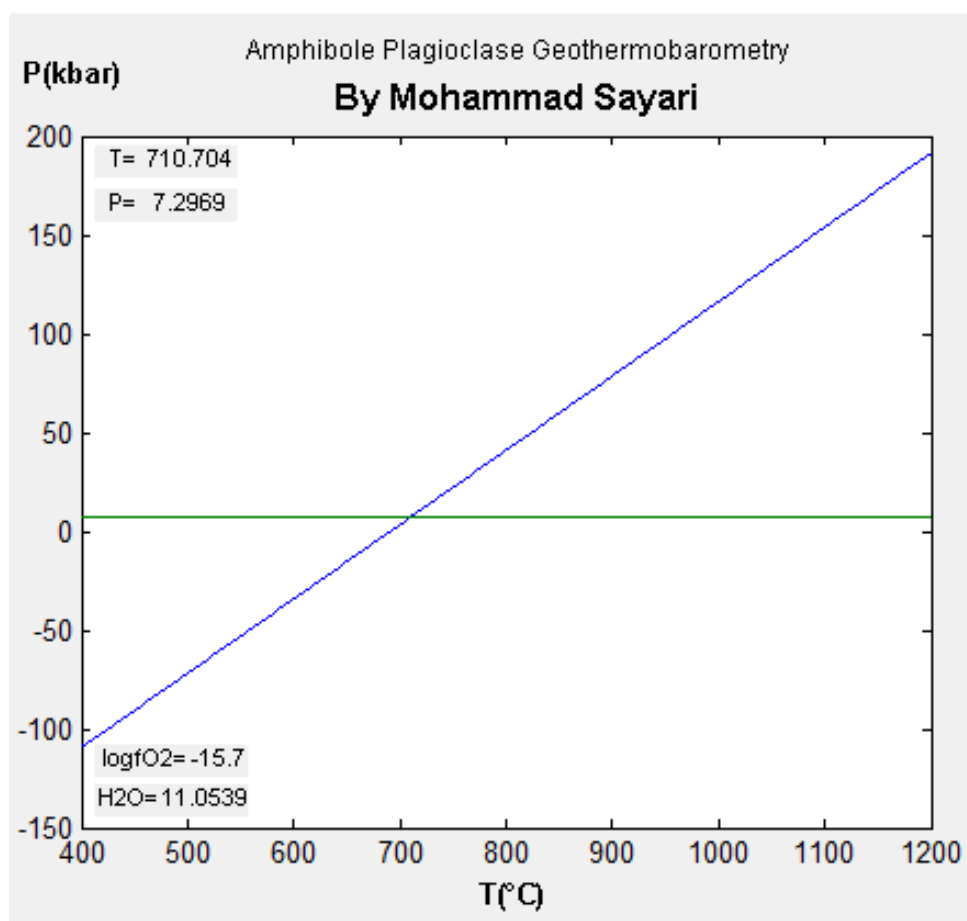


Figure 21: Pressure-temperature conditions of Selebi-North (Sayari, 2016).

Table 9: The adjacent plagioclase-amphibole composition for determining P-T conditions.

Major oxides (wt.%)	Plagioclase	Plagioclase	Amphibole	Amphibole
SiO ₂	61.20	60.30	46.76	43.49
TiO ₂	0.03	0.02	0.92	2.40
Al ₂ O ₃	24.20	24.34	6.90	8.52
Cr ₂ O ₃	0.00	0.00	0.00	0.01
Fe ₂ O ₃	0,06	0,00	20,12	18.55
MnO	0,00	0.00	1.03	0.67
MgO	0,01	0.00	9.64	11.06
CaO	5,90	0.81	11.41	11.81
Na ₂ O	8,24	0.00	0.95	1.24
K ₂ O	0,27	0.00	0.78	1.26
Total	100.61	96,08	98,75	98,92

7.4 Condition of Fe-Ni sulphides

Several textures between silicates and sulphides show that Ni-Cu sulphides were associated with metamorphism by which amphibolite was formed. Therefore, it is meaningful to examine the formation condition of sulphides with considering metamorphism. As mentioned earlier, sulphides in the ores are composed of mainly pyrrhotite, pentlandite and chalcopyrite and trace pyrite. Pyrrhotite as Ni-poor monosulphide solid solution is solid phase below $\sim 1200^{\circ}\text{C}$ (Kullerud et al., 1969). Furthermore, pentlandite and high-form pentlandite crystallize around 610°C and 865°C , respectively (Kullerud, 1963; Sugaki and Kitakaze, 1998). On the other hand, as mentioned in section 7.2, The P-T condition which formed the studied amphibole is $\sim 706\text{--}711^{\circ}\text{C}$ and 6.2-7.3 kbar, respectively. This condition can be considered as ultrahigh-temperature (UHT). Tomkins et al. (2007) suggested that only the sulfarsenides (minerals with arsenic and sulfur), which are not observed in the studied ores, are likely to melt. Therefore, it is indicated that observed sulphide minerals are not melted during the metamorphism.

7.5 Formation process of the Ni-Cu ores in Selebi North

As a comprehensive explanation, formation process of Ni-Cu sulphide ores in Selebi North area will be discussed in this section. There are two stages of the process: (Stage I) pre-metamorphism and (Stage II) during metamorphism.

In Stage I, magma of the protolith of the host rock (amphibolite) was generated in a subduction zone on the basis of the geochemical results of trace elements (Figure 21). Wakefield (1976) suggested the magma had troctolitic composition.

Based on the occurrence of sulphide blebs (Wakefield, 1976), although it is not clear about timing and mechanism of sulphur saturation in the magma, sulphide minerals finally crystallised in the mafic magma during the solidification of the protolith. During Stage II in which amphibolite was formed, existing sulphide minerals were not melted and foliated based on the texture relationship between silicate and sulphide minerals. It is generally accepted that there were two stages of metamorphism in the Limpopo Mobile Belt. However, this study can't clarify which stage of the metamorphism was associated with the process of the Stage II.

8.0 CONCLUSION

Ni-Cu mineralisation is observed mainly in amphibolite and in biotite schist. Furthermore, based on the amount of sulphides, Ni-Cu ores could be classified into disseminated, semi-massive and massive (Disseminated-figure 8 and 9, Semi-massive-Figure 11 A and B, Figure 12 A and Massive-Figure 12 E-F). The ore minerals are mainly composed of pyrrhotite, pentlandite and chalcopyrite and minor amount of pyrite. Magnetite, as an ore mineral, is also observed especially in the massive ore. Mineral compositions of amphibole and biotite are within the actinolite and phlogopite range, respectively. Chemistry of plagioclase shows two different compositions, relatively anorthosite-rich and albite components. EPMA analysis of pyrrhotite and pentlandite reveals that most of the pyrrhotite have Fe_7S_8 composition and pentlandite grains have relatively Ni-rich component, respectively. Whole-rock chemistry of host rock shows minor enrichment of the LREE and negative Eu anomalies, indicating that the protolith of amphibolite and biotite schist was generated in an ocean-ocean subduction environment, which is consistent with previous research such as Maier et al. (2008) and Kooganne (2018). The pressure-temperature conditions range 706-711 °C and 6.2-7.3 kbar. In terms of formation process of the Ni-Cu ores in Selebi North, two stages of the process can be implied: pre-metamorphism and during metamorphism. In the stage of pre-metamorphism, sulphide minerals were crystallized in the protolith of the host rock. During the metamorphism stage associated with formation of amphibolite, sulphides are not melted and foliated.

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