

Characterisation of Solid Mine Wastes Produced during Iron Ore Mining and Processing and their Potential Environmental Impacts

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Research Article

Keywords: Iron Ore, Mine Wastes, Mining, Environmental Impact, Geochemistry, Mineralogy

Posted Date: March 15th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-302151/v1>

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Abstract

Solid waste deposited on the surface acts as a potential source of environmental pollution. High concentration of toxic elements in solid mine wastes can pose serious environmental risks. This study aims at characterising solid mine wastes produced due to iron ore mining and processing for their geochemistry and mineralogy. Samples were collected using a stratified sampling strategy. X-ray Fluorescence (XRF), X-ray Diffraction (XRD), and Petrographic analysis techniques were used. XRD analysis revealed a high abundance of Hematite (29%), with low amounts of Quartz stockpile samples. Berlinite (33%) amounts were high in waste dump samples, where Quartz was in high concentrations (34%) in the overburden samples. XRF analysis revealed a high amount of iron in the stockpile and waste dump, while Silica was highest in the overburden. Petrography analysis revealed major minerals in the solid mine waste: magnetite, Hematite, and Quartz with traces of mica, olivine, feldspar, and biotite. The minerals were characterised by a lamellar structure with mutual grain boundaries. Sulfide minerals that may cause acid drainage and various heavy metals were in considerable amounts. These elements have the potential of causing adverse environmental impacts hence the need for such characterisation to devise mitigation strategies and rehabilitation.

Introduction

The characterisation of mineral and processing wastes is a key step during mining operations to mitigate risks associated with these wastes (Jamieson et al. 2015). This is made possible by providing appropriate remediation and waste management schemes. This characterisation help reveal the nature of the mine wastes and their potential interactions with the ecosystem (Hudson-Edwards and Dold 2015).

In the recent past, iron ore has been extracted in sedimentary rocks in different parts of the world over a long period (Lascelles 2011). Iron ore occurs as magnetite (Fe_3O_4), Goethite (FeO(OH)) and Hematite (Fe_2O_3)(Shrimali et al. 2016). Iron ore has very vast usage across the globe that makes it an essential commodity in industrialisation that has been continuously sought through mining (Cheneket 2018).

Mining of iron is associated with various mineral processing operations such as blasting, grinding, and magnetic separation, which results in the production of various solid mine wastes (Ferreira and Leite 2015).

According to Bett et al. (2016), significant iron ore deposits have been found in Marimanti in Tharaka Nithi County, Kitui County, Migori County, and Taita Taveta County, among other many areas.

Mine wastes constitute the largest percentage of any wastes produced by various industrial activities (Suleman and Baffoe 2017) & (Lottermoser and Lottermoser 2003).

In mining and mineral processing operations, mining wastes are sub-economic materials that contain low cutoff grades or do not contain any ore mineral (Lottermoser and Lottermoser 2003).

Mining operations, metallurgical extractions, and mineral processing produces various gaseous, liquid, and solid wastes. These are generated in different processes during mining, mineral processing, and metallurgical operations, as shown in Fig. 1.

During open pit mining and development, various mine wastes such as waste rocks, spoils, overburden, atmospheric emissions, and mine water may be emitted (Ferreira and Leite 2015). Mineral processing activities produce various processing wastes such as tailings, stockpiles of less grade materials, sludges, milling water, and emissions (David Meehan 2012).

The chemical and physical characteristics of mine wastes may vary in relation to the geochemistry and mineralogy of the resource, the size of the crushed mineral particles, processing chemicals, materials handling method, method and type of blasting techniques utilised, and the processing technology used (Jamieson et al. 2015), (Jelenová et al. 2018) and (Amos et al. 2015).

During materials handling at any mine, about 70% of the material handled is waste whose geochemical properties may be equivalent to the ore mined (Jamieson 2011). According Nordstrom (2011), drainage chemistry results from iron sulfide minerals oxidation such as pyrite, whose reaction generates acidity and various sulfates.

Most of the environmental challenges are associated with various mine wastes and their capability to react chemically with the water and air (Jamieson 2011). To carefully understand these reactions involved, it shall be needful to characterise the solid mine wastes in order to determine their geochemistry and mineralogy. This shall be done using XRD, XRF, and Petrographic techniques.

Research Methodology

Study Area

This study was conducted within the Samrudha Resources Iron Ore mining area in Taita Taveta County, Kenya. This area lies approximately 450 km southeast of Nairobi and 250 km northwest of Mombasa, at between 3.1° S and 3.3° S, and 38.1° E and 38.3° E, as shown in Fig. 2. The mine covers 20 km² and neighbors Tsavo National Park on the east and farmlands on the west. The mining of iron ore has been taking place in this area since the early 2008's (Maranga et al. 2013). The site lies within the Mozambique belt, geologically rich in industrial minerals such as iron ore and manganese (Siljander et al. 2019).

Materials and Equipment

Equipment and materials used in this study include a Laboratory jaw crusher, pulveriser, X-Ray Diffractometer (Roller 2011), X-ray Fluorescent (XRF) machine (Langhoff et al. 2006), petrological microscope (Dias et al. 2020), and solid mine waste samples.

Sample Collection

Stratified sampling strategy was employed in sample collection to allow replication and representation with the number of increments determined per ISO 3082 (ISO 2017). Sampling pits were dug, and the samples were collected and stored in Khaki bags. Approximately 200 g of each sample were taken and stored in well-labeled khaki bags sealed and ferried to the laboratory for preparation and analyses.

Sample Preparation

Representative rock samples (each 200g) were dried in an oven at 120°C to a constant weight in a furnace and then allowed to cool at room temperature. The samples were homogenised then pulverised to 200 microns.

Elemental Analysis

Pulverised sample (50g) for each designate was mixed with 5g of flux starch, and the resultant mixture was mixed in a mortar and pestle. The resulting mixture was made into pellets using a hydraulic press. The pellets were fed into the XRF machine for analysis.

Mineralogical Analysis

Mineralogy was determined using both X-Ray Diffraction (XRD) and Petrological analysis. For the XRD, samples of 50 grams were pulverised to fine sizes of between 30 to 50 µm following procedures outlined by Knorr and Bornefeld (2005). For qualitative evaluation and homogenisation of various mineral components, the samples were ground to pass through a 45 µm mesh and then placed on the sample holder for analysis using *Bruker A.X.S. D2 phaser SSD16* and relevant plots done by *Difrac Eva* software.

For petrological analysis, 30mm samples were cut from the whole samples using a diamond cutter. The samples were mounted onto glass slides, ground using a grit series (400, 600 & 800), and then covered with a slide for analysis using *Fein Optic Polarizing Light Microscope*.

Results And Discussion

Elemental Analysis of the Solid Mine Wastes

Waste Dumps

The results for elemental analysis for waste dumps are shown in Table I. The results indicated that all samples had higher amounts of Fe_2O_3 than other elements, with WD1 recording the highest amount. Silica was also in moderate amounts. Other elements such as Thorium, Chromium, and Vanadium were identified in traces.

Table I: XRF analysis for Waste Dump (W.D.) samples

Element/ Compound	Chemical Formula	WD1 Mass %	WD2 Mass %	WD3 Mass %	WD4 Mass %	Average Mass %
Iron	Fe ₂ O ₃	51.35	33.96	39.66	34.70	39.92
Silica	SiO ₂	29.10	49.50	38.56	26.33	35.87
Manganese	MnO	5.91	1.17	0.26	1.42	2.19
Barium	Ba	4.62	0.19	0.10	0.25	1.29
Titanium	TiO	2.88	0.17	0.24	0.51	0.95
Aluminum	AlO ₃	1.73	0.49	1.10	1.83	1.29
Calcium Carbonate	CaCO ₃	1.60	12.97	19.07	33.43	16.77
Sulphur	S	1.50	0.16	0.00	0.10	0.44
Phosphorous	P ₂ O ₅	1.10	1.25	0.89	1.26	1.13
Nickel	Ni	0.05	0.02	0.02	0.01	0.03
Zinc	Zn	0.04	0.01	0.01	0.03	0.02
Copper	Cu	0.03	0.01	0.00	0.01	0.01
Lead	Pb	0.03	0.01	0.01	0.01	0.02
Bismuth	Bi	0.02	0.01	0.00	0.01	0.01
Chromium	Cr	0.00	0.08	0.05	0.02	0.04
Thorium	Th	0.00	0.00	0.02	0.01	0.01
Vanadium	V	0.00	0.00	0.00	0.04	0.01

Heavy metals were present in the waste dump samples. High amounts of iron ore identified in waste dump samples inferred high dilution during mining. Only high-grade iron ore is mined at Samrudha resources mine; therefore, ore that is highly diluted with gangue minerals (Silica) is disregarded as waste. The waste dumps, which are generally the blasted material, contain chemical elements such as Sulphur that may be potential environmental pollution agents.

Stockpiles

The stockpiled materials result shown in Table II contains iron ore of low grade and iron ore fines from the processing operations at the mine.

Table II: XRF analysis for Stockpile (S.P.) samples

Element/ Compound	Chemical Formula	SP1 Mass %	SP2 Mass %	SP3 Mass %	SP4 Mass %	Average Mass %
Iron	Fe ₂ O ₃	88.75	71.94	76.92	84.53	80.54
Silica	SiO ₂	5.85	19.37	16.31	11.86	13.35
Aluminium	Al ₂ O ₃	1.73	1.90	1.65	1.40	1.67
Calcium Carbonate	CaCO ₃	0.83	1.29	0.82	1.11	1.01
Phosphorous	P ₂ O ₅	0.79	1.06	0.98	0.64	0.87
Barium	Ba	0.62	0.96	1.27	0.05	0.73
Titanium	TiO	0.56	0.90	1.03	0.00	0.62
Sulphur	S	0.26	0.63	0.00	0.00	0.22
Manganese	MnO	0.26	1.67	0.58	0.24	0.69
Bismuth	Bi	0.10	0.04	0.07	0.10	0.08
Nickel	Ni	0.05	0.07	0.21	0.08	0.10
Rubidium	Rb	0.05	0.02	0.04	0.03	0.04
Lead	Pb	0.04	0.04	0.05	0.04	0.04
Copper	CuO	0.04	0.02	0.02	0.02	0.03
Zinc	Zn	0.03	0.02	0.01	0.02	0.02
Zirconium	Zn	0.00	0.00	0.01	0.00	0.00
Vanadium	V	0.00	0.00	0.00	0.02	0.01

The stockpile samples contained very high amounts of Fe_2O_3 and low amounts of other elements. SP1 and SP4 samples were iron ore fines; despite having high amounts of iron ore concentration, the material is unwanted and is therefore waste. These fines are stockpiled near the processing plant for disposal. The other stockpiled materials (SP2, SP3) are low-grade iron ore, and small size (50mm) float iron occurring alluvially in the area. These materials are currently not utilised by the mining company and contain potential environmental pollutants, as revealed in the XRF analysis in *Table III*.

Overburden

The overburden material, most abundant in the area, generally consists of a mixture of topsoil and rocks either blasted or dozed off during access to the ore before blasting operation.

Table IV: XRF analysis for Overburden (OB) samples

Element/ Compound	Chemical Formula	OB1 %	OB2 %	OB3 %	OB4 %	Average %
Silica	SiO ₂	57.83	60.7	24.93	20.62	41.02
Iron	Fe ₂ O ₃	15.01	8.63	6.1	19.92	12.415
Potassium	K ₂ O	10.36	15.98	0.37	0.58	6.8225
Calcium Carbonate	CaCO ₃	7.42	1.76	62.86	52.54	31.145
Aluminium	Al ₂ O ₃	6.13	9.48	3.11	3.32	5.51
Phosphorous	P ₂ O ₅	1.83	1.8	1.7	1.47	1.7
Titanium	TiO	0.51	0.69	0.67	0.76	0.6575
Barium	Ba	0.38	0.24	0.17	0.19	0.245
Sulphur	S	0.25	0.37	0.1	0.01	0.1825
Manganese	MnO	0.05	0.08	0.39	0.48	0.25
Chromium	Cr	0.05	0.06	0.03	0.02	0.04
Zirconium	Zr	0.04	0.04	0.01	0.02	0.0275
Strontium	Sr	0.03	0	0.04	0.04	0.0275
Rubidium	Rb	0.03	0.04	0	0	0.0175
Copper	CuO	0.02	0.01	0.02	0.01	0.015
Zinc	Zn	0.01	0.01	0.01	0	0.0075

These materials are generally rich in SiO₂ and CaCO₃ with impurities in the form of chemical elements that may cause environmental impacts, as shown in *Table IV*.

Mineralogical Analysis of Solid Mine wastes

XRD technique was successfully used to reveal the different phases that the solid mine wastes presented. These results are shown in Figs. 6, 7, and respectively. The mass percentages for each element/compound are shown in Tables VI, VII, and VIII. A representative sample for the stockpile, waste dump, and overburden was analysed.

Stockpile Sample

From XRD analysis, the predominant crystalline element in the stockpile samples is hematite (Fe₂O₃) and magnetite (Fe₃O₄). Quartz and iron were in low amounts. This is because the ore has already been processed; therefore, it contains low amounts of gangue minerals.

Table VI: Composition of elements in the stockpile sample

Element/Compound Name	Formula	%
Hematite	Fe ₂ O ₃	29.0 %
Magnetite	Fe ₃ O ₄	21.1 %
Manganosite	MnO	16.6 %
Berlinite	AlO ₄ P	11.6 %
Calcite	CaCO ₃	10.8 %
Quartz low	SiO ₂	6.3 %
Iron	Fe	4.5 %

Waste Dump

Quartz (SiO₂) and Berlinite were in high amounts in the waste dump samples. Magnetite and Braunita minerals were in low amounts. The waste dumps generally contain unwanted minerals such as Quartz, causing the magnetite mineral, which contains iron ore, to be identified in low amounts.

Table VII: Composition of elements in the waste dump sample

Compound Name	Formula	%
Quartz	SiO ₂	42.7 %
Berlinite	AlPO ₄	23.0 %
Alite	Ca ₃ O ₅ Si	13.4 %
Nitratine	NaNO ₃	6.9 %
Hematite	Fe ₂ O ₃	5.1 %
Calcite	CaCO ₃	3.9 %
Magnetite	Fe ₃ O ₄	2.1 %
Braunita	Mn ₂ + Mn ₃ + 6[O ₈ SiO ₄]	1.8 %

Overburden

Berlinite (AlPO₄) and Quarts (SiO₂) revealed high phases in the overburden samples. Hematite and Calcite minerals were in low amounts. The presence of berlinita and quartz minerals in abundance revealed that all the materials from the overburdened material is disregarded as waste.

Table VIII: Composition of elements in the overburden sample

Compound Name	Formula	%
Berlinite	AlPO ₄	32.5 %
Quartz low	Si O ₂	31.2 %
Retgersite	NiSO ₄ · 6H2O	14.7 %
Goethite	FeO (OH)	6.7 %
Alite	Ca ₃ O ₅ Si	6.5 %
Hematite	Fe ₂ O ₃	5.9 %
Calcite	CaCO ₃	2.5 %

Petrographic Microscopy of Solid Mine Wastes

The petrographic analysis was done on the solid mine wastes to study the transparent composition of these samples. Both cross-polarised light (X.P.L) and plane-polarised light (PPL) were applied to identify the samples' minerals. Petrography microscopy analysis results are shown in Figs. 9, 10, 11, 12, and 13.

The thin section of stockpile (SP2) sample (Fig. 9) consists of Magnetite, Pyro - Garnets Quartz, Biotite, and Hematite. The dark opaque visible colour in the thin sections is the magnetite. The whitish colour indicates the biotite iron ore and bands of quartz assuming different shades. The brownish-grey colour indicates martitized magnetite in the sample hence occurring as Hematite.

A thin section of the waste dump sample (Fig. 10) shows a dominant opaque dark grey colour, indicating traces of magnetite and the rust-like colours of brown-red iron hydroxide (Hematite). The white - pink colour indicates the quartz. Feldspar is structured in a network with intrusions of quartz. There are olivine, biotite, and Zircon minerals appearing in between mineral grains of magnetite.

In Fig. 11, magnetite is the dominant mineral. It is occurring as opaque; however, hematite occurring as a brownish colour. The solid waste is characterised by specula and simple lamellae texture with mutual grain boundaries between various individual mineral intrusions suggesting that the minerals break along the grain boundaries.

The overburden material sample generally occurs, and needlelike crystals of feldspar with inclusions of quartz, mica, and shades of pyroxene as viewed in Fig. 12.

Sample of stockpile (SP1) (Fig. 13) contains high amounts of magnetite and hematite minerals occurring as opaque and brown shades. There are traces of gangue minerals such as quartz, pyroxene, garnet, and olivine minerals in the sample. The occurrence of the individual grains which are well-formed exhibit resistance to weathering. Grain boundaries also separate different minerals with varying sizes without individual grains interlocking. When exposed to various atmospheric conditions such as meteoric water

and air, this phenomenon indicates that the minerals may react at a higher rate. Therefore, toxic chemical elements pose a high risk to the environment in the event of a reaction.

Conclusion

Most of the environmental impacts of iron ore mining and processing are associated with the subsequent release of various toxic elements from the mine wastes produced. These mine wastes tend to pose serious problems, not because of the volumes produced but also the areal extents and coverage. Due to the continuous pollution and contamination, solid mine wastes from iron ore mining must be isolated and treated to reduce oxidation, erosion, toxicity, or dumped waste in well-designed waste dumps. Uncontrolled disposal of solid mine wastes can be associated with increased turbidity in various water sources and the release of harmful chemical elements, which may also be acidic (Bernd G. Lottermoser 2011). These contaminants travel through the soil, water, biosphere, and atmosphere to cause environmental impacts. Most of the adverse environmental effects caused by solid mine wastes are their tendencies to chemically react with available water or air hence producing contaminants (Jamieson 2011). These contaminants may also be inhaled or ingested by humans and react with fluids in the body (Kirsimäe 1999). Airborne dust and winds may also cause transportation of these chemical elements present in the solid mine waste to soils and surface water.

Minerals and chemical elements in solid mine wastes may occur as sulfide minerals, non-sulfide minerals such as carbonates, secondary minerals formed by chemical weathering such as goethite, and chemical compounds produced by ore processing as oxides produced through the leaching process (Jamieson 2011).

There is a presence of considerable amounts of Sulphide minerals such as Helvine ($\text{Be}_3\text{Mn}^{2+} \text{SiO}_4)_3\text{S}$) and Sphalerite (ZnS) in the stockpile and waste dump samples. Exposure of these sulfide elements to an oxygenated environment, surface runoff, and groundwater will cause the sulfides to be oxidised and produce acid waters that can be sources of contaminants such as heavy metals and metalloids. When these sulfide minerals are exposed to the oxidising atmosphere, they become unstable chemically (Parbhakar-Fox et al. 2018). During this process, chemical weathering reactions are initiated due to a lack of equilibrium with the environment. Therefore, weathering proceeds aided with various microorganisms present, meteoric waters, and atmospheric gases (Bernd G. Lottermoser 2011). Iron ore fines stockpile is at the highest risk. This is because of its increased surface area, subsequently increasing its potential for exposure to oxidation and weathering. Petrography analysis also revealed poorly crystalline samples with structural defects that contained distorted crystal lattice. This eventually leads to building up stresses in the rock structure, making the mineral susceptible to chemical attack. The mine wastes also contain phosphates, silicates, oxides, hydroxides, carbonates, and halides that can pose an environmental problem.

Recommendations

Due to the adverse impacts of solid mine wastes produced during iron ore mining, reducing their environmental and health impacts would require proper management, skills, and expertise. These include a characterisation of all solid wastes in terms of their geochemistry and mineralogy. Understanding the solid mine waste interactions to the various condition can be of key benefit to the mining company.

The following are practical ways that can be done to minimise and reduce the environmental impacts caused or likely to be caused by solid mine wastes:

Beneficiation of Low-Grade Iro Ore

Low-grade iron ore that is disregarded as waste could be beneficiated further to avoid causing environmental pollution if dumped as waste. The beneficiation method could include using bio floatation techniques and gravity concentration (Rea et al. 2015) & (Bett et al. 2014).

Utilisation of Iron Ore Dust in Cement Companies

Iron ore dust can also be sold to Cement Manufacturing Companies. This provides an alternative ready alumina-silicate raw material that is more effective and reactive than normal clinker (Luo et al. 2016).

Phytoremediation

Plants can be used to clean up contaminated environments. Restoration of dense vegetation cover can physically stabilise these solid mine wastes dumped and help reduce the pollution of the chemical elements. Different species of plants that can adapt to the atmospheric condition in the area, such as *Leucaena leucocephala* (*Leucaena*), can absorb chemical elements (Ssenku et al. 2017). This plant species accumulates heavy metals and produces large amounts of biomass, therefore a potential plant for phytoremediation (Ssenku et al. 2017).

Conventional Remediation

Conventional methods of remediation of areas where the mine wastes are located majorly focus on physical and chemical stabilisation. This entails covering up the solid mine wastes with innocuous material, generally soil or rocks from other sites, to reduce wind and water erosion. However, this may only offer a temporary solution. Complete removal of the material and soil washing to remediate the soil can be used though it is costly (Pilon-Smits 2005).

Declarations

Acknowledgement

I want to express my heartfelt gratitude to my Supervisors, Dr. Justin Maghanga and Dr. Mary Nelima, for their support, encouragement, and advice during my research. I would also like to express my appreciation to CEMEREM (Centre of Excellence for Mining, Environmental Engineering, and Resource Management) and DAAD (The German Academic Exchange Service) for offering me a scholarship.

Additionally, I would like to extend thanks to Miss Magdalene Wangui and Mr. Vincent Osebe from the Ministry of Mining (Madini House), who assisted me during sample analysis.

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Figures

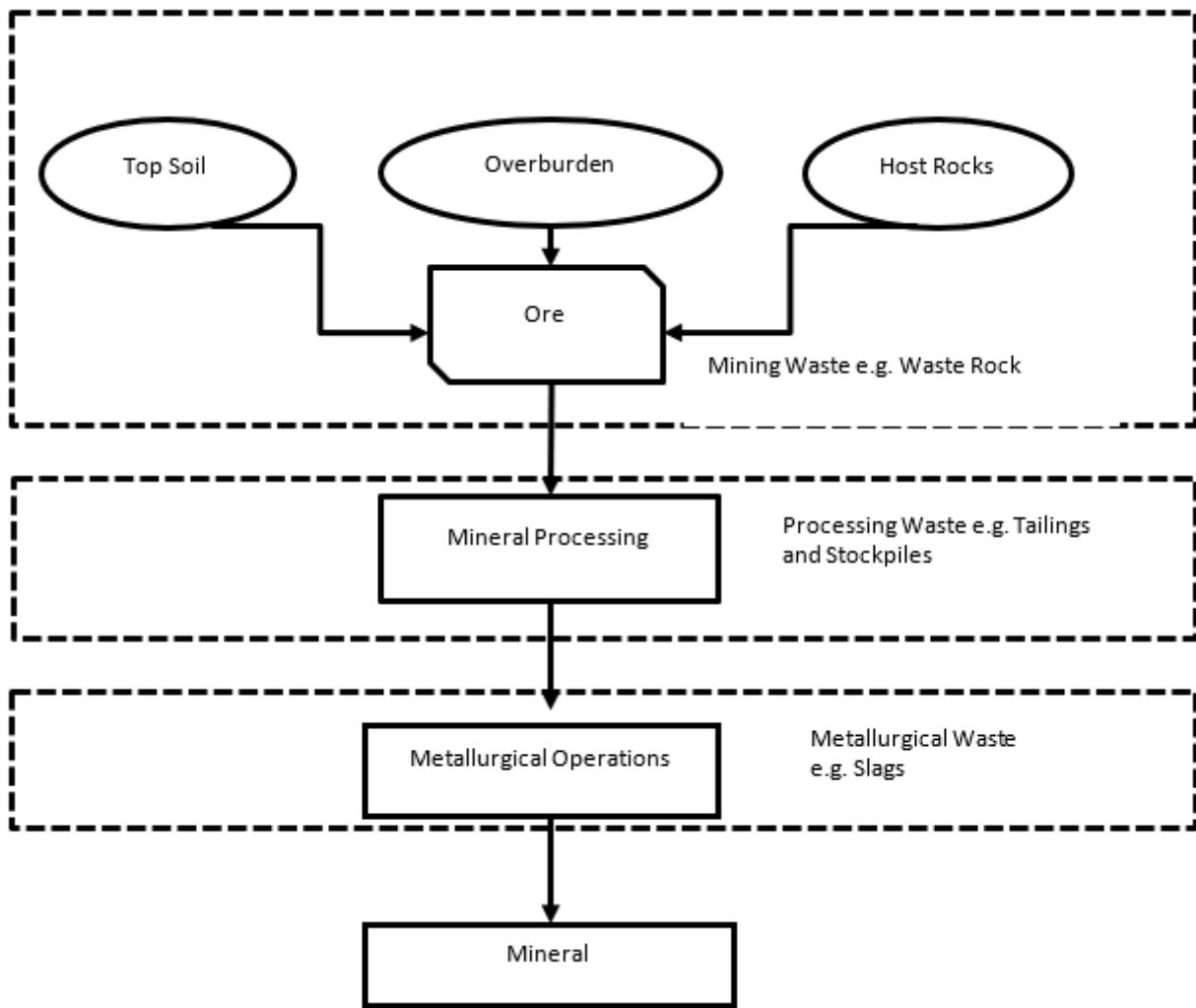


Figure 1

Waste Stream in the mining industry

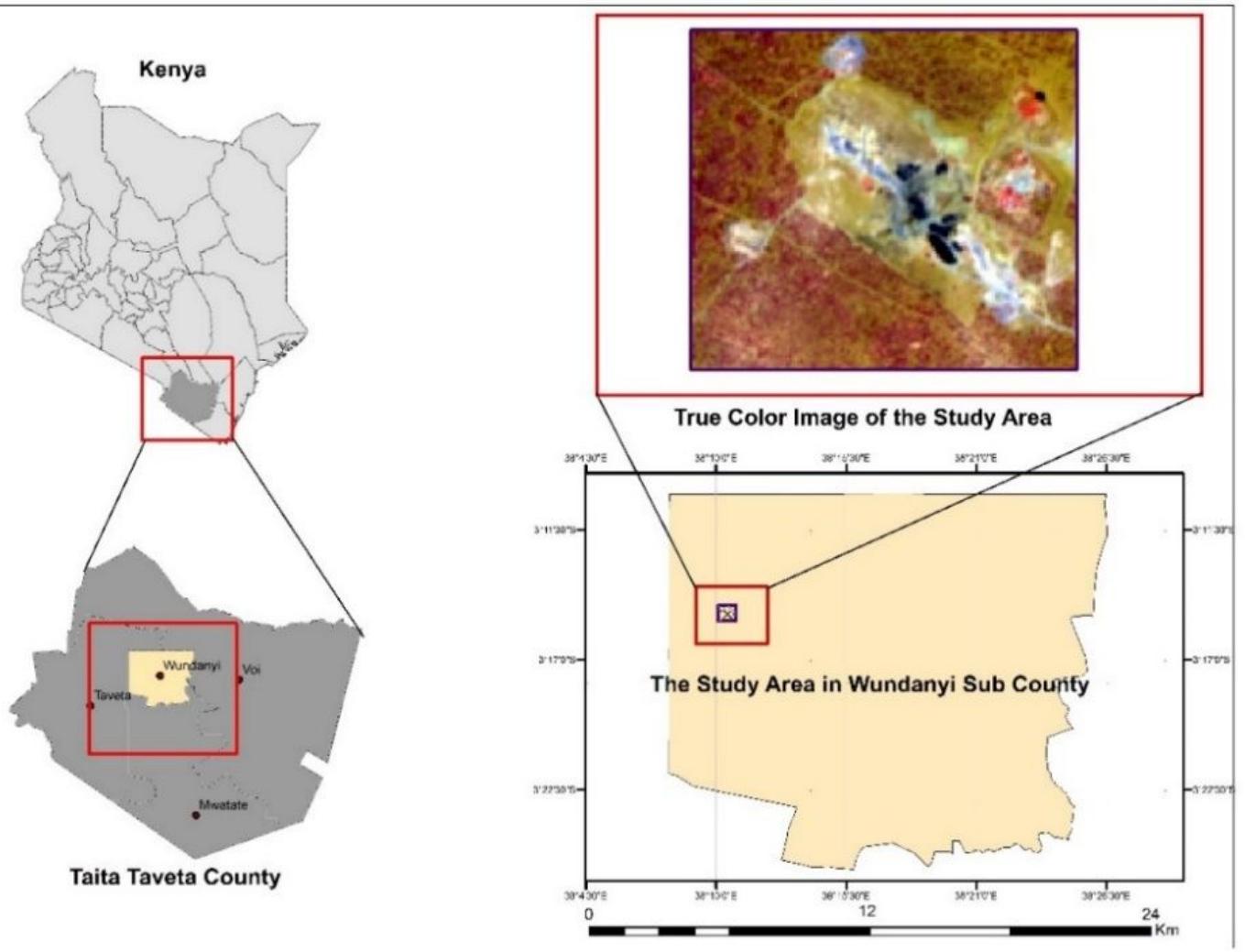


Figure 2

Map of the Study Area: Samrudha Resources, Taita Taveta County, Kenya

Elements/ Compound Present in the Waste Dumps

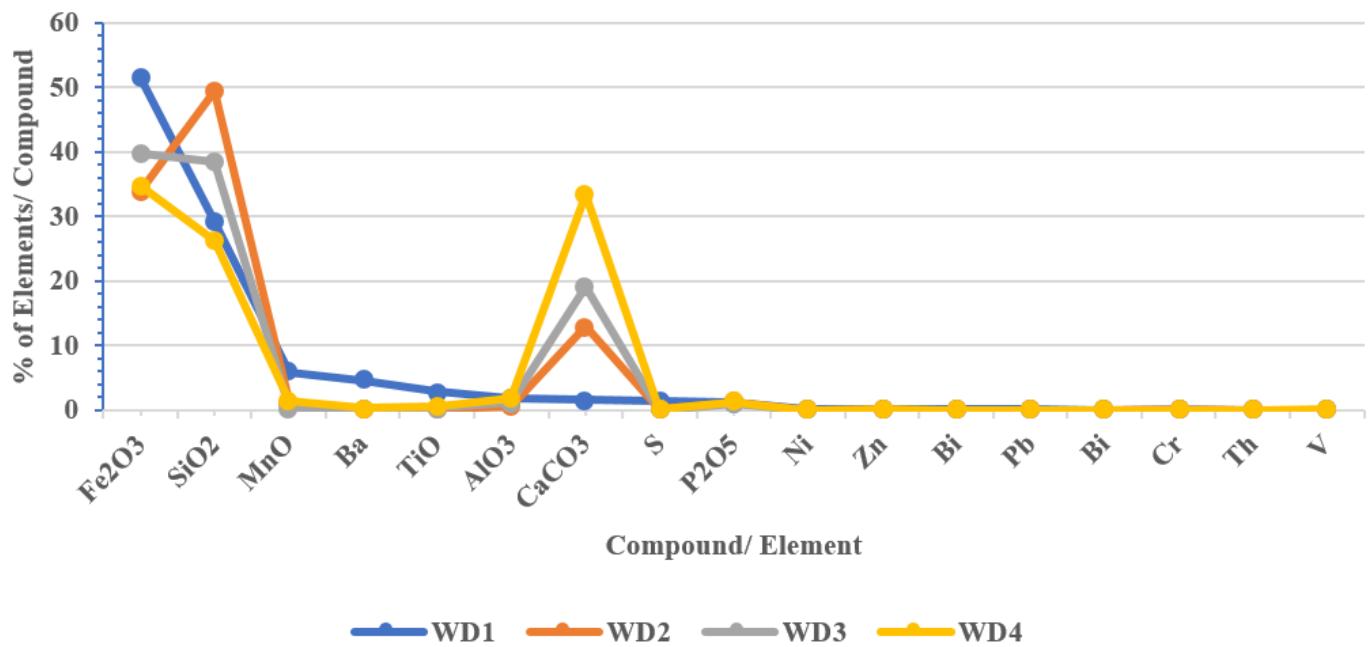


Figure 3

Waste dump samples showed high amounts of Fe₂O₃ (Avg. 39.92%) and moderate amounts of SiO₂ (Avg. 35.9%) and CaCO₃ (Avg. 16.8) with minor amounts of Vanadium (0.01%) and Bismuth (0.01%)

Elements/ Compound Present in the Stockpiles

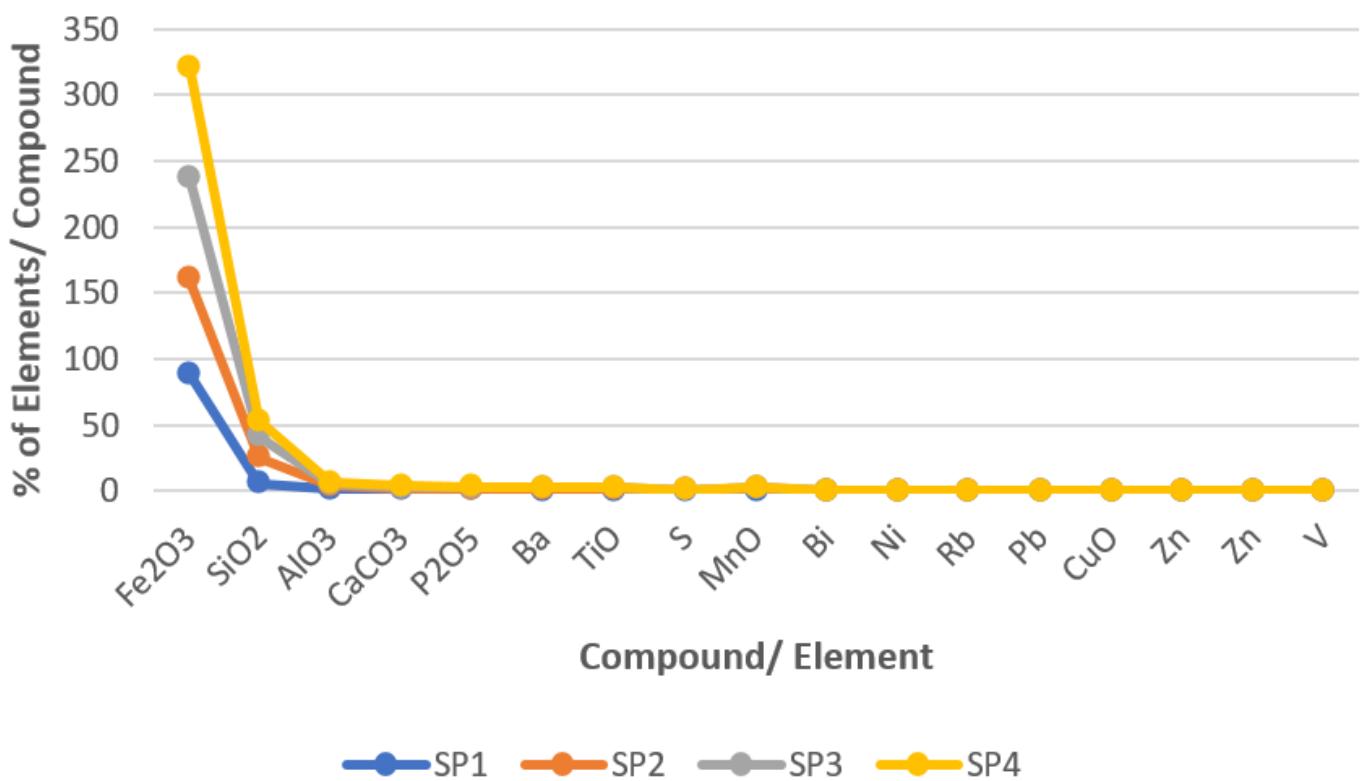


Figure 4

Stockpile Samples showed high amounts of Fe₂O₃ (Avg. 80.5%) and moderate amounts of SiO₂ (Avg. 13.3%) and Al₂O₃ (Avg. 1.7) with minor amounts of Zirconium (Avg. 0.0025%) and Vanadium (Avg. 0.005%)

Elements/ Compound Present in the Overburden

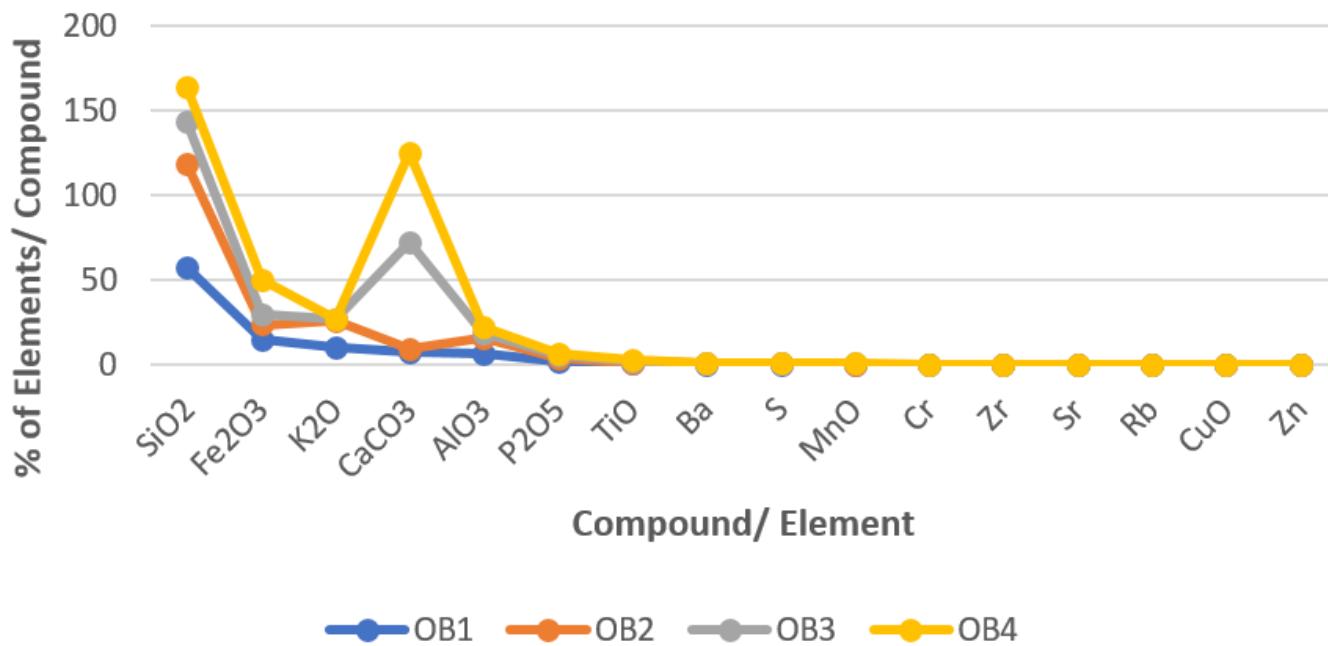


Figure 5

Stockpile Samples showed high amounts of SiO₂ (Avg.41.02%) and moderate amounts of CaCO₃ (Avg.31.1%) and Fe₂O₃ (Avg. 12.44%) with minor amounts of Zinc (Avg. 0.0075%) and Rubidium (Avg. 0.0175%)

(Coupled TwoTheta/Theta)

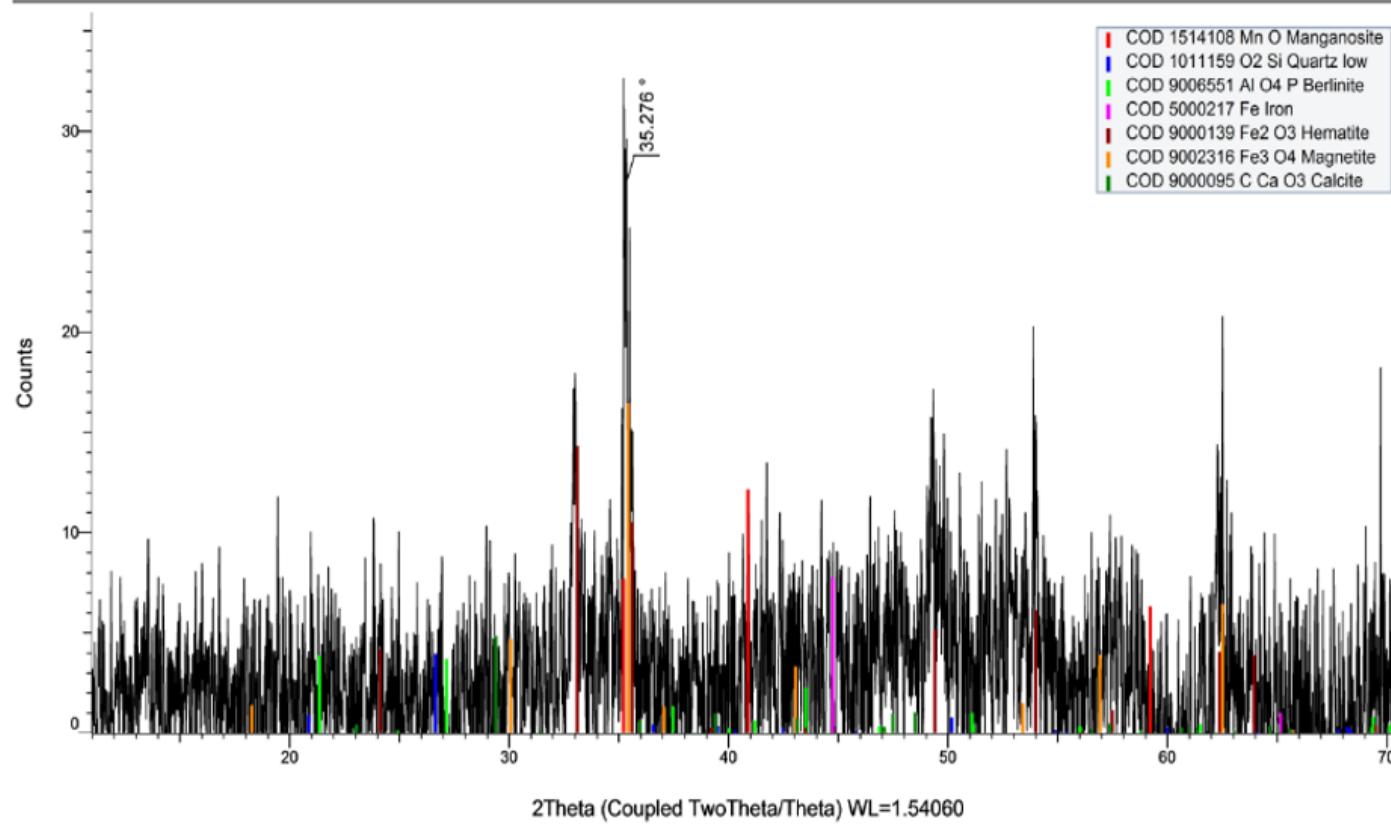


Figure 6

XRD analysis for Stockpile Sample revealed high phases of Hematite (Fe_2O_3), considerable amounts of Manganosite (Mn O) and Berlinite ($\text{Al O}_4\text{P}$), and low quantities of Quartz (Si O_2) minerals.

(Coupled TwoTheta/Theta)

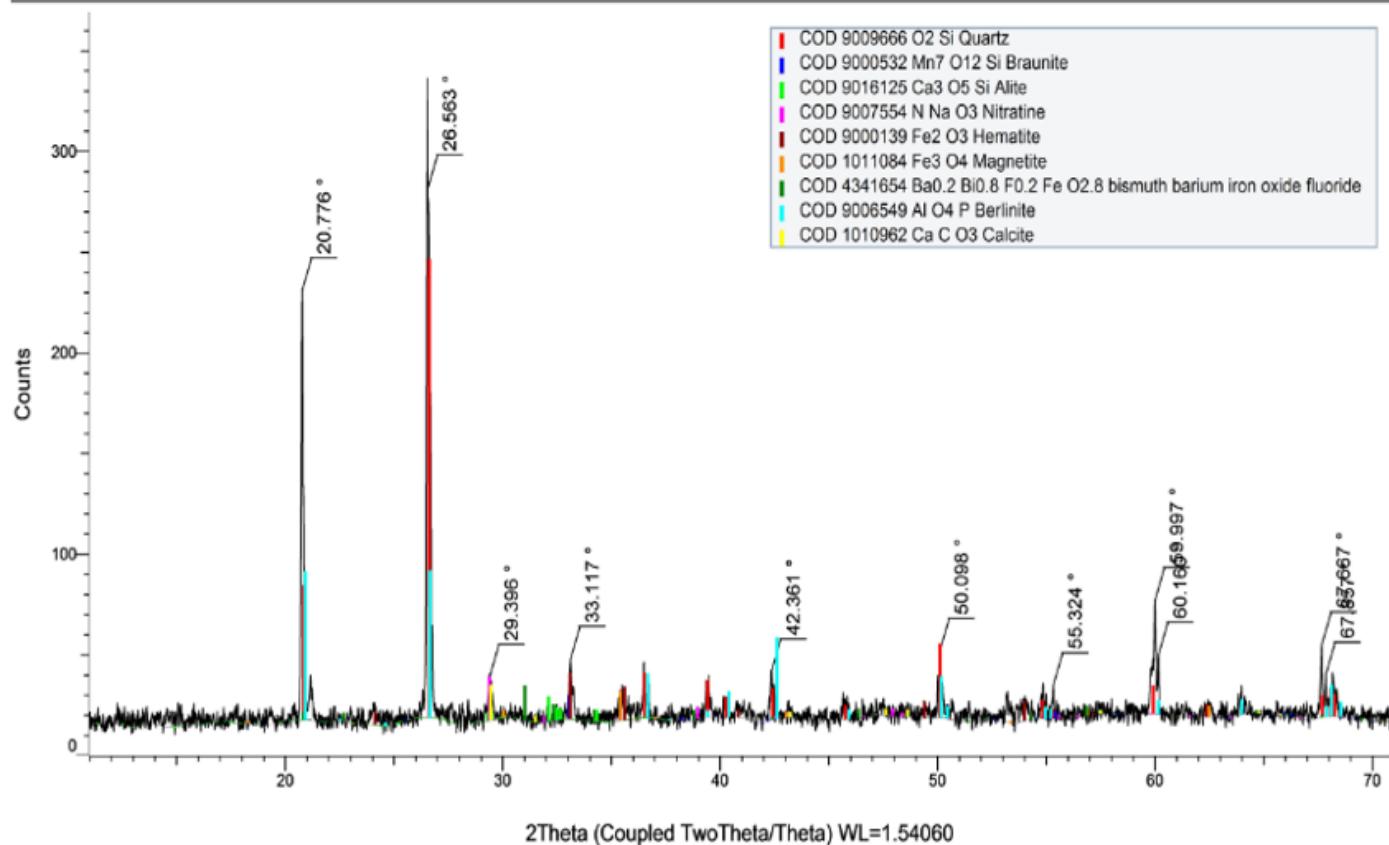


Figure 7

XRD analysis for Waste Dump Sample revealed high phases of Quartz and low phase of Braunite mineral.

(Coupled TwoTheta/Theta)

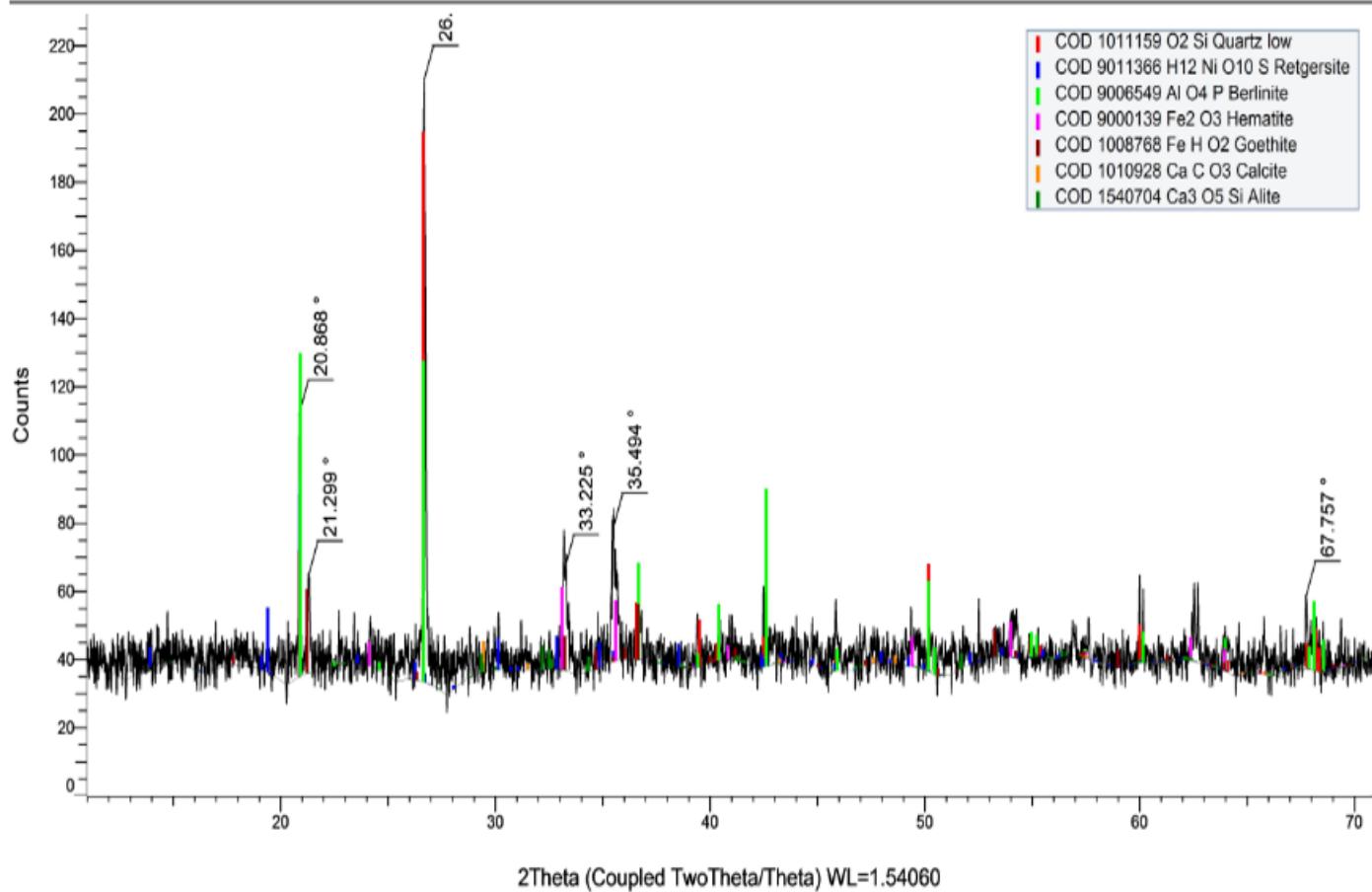


Figure 8

XRD analysis for Overburden Sample showed high phase of Berlinite, considerable phases of Retgersite and Goethite, and low phase of Hematite and Calcite.

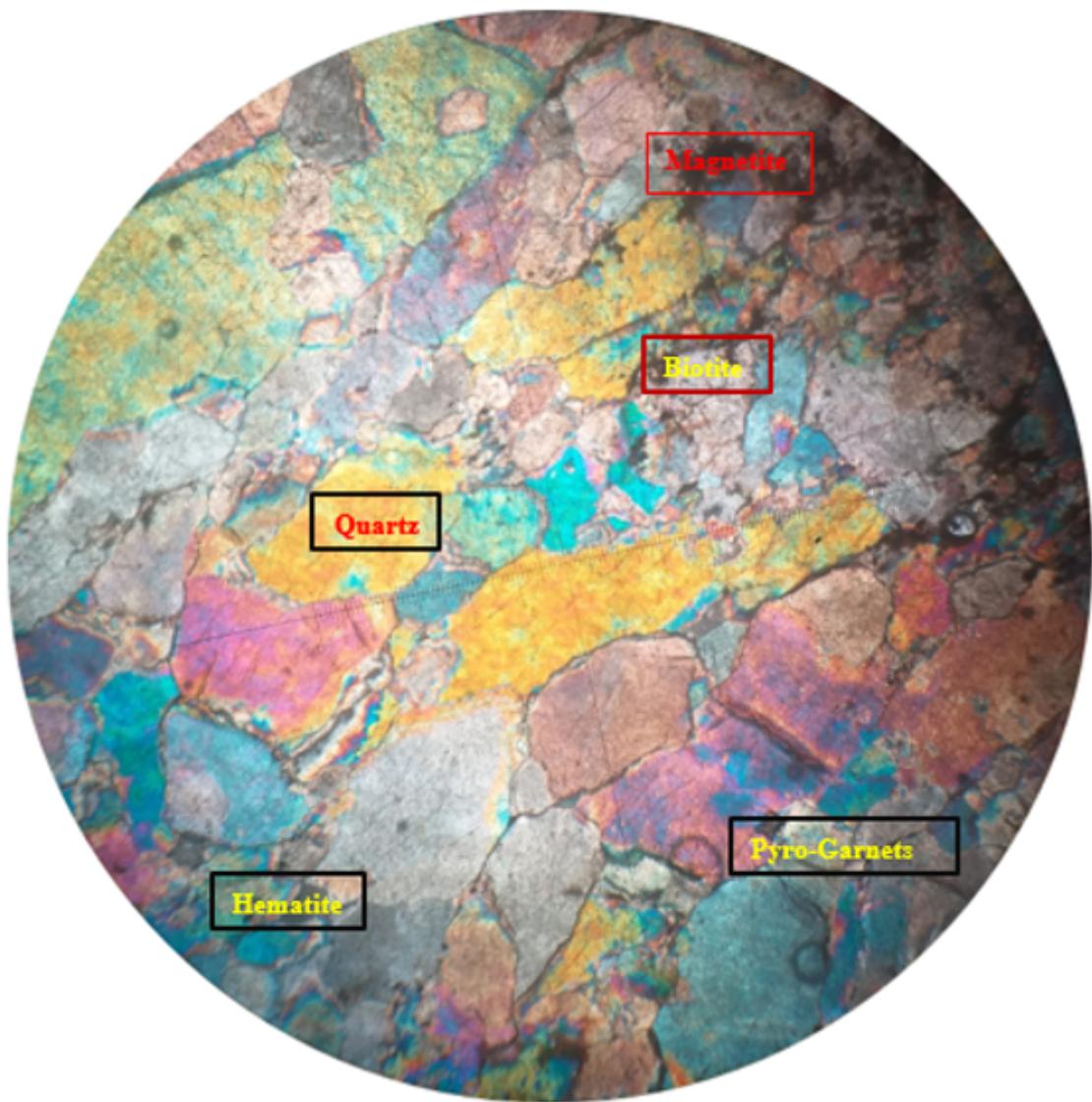


Figure 9

Thin section of Stockpile Sample 2 in X.P.L.

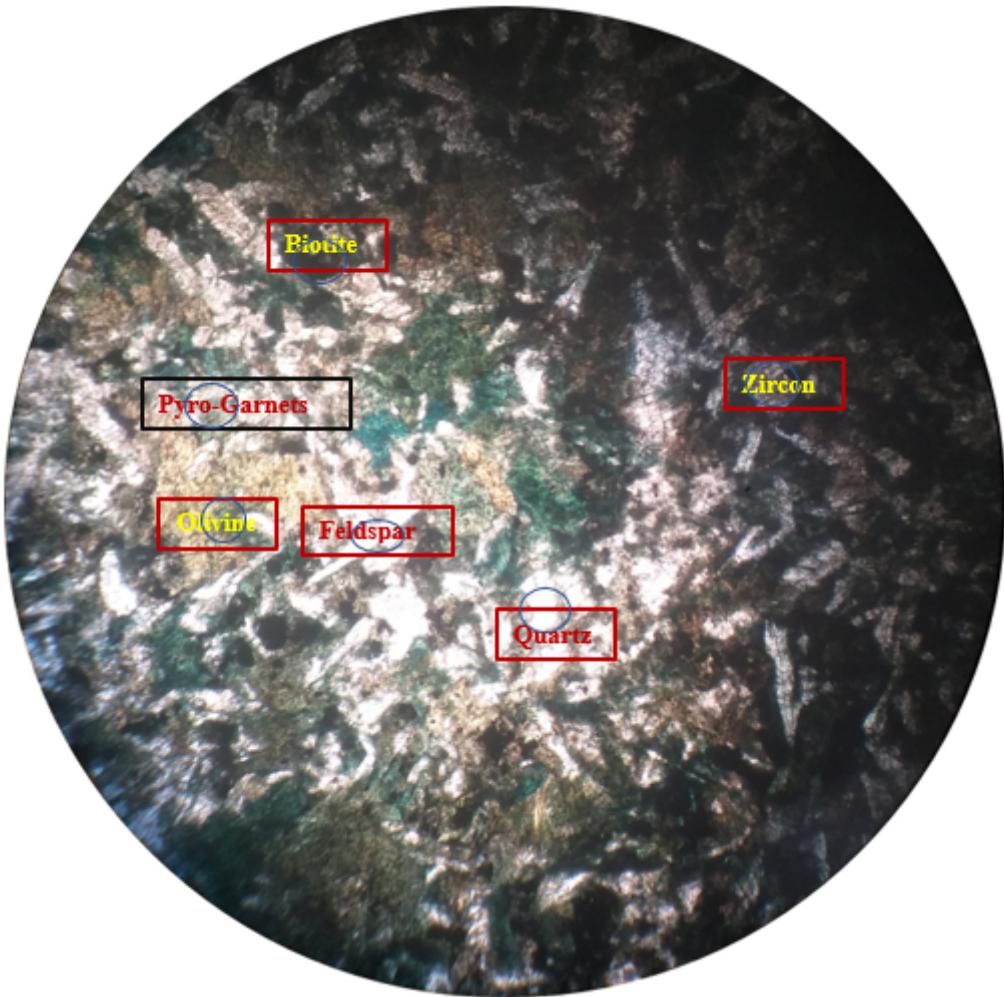


Figure 10

Thin section of waste dump Sample in PPL

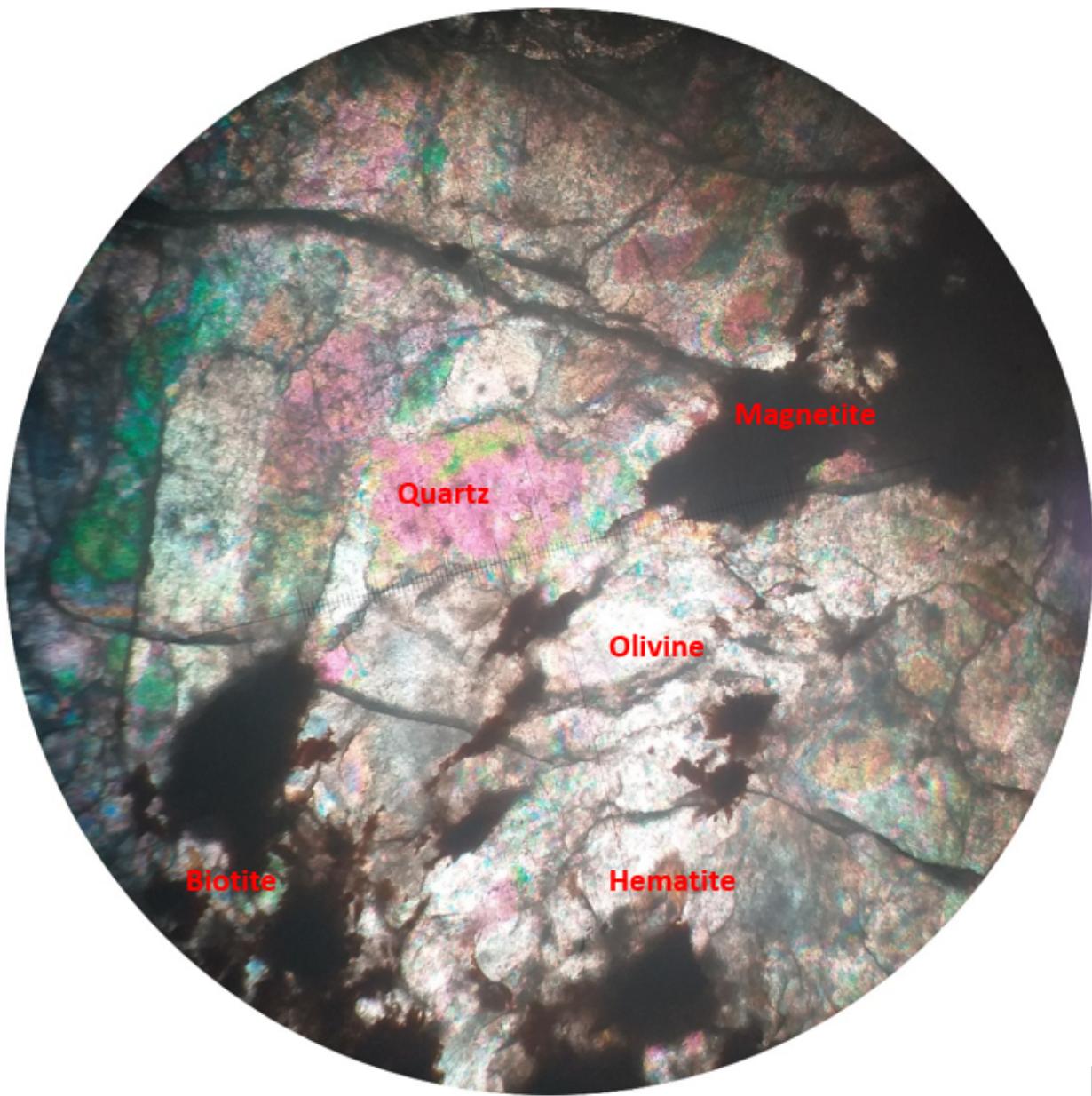


Figure 11

Thin section of Stockpile Sample 3 in X.P.L.

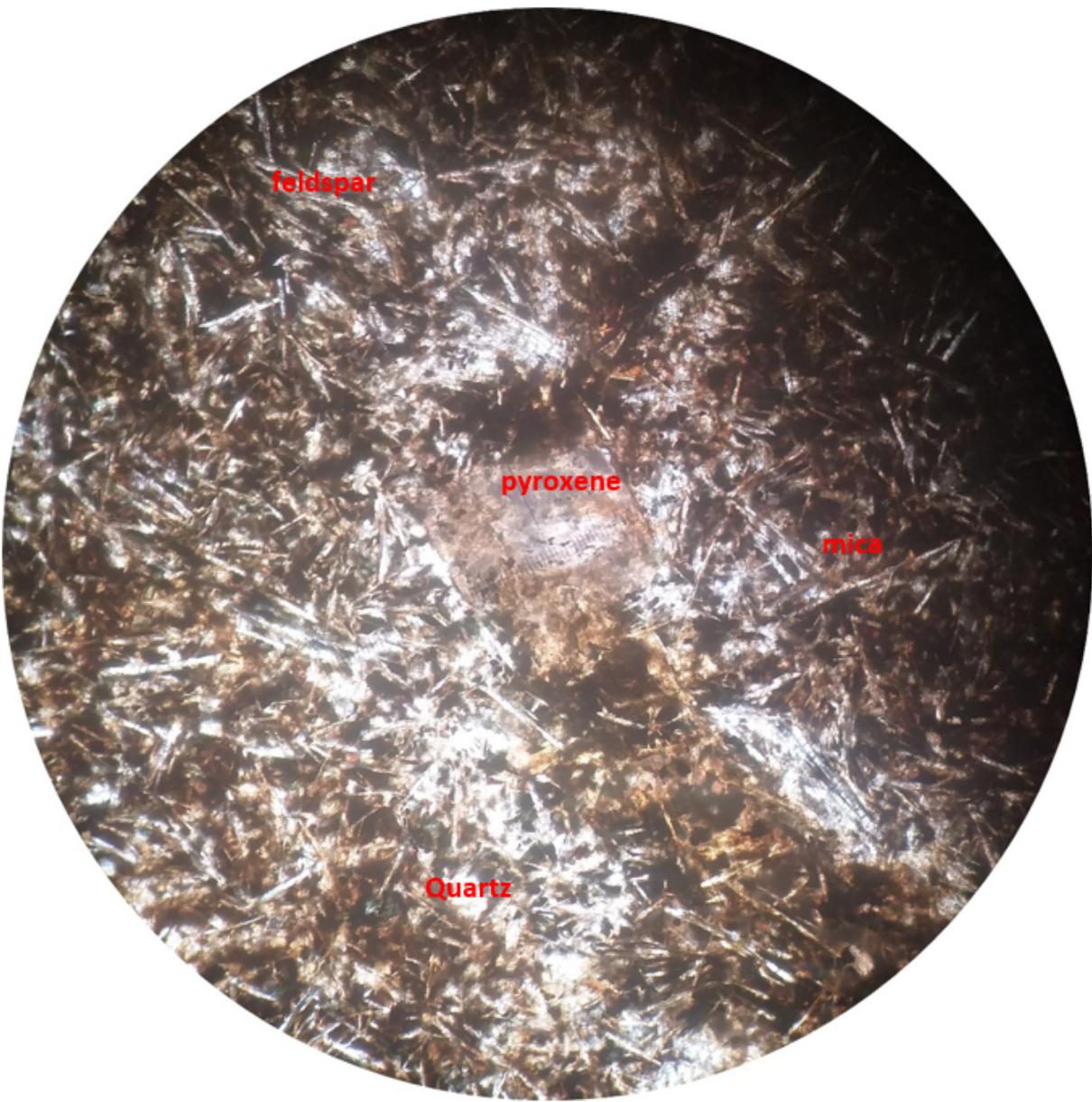


Figure 12

Thin section of Overburden material (O.B. 4) in X.P.L.

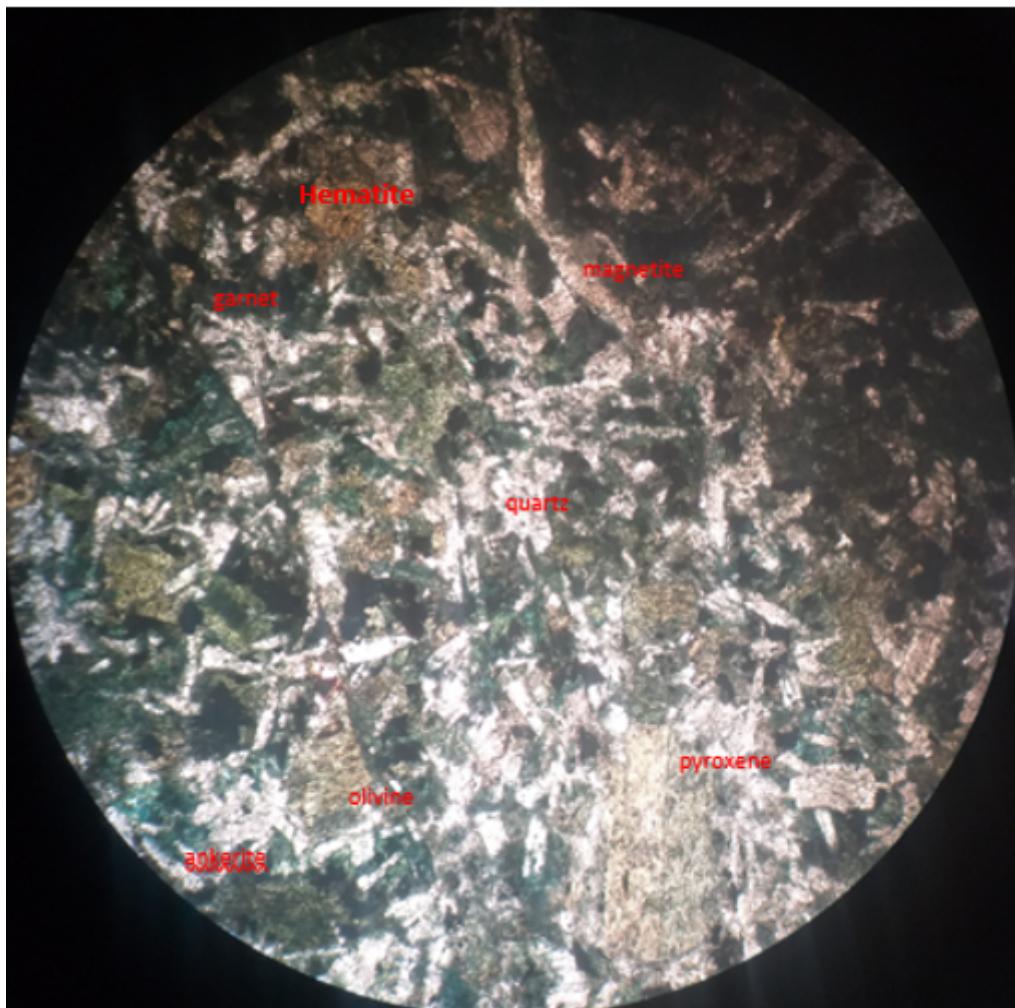


Figure 13

Thin section of Stockpile 1 (S.P. 1) in PPL