Ore forming potential of the Atchiza Suite and Sustainable management of mineral deposits in Mozambique

(Petrology, geochemistry and sustainable management of mineral deposits)

MSc Thesis
Natural Resources Management & Resource Geology
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Preface

This thesis is done as part of my final work for an MSc. in Natural resources Management; specializing in Resource Geology. The course is organized at the Faculty of Natural Sciences and Technology, at the Norwegian University of Science and Technology (NTNU). The thesis work was done at the Department of Geology and Mineral Resources Engineering at NTNU.

It comprises of two parts: "*Ore forming potential of the Atchiza Suite*" and "*Sustainable management of mineral deposits in Mozambique*". The thesis is part of the research project under the collaboration of the Norwegian University of Science and Technology (NTNU) and Eduardo Mondlane University (UEM) in Mozambique. It is funded by The Norwegian Programme for Development, Research and Education (NUFU) and the involved universities. Supervising Atchiza Project are Professor Rune, B. Larsen of NTNU and Professor Amadeu Carlos dos Muchangos of UEM. Academic supervisor for this thesis is Professor Rune, B. Larsen.

Trondheim, June 2012

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PART 1

ORE FORMING POTENTIAL OF ATCHIZA SUITE

(Petrology & Geochemistry)

Abstract

This research study presents detailed petrographic- and geochemical- analysis of 63 rock samples from the Atchiza Suite. The Suite is a layered mafic-ultramafic pluton located in the Tete Suite, of NW Mozambique. At present, the Atchiza comprises a group of three main types of rock that are classified based on their mineralogy, textures, geochemical composition. These are ultramafic cumulates (dunite and pyroxenites), mafic cumulates (medium-grained cumulate gabbro) and coarse-grained gabbro (non-cumulate gabbro).

Compared to the rest of other rocks, coarse-grained gabbro shows high enrichment of Ti (0.64-3.46 wt% TiO_2), Zr (5.9-296.1 5ppm), Sr (253.7-1268.4ppm) and V (224-952.3ppm), but relatively low depleted in compatible elements (Ni = 48.7-235.7ppm , Cr = below detection limit to 410.5ppm). Cumulate ultramafics are highly enriched in compatible elements (Ni up to 4636.2ppm, Cr up to 4721ppm).

A high Mg# in ultramafic cumulates (0.59-0.86) suggests an Mg-rich primitive parental magma, whereas a low Mg# in coarse-grained gabbro (0.23-0.37) suggests a relatively high-differentiated magma. Cumulate gabbro shows Mg# ranging from 0.40-0.72, suggesting a moderately evolved magma source (derivative magma subsequent to fractionation of ultramafic cumulates).

The Ni/Zr, Cr/Zr, Sr/Zr and Ti/Zr ratios are generally the lowest in coarse-grained gabbro when compared to cumulate rocks. The same applied; this suggests that coarse-grained gabbros were probably formed from a relatively high-differentiated magmatic liquid. In addition, the presence of an uninterrupted cryptic differentiation trend with these ratios implies that the Atchiza igneous lithologies were derived from one and the same parental melt.

Apparently, Atchiza shows great variability of Fe_2O_3, SiO_2 and SO_3 during magmatic differentiation. There is significant decrease in Fe_2O_3, an increased SiO_2 and SO_3 contents in residual magma during progressive magma fractionation. It is true that all these geochemical changes will lower down the solubility of S in the system, thus providing a favourable condition for silicate-sulfide immiscibility. Theoretically, therefore, the Atchiza may have a potential to host Ni-Cu-(PGE) sulfide deposits.

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1. INTRODUCTION

1.1. Theoretical overview

The Atchiza Suite, an early Pan-African intrusive in northern Tete Province is a layered igneous complex, mainly comprising of lower ultramafic cumulates (serpentinised dunite and pyroxenite), covered by an upper sequence of gabbroic-noritic rocks. We have identified Atchiza to be one of the prospective geological sites for Ni-Cu-sulfide mineralization. Accordingly, this section will review the favourable conditions; both geological and geochemical, necessary for the genesis of Ni-Cu-(PGE) mineralization relevant to Atchiza, as they are also studied to have played significant role for the formation of the world Ni-Cu-deposits such as Munni Munni Complex (Western Australia), Stillwater Ni-Cu-PGE (USA) and Munali (Zambia). Atchiza is a prospecting license under the holder company Mozambique Natural Resource Corporation, Lda. The property is under prospecting for the Ni-Cu-Co-Ti-V-Cr-PGM- mineralization.

1.1.1. Factors that control magmatic-sulfide mineralization

In summary, the most important geological processes for the formation of sulfide deposits in layered mafic-ultramafic intrusions are- 1) -progressively normal fractional crystallization (gravitational crystal settling), 2) -multiple recharges and mixing of new magma in a contemporary magma chamber 3) -assimilation and mixing of country-rocks. Given that the majority of the world-largest Ni-Cu-Co-PGE- deposits were formed based on the model presented in **Figure 1** and **Figure 2**, studying these processes is very important for understanding of the geological evolution and ore genesis of Atchiza.
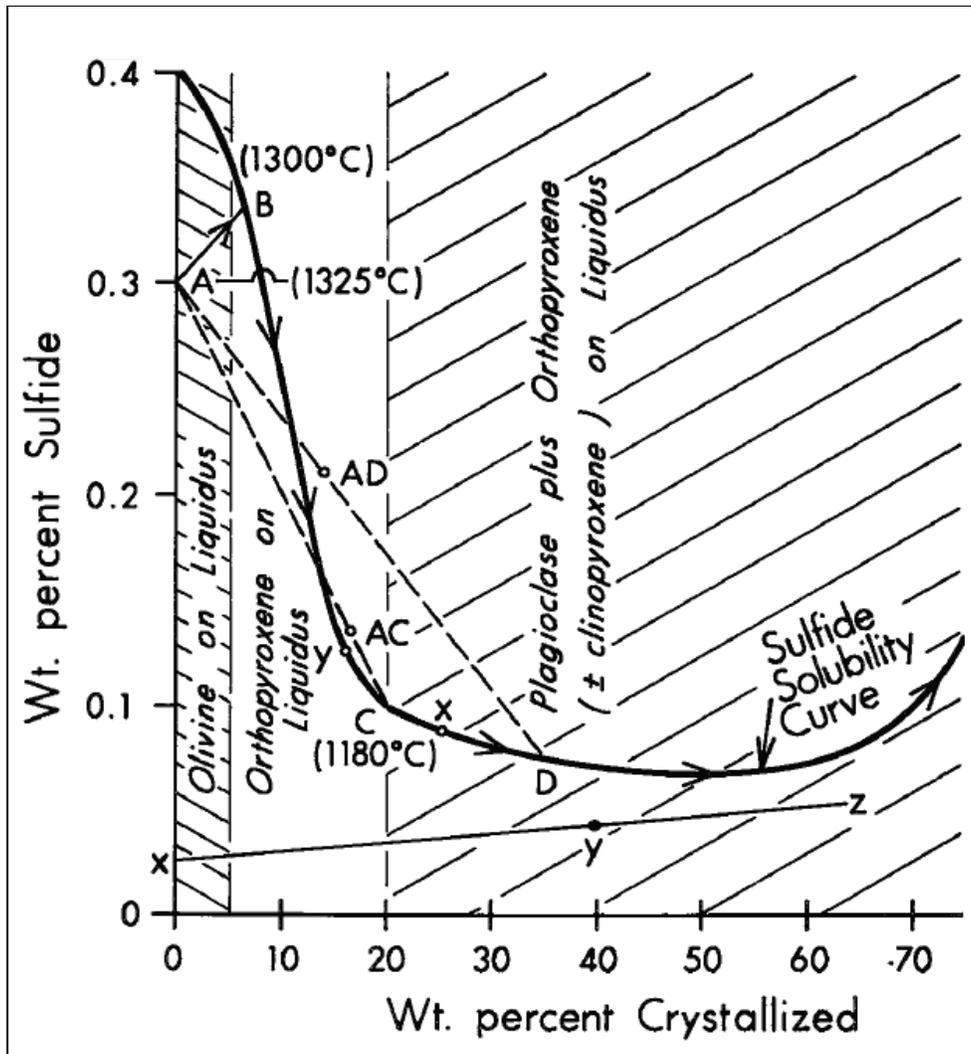
Figure 1: Solubility of iron sulfide as a function of progressive fractional crystallization (after Naldrett and von Gruenewaldt, 1989; and Naldrett et al. 1990).

Figure 1 shows the variation of sulfide solubility in magma chamber during fractional crystallization and falling temperature. The initial magma composition is assumed to be at point A, where the melt is not saturated with sulfur. Progressively, fractional crystallization will follow path A-B to reach sulfide saturation at point B, where the immiscible silicate-sulfide droplets will form.

Further fractional crystallization and fractional segregation of sulfides would lead the magma composition to move along saturation curve (i.e. decreasing the S content dissolved in residual melt) either by segregating minute amounts of sulfide droplets or becoming

oversaturated with sulfide. Magma composition above and below the solubility curve implies that the residual magma is either over-saturated or under-saturated, respectively.

Points AC and AD represent replenishment events of parental magma "A," where the melt composition will be pulled back towards A. They represent magmatic events where, likely, ore-forming amounts of sulfide liquids will form. The underlying mineral cumulates that crystallize along line XYZ before reaching- or/and beyond- point Y, will have less chance of achieving sulfide saturation.

According to the graph (**Figure 1**), the early fractional crystallization is marked by a steep decrease in sulfide solubility. This shows how sulphur solubility is sensitive to both temperature change and fractional crystallization of ferromagnesian minerals. Sulfide solubility is decreasing from approximately 0.4-0.1%, corresponding to a decrease in temperature from 1300-1180°C, consistent with fractional crystallization of cumulate olivine and orthopyroxene (0-20%). The sulfide solubility is largely remaining constant during plagioclase crystallization (20-55% of magma crystallization). During this period, the temperature is relatively low (below 1180°C) and plagioclase is starting dominating the system as the major cumulate mineral.

At higher levels of fractional crystallization (>55%), the amount of plagioclase cumulates is tending to dominate the system. Conversely, the ratio composition of FeO in the residual magma will tend to rise considerably, but at a rather slow rate. The solubility of sulfur will also tend to increases slightly.

The graph (**Figure 1**) suggests that a massive fractionation of ferromagnesian minerals (in particular olivine and orthopyroxene), accompanied by significant drop in temperature would lead to sulfide supersaturation and eventually silicate-sulfide immiscibility, a favourable condition for Ni-Cu-Co-PGE- sulfide mineralization.

However, it is important to understand that although Ni strongly partitions in sulfide liquid, it may also partition in Mg-rich olivine. This means that there is a high chance of Ni to be incorporated into olivine cumulates during the early-stages of magmatic differentiation, and therefore the Ni contents in the silicate melts (residual magma) will be significantly reduced, efficiently preventing the formation of economic Ni-ore deposits. Therefore, it is a key factor that for a Ni rich deposit to form, silicate-sulfide immiscibility condition needs to be achieved

during the earlier stages of magmatic differentiation. Complementing Ni mineralization, and because of their strong affinity to sulfur, chalcophile metals (Fe-Cu-Co-PGE's) will be strongly partitioned in sulfide melts rather than in silicate melts.

The results in **Figure 1 (Naldrett and von Gruenewaldt, 1989 and Naldrett et al. 1990)** are exactly been supported by **Li et al. (2001a)**. However, the revised experimental studies by **Li et al. (2001b)** and **Cawthorn (2002)** further confirmed that replenishment/mixing of parental magma with resident magma would not cause sulphide saturation, because the capability of hybrid magma to dissolve sulfur will increase (also documented by **Naldrett, 2004**).
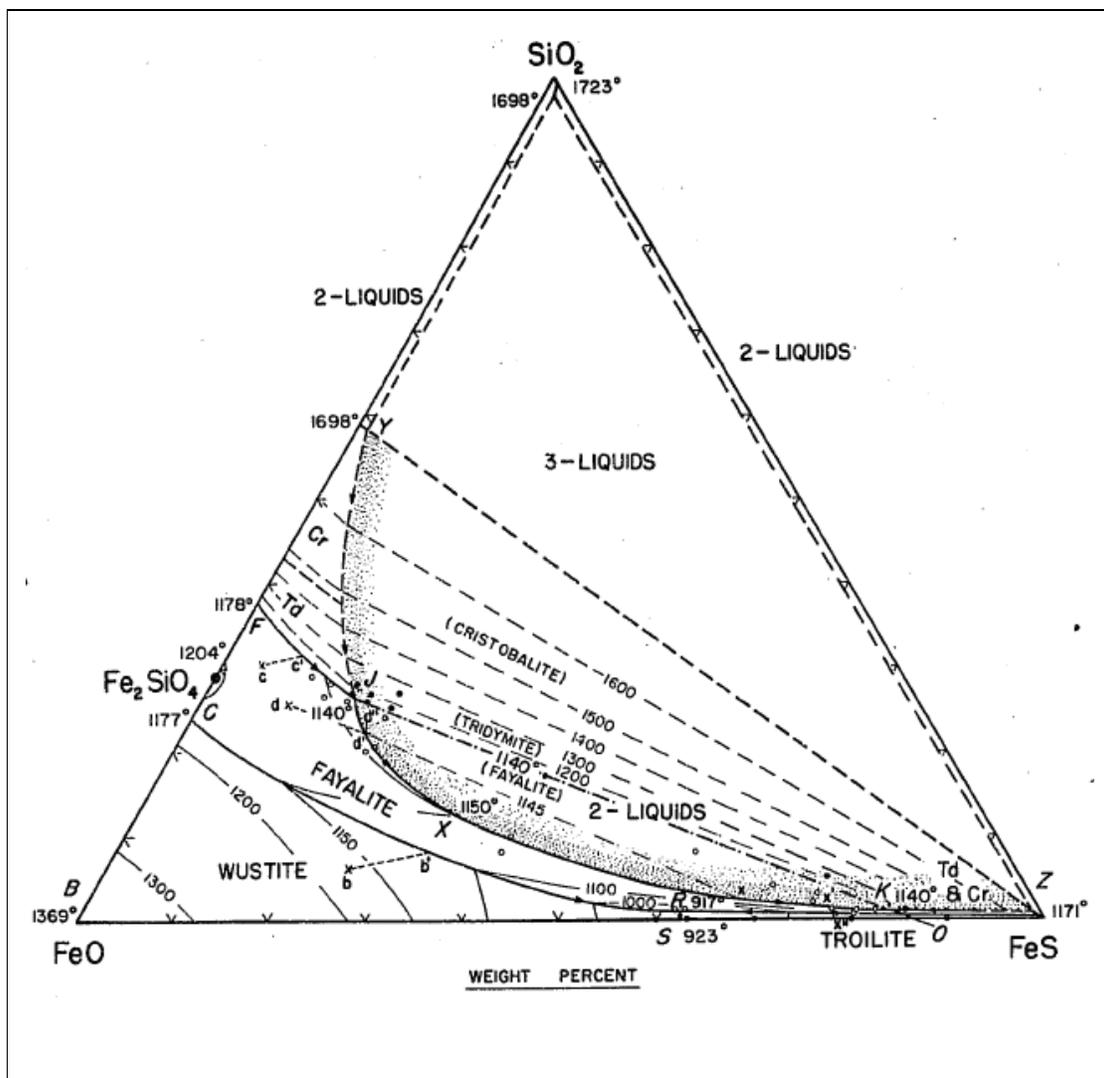
Figure 2: Liquidus relations for phase equilibria of FeS-FeO-SiO$_2$ (after McLean, 1969).

Factors that control the sulfur solubility in magmas are temperature, pressure, composition of the melt (with regards to FeO-TiO$_2$-content) and $f(O_2)$ (**Chima C.U., 2011, and references in**). In addition, **Figure 2** shows how silicate-sulfide immiscibility varies as a functions of variations of FeO, FeS and SiO$_2$ (FeO-FeS-SiO$_2$ relationship) in the magma chamber, and how addition of silica (at different composition) in the fayalite field can trigger precipitation of sulfide-rich liquid. The 2 liquid fields represent co-existence of various Fe-silicate-sulfide-rich liquids (with a likely combination of either FeS-SiO$_2$ or FeO-SiO$_2$), while a 3-liquid fields represents tri-existence of FeO, SiO$_2$ and FeS phases.

According to **Haughton et al (1974)**, solubility of sulfur in magma decreases as decreasing FeO content (**Figure 3**), whereby extraction of FeO from magma chamber will lower down sulfur solubility, hence promoting sulfur-oversaturation. This result is also supported by **Figure 2**.
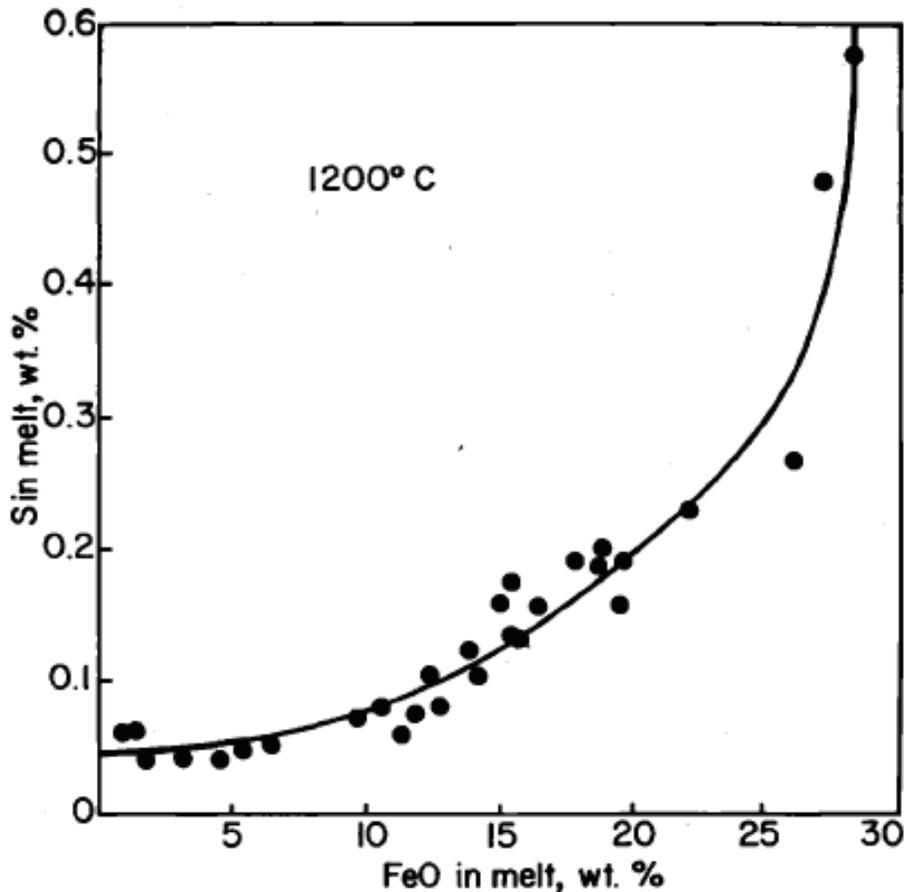
Figure 3: Change in sulfur content of residual magma as a function of FeO (Haughton et al (1974)

Whereas the solubility of sulfides in magma decreases with decreasing temperature (**Figure 1**), its relationship with pressure works in the opposite direction (**Figure 4**), whereby the amount of sulfur that dissolves in magma is decreasing with increasing pressure, and vice versa. Thus, sulfur is more soluble at low pressure than at high pressure (**Naldrett, 2004; Chima C.U., 2011, and references in**). Theoretically, therefore, it may be difficult for sulfide saturation to be achieved when magma ancients to the higher crustal levels, because pressure is decreasing. To counterpart this negative impact, it requires that magma to be contaminated with silica-rich crustal materials (commonly granitic gneisses and sedimentary materials). Through contamination the silica content of residual magma will be increased; consequently, the capacity of FeO- rich mafic mama to dissolve sulfides will be suppressed. This is clearly shown in **Figure 2**, whereby contaminating the system with either silica (felsification of mafics/ultramafic melts) or additional of S-rich materials, whilst suppressing the FeO-content of residue magma (i.e. suppressing olivine crystallization) will drive the melt composition towards FeS and SiO_2 saturation fields (i.e. broadening immiscibility gap). Another advantage of contaminating with the country rocks is that the temperature of the system will be lowered significantly, enough to promote sulfur-oversaturation.
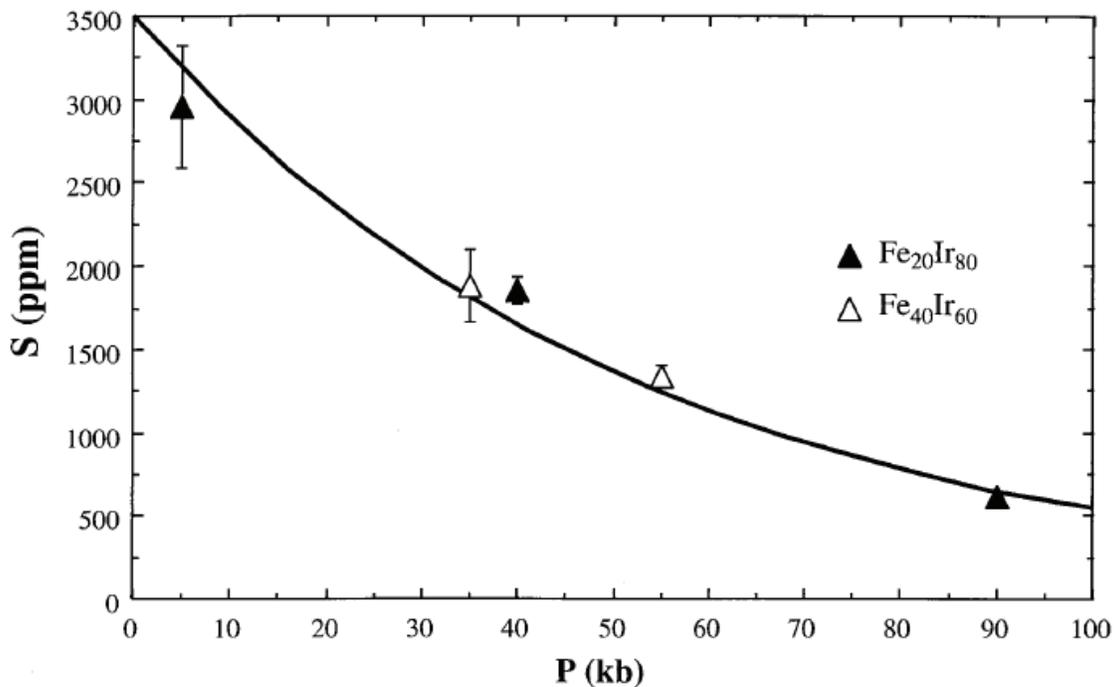
Figure 4: Dissolved sulfur in basaltic melt at different FeO content as a function of pressure at $1800^{O}C$ by Mavrogenes, J.A., O'Neill, H.S.C. (1999)

The effect of $f(O_2)$ on solubility of sulfur in silicate melt has been a matter of debate, as different researchers came out with different experimental results. **Haughton et *al*., (1974)** and **Buchanan & Nolan, (1979**) have indicated that sulfur solubility decreases as $f(O_2)$ increases; whereas **Katsura & Nagashima (1974)** and **P.J. Jugo (2010)** showed that sulfur solubility in silicate melt varies as a function of $f(O_2)$.

The factors that are discussed above are very important for the genesis of Ni-Cu-PGE deposits, as the majority of the sulfide deposits in layered intrusions throughout the World were formed by contamination and silicate-sulfide liquid immiscibility events. Some good examples of them are the Ni-Co deposits of Kambalda, Australia, Voisey's Bay, Canada, Jinchuan, China and Noril'sk-Talnakh, Russia (**Lightfoot P.C. 2007; Naldrett A.J. 1999; Ryan et al. 1995; Ryan B. (1995); Li and Naldrett 1999; Scoates J.S. & Mitchell J.N. 2000; Naldrett et al. 1996)**.

Is it relevant to apply these geological processes in the interpretation of widespread sulfide disseminations in Atchiza?

1.2.   Previous studies

Systematic studies of Atchiza are scarce. Previously, studies of Atchiza included geological mapping and some petrographic studies by **Real (1962)** and by **Hunting (1984)**. According to **Real (1962)**, Atchiza is dominated by serpentinite, gabbro and norite with minor peridotite and pyroxenite.

Atchiza was first interpreted as the northern extension of the Great Dyke of Zimbabwe (**Real, 1962**). This hypothesis was proposed due to the geographic locality of Atchiza relative to the Great dyke, and similarities in mineralization like chromium and asbestos, which also characterizes the Great Dyke.

However, during 1966, F. Real unravelled geochemical difference between these two intrusions, and concluded that Atchiza had to be younger than the Great Dyke. He added that when compared Great dyke, the Atchiza intrusion is mainly dominated by olivine and clinopyroxene with a lesser amount of orthopyroxene.

The first aero-geophysical survey covering Atchiza was sampled by the Hunting geology and geophysical surveys in 1982 and 1983 (**Hunting (1984)**. This geophysical survey included aeromagnetic and radiometric (TC, K eTh, and eU) sampling. The data remained unprocessed until 1991 when Anglo American Prospecting Services did the final work.

Other recent works over Atchiza include high-density geophysical surveys, geological mapping at 1:250 000 scale, dating and geochemical studies by the **GTK Consortium, (2006a, b and c, d)**. Atchiza pyroxene-gabbro is dated at 864+/-30Ma based on Sm- Nd isochron age technique; yielding an initial epsilon-value of -3.0, which indicates contamination of the magma with older LREE-enriched material (**GTK Consortium 2006d, Manttari, I. 2008**). Atchiza being formed during the early Pan-African Neoproterozoic extensional phase (~ 880-765Ma) is postdating the Tete anorthosite-norite Complex, which was emplaced around ~ 1.06Ga. The Fingoe Group, which is older than Atchiza, is dated to ~1327 ±16Ma .The Inchinga granite is partially intruding Atchiza, and thus is younger than Atchiza, and is thought to be Neoproterozoic to late Pan-African in age (**GTK Consortium 2006d**; **Manttari, I. 2008; Makitie, *et al.* 2008; Westerhof *et al.* 2008a**).

1.3. Objectives of the study

1.3.1. General objective

The main purpose of the study is to explore the geodynamics and geological processes that were involved during the evolution of Atchiza.

1.3.2. Specific objectives

The study is specifically aimed to:

- Characterization of geochemical processes

- Characterization of mineralogical- and textural- compositions for understanding of geological processes as the major factors for magmatic layering of Atchiza.

- Understanding of mineral-forming potentials of Atchiza

2. THE STUDY AREA

The Atchiza intrusive Suite (hereafter abbreviated to "Atchiza"), with an approximate area of ~ 330 km², is located in the Tete Province on the northern riverbanks of Lake Cahora Bassa (**Figure 5**). It comprises of a basal ultramafic sequences (dunite and pyroxene) and an upper mafic sequences (gabbro & gabbro-norites) - (**Real, 1962; Hunting, 1984 & this study)**.

It is bounded to the north by the Fingoè supracrustal belt, and to the northwestern and northeastern, it is bordering the mafic volcanics of the Rupanjaze Formation of the Fingoè Supergroup. It is covered in the East and Southeast by Matinde sandstones and shales of the Karoo Supergroup. In the South and East, it partially intrudes the massive-porphyritic-biotitic-granites, probably belonging to Inchinga granitic body (**Hunting, 1984).-Figure 5**.

The formation of Atchiza can be traced far back to the geological period of Rodinia break-up and dispersion (0.90 – 0.75Ga). Atchiza intrusive having its evolution age at 864±30 Ma, Sm-Nd, is exactly coinciding with an early Pan-African age (~ 880 to 765 Ma).This confirms Atchiza was formed during Neo-Proterozoic continental rifting (i.e. post-Rodinia break-up)-(**Johnson *et al.* 2006**).

Being located in the westernmost side of the Tete-Chipata Block in Zumbo District, Atchiza sits within east-west trending Zambezian Fault.

Figure 5: Sample location- Atchiza.
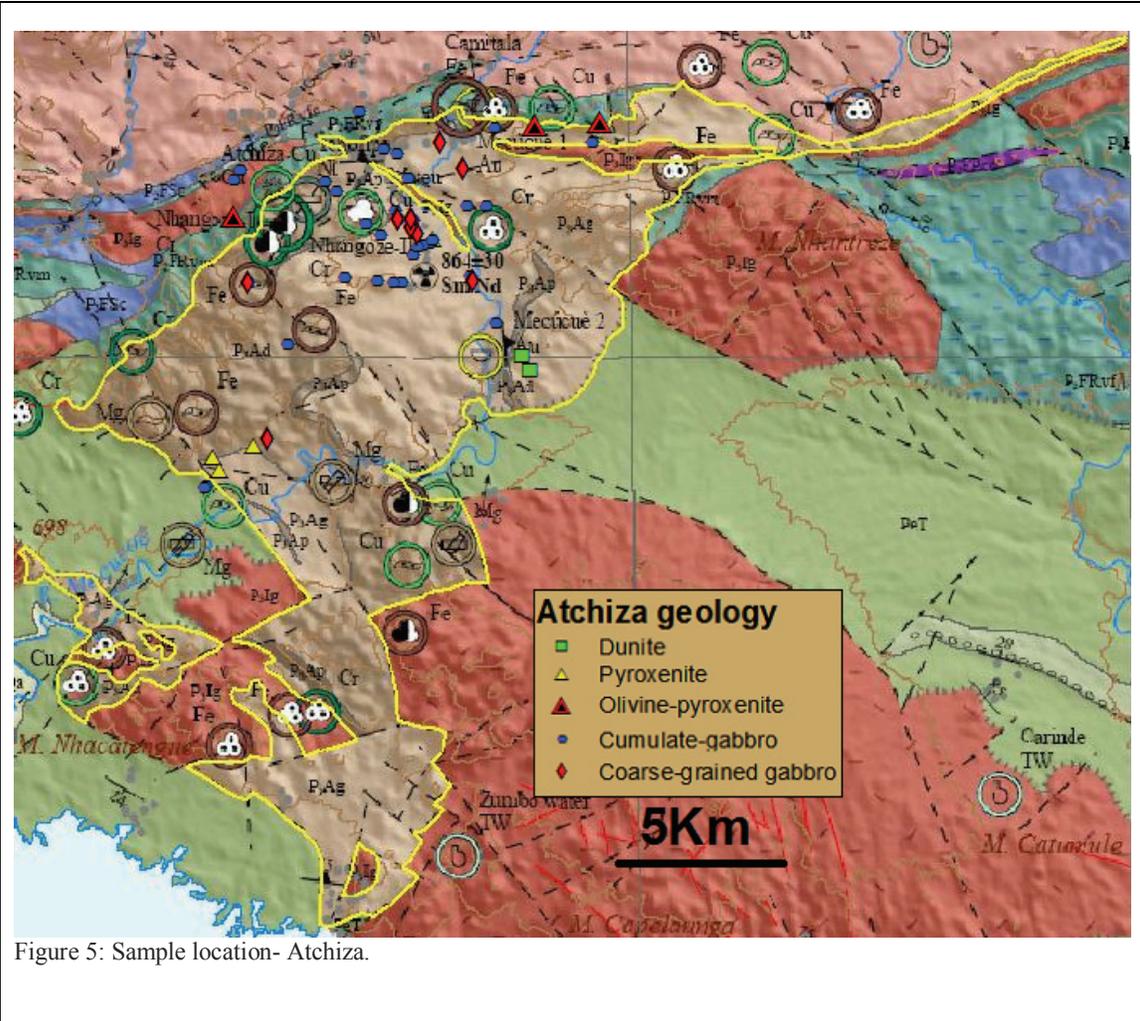
3. RESEARCH METHODOLOGY

Sampling and analytical geochemistry

A total of 63 field rock samples were collected for geochemical and petrological studies. Samples comprised of dunite, pyroxenite and gabbros. Powdering of rock samples was conducted by ACT-UIS LABORATÓRIOS DE MOÇAMBIQUE, LDA in Mozambique. Powdered samples were then transited to Norway (NTNU labs) for geochemical analysis.

Pressed solid pellets were prepared by blending powdered solid (9.6g) and wax (2.4g), for trace- and minor- elements analysis. Geochemical analysis was conducted by using BRUKER S8 Tiger 4 kW X-Ray spectrometer.

Investigation of mineralogical- and textural- compositions of rock samples was conducted by using both ore-microscopy and transmitted-light microscopy. Preparation of polished- and thin- sections was conducted at NTNU, Department of Geology and Mineral Resources Engineering.

Statistical presentation of geochemical data was performed in Geochemical Data Toolkit (GCDkit 3.00), being intergraded in R 2.13.1. Location maps were drawn by using Arc GIS 10.

4. RESULTS

4.1.   Petrography of silicate phases

Cumulate gabbro

Rock samples ATZ-11D-32B and ATZ-11D-05 were taken for petrological observations, as they were fresh samples and good representatives of cumulate gabbro. They are predominantly composed of plagioclase (50-60% modal) and clinopyroxene (40-50% modal) Plagioclases form subhedral to euhedral tabular crystals (up to 2mm across), whereas the clinopyroxene is generally anhedral (up to 3mm across). Typically, these minerals show textures ranging from granular, ophitic to sub-ophitic, with cumulate characteristics (**Figure 6** & **Figure 7**).
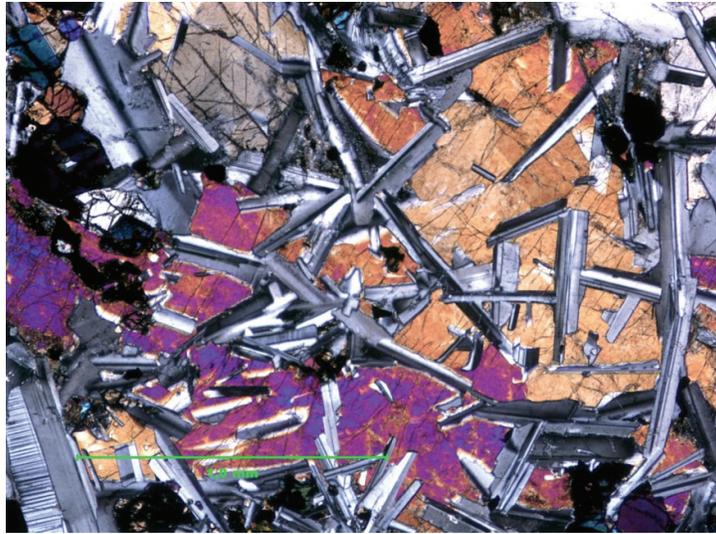
Figure 6: Ophitic to sub-ophitic texture, gabbroic sample ATZ-11D-32B
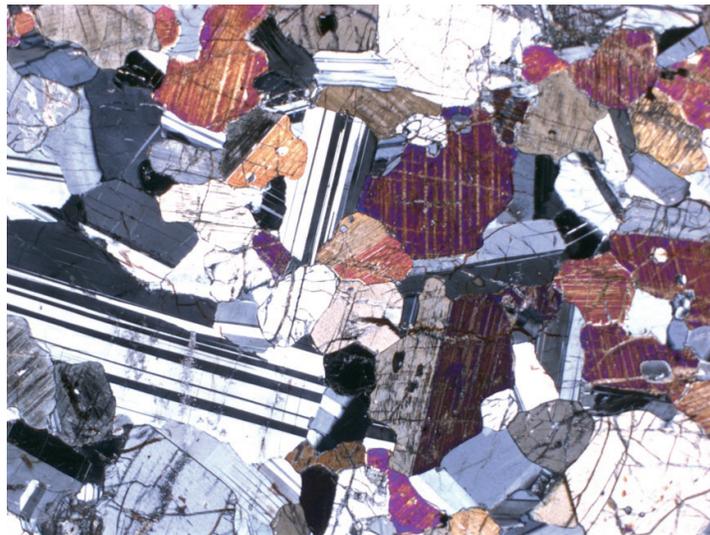
Figure 7: Cumulate texture, gabbroic sample ATZ-11D-05

Dunite

Dunite-samples ATZ-P9-034, ATZ-P9 (03608A) and ATZ-P9 (03408) were studied in details. These samples are primarily composed of cumulate olivine (85-95% modal composition) and pyroxenes (mostly clinopyroxene) - up to 2% modal. Olivine occurs as euhedral-subhedral crystals (roundish, medium-grained, 0.5-4mm across grain size). Olivine is intensively serpentinised (**Figure 8**), though the original shape of olivine crystals is firmly preserved.
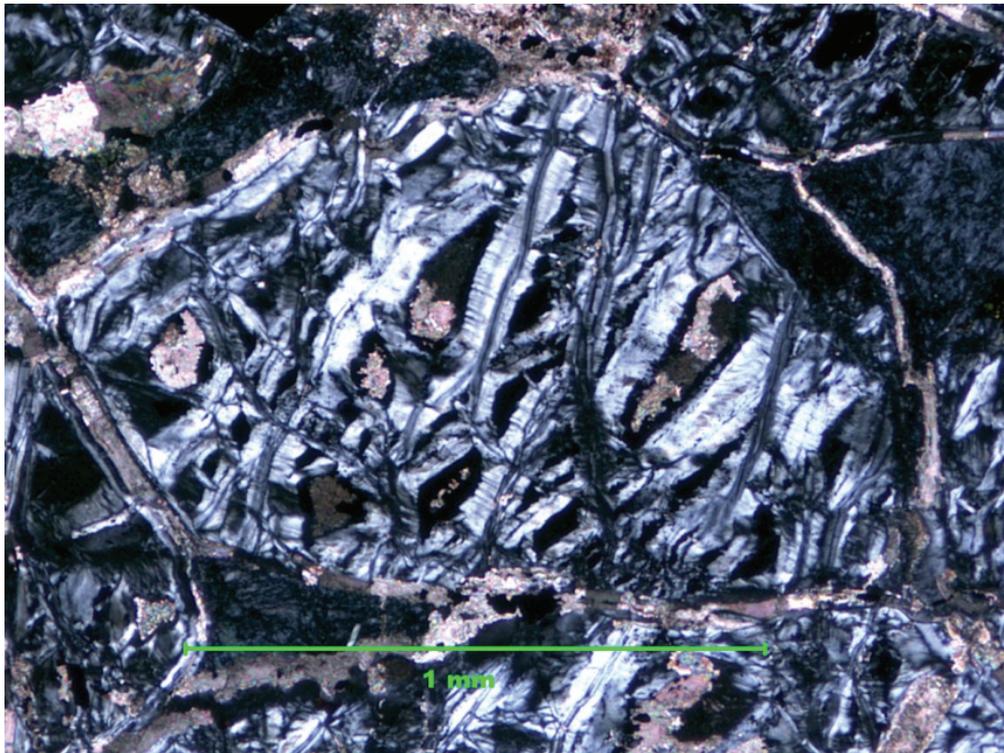
Figure 8: Serpentinised olivine

Pyroxenite

Rock sample 11D-11and ATZ-11D-12 are well-preserved representative of pyroxenites. They are predominantly characterized by subhedral to euhedral cumulus clinopyroxene (80-90% modal composition) - (**Figure 9** & **Figure 10**). Orthopyroxene is also present albeit at much lower concentrations (5-10% modal). Interstitial phase (2-5% modal) is mostly dominated by clinopyroxene, though, it is clear that chromite (1-2%) also forms an important part of intestinal phase (**Figure 10**) - See also **Figure 21**. Clinopyroxene and clinopyroxene are fine- to medium-grained (1-3mm across gain).
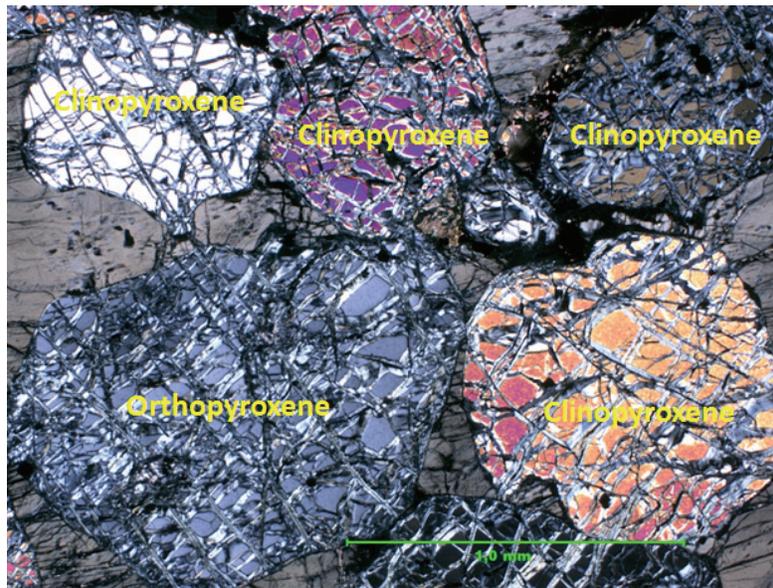
Figure 9: Clinopyroxene-orthopyroxene cumulate texture
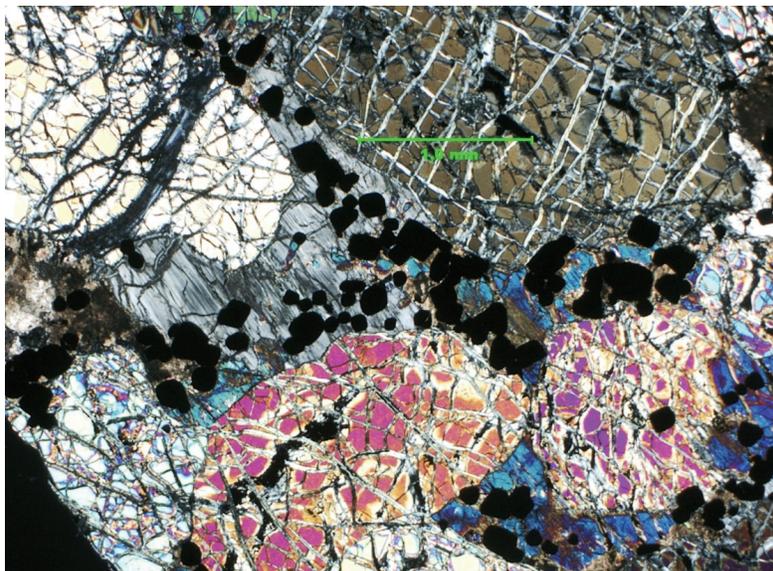
Figure 10: Intestinal phase comprises chromite and clinopyroxene, enclosed by clinopyroxene cumulate

Mafic dykes

Rock samples ATZ-Pb-006B, ATZ-P7-(02708), ATZ-P6 (02308B and ATZ- P8 (03208), characterize the mafic dykes of Atchiza (**Figure 11** & **Figure 12**). They are predominantly composed of plagioclase (50-60% modal), clinopyroxene (10-15% modal) olivine (10-25% modal) and opaque minerals (10-25% modal). Plagioclase laths (up to 1cm across) and clinopyroxenes (2-6mm across) exhibit subhedral to anhedral forms. Olivine and clinopyroxene crystals are irregular to sub-round. The matrix is comprises approximately up to 25% of total rock modal composition.

In some places, plagioclase, olivine and clinopyroxene crystals are developed into porphyritic clusters making glomeroporphyritic texture (**Figure 11**). Porphyritic masses are surrounded by a very fine-grained groundmass dominated by opaque minerals.

The very sharp contact with the host gabbroic-rocks (**Figure 12**), implies fast cooling of magmatic liquid just after emplacement, and thus these dykes may, as well, be much younger than Atchiza. At the host rock contact, plagioclase laths commonly show directional growth (**Figure 12**).
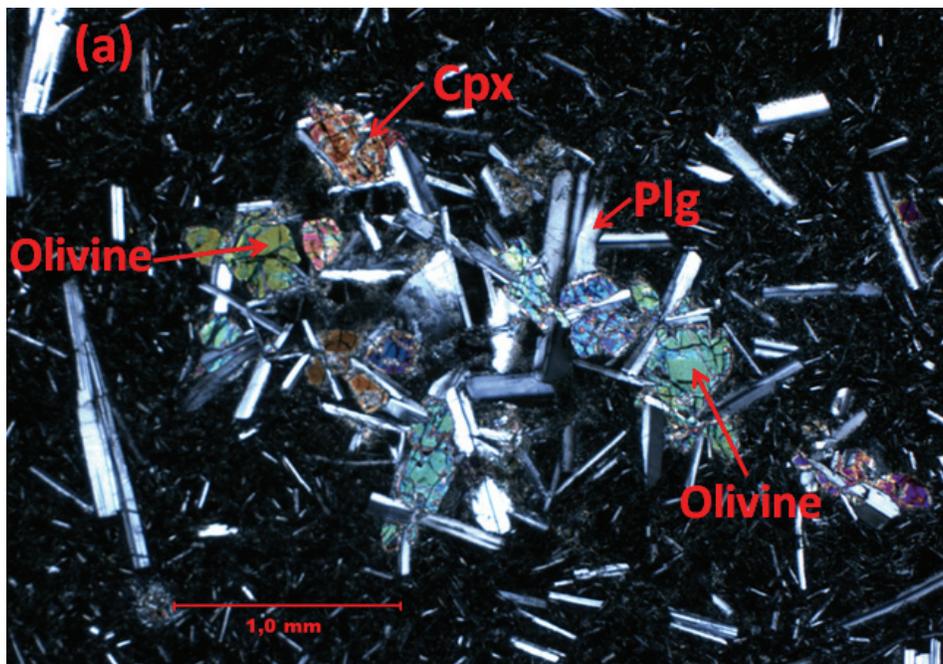
Figure 11 Glomeroporphyritic texture in mafic dyke.
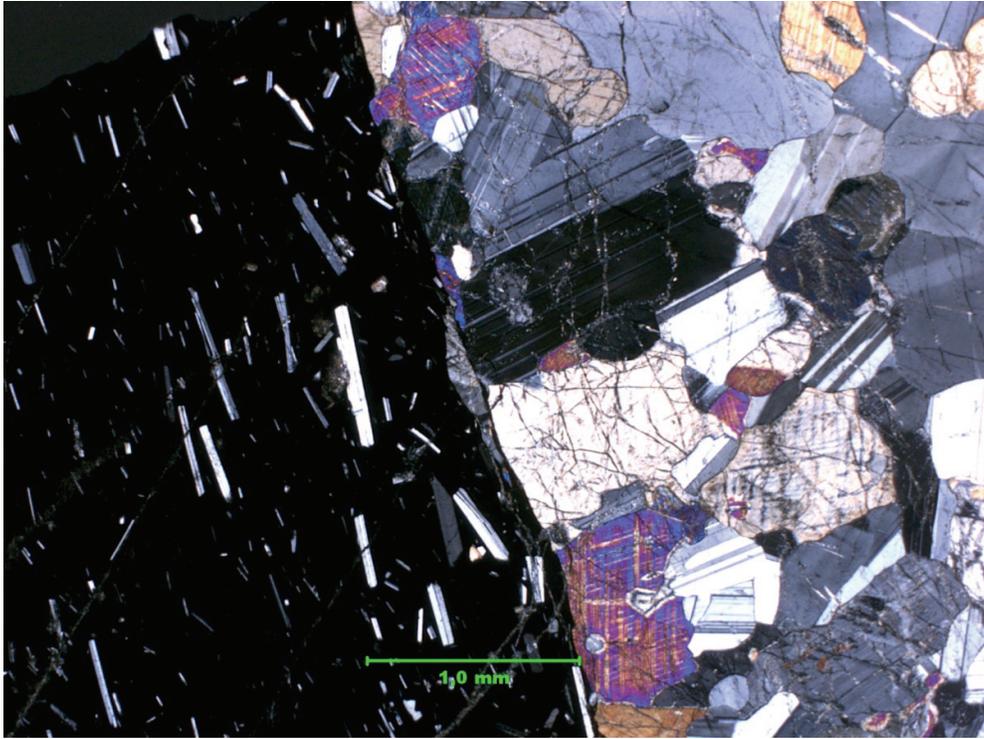
Figure 12: The contact between mafic dykes and the host cumulate gabbro

4.2. Petrography of opaque phases

Sulfide mineralizations of Atchiza are summarised in the following sections. Microphotographs, relevant to the mineralizations and textural types are included along with the descriptions.

4.2.1. Sulfide phases in gabbroic rocks

Looking at **Figure 13**, large globules (large crystals, up to 0.5mm) comprise pyrrhotite, in which pentlandite is exsolved as laths or larger masses.

The ground matrix (dark-grey) is dominated by sub-solidus secondary minerals forming by replacement of previously formed phases. They are to fine-grained for optical identification. In addition, due to this alteration process, the primary magmatic minerals evade identification. However, based on the geochemical analysis and the location of the sample in the mafic-ultramafic portion of Atchiza, it is classified as a pyroxenite-gabbro (field name). Typically, pentlandite occurs in a net-structure, intersecting the pyrrhotite crystals. Some pentlandite occurs in rims enclosing large pyrrhotite crystals.
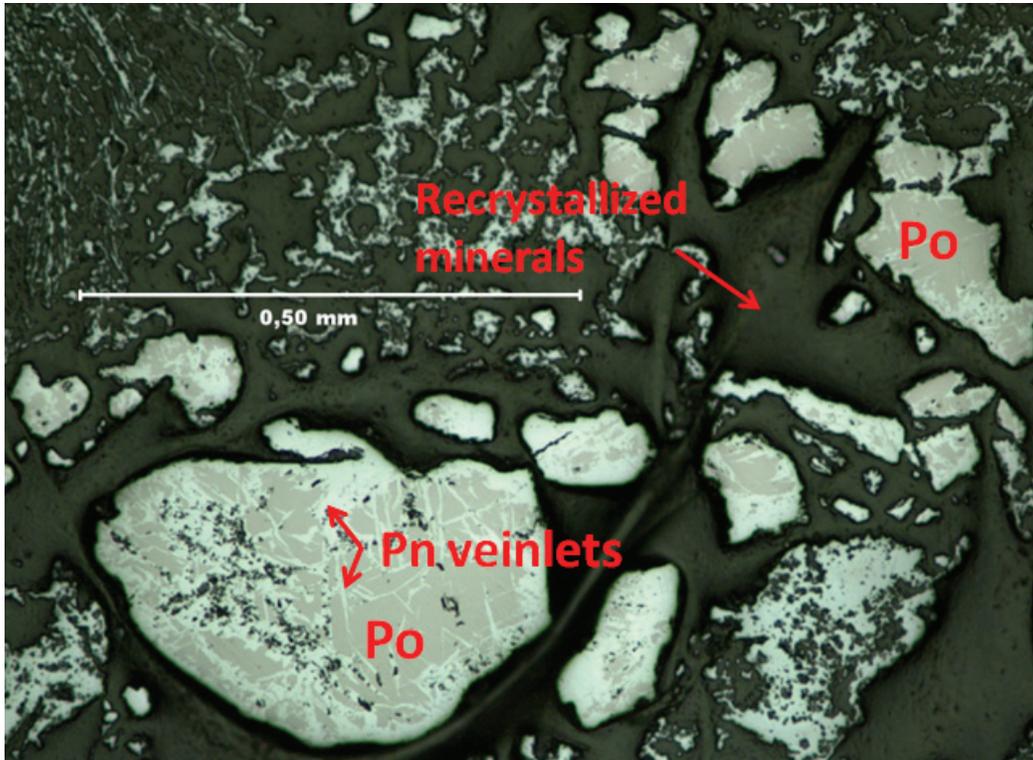
Figure 13: Silicate-sulfide immiscibility and pentlandite exsolution in pyrrhotite
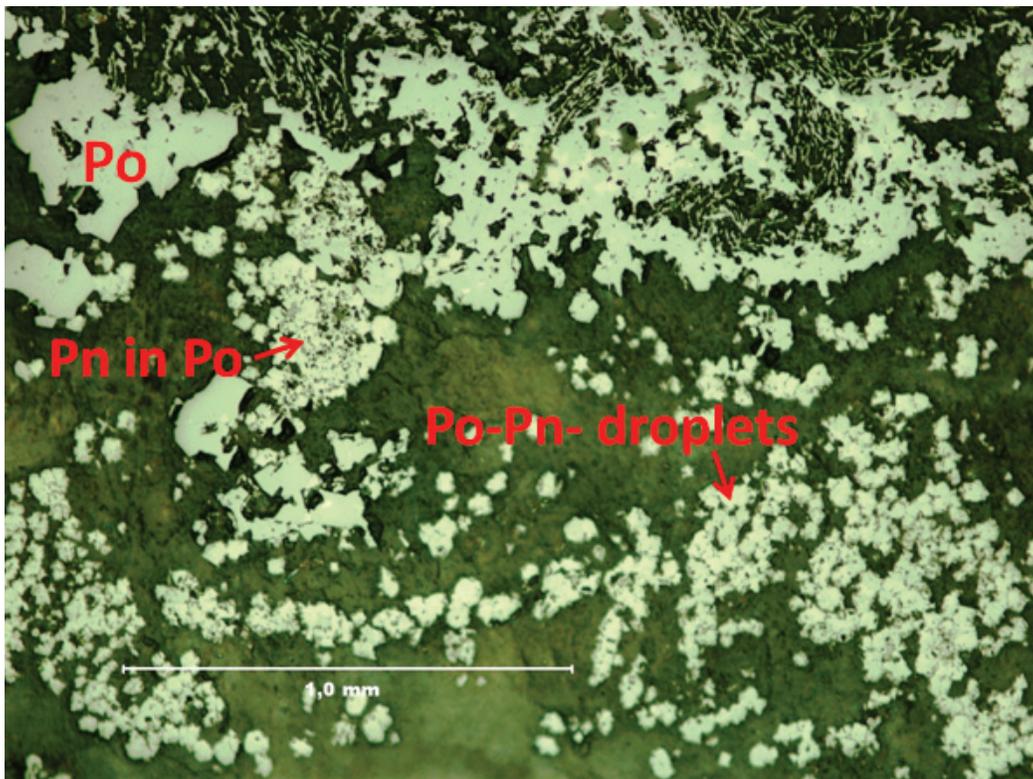
Figure 14: Pentlandite-pyrrhotite forming colonna texture

In **Figure 14**, pentlandite (Pn) and pyrrhotite (Po) are commonly developed into colonna texture, whereby sulfide droplets are visibly preserved throughout the sample.

Given the roundish coloform shapes, it is suggested that the sulfide aggregates were derived from sulfide droplets that were suspended in the crystal mush. This scenario suggests that the sulfide mineralizations in Atchiza were achieved by sulfide-silicate liquid immiscibility.

In **Figure 15**, pyrrhotite (brown-greyed crystals) exhibits hexagonal to sub-roundish forms. In this section, pentlandite (whitish yellow) dominates some sulfide aggregates, although, some pentlandite also occur as rims edging the pyrrhotite grains.
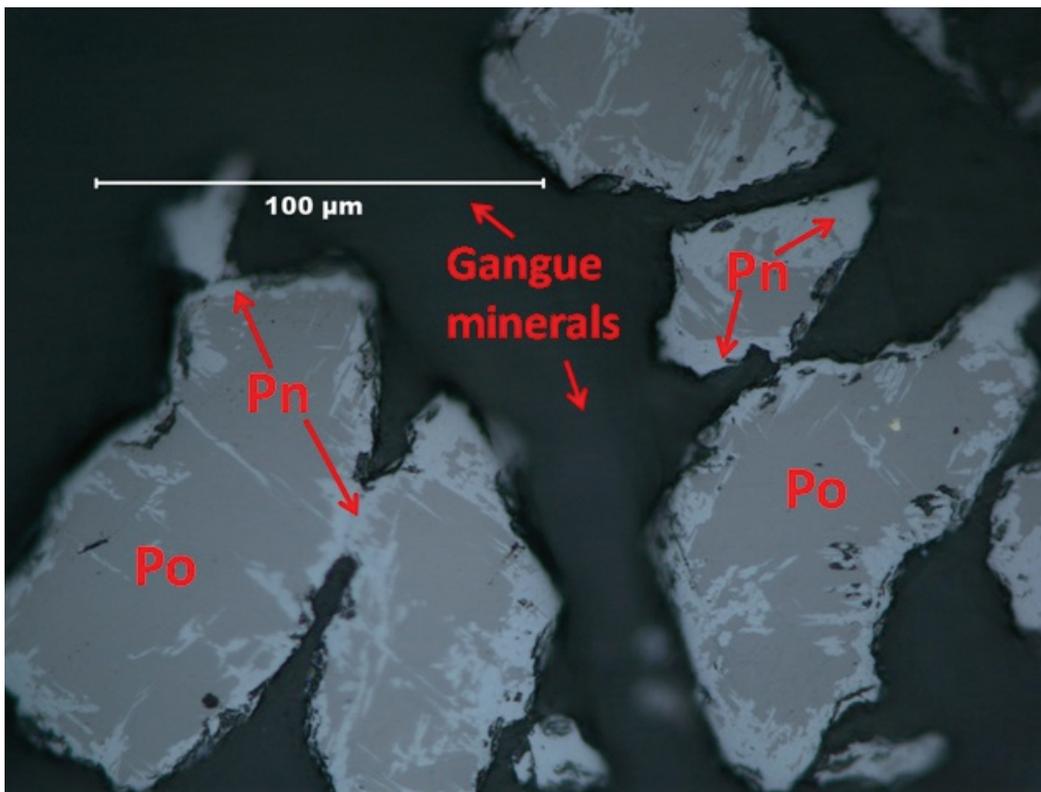
Figure 15: Hexagonal-shaped pyrrhotite crystals (Po) in sulfide-silicate immiscibility of Atchiza
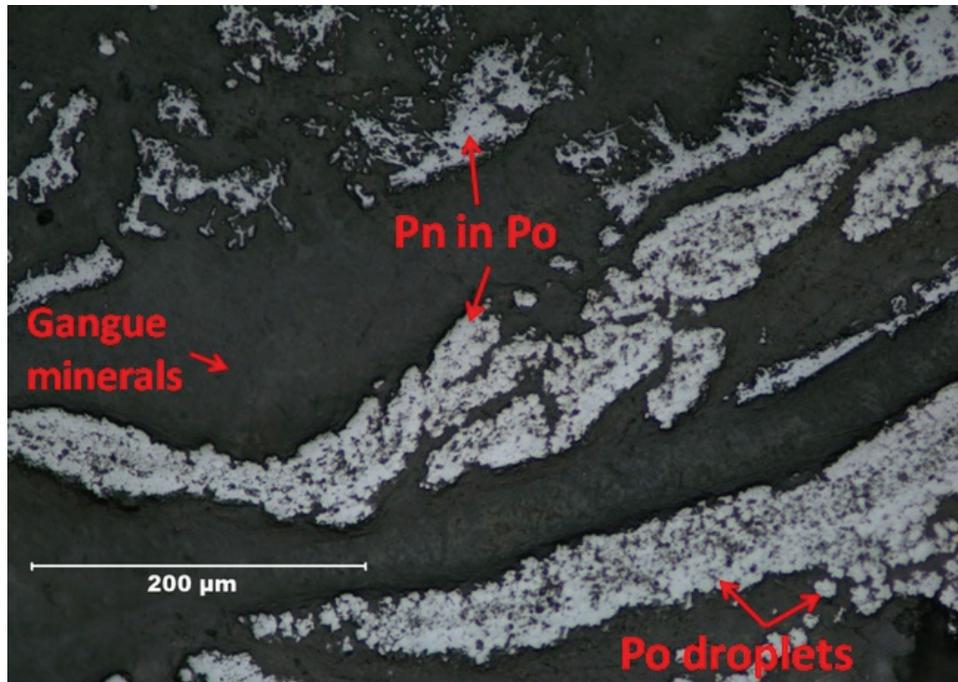
Figure 16: Aggregates of sulfide droplets in preferred-orientation

In **Figure 16**, sulfide mineralizations are clearly aligned in a more linear pattern. Given that, this sample (ATZ-Pb-02) was collected from highly deformed shear structure (North Western side of Atchiza), it is likely that the linear pattern was caused by recrystallization and shearing of the host rock, rather than being a real primary magmatic feature.
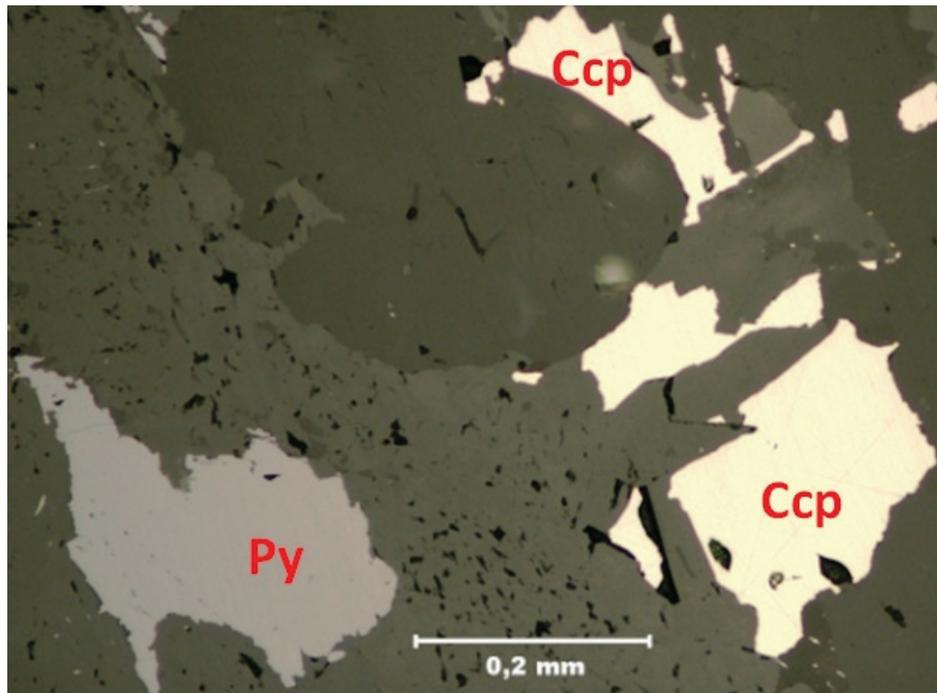
Figure 17: Chalcopyrite - pyrite mineralization, sample ATZ 051T (12860)

Figure 17 shows chalcopyrite-pyrite mineralization, one of the most common mineralization types in the Atchiza. In this part of sample, both chalcopyrite and pyrite exhibits subhedral-anhedral shapes. Chalcopyrite-pyrite mineralization occurs as disseminations, commonly associated with cumulate-gabbro.
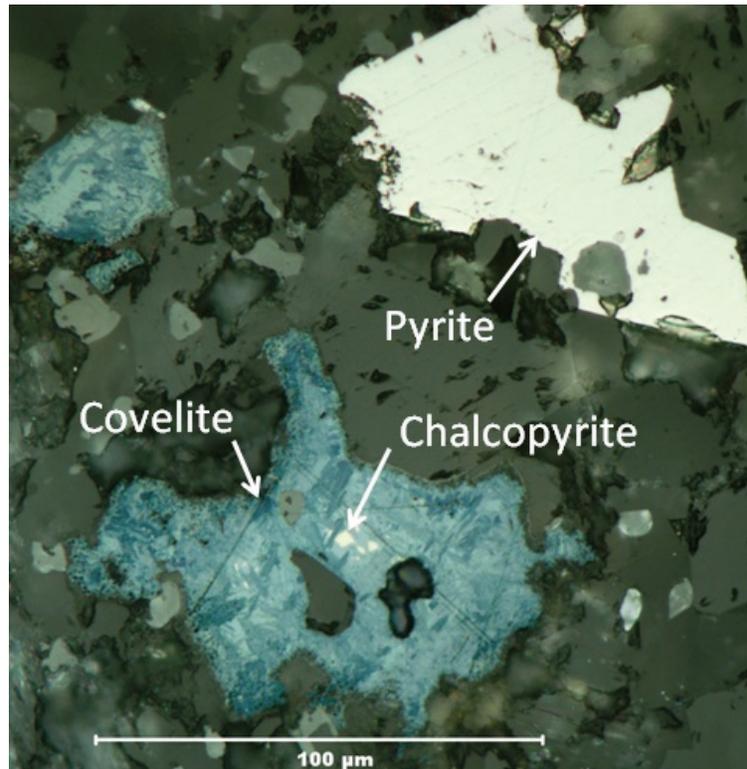
Figure 18: Chalcopyrite-pyrite-covellite-chalcosite mineralization

In **Figure 18**, chalcopyrite (remnants in covellite) and pyrite (yellow whitish, top right) are the primary minerals. Commonly, covellite (deep blue) is formed by alteration of chalcopyrite
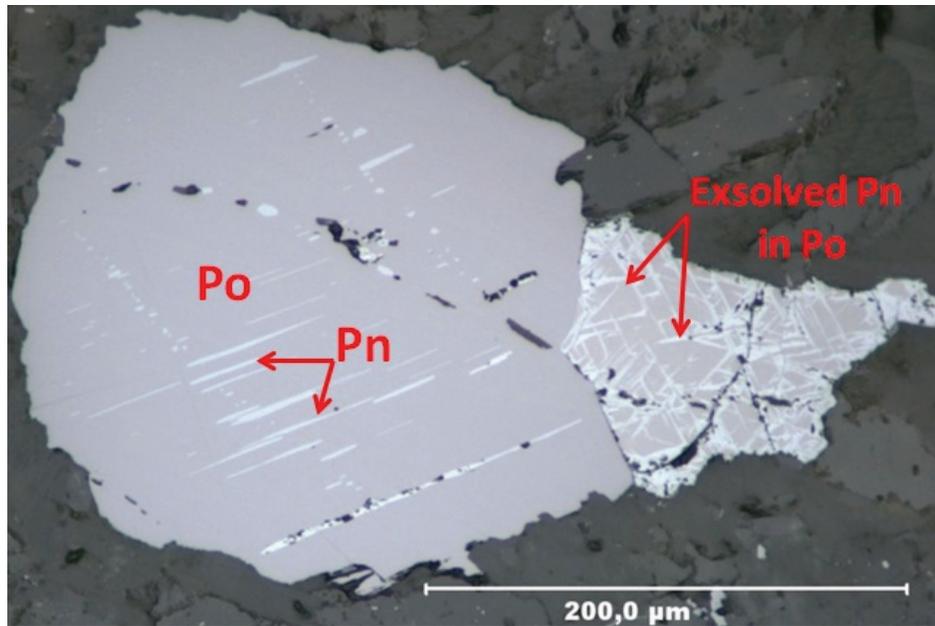
Figure 19: Different types of pentlandite exsolution, sample ATZ-Pb-06

Figure 19 shows level of pentlandite exsolution in two different pyrrhotite grains. Comparing these two exsolution textures, pentlandite is apparently more exsolved in the pyrrhotite grain to the right as compared to the pyrrhotite grain to the left. Another probable reason is that we are looking at different sections of pyrrhotite, since there is a possibility that the exsolution is crystallographically controlled.

4.2.2. Sulfide phases in ultramafic cumulates

Apparently, ultramafic cumulates of Atchiza show to characterise significant amount of disseminated sulfide. **Figure 20** shows how chromite, pyrrhotite and pentlandite are related. It is evident that pyrrhotite is overgrowing over or/and replacing chromite. Chromite (gray) is sub-euhedral, forms the inner most part of the grain. Pyrrhotite is enclosing chromite. Partly, pentlandite is exsolved from pyrrhotite (bright yellow) throughout the sample. In some places, mineralization appears to be disseminated in fractured-serpentinised olivine.

Replacement of chromite by pyrrhotite (and pentlandite) could imply that sulfide melts were introduced into the system shortly after the formation of chromite, perhaps from the intercumulus melts. Accordingly, the system must have reached sulfide saturation shortly after deposition of chromite.
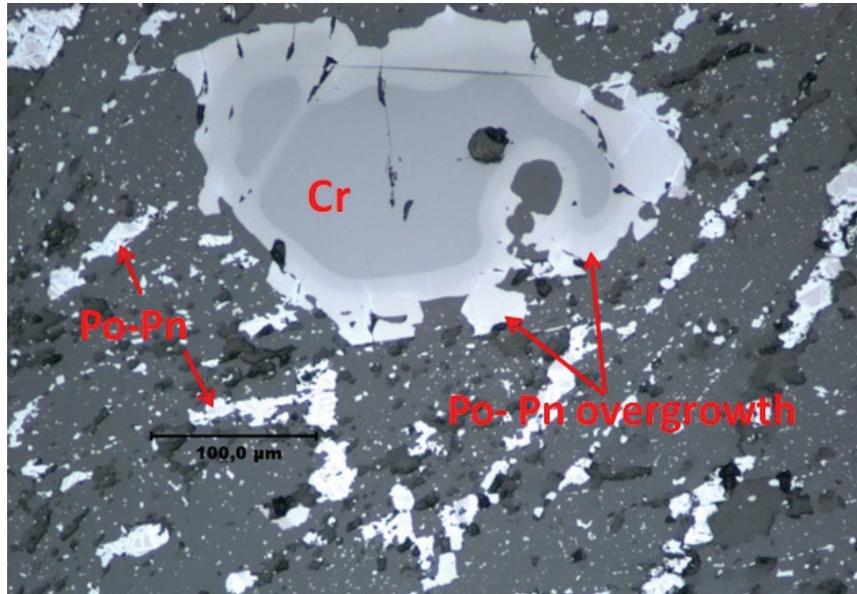
Figure 20: Pyrrhotite -pentlandite overgrowth on chromites, sample ATZ-Pb-06
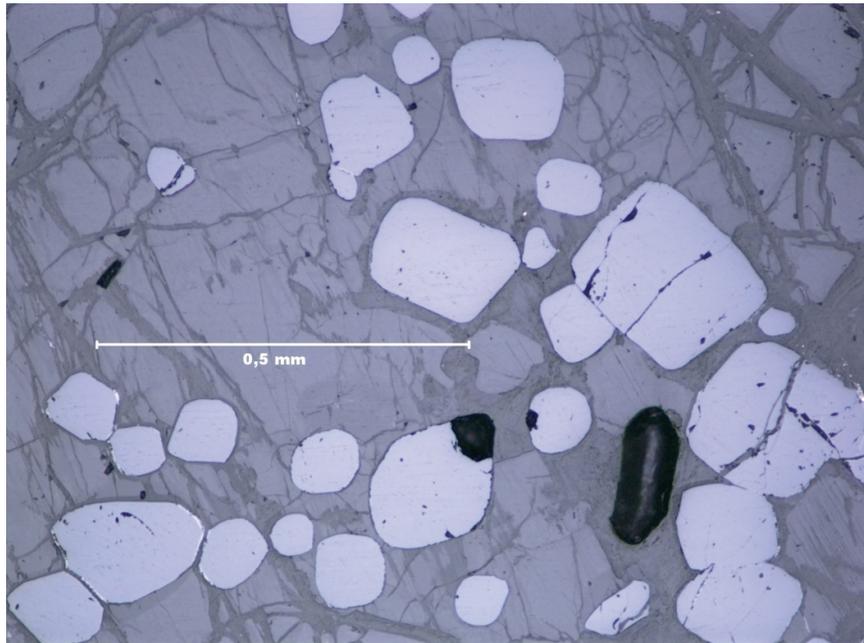
Figure 21: Chromite mineralization in cumulate ultramafics, sample ATZ-11D-12

Figure 21 shows a chromite mineralization in the Atchiza ultramafic cumulate. Chromite is fine gained (up to 0.3mm), cubic- to sub rounded in shape. Chromite occurs as inclusion in olivine crystals but also occupies part of interstitial phase. In this part of sampled section, mineralization appears to be primary, formed by fractional crystallization. Notice that, the black spots are polishing pits, only resulting from scratch (have nothing to fulfil in the interpretation).

4.3.   Whole rock geochemistry

4.3.1. Major elements geochemistry

Geochemical analysis of the Atchiza rock samples is attached in **Table 3, Table 4, Table 5, Table 6 & Table 7**.

Figure 22(A) shows the Na_2O concentration as a function of SiO_2. The Na_2O content of gabbroic rocks varies from 0.6-3.26 wt%, with the highest in the coarse-grained gabbros. As we anticipated, ultramafic cumulates show low Na_2O content. (<0.5 wt%). Note that the Na_2O content in coarse-grained gabbros is relatively more scattered, and diverge towards the y-axis (Na_2O-axis). This could suggest for chemical variability of magmatic liquids during fractional crystallization of cumulate plagioclase.

Note that, as similar as with Na_2O, the K_2O content in coarse-grained gabbro is also more scattered, diverging towards y-axis (K_2O-axis) - **Figure 22(B)**. A sharp kink at K_2O= 0.1 wt% could be suggesting for the onset of plagioclase crystallization, i.e. K_2O goes in to plagioclase; therefore the concentration of this element is suddenly increasing. The geochemical variability in this trend can also be explained as the mobility effect of Na and K elements due to alterations, subsequent after the formation of the intrusion.

Typical features that can be investigated with regard to the Fe_2O_3 contents among different rock types is the overlapping geochemical characteristic (**Figure 22C**). The Fe_2O_3 content in ultramafic cumulates (dunite and pyroxenite) and coarse-grained gabbro is more or less comparable (17.35-10.00 wt%). However, when the two are compared (in terms of Si content), the coarse-grained gabbro is much more evolved (44.99-51.39SiO_2 wt%) whilst ultramafic cumulates are less evolved (39.57-47.9SiO_2 wt%). Cumulate gabbro shows relatively low amount of Fe_2O_3 (10.48-4.36 wt %).

The concentration of MnO is increasing with increasing SiO_2 during formation of the ultramafic cumulates from 0.19 up to 0.24 wt% MnO (**Figure 22D**).Thereafter, the MnO content is falling dramatically (0.29-0.08 wt%).

Concentrations of CaO (**Figure 22E**) and Al_2O_3 (**Figure 22F**) is generally directly proportional to the SiO_2 contents, with gabbroic rocks showing high enrichment of Al_2O_3 (up to 18.08 wt%) and CaO (up to 16.76 wt%). The increase of CaO and Al_2O_3 with increasing SiO_2 content of magma can be explained as the result of fractional crystallization of plagioclase and clinopyroxene.

The TiO_2 content is highest in the coarse-grained gabbro (0.64-3.46 wt%) when compared to the cumulate gabbroic rocks **(Figure 22G)**. The TiO_2 content in cumulate ultramafics is low ($TiO_2 < 0.58$ wt%). If Fe-Ti oxides at all formed as cumulate minerals, then it must have occurred at very late during the solidification of the Atchiza.

Ultramafic cumulates show high enrichment in MgO (22.88-43.57 wt%) when compared to the gabbroic rocks **(Figure 22H)**. Cumulate gabbro is relatively low in MgO (6.96-22.88 wt%). Coarse-grained gabbro is less enriched in MgO (2.9-6.96 wt%).

The PO_2O_5 content is very low, varies significantly among different rock types **(Figure 22I)**. Two coarse-grained gabbroic samples indicated to contain relatively high concentration of PO_2O_5 (ATZ-28T = 3.46 wt% PO_2O_5 and ATZ-26T=3.08 wt% PO_2O_5). Notice that, graph is zoomed-in such that samples with high PO_2O_5 content cannot be displayed.
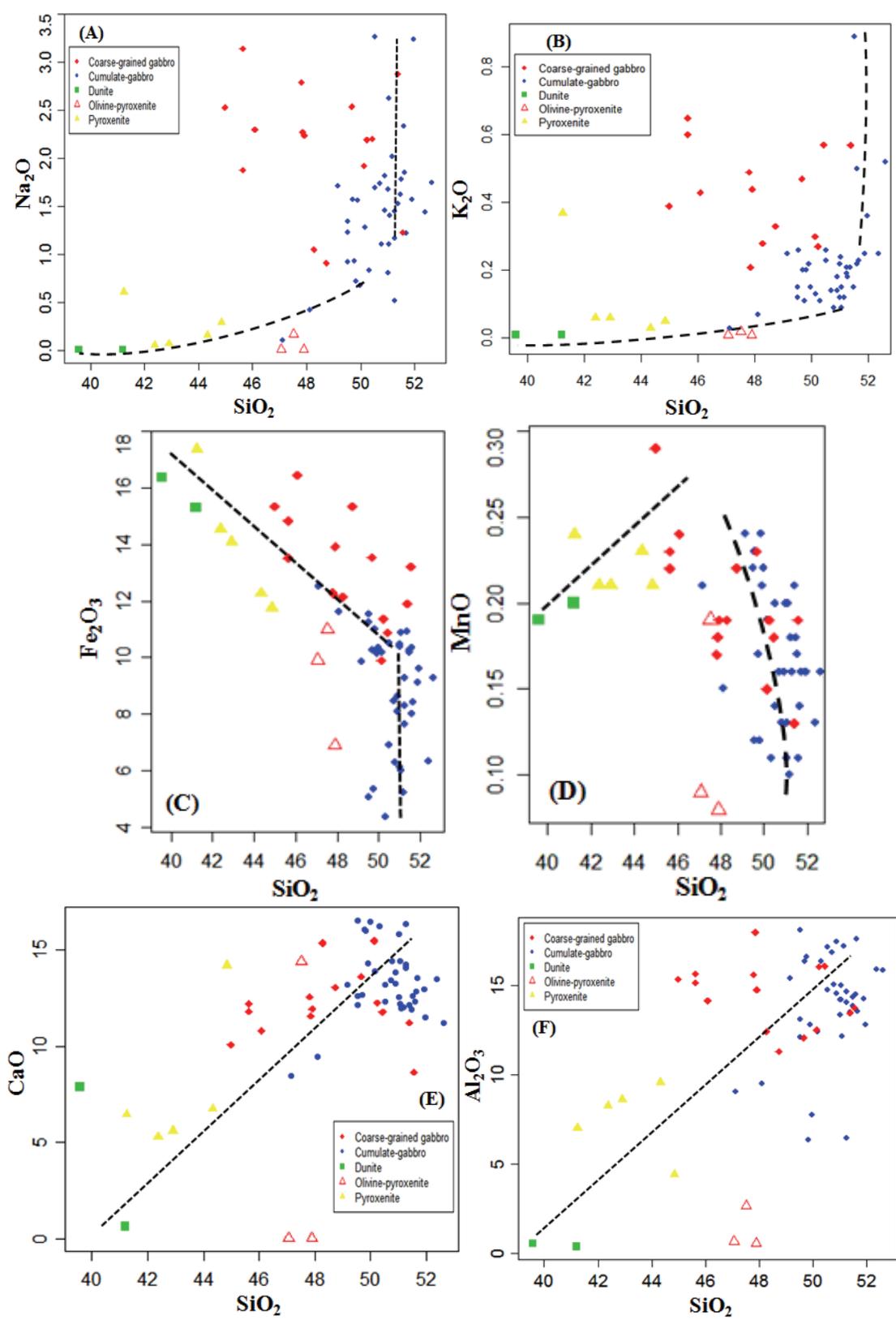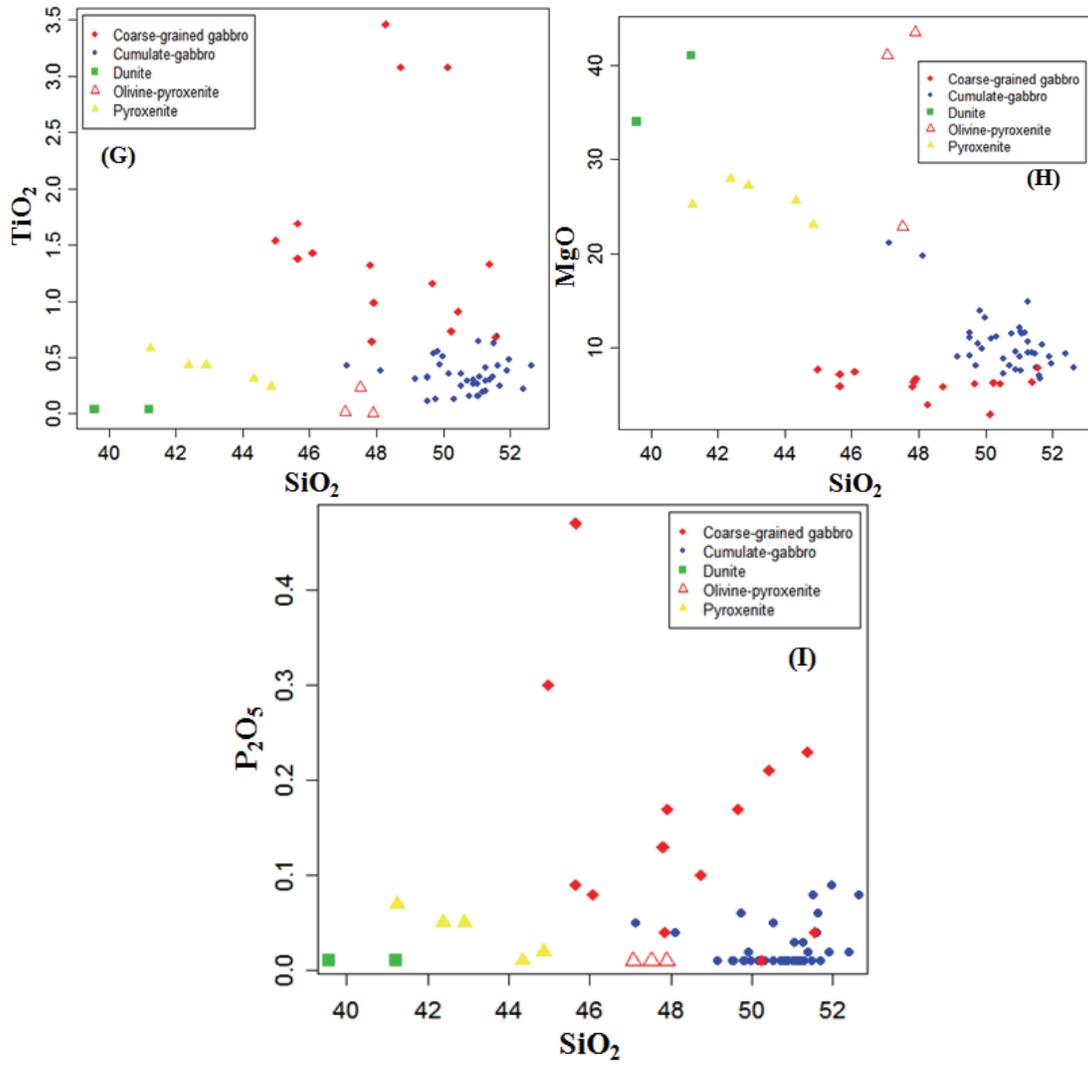
Figure 22 (A to I): Plots against SiO_2 for major elements

Plots of major elements against MgO are generated below for understanding of magmatic evolution of Atchiza. Results are presented in **Figure 23(A), (B), (C), (D), (E) & (F)**.

In **Figure 23(A)**, at least three geochemical trends can be loosely identified. The first trend is ultramafic cumulates (dunite and pyroxenite); the second trend is mafic cumulates (cumulate gabbros) and the third trend is presented by coarse-grained gabbro. Geochemical description of these trends is clearly described in the earlier chapters, in conjunction with **Figure 22(C)** and **Figure 22(H)**. Note that, overlapping characteristics in terms of mineralogy and texture (grain sizes) between cumulate gabbros and coarse-grained gabbros is obvious. The only best way they can be physically distinguished in the field is by colour. Typically, the coarse grained-gabbro is relatively much dark (probably because of high Fe-Ti-contents) whereas the cumulate gabbro is whitish-dark (probably because of low Fe-Ti-contents, but also a plagioclase-cumulate characteristic). Predominantly, the coarse grained-gabbro is located nearly the central parts of the suite.

Figure 23(B) and **Figure 23(C)** predict the likely trend for which different rock types in Atchiza were evolved. Generally, the CaO and Al_2O_3 contents increase as decreasing MgO. Apparently, it is likely that dunite (olivine) was the first rock to form, followed by pyroxenite (pyroxenite) and lastly is gabbroic rocks (plagioclase).

Concentration of TiO_2, Na_2O and K_2O is negatively correlated with MgO; generally, it increases with decreasing MgO **(Figure 23D, E & F)**.
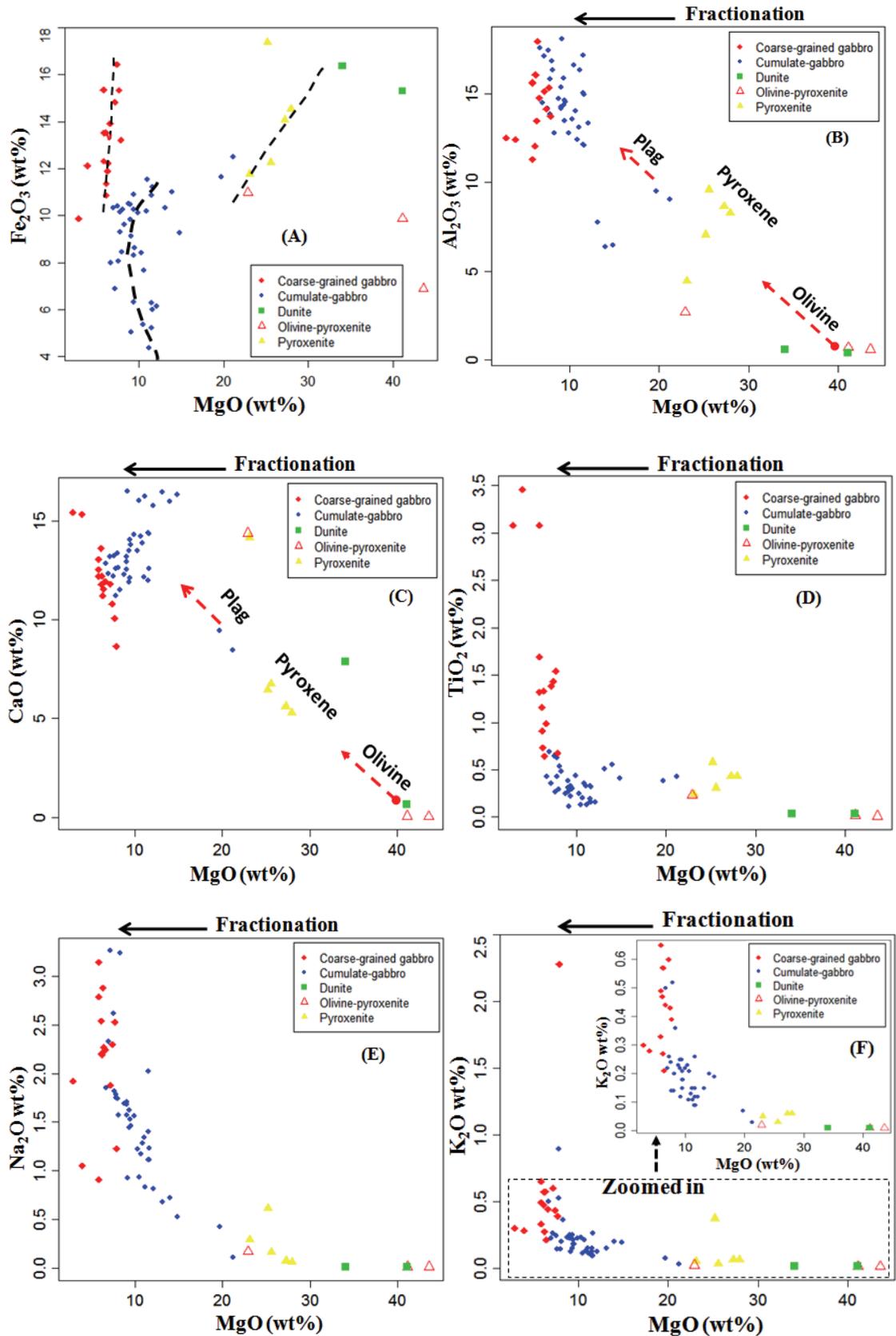
Figure 23: Binary plot shows chemical variations of rocks as a function of MgO

4.3.2. Classifying the Atchiza

The Atchiza geochemical data are also plotted on AFM diagram (**Figure 24**) in order to study evolution trends. Apparently, the Atchiza rocks have resemblance of tholeiitic series.

Figure 24: A (Na$_2$0 + K$_2$0)-F (Fe$_2$O$_3$)-M (MgO) wt% plot for mafics & ultramafic rocks (Irvine & Baragar 1971) of 63 Atchiza samples.
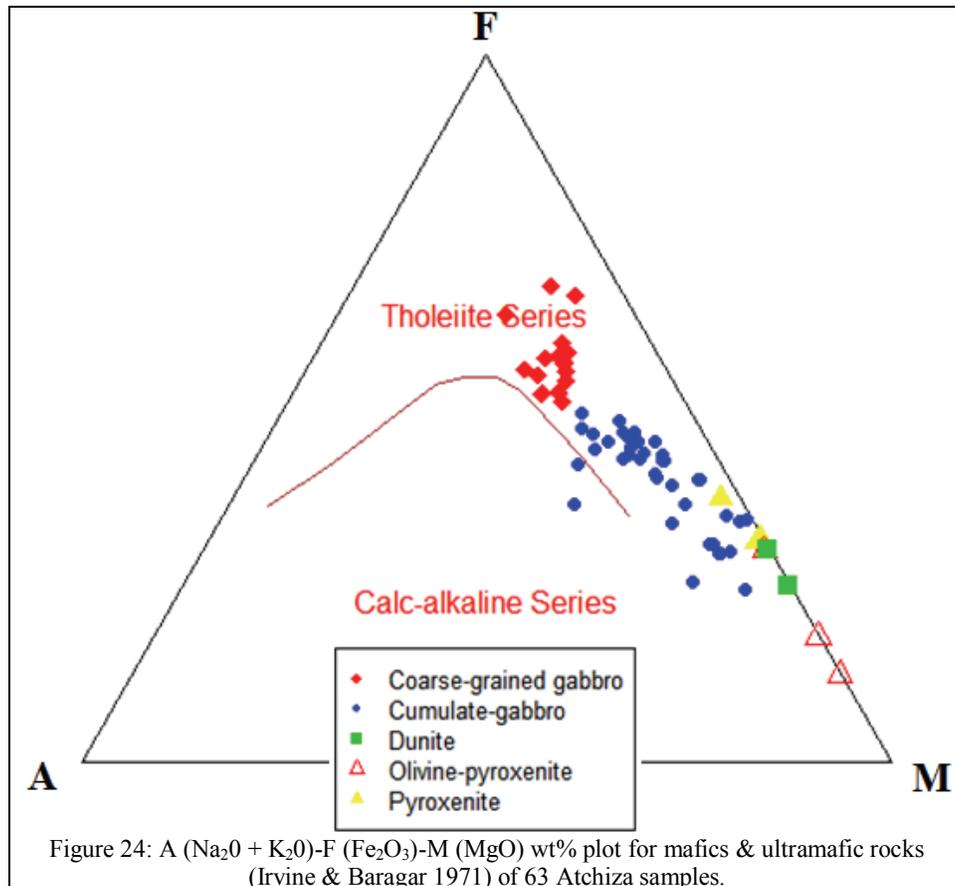
On the R1-R2 plot (**Figure 25**), 18 samples are accurately classified. Yet, the remaining unclassified 45 samples appear to plot nearly correct into the field trend of ultramafics, gabbro and gabbro-norite.

All samples plot in metaluminous field on A/CNK-A/NK diagram **(Figure 26)**. This strongly suggests that the genesis of Atchiza is from igneous activities.
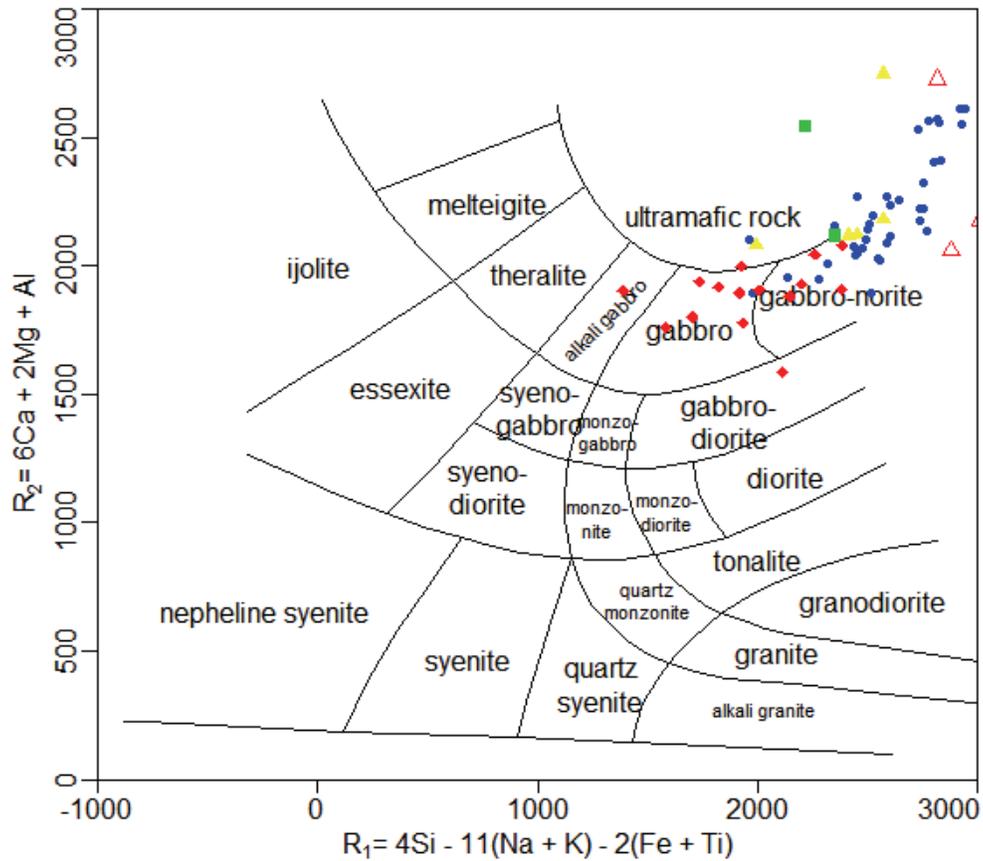
Figure 25: R1-R2 plot (De la Ronche *et al.* 1980) of Atchiza for 67 plotted samples
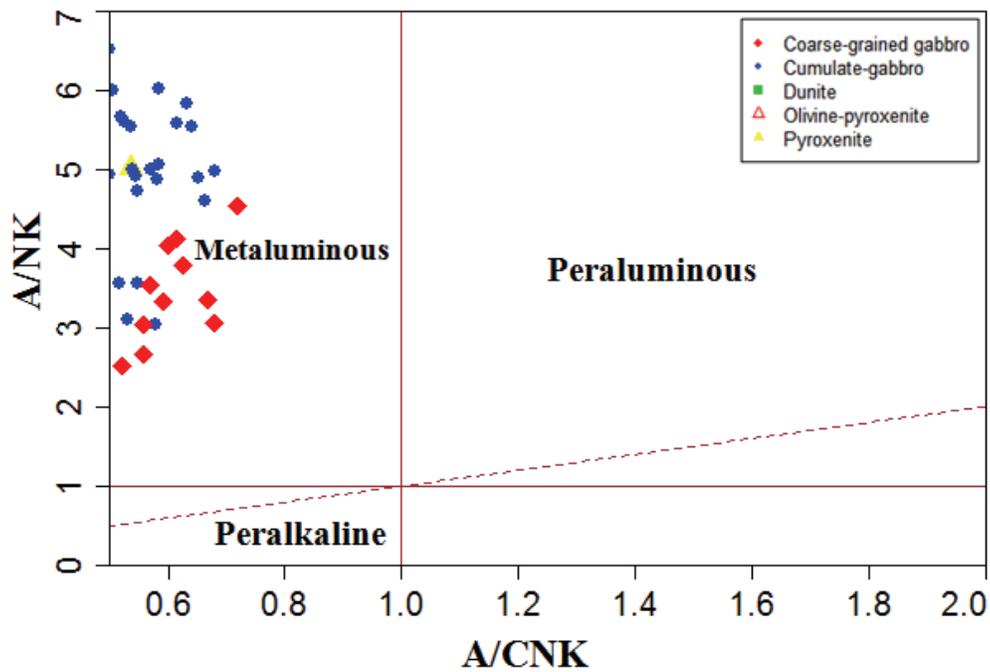
Figure 26: A/CNK-A/NK plot (Shand 1943) of Atchiza

Geochemical characteristic of Atchiza on MgO-(Fe_2O_3+TiO_2)-(Al_2O_3+CaO) ternary diagram (**Figure 27**) shows drifting arched trend from MgO apex towards the Al_2O_3+CaO apex, but diverting away from Fe_2O_3+TiO_2 apex. Generally, the trend suggests that fosterite rather than fayalite was the dominant olivine species in the system, following the majority ultramafic cumulate samples plotting towards MgO apex rather than toward Fe_2O_3 +TiO_2.
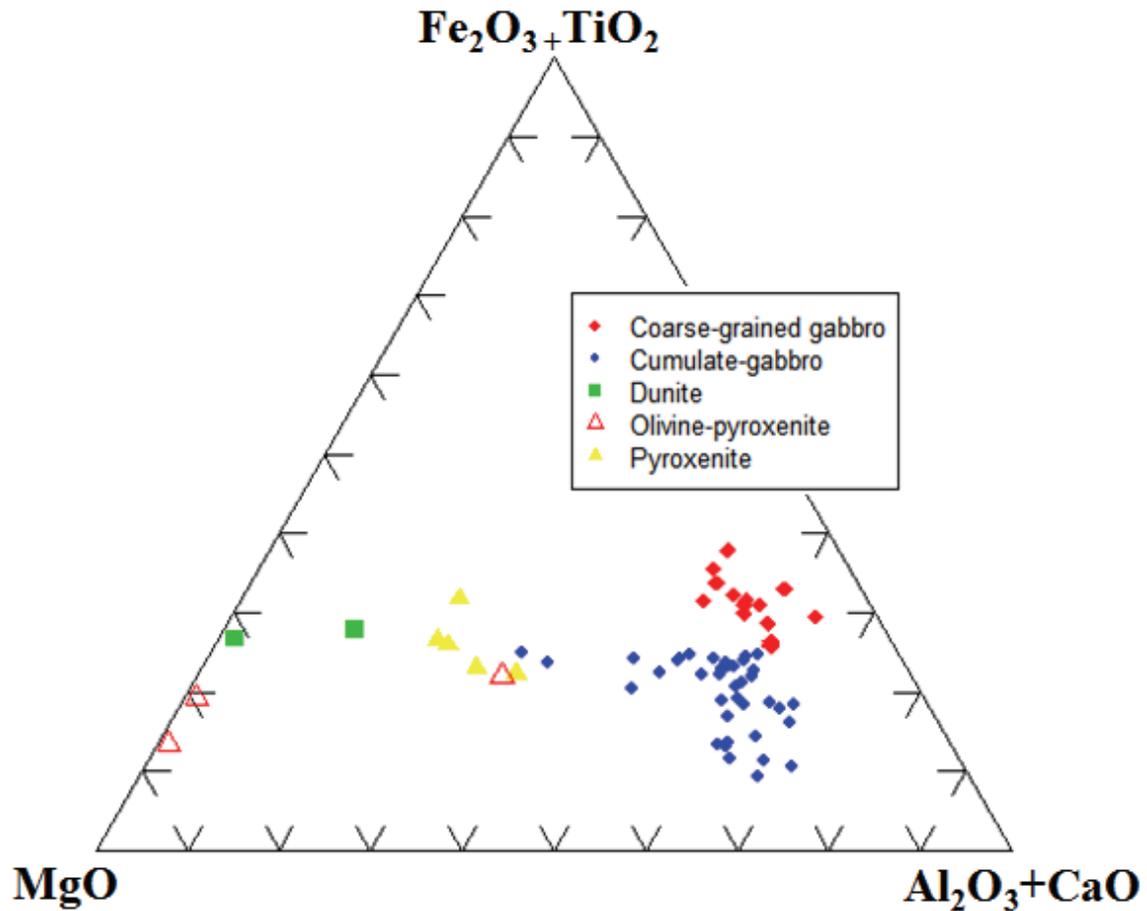
Figure 27: Tertiary plot shows chemical variations a function of MgO, Al_2O_3 + CaO, and Fe_2O_3 + TiO_2

4.3.3. Concentration of trace elements as a function of fractionation Index

Figure 28(A-F) shows the concentration of trace- elements plotted against Mg# (MgO/ (MgO + Fe_2O_3); also known as the fractionation Index. The Mg# is used here to show the level of evolution of the primitive magma. Trace elements plotted include Sr, Zr, Ti, Cr, Ni and V. The following results can be observed:

- Ultramafic cumulate, which is the least evolved rock, is characterised by the highest Mg# (0.59-0.86), whereas the cumulate gabbro characterizes a moderately evolved magma source (Mg#=0.40-0.72). With the lowest Mg# (0.23-0.37), the coarse-grained gabbros suggest their evolution from a relatively high-differentiated magma source.

- Sr, Zr, Ti and V contents of silicate melt are generally directly proportional to the degree of magma fractionation (**Figure 28A, B, C & D**), whereas, Cr and Ni concentration is inversely proportional to the degree of magma fractionation (**Figure 28E & F**).

- High Ni content (up to 4636.22ppm) occurs mainly in ultramafic cumulates but also in a few cumulate gabbros. High Cr concentration (up to 5131.5ppm) is associated with both cumulate ultramafics and cumulate gabbroic-rocks (**Figure 28E & F**).

  Compared to the rest of other rocks, coarse-grained gabbro is more enriched in Ti (0.64-3.4 wt% TiO_2), V (224-952.3ppm), Zr (up to 296.1ppm) and Sr (253-1268.4ppm)- (**Figure 28A, B, C & D**), but relatively low depleted in compatible elements (Ni = 48.7-235.7ppm , Cr = below detection limit to 410.5ppm)-**Figure 28E & F**.

- Cumulate gabbro is moderately low in Ti (<0.69 wt% TiO_2), V (<336.1ppm), Zr (<148.1ppm) and Sr (11.8-422.8ppm), whereas, ultramafic cumulate is the lowest in Ti (<0.58Wt %), V (<224.1ppm), Sr (<253.7ppm) and Zr (<44.4ppm).
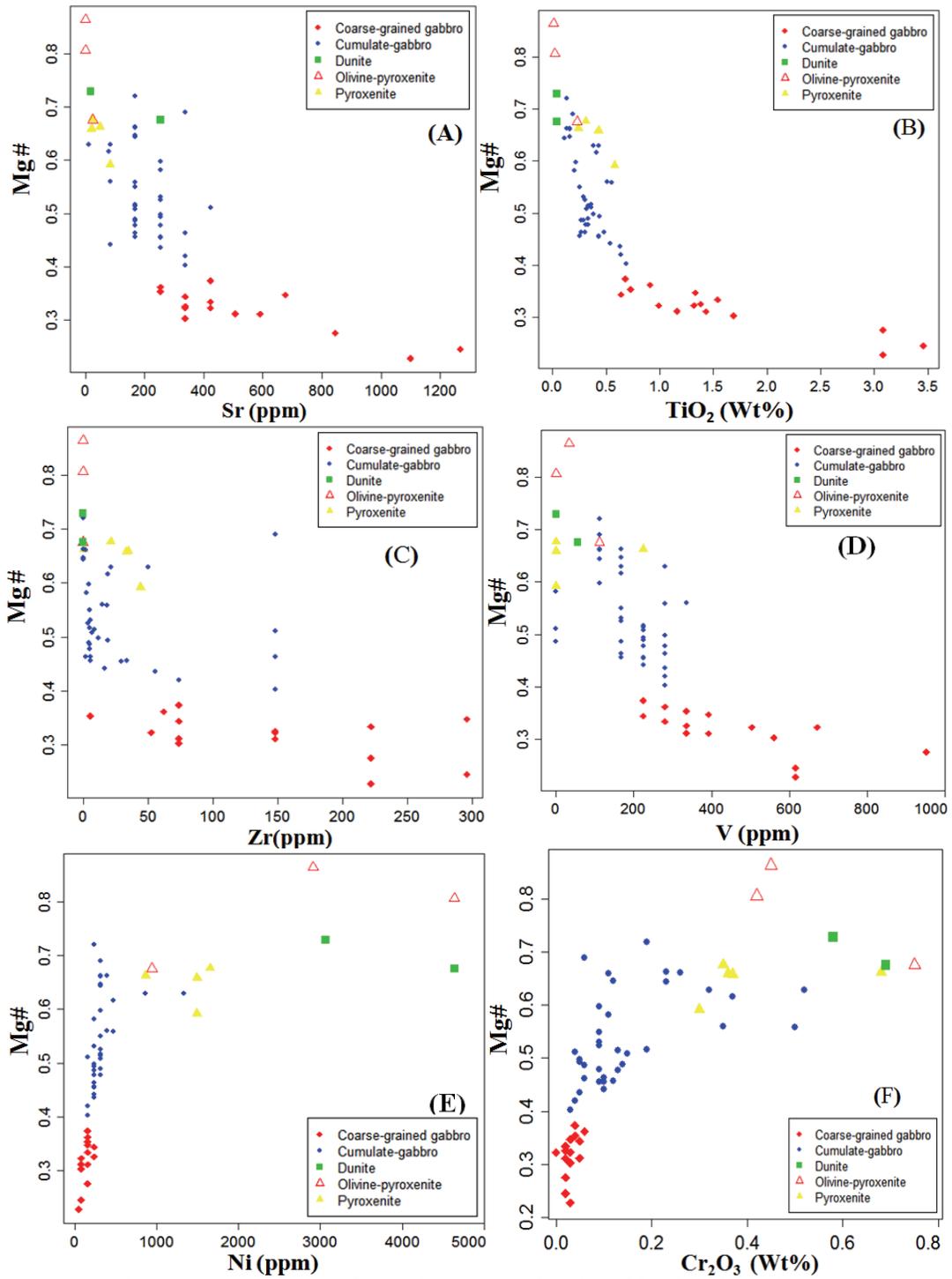
Figure 28: Concentration of trace elements as a function of fractionation Index
See texts above for description

4.3.4. Change in geochemical ratios as a function of fractionation Index

In **Figure 29A, B, C & D**, the Ni/Zr, Cr/Zr, Sr/Zr and Ti/Zr ratios are plotted as a function of the fractionation Index, being known that Zr is an incompatible element, whereas Ni, Cr, Sr and Ti are compatible elements . Accordingly, their ratios have been applied here to study evolution trends during fractional crystallization. Based on **Figure 29A-F**, the followings can be understood:-

- Ratios Ni/Zr (**Figure 29A**), Cr/Zr (**Figure 29B**), Sr/Zr (**Figure 29C**) and Ti/Zr (**Figure 29D**) are generally decreasing with increasing degree of fractional crystallization.

- Accordingly, coarse-grained gabbros are characterized by the lowest Ni/Zr, Cr/Zr, Sr/Zr and Ti/Zr ratios; suggesting their formation from magma sources that were subjected to subsequent fractional crystallization of cumulate rocks.

- The presence of uninterrupted cryptic differentiation trends for these ratios implies that the different igneous lithologies are derived from one and the same parental melt. However, it is important that the idea of uninterrupted cryptic differentiation be taken with precautions. This is because the Atchiza stratigraphic data (height and width of the intrusion), which could be useful for correlation, is not available at this stage.
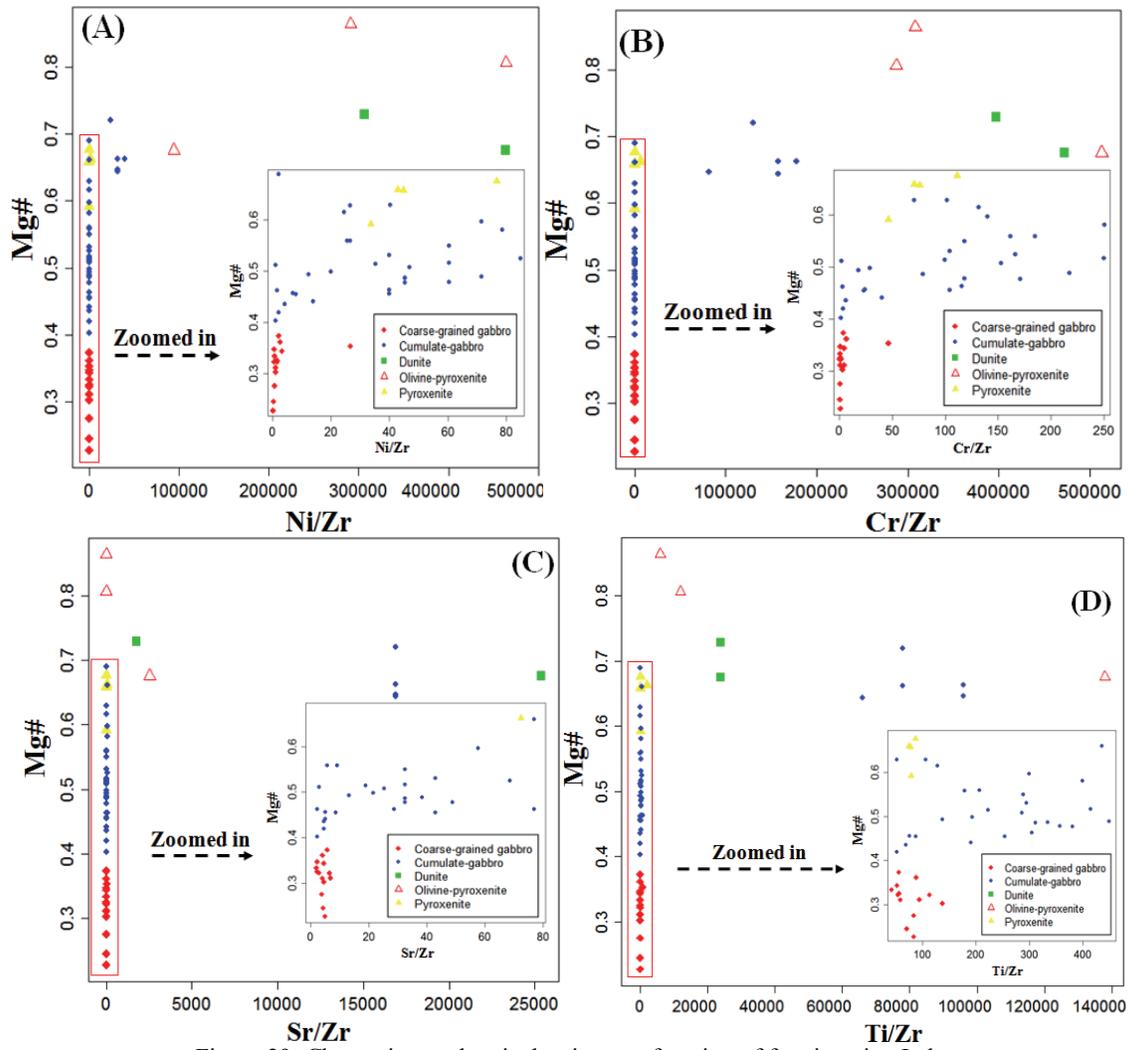
Figure 29: Change in geochemical ratios as a function of fractionation Index

4.3.5. Fe-Cu-Co-S- variation during fractional crystallization

Figure 30(A, B, C & D) shows $MgO-Fe_2O_3-SO_3-Cu$ relationship as a function of fractional crystallization. As far as concentration of sulfur in relation to the variation of Fe and Cu is concerned, the following observations are made:

- At the beginning of fractional crystallization (at approx Mg# = 0.86-0.57), whereby fractionation phase is dominated by ultramafic cumulate (**Figure 30A**), the Fe_2O_3 concentration is high (up to 16 wt%)-**Figure 30(B)**.

- With time, following subsequent fractionation, and with decreasing MgO, the Fe_2O_3 concentration decreases to below 10 wt% (at Mg# = 0.57-0.4) - **Figure 30(B)**. This zone is dominated by cumulate gabbro, in particular, the medium-grained gabbro (**Figure 30A**).

- At Mg# = 0.38-0.3, the Fe_2O_3 rise again (up to16 wt %) - **Figure 30(B)**. The dominant lithological unit here is coarse-grained gabbro. It is good to understand that, apart from being enriched in Fe, the coarse-grained gabbro also shows high enrichment of Ti and V (**Figure 28B & D**). The likely explanation for this combined enrichment (Fe-Ti-V) is that, the early fractional crystallization of early plagioclase-rich mineral assemblages might have left the residual magmas highly concentrated in Fe, Ti and V.

- At Mg# < 0.3, the Fe content starts to decrease steadily (Fe_2O_3< 8 wt %).

- Concentration of SO_3 in ultramafic cumulates is very low (0-0.1 wt%) - **Figure 30(C)**.

- As both MgO and Fe_2O_3 concentration decrease, the amount of SO_3 appears at first gradually increasing then, abruptly, SO_3 is increasing to the highest values around 0.35 wt%, (approx Mg# = 0.45-0.25). The high SO_3 values are coinciding mostly with coarse-grained gabbros, though, several cumulate samples (both mafics and ultramafics) have also indicated to be characterised by high SO_3 contents (**Figure 30C &A**).

- Concentration of Cu is consistently changing with the SO_3 content of residual magma. It is very low (<200ppm) at the beginning of fractional crystallization (Figure 30D). Abruptly, it is increasing to the highest values (1118.5ppm for ATZ-51T & 1198.4ppm for ATZ-52T). These highest Cu values are coincidently associating both highest SO_3concentration (0.25-0.35Wt %) and relatively low Fe_2O_3 content (< 10Wt %). From our observations, it is clear that the Cu anomalous value is mostly associated with cumulate gabbro and coarse-grained gabbro.

- Three samples (ATZ-P10-44B, ATZ-50T and ATZ-P9-35) show relatively high Co contents (Co = 157ppm max). In addition, these samples are coinciding with the initial SO_3enrichment (in cumulate gabbro and pyroxenite) - (**Figure 30E**). Given that, Co may form as a by-product in Ni-Fe-sulfides; the occurrence of Co with the early sulfides in cumulate minerals may possibly suggest sulfide saturation condition was attained during the early stages of fractional crystallization.

- The concentration of Pd is also relatively high; with six samples (ultramafic cumulates and gabbro cumulates) showing a considerably good grades- **Figure 30F** (ATZ-P9-35 = 80ppm, ATZ-P3-19 = 53ppm, ATZ-51T = 50ppm, ATZ-P5-22 = 46ppm, ATZ-P10-44B = 43ppm and ATZ-P2-17 = 41ppm). The good Pd grades are mainly associating with sulfides mineralization zones especially in ultramafic cumulates. This may also support the argument that sulfur saturation was achieved during the early stages of magmatic differentiation.
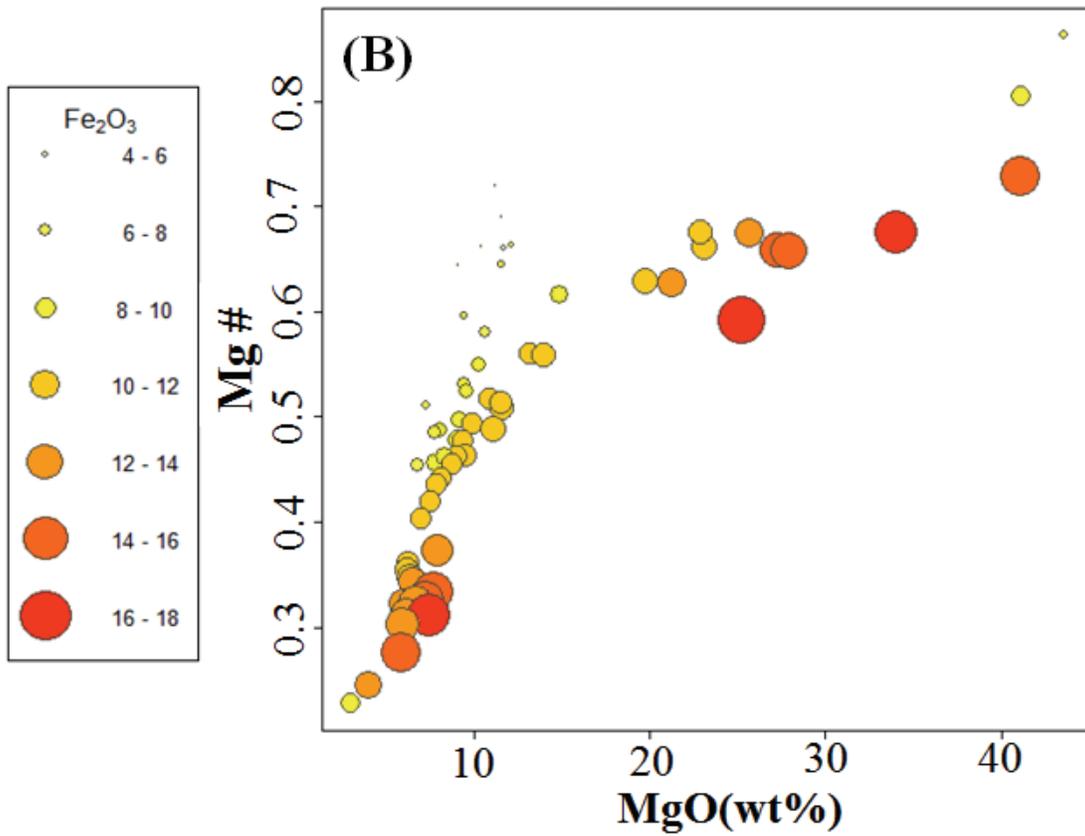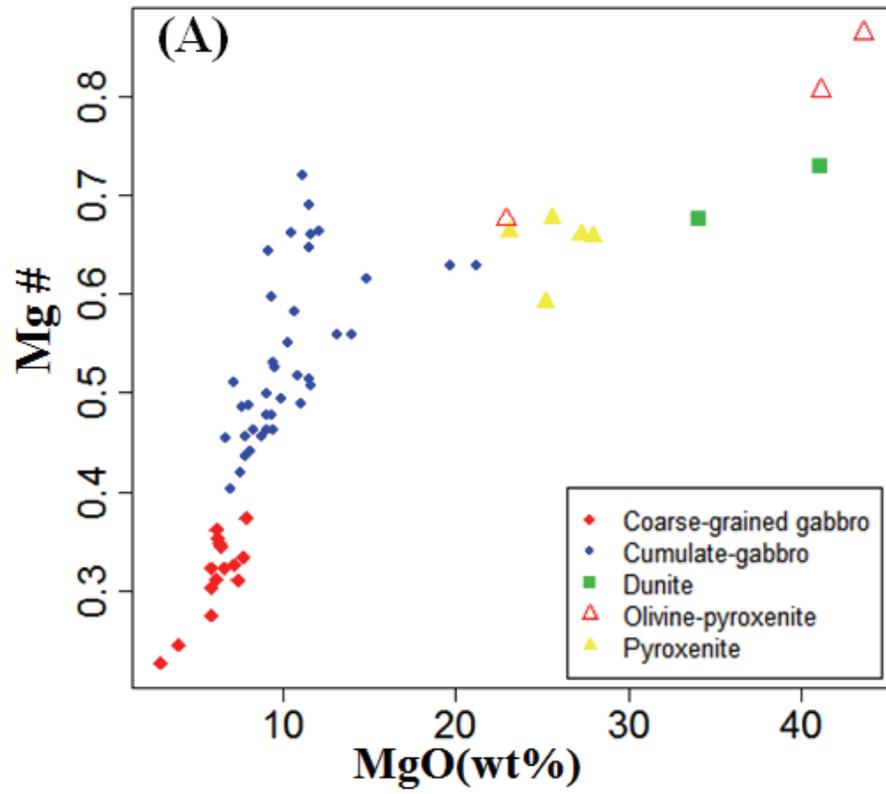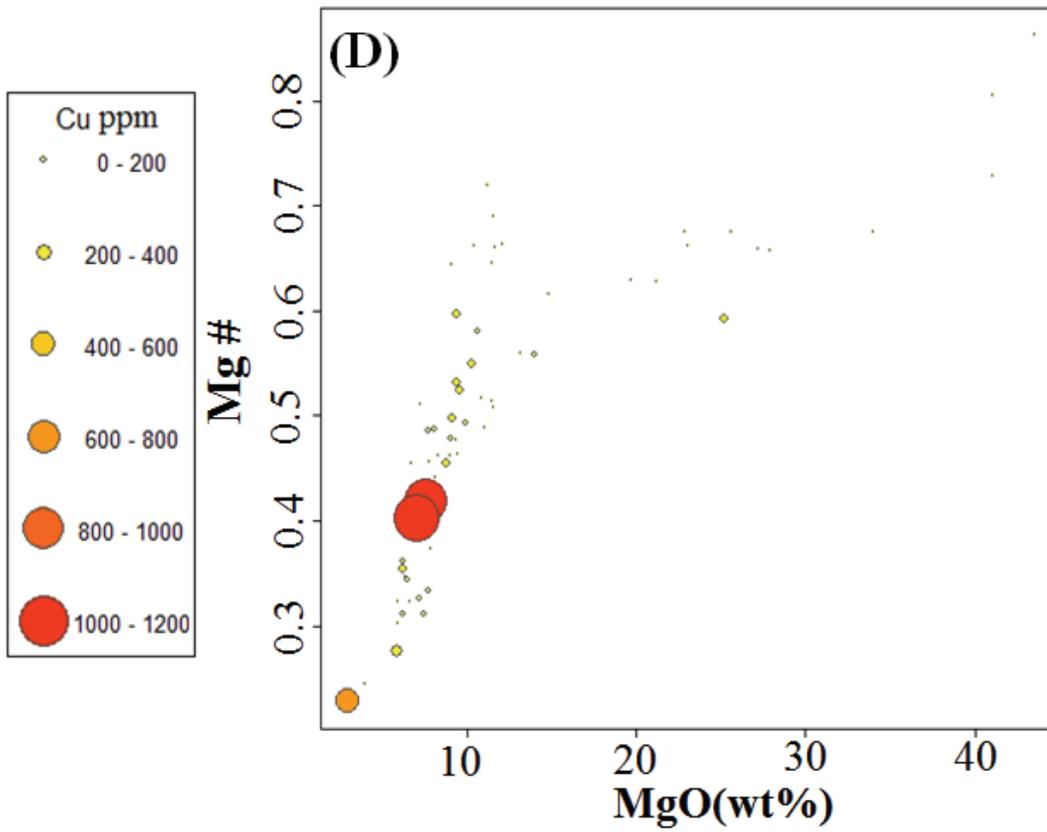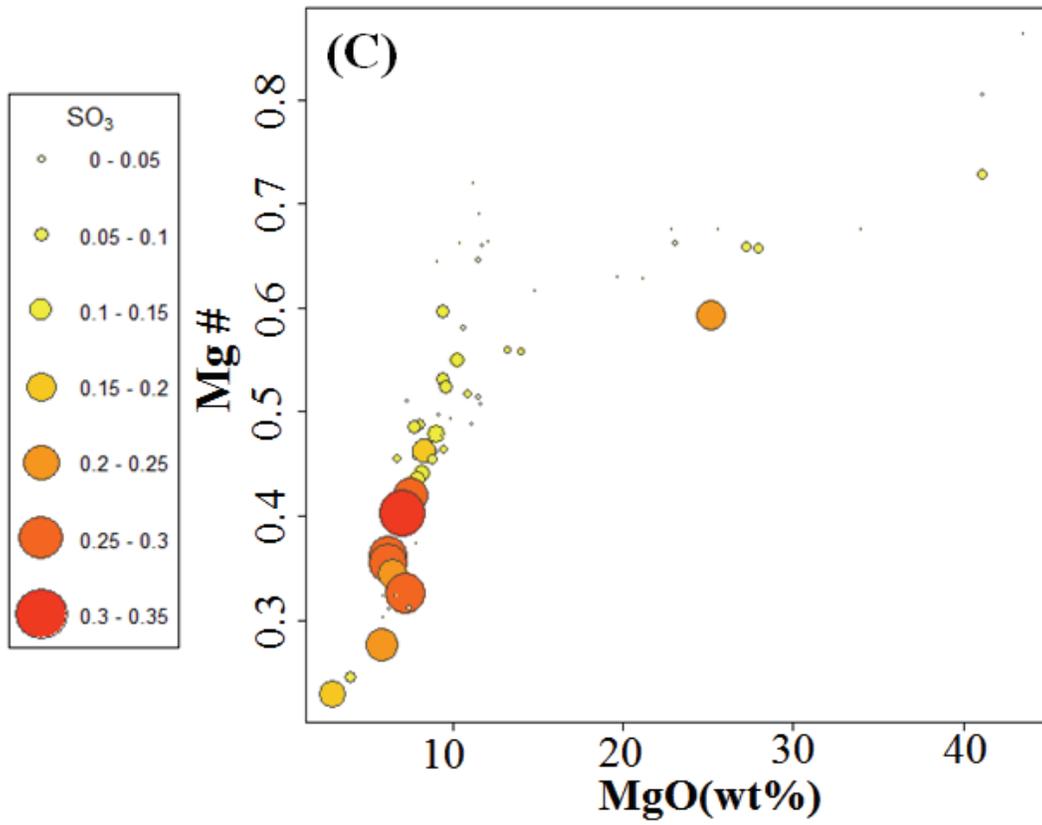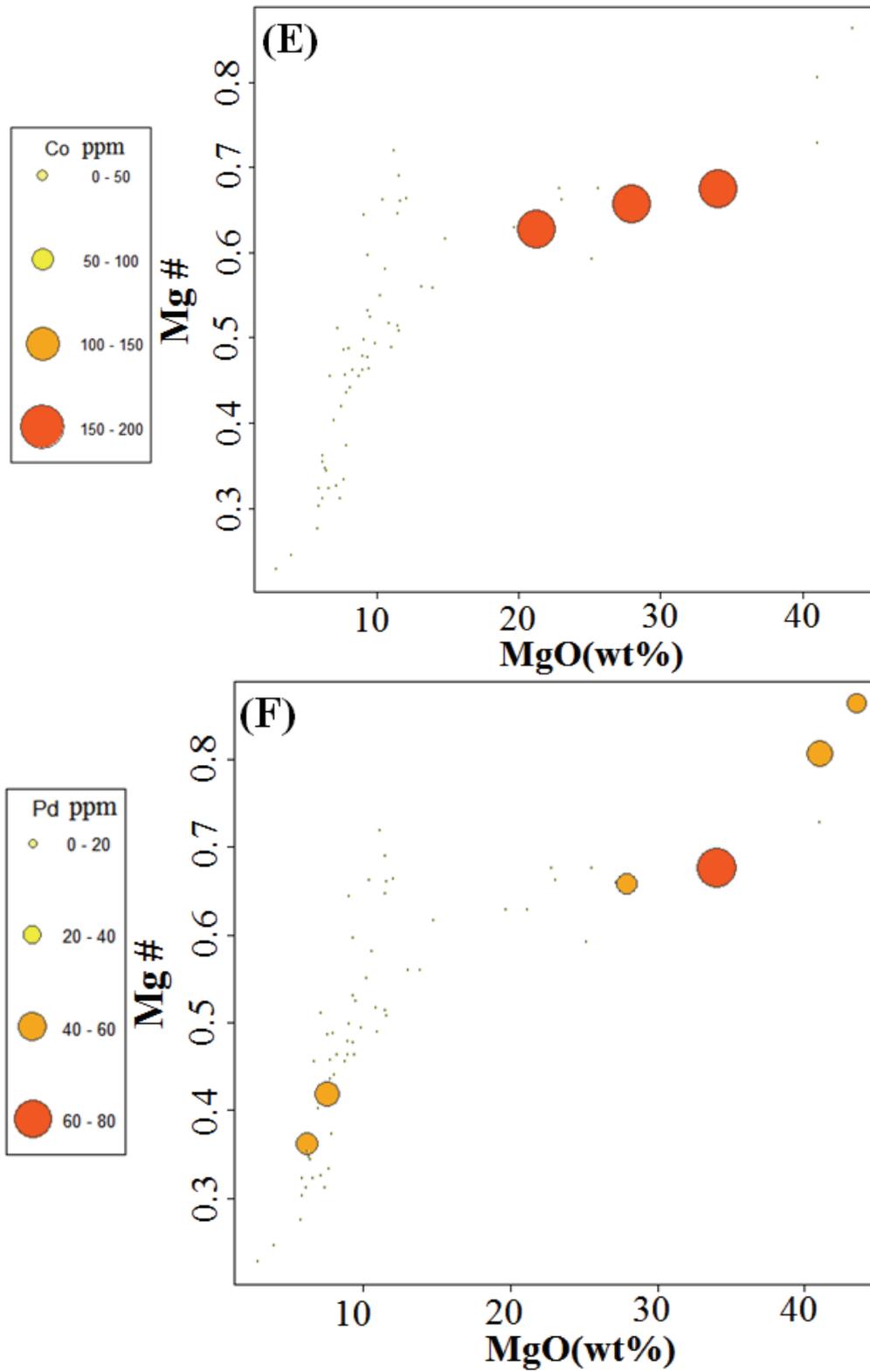
Figure 30: MgO-Fe$_2$O$_3$-Cu-Co-Pd-SO$_3$ variation as a function of fractional crystallization

5. DISCUSSION

5.1.   Formation of rock types comprising Atchiza

Atchiza was formed from mafic silicate melts probably of tholeiitic composition (**Figure 24**). However, it is to be understood that the Atchiza rocks seem to be subjected to high magmatic differentiation, thus their geochemistry and mineralogy do not exactly reflect the actual composition of the original parental melts.

The majority of the rock samples features high enrichments in Ni (max = 4636.22ppm, mean = 564.28ppm), Cr (max = 5131.5ppm, mean = 1169.18ppm), V (max = 952.54ppm, mean = 264.12ppm) and Cu (max =1198.35ppm, mean = 143.26ppm).

The SiO_2 content of the Atchiza rock samples varies between 39.57-52.62 wt%. The MgO and Fe_2O_3 contents vary between 0.77-43.57 wt% and between 4.36- 17.37 wt%, respectively. The Al_2O_3 and CaO concentrations range between 0.38-18.08 wt% and 0.04-16.50 wt%; respectively. Concentration of TiO_2, K_2O and Na_2O varies from 0-3.46 wt%, 0-2.28 wt% and 0-3.26 wt% respectively. Generally, the SiO_2, Al_2O_3, CaO, TiO_2, K_2O and Na_2O contents increase with increasing degree of magmatic differentiation, whereas, the MgO, Fe_2O_3 and MnO contents decrease with increasing degree of magmatic differentiation.

Based on this study, the Atchiza lithologies show a good correlation between geochemistry and petrography, apart from being spatially related. Ultramafic cumulates dominate most of Southern and Eastern parts of the Suite. Coarse-grained gabbro is scatteredly located in the nearly central areas and extends towards the North West. Cumulate gabbros are spatially located between coarse-grained gabbros and ultramafic cumulates. A large proportion of Atchiza (on topographical surface) is occupied by fine- to medium- grained gabbros. Apparently, the degree of magmatic differentiation is increasing towards North and West (**Figure 31**). The genesis of individual Atchiza lithologies is summarised below.

5.1.1. Ultramafic cumulates

The Atchiza ultramafic cumulates are comprised of dunite and pyroxenite. The overall geochemistry and fractionation trends suggest ultramafic cumulates were formed through normal fractional crystallization of primitive mantle-derived magma. The Atchiza ultramafic cumulates are strongly enriched in compatible elements (Ni and Cr), and are characterised by

high Mg# (0.59-0.86); suggesting an Mg-rich primitive parental melt that carried sufficient Cr and Ni to form sulfide mineralization. When compares the relative proportion between clinopyroxene and orthopyroxene, the later is present albeit at much lower concentrations (approx. 5-10% modal composition).

5.1.2. Mafic cumulates

Due to the fact that the majority of mafic cumulates, (medium- grained, cumulate gabbros) are spatially located between coarse-grained gabbros and ultramafic cumulates, they represent mineralogical- and geochemical transitions during magmatic evolution. Mafic cumulates are predominantly characterised by plagioclase and clinopyroxene, mostly in cumulate phase. However, in common, it is also possible to find other developed mineral textures such as granular, sub-ophitic to ophitic. Apparently, it is true that mafic cumulates were formed following subsequent magmatic differentiation of ultramafic cumulates, as their source supports a somewhat moderately evolved magma (Mg# = 0.40-0.72).

5.1.3. Mafic dykes

Mafic dykes form when hot magmas are emplaced against the surrounding cold solid rock, which was earlier formed. The Atchiza mafics dykes are also thought to form in the same manner. They show predominance in plagioclase and clinopyroxene, with trace amount olivine.

The fine-grained groundmass in the Atchiza mafic dykes implies fast cooling of magmatic liquids, later after emplacement.

A one-directional preferred orientation, parallel with the contact of the pre-existing host rocks, for which plagioclase laths are commonly aligned, can probably suggests for a directional growth. It could also be flowage lineation of plagioclase-phenocrysts formed during emplacement of basaltic liquids.

5.1.4. Coarse-grained gabbro

Coarse-grained gabbro in the Atchiza comprises the relatively high-differentiated parts of the Suite (Mg# = 0.23-0.37). Generally, the majority of them are non-cumulates, mainly showing predominance in plagioclases and pyroxenes. They are also enriched in Fe-Ti-oxides.

However, petrological observation shows no evidence of ilmenite or/and magnetite in these samples.

The low Ni/Zr, Cr/Zr, Sr/Zr and Ti/Zr ratios for which coarse-grained gabbro are associated, also suggests their sources from highly evolved gabbroic fluid, probably they were evolved from subsequent fractionation of cumulate gabbro.

Likewise other layered gabbros comprising coarse-grained gabbros (**Larsen and Brooks, 1994**) the Atchiza coarse-gained gabbros were formed by magmatic differentiation of cumulate gabbros. The relatively high Zr concentration in coarse-gained gabbros supports this notion (**Larsen and Brooks, 1994**).

Table 1: Summary of Atchiza geology

Rock types	Dunite & Pyroxenite	Mafic dykes	Cumulate gabbro	Coarse-grained gabbro
Texture	Ultramafic cumulate	Porphyritic- & glomeroporphyritic texture	Cumulate texture, medium grained	Non-cumulate, medium- to coarse-grained
Major minerals	Olivine & Clinopyroxene & Orthopyroxene	Plagioclase, with trace amount of olivine and clinopyroxene	Plagioclase & clinopyroxene	Plagioclase and clinopyroxene (+/- hornblende)
Trace elements	Enriched in Cr & Ni, moderately enriched in Pd		Moderately enriched in Ni, Cr, Ti, V, Cu & Pd	Highly enriched in Fe-Ti-oxides, Sr, Cu, V & Zr
Sulfides/ Mineralogy	Disseminated sulfides, pentlandite exsolution, chromite is both disseminated & intestinal.	Disseminated micro-sulfides	Pentlandite exsolution in pyrrhotite	Disseminated pyrite & chalcopyrite
Probable magma source	Mg# = 0.59-0.86, Mg-rich primitive parental melt		Mg# = 0.40-0.72, moderately evolved magma	Mg# = 0.23-0.37, relatively high-differentiated magma

5.2. Formation of Ni-Cu- sulfide deposits

5.2.1. Origin of Ni-Cu- sulfides in Atchiza

Apparently, the parental magma for Atchiza is considered highly enriched source of Mg-composition (MgO up to 43.57 wt% and Mg# up to 0.86).

Several geological processes may have been responsible for ore-forming processes in Atchiza. Based on geochemical analysis and petrological study, the Ni-Cu-Fe sulfides of Atchiza were formed through the processes of fractional crystallization, sulfide-silicates immiscibility, exsolution product during cooling and secondary alteration processes. The main ore-minerals in Atchiza include pyrrhotite, pentlandite, chalcopyrite, pyrite, chromite, covellite and chalcosite.

Whereas chromite, pyrrhotite, chalcopyrite and pyrite comprise primary mineralizations, covellite and chalcosite are formed as a result of subsolidus alteration. Pentlandite mostly forms as exsolution-products in pyrrhotite.

According to **McLean (1969), Naldrett and von Gruenewaldt (1989)** and **Naldrett *et al.* (1990)**, silicate-sulfide liquid immiscibility as one of the most important factors for formation of Ni-Cu deposits, can be attained by either fractional crystallization of the parental melts, additional to residue magma of externally derived sulfur or contamination with Si-rich materials. Consequently, as we noticed from our geochemical analysis, Atchiza lithologies show great variability of Fe_2O_3, SO_3 and Si during fractional crystallization (**Figure 30A, B & C**). These geochemical variabilities are considered favourable factors that could have played significant role for sulfide mineralizations in Atchiza. For instance, it is clear that the Fe_2O_3 concentration is decreasing during fractional crystallization, with the highest (up to 17.35 wt%) in ultramafic cumulates and the lowest (down to 4.36 wt%) in mafic cumulates. The Si content is increasing with progressive fractional crystallization. It is lowest in dunite (down to 39.75 wt%) and highest in coarse-grained gabbro (up to 51.56 %).The S contents is dramatically increasing with fractional crystallization. It is below detection limit in ultramafic cumulates and highest (up to 0.35Wt %) in cumulate gabbro and coarse-grained gabbro. All of these geochemical changes will lower down the solubility of S in the system hence favourably enhancing silicate-sulfide immiscibility.

Apparently, it is somehow tricky to pinpoint out the actual factors that led to these geochemical changes, though it is true that fractional crystallization and contamination could be the main factors responsible. However, in order to obtain strong oversaturation with S, it requires magma to be contaminated with another S-rich magma or replenishment with new Si-rich melt (**Robb, L. 2008 - Fig 1.20, Figure 1.21** & **Fig. 1.23**).

Based on mineralogy, textures and geochemical composition, mafic-ultramafic rocks in Atchiza Suite are classified into three main groups: Ultramafic cumulates (dunite, pyroxenite), mafic cumulates (medium-grained-cumulate gabbro) and non-cumulate gabbros (coarse-grained gabbro)..

Ultramafic cumulates dominate most of Southern and Eastern parts of the Suite. Coarse-grained gabbros are scatteredly located in the nearly central areas, extending towards the North West. Fine- to medium-grained gabbros are spatially located between coarse-grained gabbros and ultramafic cumulates.

The Suite shows high enrichment of Ni, Cr, Cu, Co and Pd, which may all require further follow up in the future.

Atchiza may have potential to host massive-disseminated Ni-Cu-(PGE) sulfides mineralization

Figure 31: Atchiza mineralization

5.2.2. Change of textures during cooling

Pentlandite mineralizations in Atchiza occur as exsolution product in pyrrhotite in different textural forms, including cross-netting veinlets, flames and as rims surrounding pyrrhotite crystals.

According to **Durazzo, A. & Taylor, L.A. (1982)** pentlandite can occur as a by-product of pyrrhotite through progressive re-equilibration of the previously formed mineral phases in the system due to cooling. His experimental study was done mainly to investigate different morphological forms of pentlandite and pyrrhotite in the Fe-Ni-S system and in monosulfide solid solutions with reference to "Sudbury-type ores", i.e. Fe-Ni-Cu deposits such as Sudbury-Ontario in Canada and Yilgarn Craton in Western Australia.

Accordingly, based on this study, pentlandite-pyrrhotite mineralization in Atchiza shares many similarities with textural features that are described by **Durazzo, A. & Taylor, L.A. (1982)**. These textures are presented in **Figure 32A & B**. For a comparison purpose, **Figure 32(C)** that shows pentlandite exsolution in Atchiza is also included.

The two main types of textures that pentlandite exhibit when exsolved from pyrrhotite are subdivided based on exsolution development stage. These are early- and mature- forms **(Figure 32)**. Early form is related to limited growth (less coarsening), whereas mature form is related to exsolution phases that have undergone significant growth and further coarsening.

Accordingly (**Durazzo, A. & Taylor, L.A., 1982**), the final textures and the extent to which pentlandite will be exsolved from pyrrhotite can be controlled by the following factors-

- Initial degree of super-saturation of magmatic fluids
- Metal diffusivities rate, and
- Temperature change or cooling rate
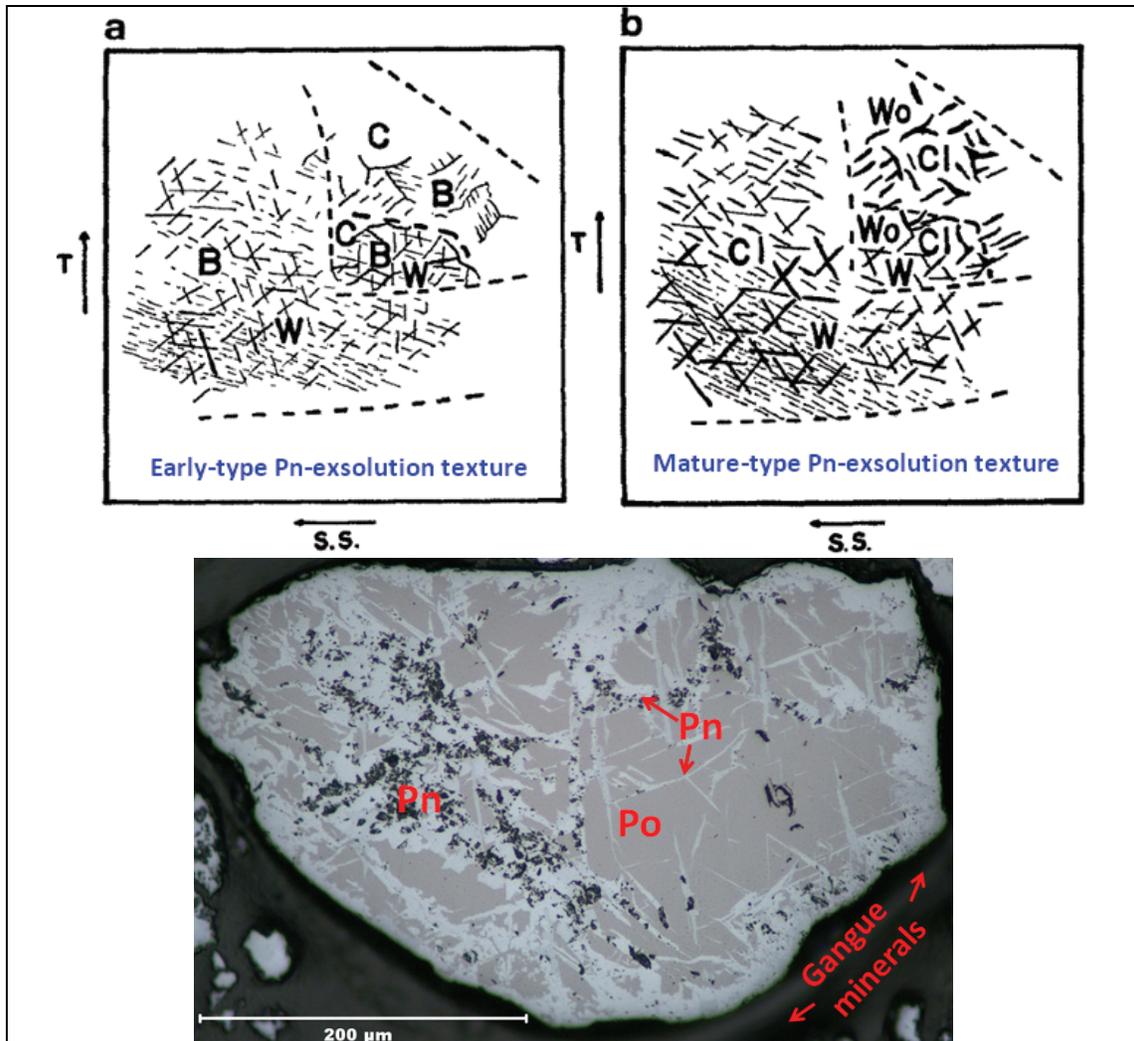
Figure 32 (a) & (b): Texture classification of exsolved pentlandite by Durazzo, A. & Taylor, L.A. (1982).

Figure 32(C) shows Atchiza pentlandite-pyrrhotite mineralization. It is included here for comparison purpose. In this section of sample, pentlandite occurs as veinlets, massive and rims surrounding pyrrhotite crystal (**See text for more description)**.

T = Temperature (x-axis); **S.S** = Degree of supersaturation (y-axis). **Cell (C)** = Pentlandite veinlets along grain boundaries, with maximum diameter approximately 5 mµ. **Bladed (B)** =Elongated and narrow pentlandite bodies along one direction, maximum width are 1 mµ. **Widmanstätten (W)** = Lattice, crystallographic, elongated pentlandite lamellae along three or more directions, with the maximum width of the lamellae of about I0 mµ. **Worms (Wo)** = Curved and irregular pentlandite, in the morphology of worms. **Coarsened linear bodies (Cl)**=Pentlandite forming aggregates of linear lamellae thin, elongated, pervasive wire-shaped pentlandite flames.

According to **Durazzo, A. & Taylor, L.A. (1982)**, the presence pentlandite-pyrrhotite exsolution textures in the majority of Sudbury-type ores signifies that mineralization were initially formed at high temperatures (around temperature >600-900ºC); before the ores being progressively re-equilibrated (due to temperature cooling effect) to reach their present textural configuration.

Early textural form can be developed particularly at low (to intermediate) degrees of super-saturation and at slow cooling rate; during which the relative driving force that permit exsolution is low **(Durazzo, A. & Taylor, L.A.; 1982)**. At temperature level between 610ºC and around 250ºC the diffusive rates of Fe and Ni ions is estimated to be very high, favourably enough to permit continuous re-equilibration that will eventually lead into significant nucleation and growth of massive pentlandite (aggregates & non-linear pentlandite bodies).

On the contrary, mature textures may develop through further growth and coarsening of early-exsolved pentlandite. Mature textures, particularly, is formed after the energy associated with initial super-saturation is lowered following early exsolution. Mature textures favourably forms at temperature around 250-150°C. At these low temperature ranges, the diffusion rate of Fe and Ni is low. The low diffusion rate of Fe and Ni may prevent continuous re-equilibration; hence producing high degrees of supersaturation within system. In this case a linearly-, elongated- and net-textured bodies of pentlandite may develop. At temperatures > 150°C, flames may develop (**Durazzo, A. & Taylor, L.A.; 1982**).

5.3. Geological similarities between Atchiza and selected global Ni-Cu-deposits

Munali Ni-Cu-Co-PGE-deposit

Munali mine, a magmatic Ni-Cu-Co-PGE-deposit (**Witherly K., 2009; Albidon limited, Annual reports 2006, 2007 & 2008)**, which is located approx. 65Km in the southwest of Lusaka Zambia sits in the same tectonic segment with Atchiza, only approx. 290Km distance apart (**Figure 33**).

According to **Witherly K. (2009)**, the Munali deposit was firstly discovered in the late 1960´s from geological mapping and geochemical surveys. It was until the very recent years -March 2008, when Munali mine came into production. Exploration techniques that have been used for prospecting of Munali deposit include geochemical sampling, airborne- and ground-geophysical methods.

Total Mineral Resource for the Munali prospect is calculated at 8.3Mt @ 1.08% Ni, 0.14% Cu, 0.06% Co, 0.49g/t Pd; 0.21g/t Pt; of which Ore Reserve (for the Enterprise Deposit) is 6.2Mt @ 1.14% Ni, 0.16% Cu, 0.06% Co, 1.39g/t Pd, 0.64g/t Pt (**31st Dec 2010 Albidon LTD's mineral statement**).

Based on this study and according to **Witherly K. (2009)** and **Johnson *et al.* 2006**, the Munali gabbro shares several similarities with Atchiza. They are analogous in terms of geochronology. Munali gabbro is dated at ca. 855Ma (**Johnson *et al.* 2006)**, the age that almost coincides with that of Atchiza gabbro (864+/-30 Ma- **GTK Consortium 2006d; Manttari, I. 2008**). Yet, when they are compared, the Munali gabbro has its petrogenesis from juvenile source with εNd(T) value of +2.5 (**Johnson *et al.* 20006)**, whereas the Atchiza gabbro seems to be contaminated, reporting a εNd(T) value of -3.0 (**GTK Consortium 2006d, Manttari, I. 2008)**.

Both Atchiza and Munali deposit are characterized by the same types of ore minerals. According to **Witherly K. (2009)**, the main ore minerals in Munali deposit are pyrrhotite, pentlandite, pyrite and chalcopyrite. The same types of ore minerals are commonly characterise Atchiza, based on this study. In both areas, pentlandite occurs as disseminated

blebs (suspended sulfide droplets in gangue minerals), veinlets or rims, commonly occurring as exsolved phases in pyrrhotite. In both places, pentlandite is the main Ni-bearing mineral.

Munali mineralised gabbro (extending over 2.5Km long strike) sits along major NW-SE trending regional faults. Mineralization is confined within boudinage-shaped sills, steeply dipping, and is related to mafics and ultramafics, though mainly hosted within the altered micro-gabbro (**Figure 34**). Sulfide mineralization in Atchiza is also associated with a mafics- and ultramafics- rocks. However, the main different between them is the Munali gabbroic sills are studied to intrude meta-sediments such as limestones, marble and quartzite (**Witherly K. 2009**; **Albidon limited, Annual reports 2006, 2007 & 2008**), whereas Atchiza is intruding granitic body.

The size of Munali ore zone is averaging at 4-6m minimum width (at sub-surface) broadening up to 15-20m maximum width (at depths below 250m) -**Witherly K. (2009)**.

Figure 33: Relative locations of Munali Ni-Cu-mine and Atchiza
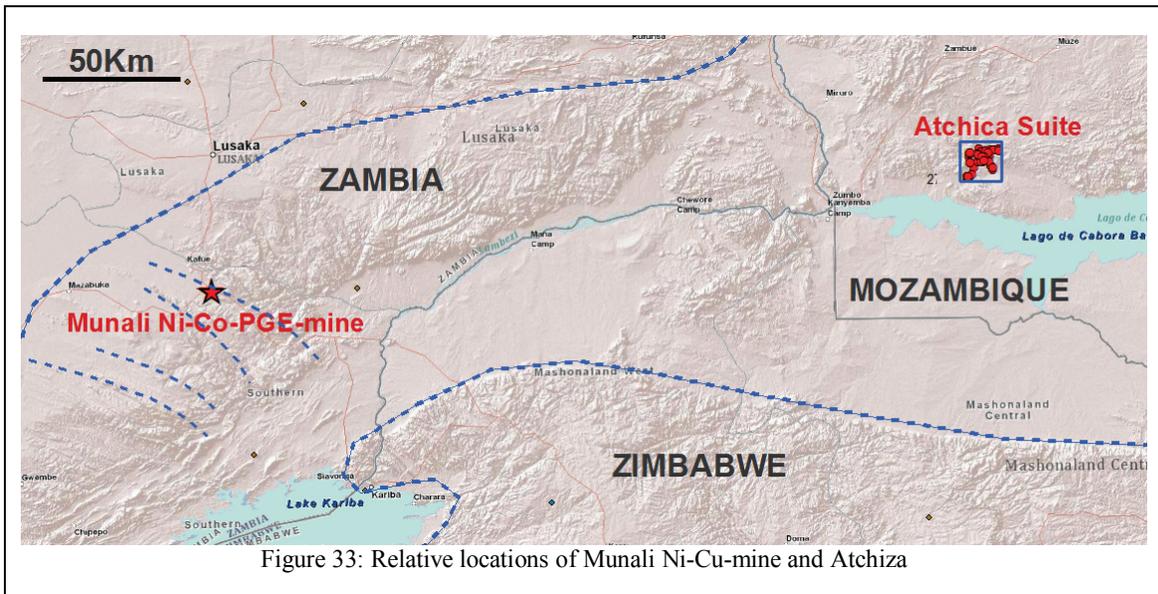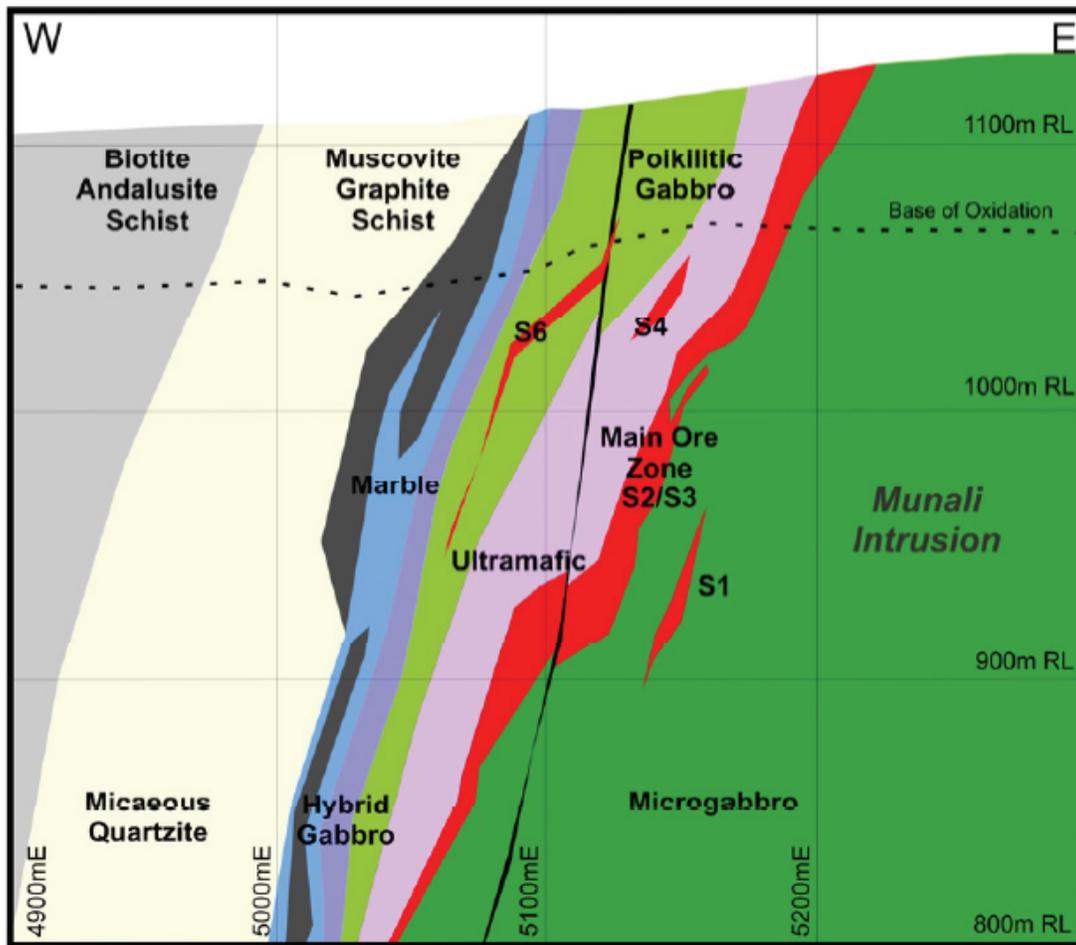
Figure 34: Geological section, of Munali showing mineralization style (Witherly K. 2009)

At present, based on this study and with no stratigraphic data available, Atchiza can also be broadly comparable with Munni Munni Complex of Australia and Stillwater Complex of America. The geological features and mineralization styles with these deposits is summarised in **Table 2**.

Table 2: Geological similarities between Atchiza with selected Ni-Cu-PGE deposits in the world

Deposit/prospect	Age	Mineralization style	Reference
Atchiza Suite (Mozambique)	Neo-Proterozoic (864+/-30Ma)	Layered mafic-ultramafic intrusion, structural controlled (transtensional), disseminated sulfides; primary ore minerals include pyrrhotite, pentlandite, chalcopyrite, pyrite and chromite. Pentlandite exsolution is commonly developed in pyrrhotite, MgO up to 43.57 wt% and Mg# up to 0.86.	**Real, (1962); Hunting, (1984); this study.**
Munali Ni-Cu-PGE (Zambia) (**Figure 33** & **Figure 34**).	Neo-Proterozoic (855Ma)	Mineralization is structural-controlled, sulfides mineralization is mainly hosted within the altered micro-gabbro, related to mafics and ultramafics. Main ore minerals include pyrrhotite, pentlandite and chalcopyrite. Pentlandite is occurring as exsolved by-product in pyrrhotite.	**Witherly K., (2009); Albidon limited Annual reports (2006, 2007 & 2008).**
Stillwater Ni-Cu-PGE (USA) (**Figure 35**)	Archean (2.705+/-4Ga)	Layered mafic-ultramafic body (differentiated & stratiform), characterized by the Basal layer (norite & bronzitite), ultramafic series (peridotite, dunite, harzburgite and bronzite pyroxenite) and the Upper banded series (norites and gabbros and anorthosite).Common mineralization in J-M reef are pyrrhotite, chalcopyrite, cubanite and pentlandite and PGE. Sulfides occur as interstitial phase in silicate. Cr mineralization is restricted in the ultramafic zone.	**Mc Callum et al., (1980); Zientek *et al*., (2002); Naldrett, (2004) and references in; Godel & Barnes (2008).**
Munni Munni Complex- Ni-Cu-PGE (Western Australia) (**Figure 36**)	Archean (2.925+/-4Ga)	Intruded in Archean granitoids, boat-shaped, lower layered ultramafic series (wehrlite and clinopyroxenite) overlain by gabbroic- rocks and minor anorthosite. Mineralization is mostly reef-type Ni-Cu-PGE sulfides, mainly distributed within the top of the ultramafic series, namely Porphyritic Websterite Zone (PWZ) markedly by a 20–80m thick zone (**Figure 36**).	**Barnes *et al*. (1990); Stephan *et al*. (1992); Barnes & Hoatson, (1994); Hoatson, (1998); Naldrett, (2004).**
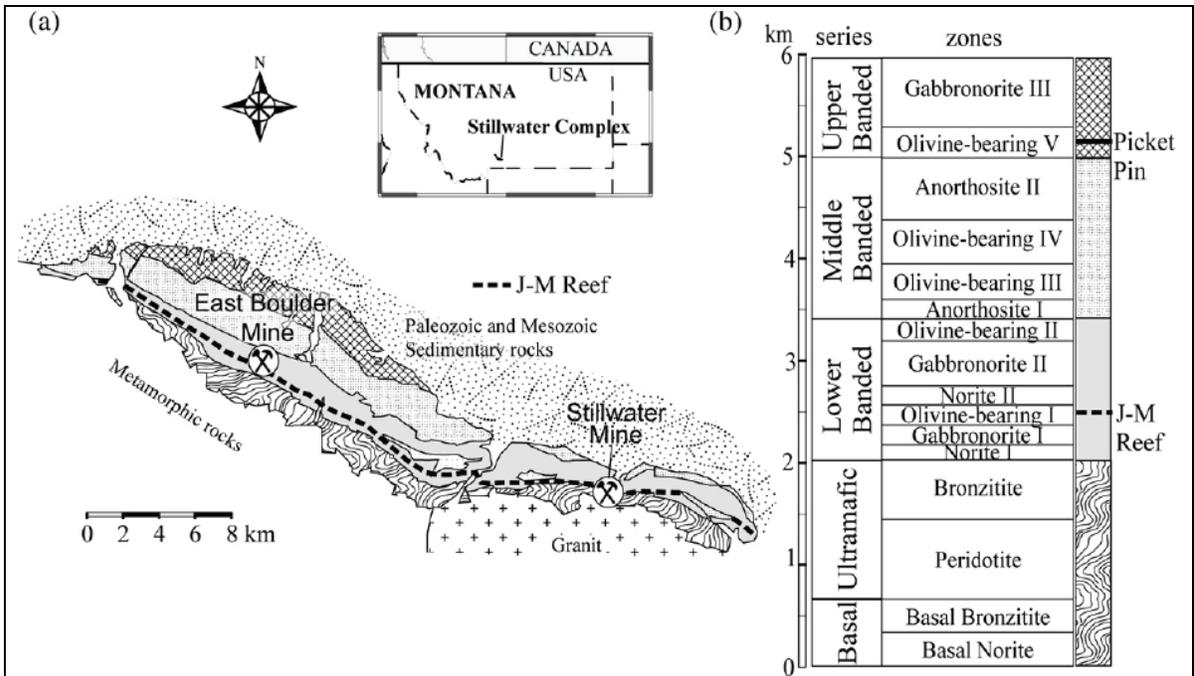
Figure 35: Stillwater Complex- (a) Simplified geological map (modified after Mc Callum et al., 1980; Zientek et al., 2002) - (b) Stratigraphy (modified after Zientek et al., 2002; Godel & Barnes, 2008).

The different layers in Stillwater Complex are good indicative of multiple geological processes that operated upwards in magma chamber. Looking at this figure (Figure 35), it is obvious that there were multiple re-injection of magmas of different geochemical compositions in the system, alongside magma mixing and fractional crystallization (Mc Callum *et al.*, (1980); Zientek *et al.*, 2002); Naldrett, (2004) and references in; Godel & Barnes (2008).
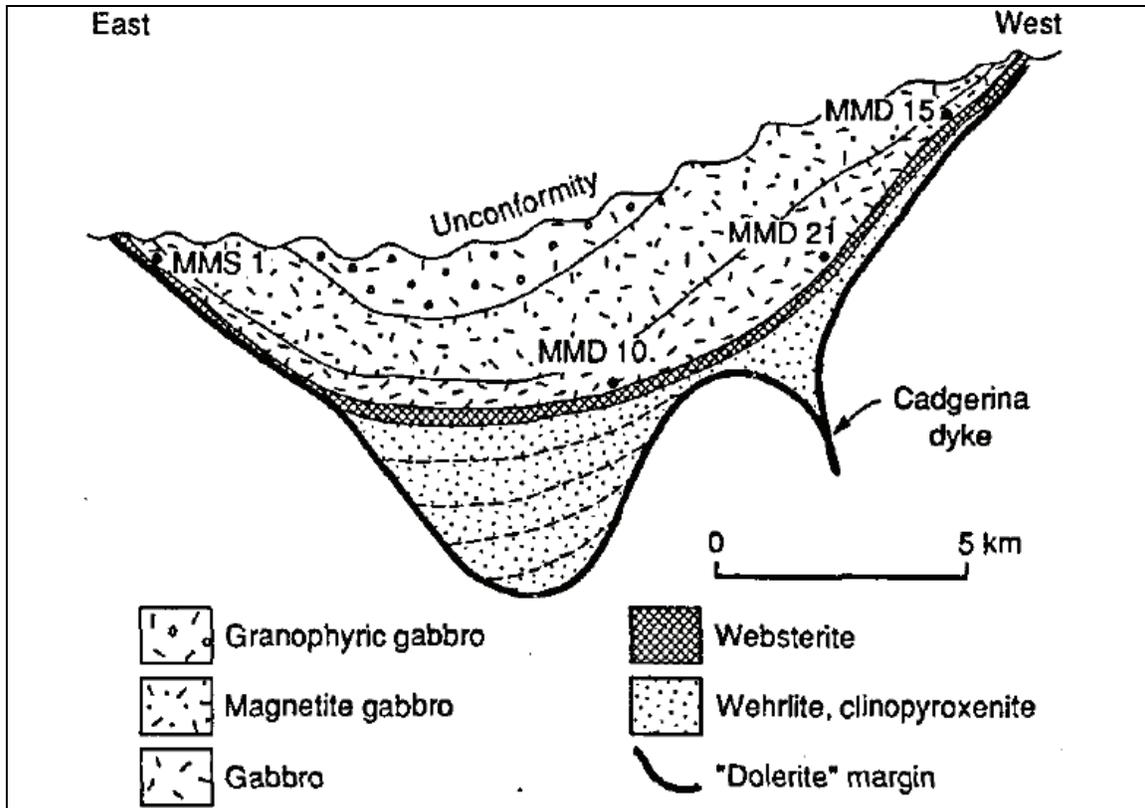
Figure 36 Schematic cross-section through the Munni Munni Complex (after Barnes *et al.* 1990, Stephan *et al.* 1992).

Lithological layers comprising Munni Complex is shown in Figure 36. The cyclically layered ultramafic lithologies (wehrlite and pyroxenite) dominate the bottom stratigraphic unit, overlain by Porphyritic Websterite Zone (PWZ), 20-80m thick.

Going to the higher stratigraphic sections, the intrusion is dominated by volumetrically large gabbroic rocks of different mineralogy and textures, including the magnetite gabbro and granophyric gabbro. The Ni-Cu-PGE mineralization is compositionally variable both vertically and horizontally, though Ni-Cu-PGE is mainly concentrated within Porphyritic Websterite Zone (PWZ).

The Cadgerina Dyke is interpreted as a feeder during the formation of the PWZ. The upper part of ultramafic series (UMS) and PWZ are more of compositionally variable, thus they are interpreted as the result of several magma replenishment vents, magma mixing, batch equilibration of sulfide liquid droplets, subsequently followed by fractional segregation and gravity settling of sulfide liquid droplets to form the Ni-Cu-PGE mineralization. The gabbroic series are thought to have been formed through replenishment of more fractionated magma, which then mixed up with the resident melts in magma chamber (Barnes *et al.* 1990, Barnes *et al.* 1992, Stephan *et al.* 1992)

6. CONCLUSION

The most important findings to be emphasized concerning the geology and genesis of the Atchiza could be boiled down to the following points: -

- The Atchiza Suite is a layered mafic-ultramafic Suite mainly comprising a group of three differentiated rocks; namely ultramafic cumulates (dunite, pyroxenite), cumulate mafics (medium-grained cumulate gabbro) and coarse-grained gabbros (non-cumulate). Apparently, the actual compositional of parental magma for the Atchiza geology is not exactly known. However, a very high Mg# in ultramafic cumulates (0.59-0.86) suggests Atchiza was originated from high Mg-rich primitive parental magma.

- Compared to the rest of other rocks, coarse-grained gabbro shows high enrichment of Ti (0.64-3.46 wt% TiO_2), Zr (5.9-296.15ppm), Sr (253.7-1268.4ppm) and V (224-952.3ppm), but relatively low depleted in compatible elements (Ni = 48.7-235.7ppm, Cr = below detection limit to 410.5ppm). Cumulate ultramafics are highly enriched in compatible elements (Ni up to 4636.2ppm, Cr up to 4721ppm). Consequently, the Ni/Zr, Cr/Zr, Sr/Zr, and Ti/Zr ratios are generally the lowest in coarse-grained gabbro when compared to the cumulate rocks. This probably suggests that coarse-grained gabbros were possibly formed from further fractionation of cumulate gabbros, for which their residual magma was, to some extent, highly differentiated.

- The presence of an uninterrupted cryptic differentiation trends implies that the Atchiza igneous lithologies were derived from one and the same parental melt. Isotopic data are required to consolidate this notion.

- Theoretically, Atchiza is considered prospective for mineral exploration of Ni-Cu-PGE sulfide deposits. Fractional crystallization, sulfides-silicate immiscibility and mineral re-equilibration (exsolution process as high temperature minerals such as pyrrhotite become unstable as temperature decreases), are some of the processes that are considered important for Ni-Cu-PGE mineralization in Atchiza. Geochemical analysis shows great variability of Fe_2O_3, SiO_2 and SO_3 during magmatic differentiation. The Fe_2O_3 content is decreasing significantly, as magma becomes more progressively fractionated, whereas the SiO_2 content is increasing. The SO_3 concentration also increases abruptly. It is true that all these geochemical changes will lower down the solubility of S in the system, thus providing a favourable condition for silicate-sulfide immiscibility.

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8. APPENDICES

Table 3: Geochemical analyses (XRF) of the Atchiza ultramafic cumulates

	Dunite		Pyroxenite				
	ATZ-P9-34	ATZ-P9-35	ATZ-40T	ATZ-16T	ATZ-P10-41	ATZ-P10-44B	ATZ-P10-44
(Wt.%)							
SiO_2	41.20	39.57	44.33	44.85	41.24	42.38	42.91
Al_2O_3	0.38	0.55	9.59	4.44	7.04	8.27	8.64
Fe_2O_3	15.30	16.37	12.26	11.75	17.37	14.54	14.07
MgO	41.08	34.02	25.59	23.07	25.19	27.96	27.23
CaO	0.66	7.88	6.76	14.17	6.45	5.29	5.61
Na_2O	0.01	0.01	0.16	0.29	0.61	0.06	0.07
K_2O	0.01	0.01	0.03	0.05	0.37	0.06	0.06
TiO_2	0.04	0.04	0.31	0.24	0.58	0.43	0.43
MnO	0.20	0.19	0.23	0.21	0.24	0.21	0.21
P_2O_5	0.01	0.01	0.01	0.02	0.07	0.05	0.05
Cl	0.03	b.d	0.09	0.03	0.08	0.06	0.07
SO_3	0.08	0.01	0.01	0.04	0.21	0.08	0.07
Sum	**98.97**	**98.63**	**99.37**	**99.16**	**99.45**	**99.39**	**99.42**
(ppm)							
Cr	3968.4	4721.0	2394.7	4652.6	2052.6	2531.5	2463.1
Ni	3064.6	4636.2	1650.2	864.4	1493.0	1493.0	1493.0
V	b.d	56.0	b.d	224.1	b.d	b.d	b.d
Cu	43.9	34.4	75.1	63.9	239.7	43.1	51.1
Zn	80.4	160.7	160.7	71.5	160.7	80.4	80.4
Sr	17.8	253.7	23.7	50.7	84.6	19.4	22.0
Zr	0.01	0.01	21.5	0.7	44.4	33.3	34.8
Ga	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Rb	b.d	b.d	b.d	b.d	11.9	b.d	b.d
Y	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Nb	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Ba	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Pb	b.d	b.d	52.9	b.d	b.d	b.d	b.d
Co	b.d	157.3	b.d	b.d	b.d	157.3	b.d
Ce	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Gd	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Ho	b.d	b.d	174.6	b.d	b.d	b.d	b.d
Sc	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Br	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Pd	b.d	80.0	b.d	b.d	b.d	43.0	b.d
Ag	b.d	b.d	42.0	b.d	b.d	b.d	43.0
Mo	b.d	b.d	b.d	b.d	b.d	b.d	b.d
As	b.d	b.d	b.d	b.d	b.d	b.d	b.d

Major- and trace- elements analyses by X-Ray Fluorescence. Oxides are normalized to 100%. b.d stands for below detection limit.

Table 4: Geochemical analyses (XRF) of olivine-pyroxenite and mafic cumulates

	Olivine-pyroxenite			Mafic cumulates			
	ATZ-P3-19	ATZ-P2-17	ATZ-PB-6B	ATZ-20T	ATZ-21T	ATZ-39T	ATZ-P8-32B
(Wt %)							
SiO_2	47.07	47.9	47.52	51.62	52.62	50.53	47.86
Al_2O_3	0.7	0.57	2.67	17.58	15.83	17.15	17.98
Fe_2O_3	9.89	6.89	10.99	7.99	9.29	6.88	12.23
MgO	41.09	43.57	22.88	6.67	7.80	7.20	6.41
CaO	0.05	0.04	14.39	12.85	11.22	13.19	11.56
Na_2O	0.01	0.01	0.17	1.85	1.75	3.26	2.27
K_2O	0.01	0.01	0.02	0.50	0.52	0.26	0.21
TiO_2	0.02	0.01	0.23	0.43	0.43	0.36	0.64
MnO	0.09	0.08	0.19	0.14	0.16	0.14	0.18
P_2O_5	0.01	0.01	0.01	0.06	0.08	0.05	0.04
Cl	0.03	0.09	0.02	0.02	0.02	0.74	0.16
SO_3	0.03	0.01	0.02	0.06	0.04	0.03	0.22
Sum	**98.97**	**99.15**	**99.1**	**99.77**	**99.76**	**99.79**	**99.76**
(ppm)							
Cr	2873.6	3078.9	5131.5	684.2	821.0	273.7	342.1
Ni	4636.2	2907.5	943	235.7	235.7	157.2	235.7
V	b.d	33.6	112	224.1	168.1	b.d	224.1
Cu	40.7	26.4	55.9	79.9	79.9	60.7	159.8
Zn	59.5	80.4	68.3	65.9	74.7	80.4	80.4
Sr	b.d	b.d	25.4	253.7	169.1	422.8	338.2
Zr	b.d	b.d	b.d	29.6	34.1	148.1	74.0
Ga	b.d	b.d	b.d	20.1	20.8	b.d	b.d
Rb	b.d	b.d	b.d	9.1	12.8	b.d	b.d
Y	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Nb	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Ba	b.d	b.d	b.d	b.d	b.d	89.6	179.1
Pb	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Co	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Ce	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Gd	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Ho	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Sc	b.d	b.d	b.d	b.d	b.d	56.1	b.d
Br	b.d	b.d	b.d	b.d	b.d	200	16
Pd	53.0	41.0	b.d	b.d	b.d	b.d	b.d
Ag	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Mo	b.d	b.d	b.d	b.d	b.d	b.d	b.d
As	b.d	14.4	b.d	b.d	b.d	b.d	b.d

Major- and trace- elements analyses by X-Ray Fluorescence. Oxides are normalized to 100%. b.d stands for below detection limit

	ATZ-P7-27	ATZ-08T	ATZ-29T	ATZ-P1-11	ATZ-P2-16	ATZ-PC2-8	ATZ-48T	ATZ-P6-24	ATZ-P9-37B	ATZ-P9-37
(Wt %)										
SiO_2	49.54	49.97	51.38	51.90	49.15	50.90	51.48	51.68	49.53	49.77
Al_2O_3	12.09	7.74	13.50	14.27	15.39	14.55	14.34	13.56	18.08	16.60
Fe_2O_3	11.23	10.34	10.91	9.12	9.83	8.61	10.27	8.41	5.04	5.34
MgO	11.59	13.12	9.41	9.06	9.01	9.51	9.38	10.27	9.12	10.45
CaO	12.60	16.46	12.12	12.95	13.18	13.80	11.92	13.52	16.50	16.05
Na_2O	1.23	0.68	1.53	1.57	1.71	1.46	1.62	1.22	0.92	0.93
K_2O	0.26	0.15	0.21	0.25	0.25	0.18	0.15	0.23	0.12	0.11
TiO_2	0.32	0.51	0.30	0.38	0.31	0.30	0.33	0.25	0.11	0.13
MnO	0.23	0.22	0.21	0.16	0.24	0.16	0.18	0.16	0.12	0.12
P_2O_5	0.01	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01
Cl	0.58	0.25	0.11	0.08	0.54	0.20	0.02	0.37	0.13	0.13
SO_3	0.03	0.05	0.06	0.03	0.13	0.10	0.02	0.11	0.01	b.d
Sum	**99.70**	**99.49**	**99.76**	**99.79**	**99.75**	**99.77**	**99.72**	**99.79**	**99.68**	**99.63**
(ppm)										
Cr	1026.3	2394.7	684.2	342.1	615.8	615.8	889.5	615.8	1573.7	1778.9
Ni	314.3	392.9	235.7	235.7	314.3	314.3	235.7	314.3	314.3	392.9
V	224.1	336.1	168.1	280.1	224.1	168.1	280.1	168.1	112.0	112.0
Cu	79.9	79.9	79.9	239.7	159.8	239.7	79.9	239.7	25.6	24.0
Zn	80.4	80.4	80.4	75.5	160.7	53.0	80.4	72.3	58.7	80.4
Sr	169.1	84.6	169.1	253.7	253.7	253.7	169.1	169.1	169.1	169.1
Zr	6.7	14.8	5.9	11.8	5.2	3.7	5.2	5.2	b.d	b.d
Ga	14.9	b.d	b.d	b.d	17.9	20.8	13.4	15.6	b.d	18.6
Rb	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Y	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Nb	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Ba	179.1	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Pb	b.d	b.d	b.d	b.d	b.d	51.1	b.d	b.d	b.d	b.d
Co	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Ce	81.4	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Gd	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Ho	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Sc	b.d	65.2	b.d	b.d	52.2	b.d	b.d	b.d	b.d	b.d
Br	b.d	b.d	b.d	b.d	b.d	b.d	b.d	19.0	b.d	b.d
Pd	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Ag	b.d	b.d	b.d	b.d	b.d	b.d	36.0	b.d	b.d	b.d
Mo	b.d	b.d	11.3	b.d	13.3	b.d	b.d	b.d	b.d	b.d
As	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d

Table 5: Geochemical analyses (XRF) mafic cumulates

Table 6: Geochemical analyses (XRF) of mafic-cumulates - (continue)

	ATZ-33T	ATZ-P7-30	ATZ-P4-21	ATZ-47T	ATZ-06T	ATZ-P7-31	ATZ-P1-09	ATZ-Pc-3	ATZ-P1-01	ATZ-41T	ATZ-P6-25	ATZ-49TB	ATZ-44T	ATZ-P6-23	ATZ-05T	ATZ-P7-28	ATZ-52T
							Fine- to medium- grained gabbro										
(Wt %)																	
SiO_2	51.97	51.17	51.25	51.08	48.11	51.02	52.38	50.78	49.71	51.01	50.16	50.71	51.26	50.31	51.51	49.52	51.6
Al_2O_3	12.81	17.20	6.44	12.15	9.5	13.34	15.9	15.07	16.35	14.19	12.4	16.85	14.04	16.35	13.86	13.12	14.49
Fe_2O_3	9.61	5.20	9.26	10.87	11.63	6.13	6.32	6.29	10.27	10.46	10.19	8.44	7.65	4.36	10.16	11.53	10.33
MgO	8.27	11.55	14.83	11.51	19.71	12.06	9.36	11.5	8.1	9.01	10.89	8.01	10.62	11.18	7.84	11.03	6.96
CaO	11.51	12.00	16.35	11.98	9.47	15.8	13.5	14.39	12.66	12.57	13.87	13.39	14.23	16.24	12.61	12.15	12.32
Na_2O	3.24	2.02	0.52	1.4	0.42	0.81	1.44	1.11	1.57	1.68	1.28	1.74	1.17	0.83	1.78	1.34	2.33
K_2O	0.36	0.12	0.19	0.15	0.07	0.12	0.25	0.09	0.2	0.22	0.13	0.14	0.21	0.11	0.89	0.15	0.22
TiO_2	0.48	0.19	0.41	0.33	0.38	0.16	0.22	0.16	0.54	0.27	0.36	0.29	0.2	0.13	0.63	0.33	0.69
MnO	0.16	0.10	0.18	0.2	0.15	0.13	0.13	0.13	0.17	0.2	0.19	0.16	0.16	0.11	0.17	0.22	0.11
P_2O_5	0.09	0.01	0.03	0.01	0.04	0.01	0.02	0.01	0.06	0.01	0.01	0.01	0.01	0.01	0.08	0.01	0.04
Cl	1.12	0.21	0.03	0.06	0.03	0.1	0.18	0.21	0.01	0.12	0.16	0.03	0.23	0.1	0.15	0.31	0.26
SO_3	0.17	0.02	0.02	0.04	0.01	0.01	0.1	0.04	0.12	0.03	0.06	0.09	0.04	0.01	0.12	0.03	0.33
Sum	**99.79**	**99.79**	**99.51**	**99.77**	**99.52**	**99.68**	**99.8**	**99.77**	**99.76**	**99.76**	**99.69**	**99.85**	**99.81**	**99.73**	**99.8**	**99.73**	**99.68**
(ppm)																	
Cr	410.5	410.5	2531.5	889.5	2189.4	1573.7	615.8	821	684.2	684.2	1300	410.5	752.6	1300	342.1	957.9	205.3
Ni	235.7	314.3	471.5	314.3	864.4	314.3	314.3	314.3	235.7	235.7	314.3	235.7	235.7	235.7	235.7	314.3	157.2
V	168.1	112.0	168.1	224.1	168.1	168.1	112	168.1	224.1	280.1	224.1	b.d	b.d	112	280.1	224.1	280.1
Cu	79.9	79.9	72.7	66.3	53.5	28.8	239.7	79.9	79.9	79.9	79.9	159.8	159.8	29.6	159.8	52.7	1198.4
Zn	80.4	45.8	56.2	80.4	80.4	52.2	65.9	60.3	75.5	80.4	80.4	61.9	61.9	42.6	80.4	80.4	34.6
Sr	338.2	338.2	78.6	169.1	84.6	169.1	253.7	169.1	84.6	169.1	169.1	169.1	253.7	169.1	253.7	169.1	338.2
Zr	148.1	148.1	19.2	8.9	21.5	b.d	4.4	b.d	17	2.2	5.2	5.2	3	b.d	55.5	4.4	148.1
Ga	b.d	16.4	b.d	b.d	b.d	b.d	b.d	11.9	17.1	12.6	b.d	14.1	16.4	11.9	21.6	b.d	23.8
Rb	9.1	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	33.8	b.d	b.d
Y	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Nb	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Ba	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Pb	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Co	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Ce	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Gd	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Ho	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Sc	b.d	43.7	87.3	b.d	b.d	b.d	b.d	b.d	46.3	43.7	b.d	b.d	b.d	b.d	19	b.d	58
Br	100.0	12.0	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	34
Pd	b.d	b.d	b.d	b.d	b.d	b.d	b.d	35	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Ag	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Mo	b.d	b.d	b.d	b.d	b.d	b.d	b.d	10.7	b.d	10	b.d	b.d	14	12.7	b.d	b.d	b.d
As	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d

Table 7: Geochemical analyses (XRF) of coarse-grained gabbro

Fine- to medium- grained gabbro

	ATZ-33T	ATZ-P7-30	ATZ-P4-21	ATZ-47T	ATZ-06T	ATZ-P7-31	ATZ-P1-09	ATZ-Pc-3	ATZ-P1-01	ATZ-41T	ATZ-P6-25	ATZ-49TB	ATZ-44T	ATZ-P6-23	ATZ-05T	ATZ-P7-28	ATZ-52T
(Wt %)																	
SiO_2	51.97	51.17	51.25	51.08	48.11	51.02	52.38	50.78	49.71	51.01	50.16	50.71	51.26	50.31	51.51	49.52	51.6
Al_2O_3	12.81	17.20	6.44	12.15	9.5	13.34	15.9	15.07	16.35	14.19	12.4	16.85	14.04	16.35	13.86	13.12	14.49
Fe_2O_3	9.61	5.20	9.26	10.87	11.63	6.13	6.32	6.29	10.27	10.46	10.19	8.44	7.65	4.36	10.16	11.53	10.33
MgO	8.27	11.55	14.83	11.51	19.71	12.06	9.36	11.5	8.1	9.01	10.89	8.01	10.62	11.18	7.84	11.03	6.96
CaO	11.51	12.00	16.35	11.98	9.47	15.8	13.5	14.39	12.66	12.57	13.87	13.39	14.23	16.24	12.61	12.15	12.32
Na_2O	3.24	2.02	0.52	1.4	0.42	0.81	1.44	1.11	1.57	1.68	1.28	1.74	1.17	0.83	1.78	1.34	2.33
K_2O	0.36	0.12	0.19	0.15	0.07	0.12	0.25	0.09	0.2	0.22	0.13	0.14	0.21	0.11	0.89	0.15	0.22
TiO_2	0.48	0.19	0.41	0.33	0.38	0.16	0.22	0.16	0.54	0.27	0.36	0.29	0.2	0.13	0.63	0.33	0.69
MnO	0.16	0.10	0.18	0.2	0.15	0.13	0.13	0.13	0.17	0.2	0.19	0.16	0.16	0.11	0.17	0.22	0.11
P_2O_5	0.09	0.01	0.03	0.01	0.04	0.01	0.02	0.01	0.06	0.01	0.01	0.01	0.01	0.01	0.08	0.01	0.04
Cl	1.12	0.21	0.03	0.06	0.03	0.1	0.18	0.21	0.01	0.12	0.16	0.03	0.23	0.1	0.15	0.31	0.26
SO_3	0.17	0.02	0.02	0.04	0.01	0.01	0.1	0.04	0.12	0.03	0.06	0.09	0.04	0.01	0.12	0.03	0.33
Sum	**99.79**	**99.79**	**99.51**	**99.77**	**99.52**	**99.68**	**99.8**	**99.77**	**99.76**	**99.76**	**99.69**	**99.85**	**99.81**	**99.73**	**99.8**	**99.73**	**99.68**
(ppm)																	
Cr	410.5	410.5	2531.5	889.5	2189.4	1573.7	615.8	821	684.2	684.2	1300	410.5	752.6	1300	342.1	957.9	205.3
Ni	235.7	314.3	471.5	314.3	864.4	314.3	314.3	314.3	235.7	235.7	314.3	235.7	235.7	235.7	235.7	314.3	157.2
V	168.1	112.0	168.1	224.1	168.1	168.1	112	168.1	224.1	280.1	224.1	b.d	b.d	112	280.1	224.1	280.1
Cu	79.9	79.9	72.7	66.3	53.5	28.8	239.7	79.9	79.9	79.9	79.9	159.8	159.8	29.6	159.8	52.7	1198.4
Zn	80.4	45.8	56.2	80.4	80.4	52.2	65.9	60.3	75.5	80.4	80.4	61.9	61.9	42.6	80.4	80.4	34.6
Sr	338.2	338.2	78.6	169.1	84.6	169.1	253.7	169.1	84.6	169.1	169.1	169.1	253.7	169.1	253.7	169.1	338.2
Zr	148.1	148.1	19.2	8.9	21.5	b.d	4.4	b.d	17	2.2	5.2	5.2	3	b.d	55.5	4.4	148.1
Ga	b.d	16.4	b.d	b.d	b.d	b.d	b.d	11.9	17.1	12.6	b.d	14.1	16.4	11.9	21.6	b.d	23.8
Rb	9.1	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	33.8	b.d	b.d
Y	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Nb	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Ba	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Pb	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Co	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Ce	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Gd	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Ho	b.d	b.d	87.3	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Sc	b.d	43.7	b.d	b.d	b.d	b.d	b.d	b.d	46.3	43.7	b.d	b.d	b.d	b.d	b.d	b.d	58
Br	100.0	12.0	b.d	b.d	b.d	b.d	b.d	35	b.d	b.d	b.d	b.d	b.d	b.d	19	b.d	34
Pd	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Ag	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Mo	b.d	b.d	b.d	b.d	b.d	b.d	b.d	10.7	b.d	10	b.d	b.d	14	12.7	b.d	b.d	b.d
As	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d	b.d

PART 2

SUSTAINABLE MANAGEMENT OF MINERAL RESOURCES – MOZAMBIQUE

Abstract

Unlike water and forests, minerals are finite resources; they cannot be replaced back to their natural forms once they are depleted. For that reason, sustainable management of mineral resources is very important so that stakeholders in the extractive sector are guaranteed the same opportunities in sharing benefits. As part of this study, and with respect to Atchiza Suite, this section is discussing sustainable management of mineral deposits in Mozambique.

Investment in Mozambican extractive industry should primarily be done with the main objective of poverty reduction for Mozambican citizens. Thus, the Mozambican Government needs to realize that proper management of mineral deposits will provide sufficient income for the country, enough to fund other development projects. Rather than being mismanaged, this massive collection of mineral revenues needs to be appropriately re-invested back to diversify other economic sectors. If this mineral revenue is managed wisely, the national annual budgets will be sufficiently supported. Most importantly, the country's reliance on international loans and aids will be reduced significantly.

Decision-making for development of the country's mineral projects should not be central-governed; rather it should be transparent to the public and open for opinions and suggestions. As the main stakeholder in Mozambican extractive sector, local communities and civil societal groups should also be given opportunities to participate in decision-making, important for the development of mining projects.

Mineral agreements for which the Mozambican State has been signing with multinational companies for development of the country's mineral projects need to be published and be available publicly. In addition, negotiation of mining agreements must be transparent and involve all stakeholders. Investment and development of the country's mineral projects must be performed through partnerships and Joint ventures between multinational mining companies, national-based companies and the Mozambican State.

Development of mineral deposits must incorporate environmental sustainability. Despite its high mineral potential (e.g. Ni-Cu-PGE-Ti-V), Atchiza also is surrounded by a wide range of other natural resources. The Cahora Bassa Dam, which is located just adjacent to Atchiza Project, is the main source of clean energy not only for Mozambique domestic market, but also for the majority of Sub-Saharan countries. All of these natural resources require good practice of Environmental sustainability in mining activities.

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1. INTRODUCTION

1.1.   Literature review

Minerals are not renewable resources; unlike water and forests, they are finite. Once they are extracted to depletion, they cannot be replaced in their natural form. For that reason, optimal and sustainable management of mineral resources is a matter of concern, such that all stakeholders in the mineral sector are guaranteed equal opportunities in sharing the benefits.

As part of this study and with respect to the mineral potential of Atchiza, this section will give an overview of the key factors for sustainable management of mineral resources in Mozambique, with special focus on the challenges (in terms of conflicts) related to development of the mineral extractive industry. However, the same situation as in Mozambique may also be applicable to other African countries.

1.1.1.   What is a mineral resource?

To understand what a "mineral resource" is, first we need to define the two terms "***mineral***" and "***natural resources***."

Natural resource is "***A material source of wealth, such as timber, fresh water, or a mineral deposit, that occurs in a natural state and has an economic value***" (The American Heritage® Dictionary of the English Language, 4th Edition copyright ©2000 by Houghton Mifflin Company).

Simply, a natural resource is a substance in its "raw state, unmodified" that naturally comes from earth, and needs to be refined before human use. Generally, we categorize natural resources as renewable and non-renewable. Renewable natural resources are those that are naturally regenerated such as biodiversity, water, fishing and soils. Non-renewable natural resources are those resources that exist in definite volumes. Once they are exhausted from the earth they cannot regenerated in a reasonable human time perspective. Good example of non-renewable resources is metal deposits, hydrocarbons and coal.

"***A mineral is an element or chemical compound that is normally crystalline and that has been formed as a result of geological processes***" (**Ernest H. Nickel, 1995***).

"*A mineral is an element or compound, amorphous or crystalline, formed through biogeochemical processes*" (**Skinner, 2005**).

Broadly, minerals can be divided into two main categories:

Organic minerals

Organic minerals are bio-minerals in origin (hydrocarbons) such as coal, natural gas and petroleum.

Inorganic minerals

Inorganic minerals are classified as crystalline minerals formed by natural geologic processes. They include sulfide-metallic metals such as gold (Au), silver (Ag), copper (Cu), zinc (Zn), cobalt (Co), nickel (Ni), lead (Pb) and molybdenum (Mo). Other metallic minerals include Platinum Group metals (PGM), Rare Earth Elements (REE) and many trace elements. Radioactive elements such as uranium (U), thorium (Th), radium (Ra) and radon (Rn) also fall under this category. Other inorganic minerals include halite (e.g. chloride- table salts, bromide and fluoride), phosphates (e.g. apatite), silicates (e.g. quartz and feldspar), sulphates (e.g. fertilizers & gypsum), carbonates (e.g. marble, limestone and dolomite), nitrates (e.g. fertilizers) and oxides (e.g. hematite, magnetite, chromite, ilmenite and rutile).

Therefore, as far as natural resources management is concerned, a mineral resource is a non-renewable, naturally occurring substance comprising minerals that can be used for human development.

1.1.2. Why is the Mozambican mineral sector less developed?

As far as mineral resources is concerned, Mozambique is endowed with a vast potentials of mineral resources including coal, base metals, precious metals, rare earth elements, natural gas, petroleum oils, gemstones, titanium and many other industrial minerals. Despite this huge mineral endowment, overall, the mining sector of Mozambique remains underdeveloped and systematic prospecting after new deposits are scarce. According to **ECA (2004)**, prior to independence in 1975, the mining sector in Mozambique was regarded as the "forgotten sector of the economy," with only limited data available for the country's mineral wealth. Several factors have contributed to this unfortunate development, both prior, during and after national independence. Amongst other factors, include

- Portuguese strategies in Mozambique during the colonial period, where Portugal did not show much interest developing Mozambique. Rather the country was treated as a colonial

territory. Mozambique has had yet to receive its national independence by 25th June 1975 under FRELIMO party.

- Other factors preventing the development of the mineral sector include the civil war, which erupted during 1977 just two years after the end of Mozambican independence war in 1975. The civil war lasted for 16 years up to 1992. The Civil War was between two civil parties: The Armed Forces of Mozambique under FRELIMO (Front for Liberation of Mozambique) fighting against RENAMO (Mozambique National Resistance) under sponsorship of the Central Intelligence Organization of Rhodesia (recent Zimbabwe– South Rhodesia and Zambia – North Rhodesia) and South Africa, but also, supported by the United States. Actually, the Mozambican Civil War was intertwined with the Cold War (1945-1991), between the NATO partners and the Warsaw-pact, lead by USA and the Soviet Union, respectively. It was not until October 1992 that both groups concurred to sign peace treaty.

- Adding to these obvious obstacles for economic development, Mozambique also experienced several prolonged periods of drought, particularly in the 1980's, and disastrous flooding event during 2000.

1.1.1. *Mozambique Government's Initiatives to reform mineral policies to promote investment in mineral sector*

In order to promote foreign investment in the mining sector, Mozambican Government made a number of initiatives to reform its mineral policies, hand in hand with restructuring of the state bureaucracy in addressing the mining sector (**Table 8** & **Table** 9).The old (colonially-adopted) mineral policies and legislative procedures in the mineral sectors are considered outdated and lacked incentives to adequately attract new investments. The new mining legislation was passed in 1986. The decision to reform mineral policies followed shortly after Mozambique had joined the International Monetary Fund (IMF) and the World Bank (WB) in 1984 (previously Mozambique worked under the colonial Mining Law, enacted in 1906. The 1986 law was successively followed by endorsement of Mining Regulations in 1987, and then, an enactment of Mining Certificate Regulation Act in 1994. From 1994 onwards, Mozambique continued to make a number of amendments in the mineral regulations and policies (**Table 8**) mainly aimed to promote growth in the extractive sector.

Table 8: Reformation of Mining Laws, Policies and Regulations by Mozambican Government to promote mineral investment

	Series of legislative reforms in Mozambican mineral sector
1	Original Mining Law of 1906 (colonial period)
	National Independency- 1975, trailed by 16 years of Civil War from 1977-1992
2	Mining Law 1986, 16-April (no.2/86)
3	Mining Regulations of 1987
	The first democratic Presidential election in 1994
4	Mining Certificate Regulation Act of 1994
5	The Minerals and Precious Metals Law of June-1995
6	Resolution n.º 4/1998 of 24 February (*the "Geological and Mining Policy"*)
7	Law n.º 14/2002 of 26 June (*the "Mining Law"*)
8	Decree n.º 16/2005 of 24 June (the "Regulation on Trade of Mineral Products")
8	Decree n.º 62/2006 of 26 December (*the "Mining Regulations"*)
10	Law n.º 11, 12 & 13/ /2007 (*the "Tax Regime for Mining"*)
11	Decree nº 5/2008 of 9 April (the "Regulation of Tax Regime for Mining")
12	New Mining Bill is currently under discussion to replace the *Mining Law- 26 June 2002*. It is expected to be out and be approved within 2012

Data source by SAL & Caldeira, Advogados e Consultores, Limitada (April 2010) & Mozambique Ministry of Mineral Resources ("MIREM")

Table 9: Incentives and exemptions to promote mineral investment in Mozambique

	Forms of incentives provided to mineral right holders
1	Corporate income tax is set at 32%, with significant reduction of up to 50% allowed for the first ten years from the start of production
2	Exploration and development expenditures can be accumulated and carried forward until the first year of production
3	Tax stability for the life of the project
4	A free choice of depreciation rates
5	Exemption on import duties and indirect taxes from mining or exploration equipment and goods, cars, raw materials e.g. explosives, and other capital materials related to mineral production. Applicable for the first 5 years from the date of commencement of business
6	Exemption of the dividend withholding tax, normally levied at 18-20% for ten years
7	Exemption from Sales Tax, duties and taxes on mineral exports
8	Levels of royalties payable to state are defined as follows: All mineral production - 3%, excepting Precious metals- 5%, gemstones- 6%, Coal-3% and diamonds- 10 to 12%
9	Legal protection for property and rights of mining titles covered by investment projects
10	Expatriates up 5% of total employees for projects with more than 100 total workforces Expatriates up 8% of total employees for projects with 10-100 total workforces Expatriates up 10% of total employees for projects consisting up to 10 total workforces

Data source: Mozambique Ministry of Mineral Resources (MIREM) & Peter Leon (2012).

Since then, after implementing its mining legislatives, Mozambique is now ranked as a solid number one of the world's top ten annual average national GDP growth (**Ernesto Gove, 2011**), best in Sub-Saharan Africa (**Figure 37**). Investment in the mineral sector is an

important component of the economic growth of the country. For example, the average national GDP growth rate from 1993-1999 was recorded at 6.7%. Meanwhile, from 1999-2002 the average GDP continued to grow at 7-10% (**ECA, 2004**). According to IMF and World Bank Group, Mozambican average annual GDP growth between 2000 and 2010 has flourished at approximately7.2%, with the highest growth rate recorded at 8.4% during 2005 (**Table 10**). Total duration required to start a new business has also improved tremendously. For example, time that required processing an exploration licence has improved from 153 to 13 days during 2003 and 2011, respectively (**Table 10** & **Figure 38**). Before independence in 1975, the Mozambican mining sector contributed with <1% of the national GDP (**ECA, 2004**). Despite increased foreign investments, contributions from the mineral sector to the economy is still not great; only contributing less than 2% of the Mozambican GDP when compared to other sector such as agriculture (31%) (**Table 11** & **Figure 39**).However, it is projected that the contribution from the sector will more than double in 2011 (**Adam Smith International, 2011**). In this context, it is pertinent to stress that the average time span from green field prospecting to full-scale production of a mine is 10-20 years. I.e. having just recently seen serious prospecting campaigns in Mozambique, it may be another 10 years before mining becomes a major contributor to the national economy.

Additionally, the national geophysical and geological databases are also improved and updated to an acceptable standard and newly mapped geological resources are identified. Moreover, the Mozambican Government currently improves the infrastructures such as upgrading ports, railways and road facilities, power lines, telecommunication networks and provision of quality water systems. These new initiatives have successfully encouraged foreign investment in the Mozambican mining sector (**ECA, 2004**). However, it requires strong governance to sustain this positive development.
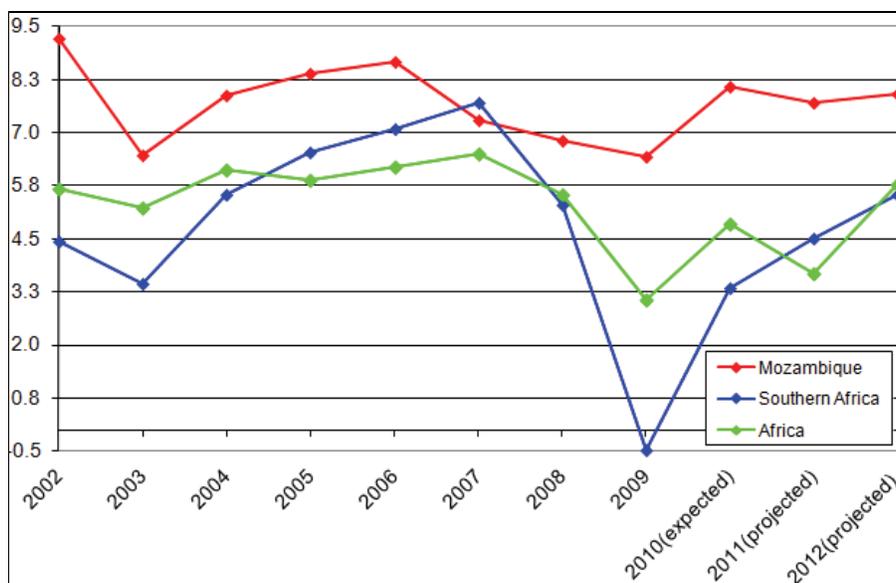
Figure 37: Mozambique GDP performance, comparison to Southern Africa and the whole of Africa.
Data source: African Economic Outlook (2011).

Table 10: Mozambique economic growth

	2000	2005	2008	2009	2010
Population, total (millions)	18.20	20.77	22.33	22.86	23.39
Population growth (annual %)	2.6	2.6	2.4	2.3	2.3
GDP (current US$) (billions)	4.25	6.58	9.89	9.79	9.59
GDP growth (annual %)	1.1	8.4	6.8	6.4	7.2
Time required to start a business (days)	-	153	26	26	13

Economic growth of Mozambique has seen to increase annually. **Data source: The World Bank Group (2010).**
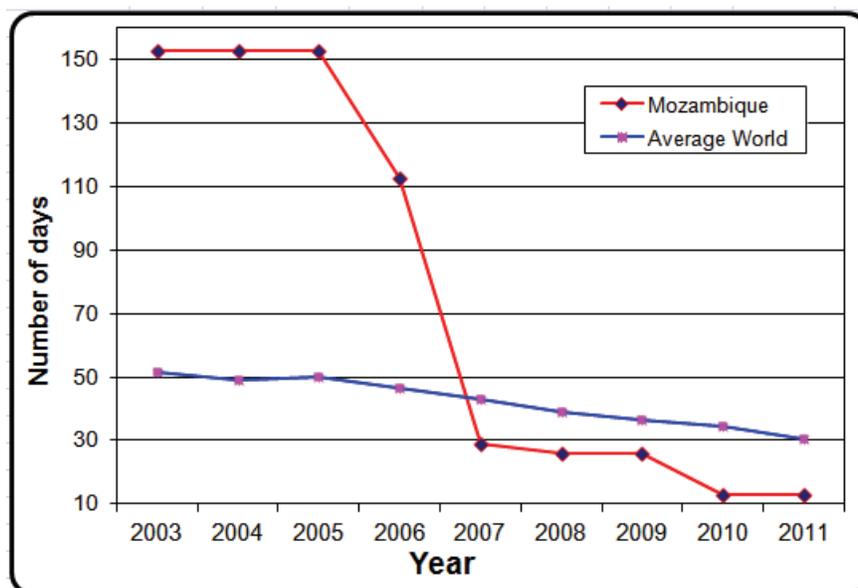
Figure 38: Number of days needed to start new business- e.g. provision of mineral licences
Data compiled from The World Bank Group (2012)

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Despite large contribution from the agricultural sector, Mozambique still has a large segment of the population who owe their daily income to artisan mining, the majority living in rural areas. According to **ECA, (2004)** and **Dreschler, (2001)** it is estimated that more than 50,000-100,000 individuals are directly involved in small-scale mining (**Table 12**). Artisan mining in Mozambique is primitive, mainly implemented by manual digging, washing and panning (**Figure 42**).

Table 11: Principle sectors contributing to Mozambique GDP

	1999	2001	2002	2003	2004	2005	2006	2006	2007	2009
Agriculture/fishing	31	24	22	26	22	19.7	27.4	27.38	27.4	29.4
Mining & quarrying				1	1	0.9	1.1	1.05	1.6	1.5
Manufacturing	10	14	11	15	13	12.8	15.0	15.03	14.5	14.1
Electricity and water	3	2	3	2	5	5.9	5.7	5.70	6.2	4.7
Construction	9	9	16	13	7	6.4	3.3	3.30	2.9	3.1
Trade		21	20		21	21.2	12.1	12.07	13.2	16.1
Comm. & Transport	9	11	11		8	16.4	9.9	9.91	10.7	10.2
Hotels & restaurants		1			1	1.2	1.7	1.66	1.6	1.6
Government services	6	7	6		7	6.6	9.7	9.69	9.2	10.2
Finance & business	19	4	5		5	3.3	12.3	12.32	11.1	7.5
Other services	13	7	6	44	4	5.4	1.9	1.89	1.7	1.6

Source: Data compilation from Organisation for Economic Co-operation and Development (OECD) & African Economic Outlook 2011
http://www.oecd.org/newinfobycountry/0,3760,en_2649_201185_1_70657_1_1_1,00.html
http://www.africaneconomicoutlook.org/en/countries/southern-africa/mozambique/
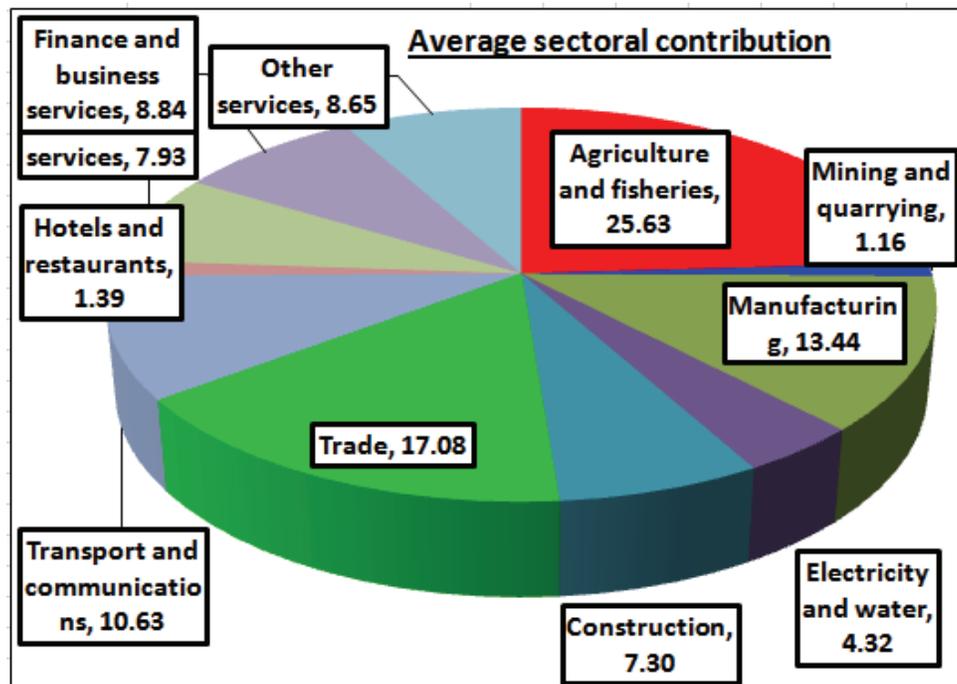
Figure 39: Contribution per sector- data is average estimate of 1999-2009 from Table 11

Table 12: Number of small-scale miners and contribution of mining sector to GDP

	Mozambique	Malawi	Tanzania	South Africa	Zambia	Zimbabwe	Total
Mining contribution to GDP	<2.0%	0.9%	2.8%	8.0%	12.1%	8.0%	
% informal small-scale miners (estimated)	95.0%	90.0%	90.0%	n.a.	60.0%	85.0%	84.0%
Number of small scale miners (estimated)	60,000	40,000	550,000	10,000	30,000	350,000	1,040,000
Formal large & medium scale mining employment	87,000	14,000	365,000	1,350,000	300,000	350,000	2,466,000
% women in ssm (estimated)	30.0%	10.0%	25.0%	5.0%	30.0%	> 50%	25.0%

Data source: Dreschler, (2001)

1.2. Why do conflicts arise over natural resources?

Buckles and Rusnak (1999) has highlighted a number of factors imposing conflicts over natural resources:

- Politically –related factors, "Actors with greatest access in power are also the best able to control and influence natural resources decisions in their favour" Disruptions and conflicts happen when other groups of stakeholders do not get access to resources utilization. Additionally, disruptions can also arise if some of the stakeholders do not realise benefits from natural resources.

- Increased demand and resource scarcity- This will lead to an increased competition over natural resources because of competing interests from different stakeholders. In this context, conflicts over natural resources can cover a broad range of stakeholders from local to national to international dimensions.

Gavin Hibon (2002) argued that perhaps no other industry precipitated as much disputes over land use than mining, and that failure to deal with conflict at the mining sites often caused severe communal disruptions. Unsustainable and inequitable utilization of natural resources not only may initiate conflicts, but may also impede development of other societal segments.

As far as the Mozambican extractive sector is concerned, different groups of stakeholders were directly involved in the development and exploitation of mineral resources. They include - local communities (Mozambican citizens), World Bank Group, foreign mining companies and Mozambican State. The ownership for the majority of foreign mining companies in the Mozambican extractive sector is from North America (USA and Canada), South America (Brazil), Europe, Australia, India and China (**Table 15**). While these multinational mining companies seek access to develop and extract mineral resources, Mozambican citizens' claim to not benefitting from mineral extractions (**Claude Kabemba & Camilo Nhancale, 2012; Agenia de Informacao de Mozambique 17 January 2012; Baetica - Consultoria em Mineração, Lda, 2010; Simon Vilakazi & Victoria Buhanza, 2011**).

UNECA (2009), "**… extractive industry is strategically important to developing countries as a major revenue-earning source and to developed countries as a major source of raw materials**."

Based on the above statement by **UNECA (2009)**, it is clear that when investments in the Mozambican extractive industry is regarded as an important source of funds to support the country's annual budgets, the foreign mining companies consider extractive metals, coal and hydrocarbons as raw materials, important for economic growth and future industrial development in their developed countries. In that case, unsustainable exploitation and inequitable sharing of those mineral resources among the involved stakeholders not only can initiate conflict but also can impede economic development.

1.3.   Objective of the study

1.3.1. General objective

As this study is directly connected to the mineral potential of Atchiza, this chapter will give an overview of sustainable management of mineral deposits in Mozambique. Special focus will be given to environmental sustainability of mineral resources exploitation, as well as, conflicts among different stakeholders arising from exploitation of mineral resources.

1.3.2. *Specific objectives*

- Identifying environmental sustainability for the mining activities in the Atchiza Suite

- Identifying different stakeholders in the Mozambican extractive industry

- Identifying sources of conflicts in the Mozambican extractive industry

- Possible solutions for sustainable management of mineral deposits in Mozambique

2. METHODOLOGY

Literature review, supported by secondary data from relevant sources.

3. RESULTS

3.1. Sustainable management of mineral resources in Mozambique- challenges and sources of conflicts

According to ECA, (2003), challenges that are related to extractive industries are broadly categorized as follows:-

1. ***The creation Challenge****-* Discovery of mineral deposits requires sufficient knowledge about the geology of mineral deposits, human resource capital, financial resources and adequate technological capacity. Additionally, development and exploitation of mineral resources requires social and environmental consideration. All of these factors are cost demanding in terms of both financial resources and time.

2. ***Distribution Challenge****-* Benefits and surpluses that are harvested from mineral resources require to be shared in a manner that brings equity to all stakeholders. It is also a challenge to follow the flow of money changing hands throughout the value chain of mining.

3. ***Macroeconomic and Political Challenge****-* Challenges in a sense of mineral markets and political constraints, including sources of market- both internal and external, fluctuation in prices, challenges regarding to mineral policies and regulation frameworks.

4. ***Investment Challenge****-* Given that minerals are finite resources, investment in extractive resources needs to be accomplished in a sustainable manner. It requires that portions of the revenue is plowed back in to social services such as education, health services, power and energy, roads, ports and railways.

Despite huge achievement in promoting its mineral sector, the Mozambican administration still faces a number of challenges in managing its mineral resources. All of the above four challenges by **ECA, (2003)** appear to be relevant to the Mozambican extractive sector.

However, it is pertinent to emphasize that conflicts and challenges in the extractive industries are similar, not only for African countries but also for the majority of developing nations.

While mineral investment in Mozambique is still in its infancy, it is important that the mineral wealth is exploited wisely and sustainably, in a reflection of building the future economy for the Mozambican citizens. The main objective of mineral investment in Mozambique should be poverty reduction. Accordingly, mineral investment in Mozambique should be recognized as a unique opportunity for all stakeholders.

Explicitly, sustainable management of the Mozambican extractive sector requires the following challenges to be addressed: - Vulnerability to environmental resources due to mining operations, lack of transparency and poor governance in management of mineral resources, lack of participation of local communities and lack of equitable sharing of benefits extracted from the mineral resources. These challenges require to be addressed correctly both at national (internally) and international (externally) levels in order to ensure that investment in the extractive industry is responsibly managed. These challenges are reviewed in the following sections.

3.1.1. Environmental sustainability of mineral deposits

Extraction of mineral resources may cause negative consequences for the environmental resources and surrounding communities, if they remain inappropriately managed. As a result, local communities and other natural resources that dwell adjacent to mining operations can be severely affected.

Taking an example, Mozambique has several rivers that are extremely polluted due to illegal artisan mining activities. The rivers cover most of the central provinces of Mozambique, and include Pungue River, Lucite River, Revue River, Zambezi River, Nhacuarara River and Chimeza River in Manica, Sussundenga district. It is reported that pollution in these rivers has increased to extreme levels such that the water is no more suitable for human consumption (**Figure 42 & Figure 43**). According to **UNIDO (2005)**, **Spiegel, S.J. et al. (2006), Shandro, J.A. et al. (2009**) and **Agencia de Informacao de Mocambique, Maputo**

(2011) water pollution for the majority of rivers in the central parts of Mozambique is mainly caused by uncontrolled workings from artisan miners; mainly by excavating the river banks, washings, panning and processing of alluvial gold.

It is important to realize that water polluted by artisan mining may contain high concentrations of Hg, As, Ni, Cr, Pb, Co, Ti and many other environmental metals. When excessively inhaled or consumed (directly or indirectly) by human beings these metals can severely impose health-problems. Knowledge and training is needed for the artisan miners to make them aware of the negative consequences of environmental pollution to human health.

In order to regulate and control any form of environmental destruction from mining activities, the Mozambican Government has implemented several legislative and policy measures, as outline below-

The Mozambican Environment Law (approved by Law 20/97 of 01 October, the "EL")

Environmental Law seeks to prohibit any form of pollution to the environmental resources, as well as, any types of activities that accelerate erosion, desertification and deforestation or any other forms of environmental degradation. Mining activities shall be undertaken in accordance with protection and preservation of the environment resources, including social, economic and cultural aspects. Wastage and loss of natural resources must be kept at a minimum in order to protect natural resources against unnecessary damage.

The Mozambican Regulation on the Process of Environmental Audit – 12th August 2003

It requires that Environmental Audits and Environmental Inspections be undertaken at anytime during and after mining project has been suspended. The main objective of environment auditing is to supervise and monitor that mining operations comply with environmental rules. During mine closure, all shafts, adits, and all ventilation systems must be sealed in a permanent manner. Water dams and tailings or spoils must be made safe to withstand collapse and permanent signs must posted warning of danger (**SAL & Caldeira, Advogados e Consultores, Limitada April 2010**).

Environmental Regulations for Mining Activities, (approved by Decree 26/2004 of 20 August, the "ERMA")

The ERMA requires that Environmental Impact Assessments (EIAs) be undertaken (by Environmental Specialist) to examines the consequences of implementing any mining

project. According to ERMA, the EIA is the mandatory exercises prior establishment of any mining operations. (**SAL & Caldeira, Advogados e Consultores, Limitada April 2010**).

Taking into consideration (a) - the location of the Atchiza Suite, - just adjacent to Cahora Bassa Lake (**Figure 41**). (b) – societal and economic values that the Cahora Bassa Lake offers to Mozambique, (c) - the importance of Metamboa River, Mecucue River and Mucangadzi River that transgresses the Atchiza landscape continuously feeding the Cahora Bassa Lake (**Figure 41** & **Figure 40**). (d) - high enrichment of some heavy metallic elements such as Fe, Ni, Co, Cr, Cu, Mn, Zn, Ti and many other trace elements, in the Atchiza intrusion. In fact, the whole of the ecological system may become potentially affected if mining activities in Atchiza will not be undertaken sustainably. Uncontrolled mining activities, such as drilling, blasting and tunnelling, may result in increased river sedimentation. Sediments can be transported downstream, accumulate and perhaps shallow the Cahora Bassa Lake. Ultimately, the Cahora Bassa Lake may become a much smaller basin. With time, the electrical production capacity of the Cahora Bassa Dam may decline.

Uncontrolled mining operations may also lead to increased river turbidity, which in turns may endanger aquatic wild life. It is true that heavy metallic elements such as Fe, Ni, Co, Cr, Cu, Mn, Zn, and Ti, which characterize Atchiza, can become soluble in river streams at high concentration and may reach toxic levels. Once again, this can also pose another threat to human health once they are excessively consumed.

It is also important to know that geological structures and shear zones in Atchiza can act as potential sites for underground percolation of polluted water, thus underground water system may be polluted, as well. Given that geological structures can penetrate kilometres depth, percolation of polluted ground water must be evaluated.

Given these potentially negative consequences from mining activities, and in order to prohibit destruction of the environmental resources, it is important that EIA is involved before any mining operation begins in the Atchiza.

Figure 40 Common vegetation type in Atchiza and neighbouring areas

Figure 40 shows typical vegetation cover and landscape nature of Atchiza Suite and the neighbouring areas. Atchiza is mountainous area. It is sparsely populated with minimal cultivation. Vegetation is natural and still naturally intact. The climate resemble to humid subtropical (savannah). Average temperature is almost constant throughout a year above 29^{0}C. It is cold during night, with temperature significantly drops at lower levels (Photo source: GTK)
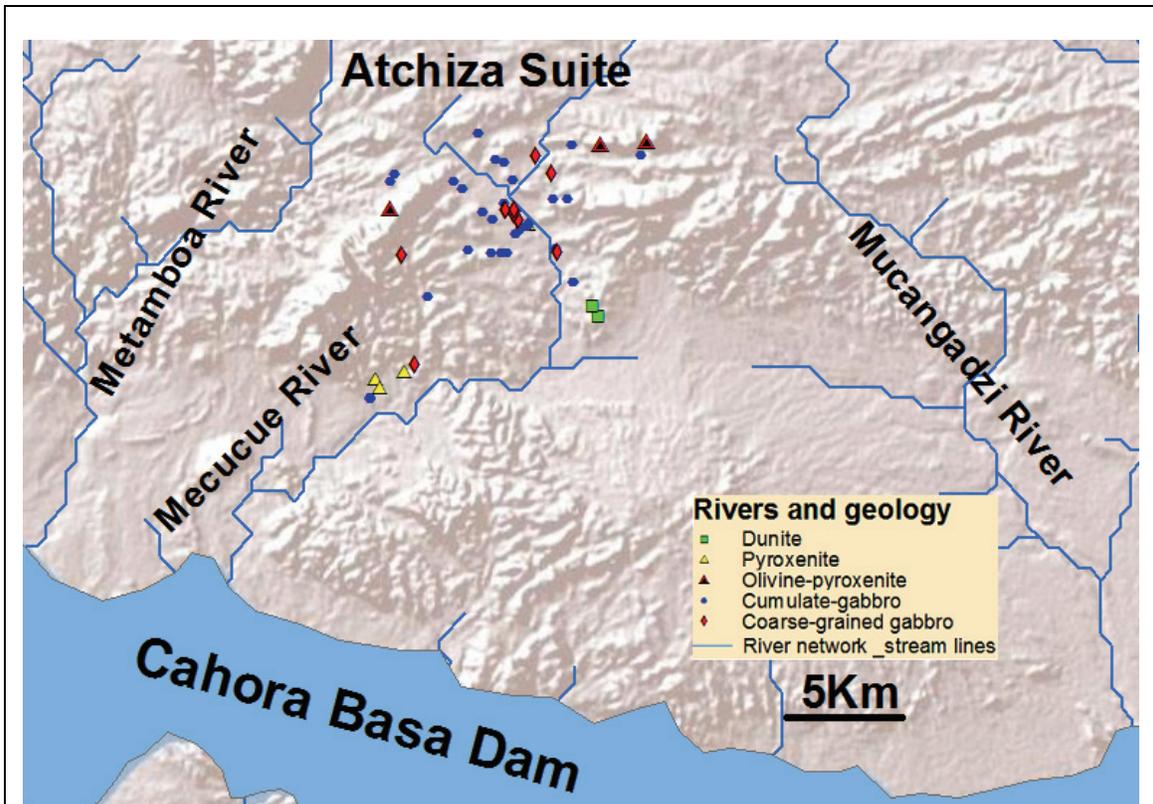
Figure 41: Location of Atchiza prospect relative to other natural resources.

Figure 41 shows location of Metamboa River, Mecucue River and Mucangadzi River relative to sampling location. Mecucue River flows across Atchiza's landscapes, while Metamboa and Mucangadzi Rivers flow adjacently. These river streams are perennial, and are a few among others that feed Lake Cahora Basa throughout a year.

Cahora Bassa Dam being a fourth-largest dam in Africa; after Lake Volta -Ghana, Lake Kariba-Zimbabwe/Zambia and Lake Nasser (Aswan Dam) of Egypt, carries diversities of natural resources (e.g. aquatic species like fishes, hippopotamus & crocodiles).

Cahora Bassa Lake has potential for tourism attraction whereby Mozambican Government is earning revenues from international hunting and tourism business.

Being constructed during 1975, Cahora Bassa Dam can generate up to 2,075 MW power capacities. This power serves as clean energy, not only to Mozambican nation but also to other Sub-Saharan countries such as South Africa (up to 1,500MW), Zimbabwe (200MW), Botswana (40MW) and a split of 80 MW is shared by Zambia and Malawi collectively (*SADC Today Volume 10 No. 6, June- 2008*).

Therefore, it is important that mining activities Cahora Bassa Lake be taken under social- and environment- considerations.
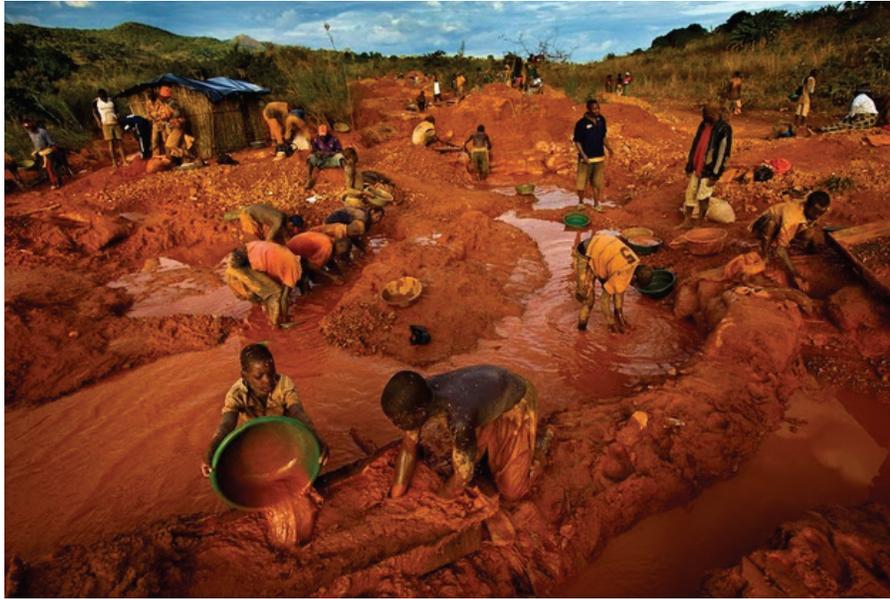
Figure 42: Artisanal miners panning for gold in Manica Province
Source: http://www.mizozo.com/

Figure 43: Polluted downstream flowing river (Manica Province) due to artisanal mining activities
Source: http://www.mizozo.com/

Water in river streams changed into red earth colour due to intensively digging and panning of gold-bearing placer materials. Apparently, this water is unfit for human consumption following poorly organised artisan mining activities. Water in these river streams also prohibits aquatic wild life from growing, due to high level of turbidity caused by artisanal mining activities. Should this if happen in Atchiza Suite, it is going to pollute river streams and increased silting

3.1.2. Lack of transparency, poor governance, lack of accountability and mismanagement of mineral resources

According to **UNECA (2009)**, "*Good economic governance exists in economies where the institutions of government:-*

- *Manage funds and resources efficiently and effectively.*

- *Can be monitored and held accountable.*

- *Respect the rules and norms of economic activity.*

- *Promote economic activity unimpeded by corruption and other activities inconsistent with the public trust.*"

Lack of transparency, poor governance, unaccountability and mismanagement of a nation's revenue includes some of the critical challenges for the extractive industries, not only for the Mozambique Government but also for the majority of developing African nations. Public and stakeholders in extractive industries have had negative perceptions that the awarding of mineral agreements has not been done transparently. Besides, the benefits received by African States from the extractive industry are not appropriately disseminated to lower societal groups, and in particular to the village level. Documentation of this calamity is presented in **Table 13** & **Table 14**, where official financial records show that portions of the revenue is missing.

Table 13: Reconciliation of payments by extractive industries and receipt in Mozambican government–2008- initial auditing

Source of benefit	Payment by Companies (A)	Received by the Government (B)	Differences (A)-(B)
Processing and Licence Fees	1,655,576.00	0.00	1,655,576.00
Surface tax	6,687,596.00	1,661,662.00	5,025,934.00
Tax on Production	123,376,446.00	90,638,006.00	32,738,440.00
Corporation Tax (IRPC)	72,255,606.00	0.00	72,255,606.00
Dividends	0.00	0.00	0.00
Total	**203,975,224.00**	**92,299,668.00**	**111,675,556.00**

Source: Chilenge B. (2011); Tomás Selemane & Dionísio Nombora, (2011). Numerical figures are reported in Mozambican currency (meticais).

Table 14: Reconciliation of payments by extractive industries and receipt in Mozambican government–2008- follow up and rechecking

Source of benefit	Payment by Companies (A)	Received by the Government (B)	Differences (A)-(B)
Processing and Licence Fees	1,655,576.00	0.00	1,655,576.00
Surface tax	6,687,596.00	5,674,742.00	1,012,854.00
Tax on Production	98,439,244.00	95,883,146.87	2,556,097.13
Corporation Tax (IRPC)	70,378,721.73	71,058,470.14	-679,748.41
Dividends	0.00	0.00	0.00
Total	**177,161,137.73**	**172,616,359.01**	**4,544,778.72**

Source: Chilenge B. (2011); Tomás Selemane & Dionísio Nombora, (2011). Numerical figures are reported in Mozambican currency (meticais).

Auditing in Table 13 & Table 14 shows reconciliated financial accounting for 2008 period. It is clear from these tables that reconciled figure is not balancing. You can see that there is huge discrepancy between payments made by mining companies against total revenue Mozambican Government is declaring to receive. Whereas Table 13 shows initially completed auditing (with 111,675,556.00 MT discrepancies), Table 14 (with 4,544,778.72 MT discrepancies) shows a follow up and/or rechecking (re-auditing) of missing revenue.

Data reveals that discrepancy was reduced significantly after re-auditing /rechecking was done. This implies that a considerable amount of revenue was recovered back, just after conducting re-auditing. Even though, still other money (4,544,778.72 MT) went off completely disappearing. According to Tomás Selemane & Dionísio Nombora, (2011), no any justification was provided by Mozambican Government officials for whereabouts of this misplaced money.

This auditing was performed to include only direct payments, in terms of money payable to Mozambican Government. The survey was also performed only to include companies that are in production phase, but also those companies that had shown consistency in their bookkeeping. Of the six companies that were included in the auditing, two were petroleum companies (Sasol PetroleumTemane & Companhia Moç. De Hidrocarbonetos) and the four were mining companies (Vale, Kenmare Moma Mining, Highland African Mining CO and Rio Tinto).

Based on **Table 13 & Table 14**, it evident that about 50% or more of the payments by mining companies remain unaccounted for. Another weakness that we see in **Table 13 & Table 14** is numerous inconsistencies that exist throughout the entire process of collecting mineral revenue, whereby there is financial-mismatch for the same type of payment.

These financial discrepancies painfully demonstrate how inappropriately the Mozambican Government is dealing with the country's financial resources. It is clear that there is a lack of control and accountability when it comes to issues dealing with mineral revenues.

3.1.3. *Lack of partnerships and participation*

This section gives an overview of the importance of public participation and partnership in the extractive industry, and demonstrates that it may be the most important element in the sustainable management of natural resources. To be addressed, will include public perceptions from Mozambican people, taking into consideration the whole context of decision-making and sharing of benefits from mineral resources.

In March 28th 2011, the Bank of Mozambique on behalf of the Mozambican Government had hosted the XIII International Seminar of the African Economic Research Consortium (AERC). The main agenda concerning this meeting was "***Options and Policy Implications for sustainable management of African natural resources***." The agenda was presented by the Governor of Bank of Mozambique, Mr. Ernesto Gove to the attendant Excellencies from several African nations: Ministers, Vice-Ministers, Deputy-Governors of African Central Banks and Permanent Secretaries of African Countries. In his speech, Mr. Ernesto Gove had an opinion that, "***A truly more genuine and inclusive partnerships is that, not only it ensures adequate and lucrative exploration of our natural resources and a visible economic empowerment of our countries, but also it guarantees stronger participation of the national private initiative, as well as, the participation of domestic experts and managers in the process, side by side with the international experienced companies, experts and managers that we count in*" (Ernesto Gove, 2011**).

According to Mr. Ernesto Gove, a more suitable policy for exploitation of natural resources should aim not only at attracting foreign investment but also should seek to enhance

sustainable economic growth of Mozambique through partnership and empowering of Mozambican citizens.

More opinions about partnerships was presented by the Mozambican Minister of Mineral Resources, Hon. Esperanca Bias, at the 2nd Mozambique Coal Conference in Maputo, 5-6th July 2011.*" One of the policy guidelines of the current legislation in the mining sector is to achieve a fair sharing of mining benefits between investors and government, while maintaining terms competitive and attractive to foreign investment"* (Source: **http://www.mirem.gov.mz.**) Note that original document is in Portuguese, but has been translated by using Google.

According to Hon. Esperanca Bias, and on behalf of the 2nd Mozambique Coal Conference in Maputo, it is important that Mozambique is entitled to a certain percentage of participation by collaborating with foreign-based mining companies or any consortia holding mining concessions for exploitation of mineral resources that are considered strategic. A good example of this is extraction of country's natural gas, whereby, this strategic resource is produced in Mozambique before being exported to South Africa. Extraction of natural gas in Mozambique and transportation (by piping) is done by Sasol, a South African based company. According to Hon. Esperanca Bias, it is good idea for Mozambique Government to engage into collaboration (partnership) with Sasol. By doing that, Mozambican citizens will benefit from the huge export of natural gas to South Africa.

Another comparable outlook on sustainable management of mineral resources in Mozambique was presented at the conference "**The Alternative Mining Indaba- 2011**" by Rogerio Ossemane and Nelsa Massingue from Instituto de Estudos Sociais e Económicos (IESE), Mozambique. The conference was held in Cape Town, South Africa from 7th – 9th February 2011 (**Simon Vilakazi & Victoria Buhanza, 2011**). It was organised by Economic Justice Network of FOCCISA in partnership with the Norwegian Church Aid- Southern Africa, Bench Marks Foundation and (IANRA) International Alliance on Natural Resources in Africa. In summary, Nelsa Massingue and Rogerio Ossemane held that -
1) -the extractive industry sector in Mozambique has acquired a reputation for being non-transparent and unaccountable, hence mineral resources are being extracted without benefitting the larger community. 2) - The Government did not honour her citizens after allowing Australian and Brazilian companies to exploit coal resources. 3) - The Government

forced-relocated local communities from land they had occupied for generations to areas abandoned of infrastructure 4) - endorsement of mining contracts in mineral projects was not a transparent process. 5) - mining companies enjoy large tax redemptions and do not pay much in corporate taxes and create few job opportunities. 6) - energy, generated in Mozambique is exported to other countries at a low price before it is imported from the same countries at a higher price!

Based on "**The Alternative Mining Indaba- 2011,**" participation and transparency during the handling of mining licences is one of the key factors for sustainable development of the Mozambican extractive sector. As both **Simon Vilakazi & Victoria Buhanza, (2011)** and **Ernesto Gove (2011)** highlighted, transparency in management of mineral resources by Mozambican Government, is only facilitated when all stakeholders are fully involved in decision-making, in particular during the process of awarding mining contracts. Mozambican citizens must be informed of the terms and conditions for which mining licences were offered so that they are aware of the benefits as well as the risks associated with in the exploitation of their mineral resources.

3.1.4. Allocation and sharing of benefits from extractive sector

Sustainable management in the extractive sector requires that the benefits from mineral resources are shared in fairly amongst stakeholders. Revenue from royalties paid by the mining companies to the Central Governments, must be plowed back to fund welfare growth at all levels for the citizens. In this context, it is true that the Mozambican Government does not retain large percentage of mining revenues only at National Directorate levels; rather that money should be disseminated back to reach the lower societal groups at district- and village-level. There, the money may be appropriately allocated for socio-economic development, such as health facilities, education and safe drinking water. On the national level, the society will benefit from the construction of roads, railways, harbours, installation of national power lines, establishment of research centres and higher educational facilities and much more.

However, there is a general public acceptance that mineral resources in the African countries are solely controlled by a few individual groups, mostly government officials and political leaders, who are mostly concerned with their own welfare. This is one of the most serious impediments towards healthy economic growth in African countries.

3.2. Lesson from Moatize Coal Mine conflict

The conflict in the Moatize Coal Mine in Mozambique illustrates the classical conflict between local communities and foreign multinational mining companies, whereby at centre stage, were having two international mining giants (Australian Rio Tinto and Brazilian Vale) and the Cateme villagers that were forcefully resettled c. 40 Km (25 miles) away from the Moatize Coal Mine. According to **Claude Kabemba & Camilo Nhancale (2012)** and **Agencia de Informacao de Mocambique (17 January 2012)**, on 10th January-2012 a group of more than 500 resettled Cateme villagers blocked the main roads and prevented Vale coal trains from leaving Moatize Coal Mine for a 24 hours period. They blocked roads and railways in protests against insufficient compensation for loss of property and all types of infrastructure including social services.

The Cateme villagers were displaced to unfertile lands that were unsuitable for cultivation in an area lacking proper roads and basic infrastructure. Furthermore, water is scarce in this area and water had to be delivered by trucks, which again heavily affects their livestock. Schools, hospitals and electricity-plants were not built to a completion. According to **Claude Kabemba & Camilo Nhancale (2012)**, the Mozambican administration and Vale committed to establish quality accommodation and all other social services before starting of the Moatize Coal Mine, however, obviously this has not materialized. According to the **Agencia de Informacao de Mocambique (17 January 2012)**, the conflicts has been ongoing since mid-2010 and yet remain to find its resolution.

Based on the Moatize Coal Mine conflict and similar conflicts from elsewhere in Africa, we may extract the following lessons -

- Compensation of property and societal infrastructure, in most cases, is not fairly done.

- Mostly, development of mining projects in Mozambique was effectuated without real inclusion of the local citizens and decisions were a matter between the foreign mining companies and the Central Government.

As mentioned in the early discussions, failure to initiate collaboration, partnerships and lack of social relationship between different stakeholders in the extractive sector has been, one of the main factors that provoked civil unrest all-overs the African continent. Mineral conflicts which is happening in Moatize Coal Mine is a type example of similar conflicts in most African countries as, for example, DR-Congo, Zimbabwe, Angola, Liberia, Nigeria, Tanzania, Kenya, Niger, Sierra Leone, Chad, Guinea and many other third world countries

throughout the world. At the roots of these conflicts, we have fights over rights to the land and the mineral rights and, typically, they prevail for years and involve the most serious civil atrocities.

3.3. Measures taken to enhance transparency and good governance in Mozambican extractive sector

Lack of transparency in the extractive industry appears to be a serious matter for the majority of developing countries including Mozambique. In most cases, lack of transparency and unaccountability in resources-rich countries is associated with corruption, being the major obstacle in the sustainable development of mineral deposits.

NECA (2009), "*The level of corruption in the African extractive sector is enormous as well as having massive international dimensions.*"

UNECA (2009) "*Corruption is a major challenge to governance and development in Africa. It erodes the capacity of the state to deliver services efficiently, provide security and maintain peace, order and social stability. When deep-seated, corruption generates poverty and turns resource-rich countries into low-income, backward societies. Many African countries are trapped in this cycle of corruption, poverty and underdevelopment*".

UNECA (2009) "*Corruption undermines the ability to achieve the Millennium Development Goals because resources meant for education, health, rural roads and electricity are diverted for personal use. It also increases the cost of doing business and is a disincentive for direct foreign investment*".

Due to lack of transparency in the extractive industry, the World Bank Group and some of its group members have supported several initiatives, which deliberately seek to address practical matters relevant to improved governance, accountability and transparency in management of mineral revenue in resource-rich countries.These initiatives include Publish-What-You-Pay (PWYP) and Extractive Industries Transparency Initiative (EITI).

UNECA (2009): "*The PWYP initiative was prompted by the lack of transparency that usually characterizes financial transactions between multinational corporations and governments, especially in the extractive sector in the developing world. Citizens barely*

know how much mining companies pay in rent on natural resources to their governments and where the money ends up".

World Bank. (2008): "*EITI is a global initiative established in 2002 to promote and support improved governance in resource-rich countries through the full publication and verification of company payments and government revenues from oil, gas and mining.*"

According to **UNECA (2009)**: *The primary objective of EITI is "to increase transparency in the payments made by companies and revenues received by governments relating to the exploitation of extractive resources such as oil, gas and minerals."*

World Bank. (2008): "*EITI programs sometimes lead to more efficient tax collection from extractive industry companies. By making information on payments and revenues public, they can also make it easier to detect corruption.*"

In Mozambique, PWYP was launched November 28, 2008, being sponsored by the British Government. The PWYP campaign in Mozambique calls for all transactions and financial deals that are signed between the Mozambican State and the mining companies is fully public. Thus, through PWYP, the Mozambican public will be in a position to hold their government accountable for mismanagement of benefits from the extractive industry (**Publish What You Pay and Revenue Watch Institute, (2006)**. A good example of where the PWYP programme is applicable in Mozambique is demonstrated in **Table 13 & Table 14**. According to PWYP, and in most cases, mismatch of the type shown in the tables, commonly is associated with cheating, dishonest behaviour and the involvement of corruption between hosting Governments and foreign mining companies.

Apart from having an affiliation with PWYP, Mozambique is also a candidate country in the World Bank list of EITI (http://eiti.org/Mozambique). As for PWYP, the World Bank Group through its EITI review programme has identified some recommendations that Mozambique Government needs to abide. The World Bank recommends to streamline the regulatory framework, remove capacity bottlenecks towards successful negotiations of new mineral agreements and to make sure that all stakeholders in the extractive sector are involved. Accordingly, the World Bank Group is willing to support the Mozambican Government in handling large-scale mining licenses in accordance with the mining regulations, as well as,

updating the current legal and regulatory framework for effective sustainable management of the extractive sector.

Another requirement from the EITI is timely publication of revenues received by the government from the mining and exploration companies. EITI requires that royalties generated from mining projects must be correctly recorded, published and made publicly available. Accordingly, based on EITI, the Government needs to develop the mining sector in a sustainable and transparent manner through improved governance and appropriate management of revenue from mineral resources **(EIR**, **2003**, **2006**, **2008**, **2009** & **2010**).

3.4. World Bank view about publication of mineral agreements

Apparently, the majority of the mining agreements that are signed between foreign mining companies and the African States are kept confidential, with not much information available for the common citizen. Lack of transparency and prevalence of opacity in mineral agreements prevents citizens to evaluate terms and conditions for which these mineral agreements were signed. Absolutely, this is considered one of the biggest obstacles that hinder sustainable development of mineral resources in the Mozambican extractive sector.

World Bank Group (2011): *"Increasingly, civil society and other stakeholders are requesting the disclosure of contracts that award companies the right to explore and develop extractive resources. Several countries have already adopted this approach, including Liberia, Timor-Leste, Guinea, Peru and others. As mentioned earlier in the report, IFC has decided under its revised Sustainability Framework, effective January 1, 2012, to also require its EI clients to publish relevant contracts."*

Based on the above statement, it is clear that World Bank Group has been only insisting transparency when awarding mineral agreements (e.g. EITI and PWYP), whereas the disclosure of mining agreements has been regarded as not a mandatory agenda. It is true that neither World Bank nor multinational foreign mining companies clearly states, for what good reasons disclosure of mining agreements should have not been done. Some of the questions that arises here due to the opaqueness that surrounds these agreements are-

- Why mineral agreements in the majority of the African extractive sector are not made public?

- What is the motivation behind the secrecy of terms and conditions for which the mineral agreements were signed?

The only answer to these questions is that both government officials and the extractive industry are committed to illegal transactions for personal gain on the government side and a non-societal purely profit oriented corporate attitude from the industry.

Table 15: List of foreign mining companies in Mozambique (List is not complete)

Company Name	Country of base	Activity	Mineral commodity	Project	Market source
Cabot Corporation	USA-Boston	Production	REE, Ta-Nb in pegmatite	Marropino Mine	Shipment to USA
Sasol Ltd	South Africa	Production	Natural gas	Pande & Temane Gasfields	Piped to South Africa
Kenmare Resources PLC	Ireland & German	Production	Ti, ilmenite, rutile & Zr	Moma mineral, sand deposit in coastal zones	Shipment- global
VALE	Brazil	Production	Coal	Moatize Coal Project	Brazil, India, global
Rio Tinto	Australia	Development	Coal		
BHP Billiton SA LTD	UK-London	Production	Heavy minerals in sands, Mozal Al-Project	Corridor Heavy Mineral Project & Mozal Al-Project	Exportation –global
Mitsubishi Corporation	Japan	Production	Mozal Al-Project	Mozal Al-smelting Project in Beluluane, Matola	Exportation –global
International Finance Corporation (IFC)	World Bank Group	Production	Mozal Al-Project	Mozal Al-smelting Project in Beluluane, Matola	Exportation –global
Pan African Resource PLC	UK-London	Prefeasibility	Au	Manica Gold Project	
Jindal Steel and Power LTD	India	Development	Coal	Zambezi Valley Project	Exportation –global
Tata Steel LTD	India	Development	Coal	Benga Coal project	Exportation –global
Riversdale Mozambique LTD	Australia	Development	Coal	Benga Coal Project	Exportation –global
Wuhan Iron and Steel Corp (WISCO)	China	Development	Coal	Benga Coal Project	China
Baobab Resources PLC	UK/Australia	Development	Cu-Au-Ag-Fe-Ti-V	Bandire-Sussundenga-Tete-Muande-Mundonguara- +other	
CAMARGO CORREIA	Brazil	Production	Cement producer		Local and International
Anadarko	USA-Houston	Exploration	Oil and gas	Ruvuma basin & offshore area	
African Eagle Resources PLC	UK-London	Exploration	Au-Cu-Ta-Sn-Nb	Majele & Fingoe Project	
Ncondezi Coal Company LTD	UK-London	Exploration	Coal	Ncondezi Coal Project	
Opti-Metal Trading Ltd	Switzerland	Exploration	Au and associated metals	King Solomon Project	
Great Basin Gold LTD	Canada-Vancouver	Exploration	Au	Tsetsera Property	
African Queen Mines LTD	Canada-Vancouver	Exploration	Au and associated metals	King Solomon Project	
Pacific Wildcat Resources Corp	Canada-Vancouver	Exploration	Ta-Li-Nb in pegmatite	Muane Project	
Rock Forage Titanium Lda	Canada-Vancouver	Exploration	Heavy minerals in sands	Chibuto heavy sands	
Southern Crown Resources LTD	Australia-Perth	Exploration	REE	Xiluvo Project	
Globe Metals & Mining LTD	Australia-Perth	Exploration	REE		
Lithic Metals and Energy LTD	Australia-Perth	Exploration	Ni-Co-Fe-Cu-Au explorer		
Mantra Resources Limited	Australia-Perth	Exploration	Radioactive elements		
Statoil	Nordic	Exploration	Hydrocarbon	Deep offshore, coastal zones	
NorskHydro	Nordic	Exploration	Hydrocarbon		
Eni	Italy	Exploration	Oil and gas	Coastal zones	

A list of foreign mining companies operating in the Mozambican extractive sector is given in **Table 15**. This list is not exhaustive; though, it provides very valuable information about the types of mineral resources and the nature of mining activities that are undertaken by mining companies. Accordingly, exploration- and mining- companies in the extractive are from all over the world, including Europe, South America, North America, Australia, India, Japan, China and South Africa. It is important that Joint ventures and sharing-based partnership be established between these companies and the Mozambican State for sustainable development of the Mozambican extractive sector.

4. DISCUSSION

It is clear that the Mozambican extractive industry is still in its infancy, with the majority of mining projects in its early exploration stages. If mining projects in Mozambique are appropriately managed, the country has great economic prospects and the financial ability and national economy will be grow.

In addition, given that minerals are non-renewable resources, it requires a committed and responsible government to insure mineral revenues are managed responsibly for poverty reduction to the common gain of the Mozambican society. The Mozambican Government needs to realize that proper management of mineral revenues will provide sufficient income, which will be enough to fund development projects throughout the nation. If also used appropriately, annual budgets will be fully supported, and the country will see employment opportunities are multiplying. On top of that, this massive collection of mineral revenues will reduce the country's reliance on international loans and aids.

The following initiatives must be addressed for sustainable development of the Mozambican extractive sector -

- Foremost, the public at large need full access to mining data. Revenues and royalties from mining activities, as well as, public expenditures need to be transparent as a rule and not the rare exception. Through this, illegal transactions of government's officials will be minimised. Additionally, this will empower the public to hold their government accountable for mismanagement of nation's resources. It is obvious that publication of mineral data will help reducing all sorts of corruption. Ultimately, a large proportional of mineral revenue will be re-invested to improve the economic development of the nation for the benefit of the society.

- The public must have access to evaluate terms and conditions for which mineral agreements were made. It is important that all mining agreements are published so that the public is informed about terms and conditions and the negative as well as positive impact on their community. Most importantly, transactions in the extractive sector such as the awarding and negotiations of mining contracts must be performed in a transparent involving all stakeholders. Accordingly, all stakeholders from individuals dwelling in the village to top government officials and politicians must, by law, have an equal right to participate. Decision-making for development of mineral projects should not be government-centred;

rather it should reach agreements through open public dialogue, organised seminars, city-meetings and national conferences.

• Mineral development in the Mozambican extractive sector (and Africa in general), should be implemented through public-private partnerships and joint ventures. The forms of Joint ventures and partnerships should be done between nationally based companies, foreign-based companies and the Mozambican State. It is the responsibility of the World Bank Group and Central Governments to make sure that, partnerships and joint ventures are firmly established, for the sustainable management of the African extractive industry. This will ensure that the mineral resources are shared equally, but also will help reducing conflicts. Through Joint ventures and partnerships, mining opportunities will open in favour of both sides, with Mozambican citizens also benefiting from their extractive resources. Additionally, it is very important that mining companies are operated within policy guidelines of corporate social responsibility by involving the civil societies in their operations. Foreign mining companies must involve indigenous communities in their daily operation.

• Apparently, citizens of Mozambique are not fairly compensated. When mining operations require resettlement program, it is important that compensation is undertaken in a fair-manner. Local communities need to be fairly compensated for their loss of property, and proper infrastructure should be re-established. Accordingly, new settlements must be constructed with all necessary available social services such as schools, health facilities, clean water, roads and recreational facilities. Privileged employment opportunities is important for local communities living next door to the mining sites.

• In some cases, mining operations will need displacement of small-scale artisan miners from their workings. This is also a main source of conflict. It may be advisable for large mining companies and the Central Governments to grant new mining leases for small-scale miners before they are displaced. Displaced small-scale artisan miners should also be given grants and loans for running their new projects, as we know that starting new projects has been always expensive. Forms of loans and grants may be water-pumping machineries and electrical generators. Loans and grants that are offered must be affordable to small-scale miners.

5. CONCLUSION

A combination of all factors that have been discussed in the above paragraphs are very important to facilitate sustainable development of mineral resources in Mozambique, but also in Africa at large. This study has identified the following findings and conclusions:-

- Main stakeholders in the Mozambican extractive industry includes the central government, multinational large-scale mining companies, local community groups and artisan small-scale miners (indigenous citizens and civil society groups), International funding agencies such as the World Bank.

- Investment in the Mozambican extractive sector need to performed in partnerships-style and Joint ventures between the Central Government, multinational mining companies and nationally based mining companies.

- Given that, mineral resources are finite, foreign mining companies and the government need to insure investment in the extractive sector is wisely performed, mainly with the aim of fighting poverty. Foreign mining and exploration companies in the country need to establish their mining activities in a more social- and economically- responsible manner by ensuring that their operations significantly contribute to the social welfare of the local communities as well as the nation at large. Mineral revenues must be re-invested in order to strengthen the economic-and social- development country. Examples where mineral revenue should be invested includes primary and secondary schools, research institutions, universities, colleges and vocational training centers that will ensure that the Mozambican citizens are empowered with quality professional skills. This will create more employment opportunities. Revenue from the extractive sector should also be used in construction of other social services such as power lines for energy distribution in the country, construction of road- and railway-networks and harbors. Other social infrastructures include expansion of health services such as clinics and hospitals as well as supply of clean water.

- In order to increase the level of transparency in management of revenues in the Mozambican extractive sector, it is important that online database is established. Online database will be essential, in particular, for management of financial accounting in the extractive sector. Mining databases must take into account the total amount of revenues and royalties that mining companies are paying to the government along with the money the

Mozambican Government claim to receive. Mining databases must be publicly accessible, primarily seeking to address key issues regarding uncertainties in the extractive industry such as unnecessary government spending. For the majority of African countries, apparently, the bulk of the mining data is handled in hardcopies only. This is an open door to inconsistencies in dealing with country's financial earnings. Making it digital in a mining database will increase the level of transparency and accountability of the country's mineral resources. Database will also provide a reasonable basis for tracking unnecessary expenditures from government officials and other matters pertaining to mismanagement of mineral revenues, including corruption issues. Additionally, this database will need to be uploaded with all mineral agreements that are signed between host countries (in this case, the Mozambican State) and foreign mining companies. Online mining database, among other components, should also state terms and conditions for which particular mineral projects were granted. Database should clearly show how revenues from the extractive sector were effectively re-invested to benefit local communities and for social- and economic- development of the nation.

- The central Mozambican government, the World Bank Group and international mining companies should ensure that negotiations of mining agreements is done in transparent manner by actively involving all stakeholders.

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