THE EFFECT OF GANGUE MINERALOGY ON THE DENSITY SEPARATION OF LOW GRADE NICKEL ORE

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Abstract

With the decrease over time of high grade, easy to process base metal sulfide ores, mineral processing operations have been forced to process low grade, disseminated and more mineralogically complex ores. Dense medium separation (DMS) is one of the techniques that can be used to upgrade low grade ores, such that they may become economic to process. The success of density separation however, is closely related to the mineralogy of the ore. The aim of this process mineralogy study is to investigate the effect of mineralogy on the DMS of ore from the Main Mineralised Zone (MMZ) of the Nkomati Nickel Mine in Mpumalanga, for which it was previously shown to be unsuccessful. The results from this study showed an overall upgrade of Ni from 0.4 to 0.7% Ni in the flotation feed sample, at a recovery of 87%.

A qualitative mineralogical characterisation of the over- and underflow showed that the original igneous minerals such as pyroxene and olivine increase in abundance in the higher density classes, whereas the abundance of the lower density alteration minerals e.g. chlorite, quartz and carbonates decrease. Pentlandite, which is the main host of nickel, is closely associated with pyrrhotite, both of which are recovered predominantly to the underflow. Particle density (determined by mineralogy, liberation and associations), particle size and particle shape were all noted as important factors controlling the separation and could be related back to the original ore textures (net-textured versus disseminated sulfides, granular versus flame pentlandite and degree of alteration). An understanding of the influence of these mineralogical factors on the separation efficiency of a centrifugal separator such as a dense medium cyclone and their variability in a geologically and mineralogically heterogeneous ore deposit, will aid in the effective processing of these low grade and complex base metal sulfide ores.

1. Introduction

Density separation is widely used to pre-concentrate ore minerals and reject unwanted gangue prior to the main processing stage of an ore (e.g. flotation). For base metal sulfide ores, dense medium separation (DMS) is used to separate the sulfide minerals, which are relatively dense, from the less dense silicate gangue minerals. With pre-concentration it is possible to reject a large portion of the run-of-mine (ROM) mass, with a metal grade that is equal to or less than the tailings grade that would have been achieved by the main processing stage, in this case, flotation (Creswell, 2001). The consequent metal upgrade of the feed can result in the exploitation of deposits previously considered to be uneconomic. The Tati Nickel Mine in

Botswana is an example of where Ni ore is successfully pre-concentrated using DMS before being fed into a flotation plant. Other benefits include the energy and cost savings due to the reduction of silicate gangue fed to the milling and flotation plant, as well as the improved feed grades that potentially result in improved metal recovery and concentrate grade. A reduction in the amount of silicate gangue introduced into the circuit will also lower the reagent costs associated with depressant addition (Creswell, 2001).

The efficiency of DMS varies according to the characteristics of the ore. For low grade ores with complex mineralogy, the properties of the gangue minerals are important factors that determine the behaviour of the ore during the separation. Process mineralogy is used as a tool during different stages of mineral processing to explain or predict the behaviour of ores. In this study, the focus is on the evaluation of low grade nickel deposits to qualitatively understand how mineralogical factors affect DMS. The Main Mineralised Zone (MMZ) of the Nkomati nickel deposit is used as a case study, as DMS was previously shown to be inefficient for this ore type (Sibanyoni, 2006). The mineralogical investigation is therefore concentrated on the properties of the gangue minerals and their influence on the DMS process.

2. Geology and mineralisation

The Uitkomst Complex is a layered mafic intrusion and a satellite body related to the intrusion of the Bushveld Igneous Complex, and host to the Nkomati mineralisation (Li et al., 2002). Structurally, the Uitkomst Complex is a plunging tubular body with a width and thickness of approximately 800 m and at least 8 km in length, and is made up of seven lithological units (Li *et al*., 2002). According to Sarkar *et al*. (2008) the oldest unit is the basal gabbronorite, which is overlain by the lower harzburgite, chromitiferous harzburgite, main harzburgite, pyroxenite, main gabbronorite and upper gabbronorite units.

The MMZ is hosted by the lower harzburgite unit and is one of the areas containing economic disseminated sulfide mineralisation. The lower harzburgite is a heterogenous unit consisting of different ultramafic rocks (igneous rocks composed mainly of ferromagnesian minerals e.g. olivine and pyroxene) including poikilitic harzburgite, feldspathic harzburgite, wehrlite, lherzolite, olivine websterite, and rare amphibolite (Sarkar *et al.*, 2008; Li *et al.*, 2002; Gary *et al.*, 1972). Numerous calc-silicate xenoliths occur in the host rock; these xenoliths are also sulfide-containing, mostly close to the contact with the host rock. This leads to variable lithology, textures and metal grades throughout the MMZ (Sibanyoni, 2006). The other areas containing sulfide mineralisation are the Basal Mineralised Zone (BMZ) within the basal gabbronorite unit and the Chromititic Peridotite Mineralised Zone (PCMZ) of the chromitiferous harzburgite (Bradford *et al*., 1998; Maier *et al*., 2004). The Massive Sulfide Body (MSB) is hosted by the sedimentary rocks and granite/gneiss below the intrusion (Theart and de Nooy, 2001).

The ore minerals occurring within the Uitkomst Complex are, in decreasing abundance, pyrrhotite, pentlandite, chalcopyrite, magnetite, ilmenite, chromite, digenite and pyrite. Minerals present in minor amounts include violarite, mackinawite, galena, sphalerite, platinum-group minerals, awaruite, native copper, arsenopyrite, cobaltite and millerite (Gauert et al., 1995). Pentlandite is the main host of nickel in the MMZ, with pyrrhotite containing small amounts of nickel in solid solution. Nickel concentrations range in magnetic pyrrhotite from 0.26 – 1.20 wt% and in non-magnetic pyrrhotite 0.55 – 0.90 wt% (Becker *et al.*, 2010). The pentlandite is commonly associated with pyrrhotite as flame-like exsolution lamellae but forms granular aggregates enclosed in, or interstitial to, the pyrrhotite as the nickel grade of the ore increases (Gauert *et al.*, 1995).

The economic Ni mineralisation is mined at the Nkomati Mine, where initial mining activity was centred on the MSB. More recently, the mining has been focused on the lower grade MMZ and PCMZ ores. Average nickel and copper grades for the MMZ are 0.66-0.68% and 0.22-0.24% respectively (Hammerbeck and Schürmann, 1998).

3. Methods

3.1 Sampling and sample preparation

The Nkomati MMZ ore was sampled from the conveyor belt leaving the primary crusher. The conveyor belt was halted and ~1 tonne of ore was sampled over a length of 3 m. The sample was crushed to -12 mm using jaw crushers. This particle size was chosen as this bulk sample is part of a larger comparative study using -12+1 mm DMC feed samples. The head sample was then blended and sub-sampled for chemical analyses by removing a 20 kg sub-sample and splitting it into two using a riffle splitter. This was further divided by a rotary splitter to produce a representative sub-sample of the original bulk ore. The remainder of the sample was then screened into -1 mm and -12+1 mm size fractions and each of these sub-sampled for chemistry. Samples submitted for chemistry were pulverised using a swing mill. A further 50 kg of the -12+1 mm sample was removed for heavy liquid separation (HLS) and the remainder of the -12+1 mm bulk sample was used for the DMS testwork.

3.2 Heavy liquid separation (sink-float analysis)

Laboratory heavy liquid separation (HLS) was carried out on a representative sub-sample of the ore, in order to establish whether a nickel upgrade could be achieved by density separation methods and at what density cut-point. The medium used was tetrabromoethane (TBE), which has a specific gravity (SG) of 2.96. TBE was diluted with acetone for lower density separations and -25 µm atomised ferrosilicon (FeSi) was added for separations higher than 2.96. The quality and size of the FeSi creates a stable suspension with a very low settling rate for the FeSi. The medium is therefore stable for the duration of the test, and the test is considered a perfect separation. The SGs used for the HLS were 2.7, 2.8, 2.9, 2.95, 3.0, 3.1, 3.2, 3.3 and 3.4 (Figure 1).

3.3 Dense medium separation

The bulk of the ore was put through a DMS plant, which consisted of a Multotec cyclone of 360 mm diameter with a 100 mm spigot. Cyclone 150D FeSi was used as a medium and the circulating feed density was recorded as 2.6 with a feed pressure of 100 kPa. The FeSi is continuously recycled during the running of the plant. The aim was to achieve a meaningful nickel upgrade to the dense medium cyclone (DMC) underflow in order to compare the mineralogical properties of the separation products. Sink-float analyses were then performed on the overflow and underflow to determine the efficiency of the separation.

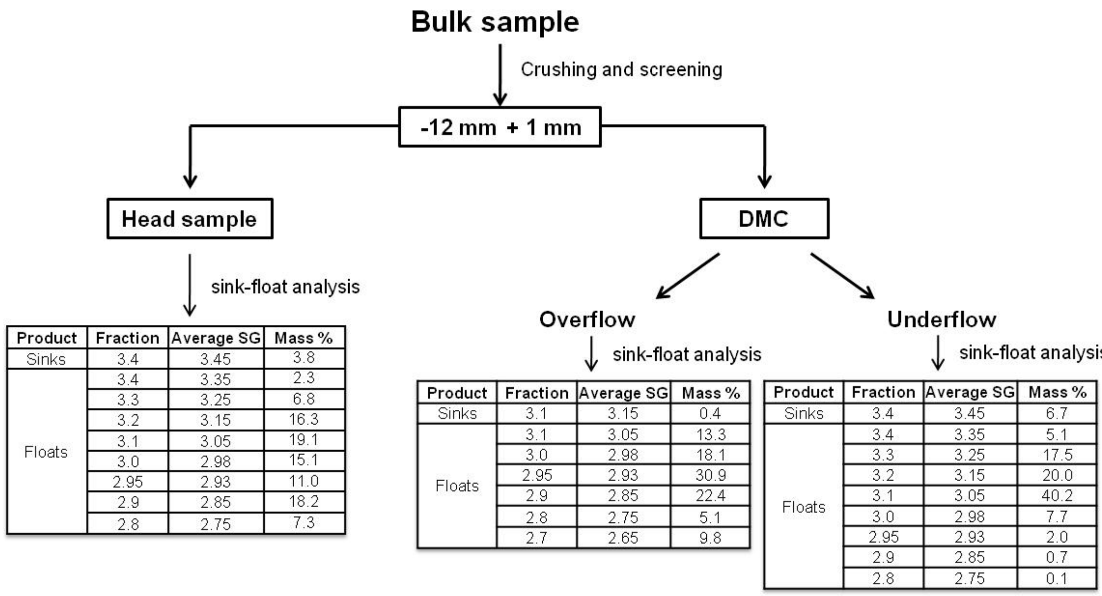

Figure 1 Derivation of samples for mineralogical analysis

3.3 Chemical analysis

The bulk ore samples and their products were analysed by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) for major elements, Cu and Ni. Total S was determined using “LECO” combustion.

3.4 X-ray diffraction

A representative split of each sample was pulverised and then micronised using a McCrone micronising mill. X-ray diffraction (XRD) analysis was used to determine the differences in the bulk mineralogy of each sample. A Bruker D8 Advance diffractometer with a Vantec detector was used at the University of Cape Town’s Chemical Engineering Department. Semi-quantitative mineral proportions were derived using the relative intensity ratio (RIR) method, which compares specific mineral peak intensities with the intensity of corundum (Hubbard and Snyder, 1988). The detection limit for this technique is approximately 3 mass %.

3.5 Petrography

Polished thin sections were prepared for transmitted and reflected light microscopy in order to qualitatively observe the textures and associations between the ore and gangue minerals. The microscopic observations were also used to confirm the presence of minerals detected by XRD, and identify those below the XRD detection limit.

4. Results: Heavy Liquid Separation

The sink-float analysis results on the head sample indicate that, at a density cut-point of 3.0, 48 mass % of the ore reported to the sinks and 52% to the floats (Figure 2). The Ni head grade was measured at 0.4% and the cumulative grade achieved at a cut-point SG of 3.0 is 0.74% at a recovery of 83%. This density cut-point was chosen for the DMS testwork in order to maximise the waste rejection while obtaining a low Ni grade in the overflow.

The pentlandite and pyrrhotite grades and recoveries that would be expected in the DMC underflow at a cut-point of 3.0 have been estimated from the results of the sink-float analysis on the head sample (Figure 3). This has been calculated assuming that pentlandite is the only host of Ni in the sample and chalcopyrite is the only Cu mineral present. These mineral proportions were then calculated based on the Ni and Cu grades of each density class and their combined S content subtracted from the total S grade of each sample. The remaining S was assigned to pyrrhotite and the pyrrhotite abundance calculated based on the amount of S available. The ideal chemical compositions of these minerals were used for the calculations. A pentlandite grade of approximately 2% should be present in the underflow, with a recovery of 83%. The pyrrhotite grade is estimated at ~12%, with an 88% recovery.

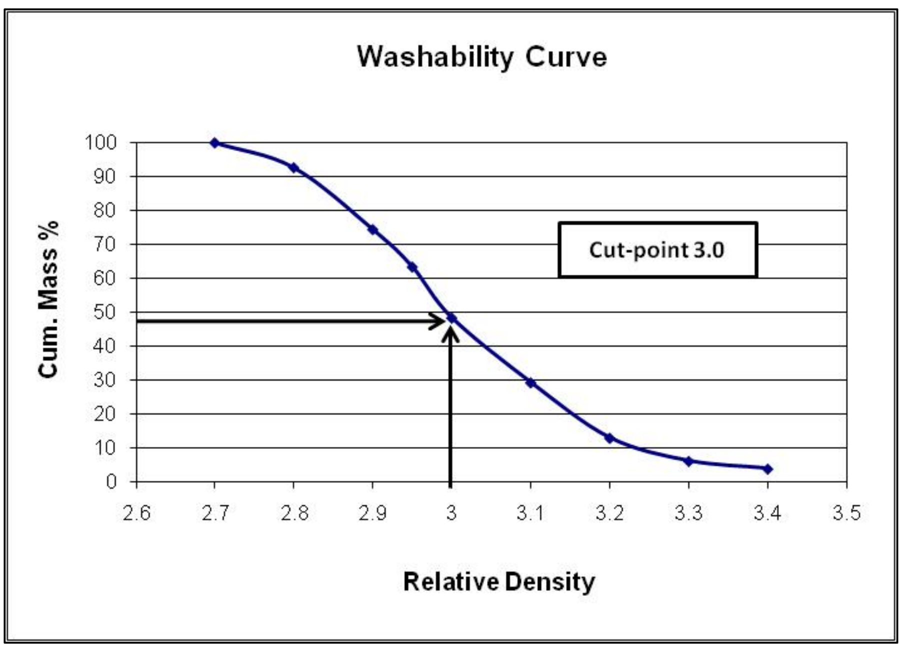

Figure 2 Washability curve (left) and grade and recovery curves for Ni and Cu (right)

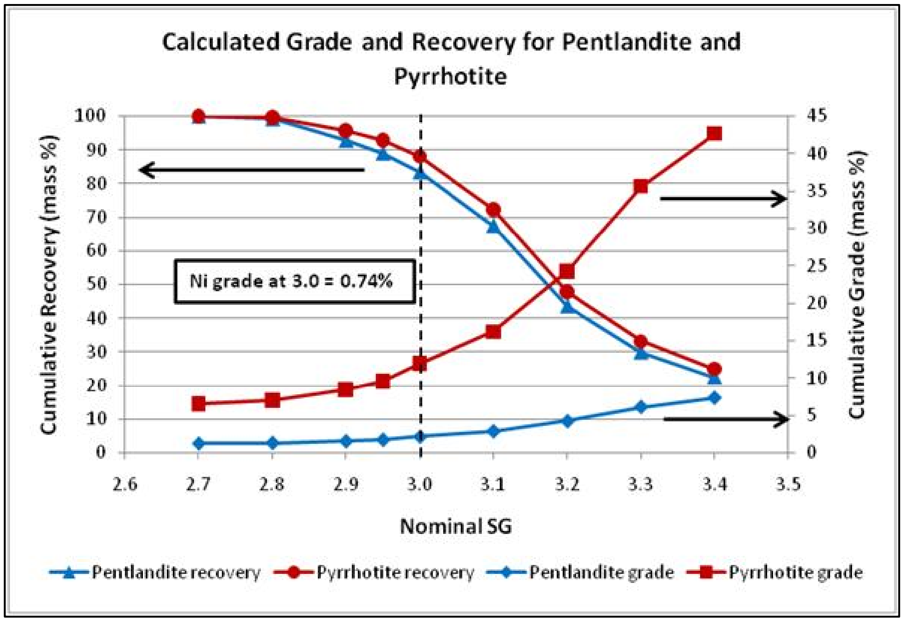

Figure 3 Cumulative grade and recovery curves calculated for pyrrhotite and pentlandite from the sink-float analysis

5. Results: Dense Medium Separation

A summary of the DMS results is given in Table 1. The mass recovery to the sinks was 48% at a density cut point of 3.0 g/cm^3, which is in agreement with preliminary HLS testwork conducted on the feed sample. The Ni was upgraded from 0.39% to 0.67% at a recovery of 83%. No significant Cu upgrade was achieved.

Table 1 Summary of DMS testwork at a cut point of 3.0 g/cm

Fraction	Mass	Grade [%]			Recovery [%]		
	[%]	S	Cu	Ni	S	Cu	Ni
Sinks	48	5.63	0.23	0.67	85	68	83
Floats	52	0.95	0.10	0.13	15	32	17
Total (Feed)	100	3.20	0.16	0.39	100	100	100

The Ni grades and recoveries, as well as mass distribution of the bulk sample, were calculated for different streams of the flowsheet, from the ROM material to the calculated flotation feed sample (Figure 4, Table 2). The data have been mass-balanced with variability in the measured and smoothed grades less than 5%.

Overall the Ni showed a 54% upgrade from 0.4% in the ROM to 0.7% in the flotation feed, with an 87% Ni recovery to the flotation plant. Approximately 44% of the ROM mass was rejected in the DMC overflow, with the Ni grade of the overflow at 0.1%.

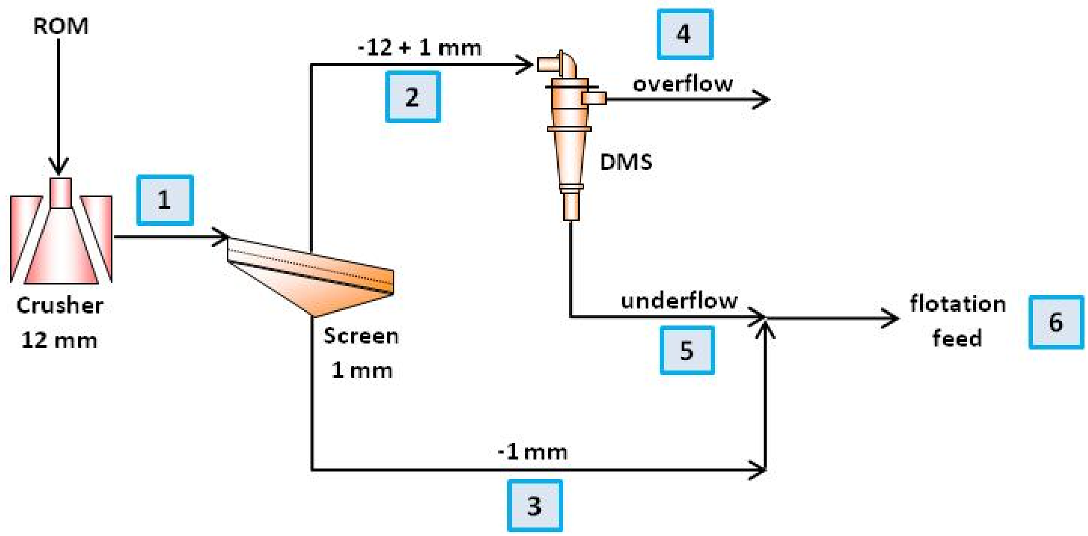

Figure 4 Flowsheet for the testwork showing different streams

Table 2 Mass, grade and recovery information at different points in the flowsheet

Stream No.	Stream Name	Mass [%]	Ni Grade [%]	Ni Recovery [%]
1	ROM	100	0.43	100
2	-12+1mm	84	0.39	76
3	-1mm	16	0.62	24
4	DMC overflow	44	0.13	13
5	DMC underflow	40	0.67	63
6	Flotation feed	56	0.66	87

Partition coefficients were calculated from the sinks-float analysis results in order to plot a partition curve. This describes the efficiency of the DMS process. The partition coefficient is the percentage of the feed of a specific density that reports to the underflow; in a partition curve this is plotted against particle density. In an ideal separation, all particles with a density higher than the separating density report to the sinks, and the lighter material to the floats, without any particles being misplaced. In an actual separation, particles far from the separation density are effectively separated and near density material is less efficiently separated (Wills, 2006).

From the partition curve, the probable error of separation or the Ecart probable (Ep) is calculated. This is half the difference between the densities where 75% and 25% is recovered to sinks (Wills, 2006). The lower the Ep, the more efficient the separation is. The Ep calculated from the MMZ results is 0.04, which shows an efficient separation (Figure 5).

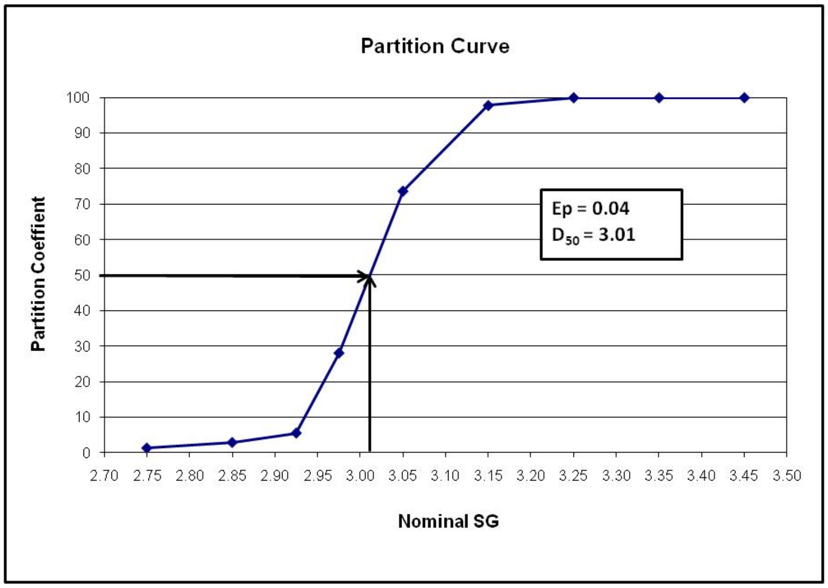

Figure 5 Partition curve for the DMS

5. Results: Mineralogy

5.1 Bulk mineralogy

The dominant silicate minerals present in the Nkomati MMZ ore are chlorite, serpentine, amphibole, clinopyroxene, talc and quartz. Pyrrhotite, pentlandite and chalcopyrite are the dominant sulfides, with minor pyrite, sphalerite and arsenopyrite (Figure 5, Table 4).

Electron microprobe analyses were used for attaining specific mineral names for some of the gangue minerals. Chlorite was identified as the Mg-Fe-Al variety, clinochlore. Most of the plagioclase in the samples is of albite (Na-plagioclase) composition. Two calcic amphiboles were identified – tremolite (Mg-rich) and actinolite (Fe and Mg). The clinopyroxene was identified as augite.

In general, the DMC overflow contained larger proportions of the less dense minerals quartz, plagioclase, chlorite and calcite (SG = 2.62 -2.71) compared to the sinks, as determined by XRD analysis (Figure 5). Clinopyroxene (SG = 3.40) was below the XRD detection limit (~3 mass %) in the overflow. This proportion indicates a good separation of the denser silicate minerals towards the sinks, although XRD measurements show bulk mineralogy only and are independent of liberation state. Similarly, a good separation of the sulfide minerals also occurred towards the underflow. No sulfides were detected by XRD in the DMC overflow.

Little difference was noted in abundance between the overflow and the underflow for those minerals of a density similar to the cut point of 3.0 (amphibole, biotite).

XRD analyses of the various HLS floats and sinks fractions are illustrated in Figures 6 and 7. Similarly to the bulk analyses, the floats show the abundance of the lighter minerals, quartz, chlorite, calcite and plagioclase which decreases steadily towards the density cut point of 3.0 where amphibole is the most abundant silicate mineral (Figure 6). The DMC underflow shows an increase in the abundance of the denser silicate minerals (e.g. clinopyroxene), in addition to a marked increase in the abundance of pyrrhotite and pentlandite. Olivine and magnetite were not detected by XRD.

Table 4 List of minerals present in the Nkomati MMZ ore and their average SG

Mineral	Ideal Chemical Formula	SG
Plagioclase	$(Na,Ca)Al(Si,Al)_3O_8$	2.62
Clinopyroxene	$(Ca,Na)(Mg,Fe,Al,Ti)(Si,Al)_2O_6$	3.40
Orthopyroxene	$(Mg,Fe)_2Si_2O_6$	3.55
Olivine	$(Mg,Fe)_2SiO_4$	3.27
Amphibole	$Ca_2(Mg,Fe)_4Al(Si_7Al)O_{22}(OH,F)_2$	3.04
Chlorite	$(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2$	2.65
Serpentine	$Mg_3Si_2O_5(OH)_4$	2.53
Talc	$Mg_3Si_4O_{10}(OH)_2$	2.75
Dolomite	$CaMg(CO_3)_2$	2.84
Calcite	$CaCO_3$	2.71
Quartz	SiO_2	2.62
Biotite	$K(Mg,Fe)_3AlSi_3O_{10}(OH,F)_2$	3.09
Zoisite	$Ca_2(Al,Fe)Al_2(SiO_4)(SiO_7)(O,OH)_2$	3.40
Ilmenite	$FeTiO_3$	4.72
Magnetite	Fe_3O_4	5.20
Chromite	$FeCr_2O_4$	4.79
Pyrrhotite	$Fe_{1-x}S$	4.61
Chalcopyrite	$CuFeS_2$	4.10
Pentlandite	$(Fe,Ni)_9S_8$	4.80
Sphalerite	ZnS	4.08
Pyrite	FeS_2	5.01
Arsenopyrite	$FeAsS$	6.07

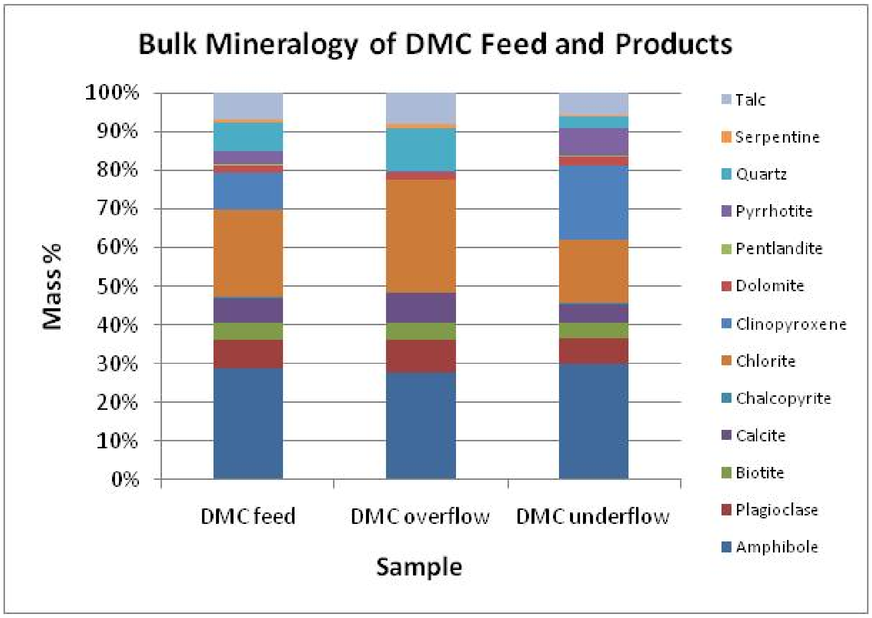

Figure 5 Recalculated bulk mineralogy for the DMC feed, overflow and underflow

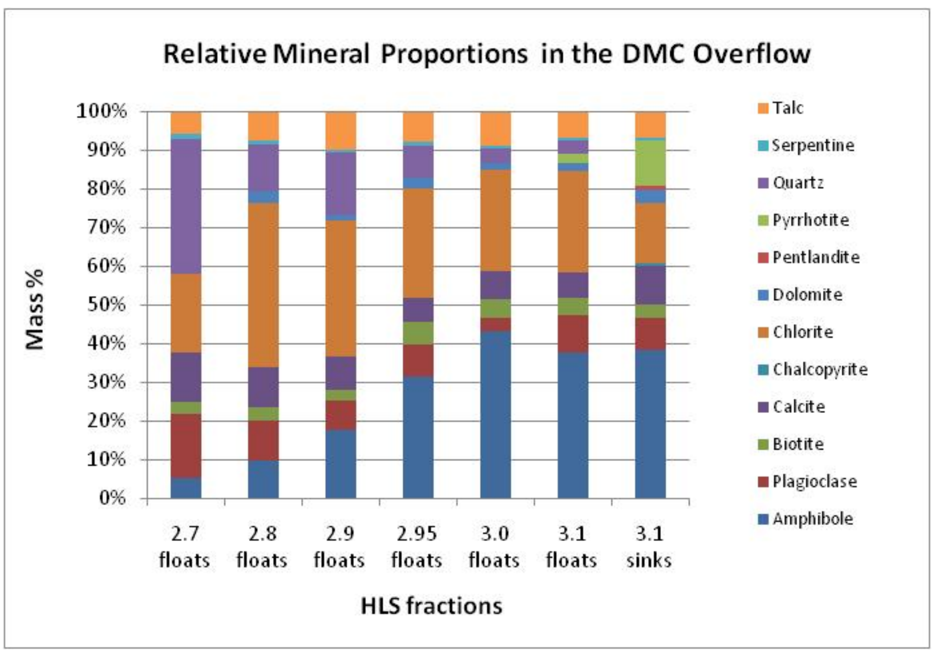

Figure 6 Relative proportions of minerals in the DMC overflow

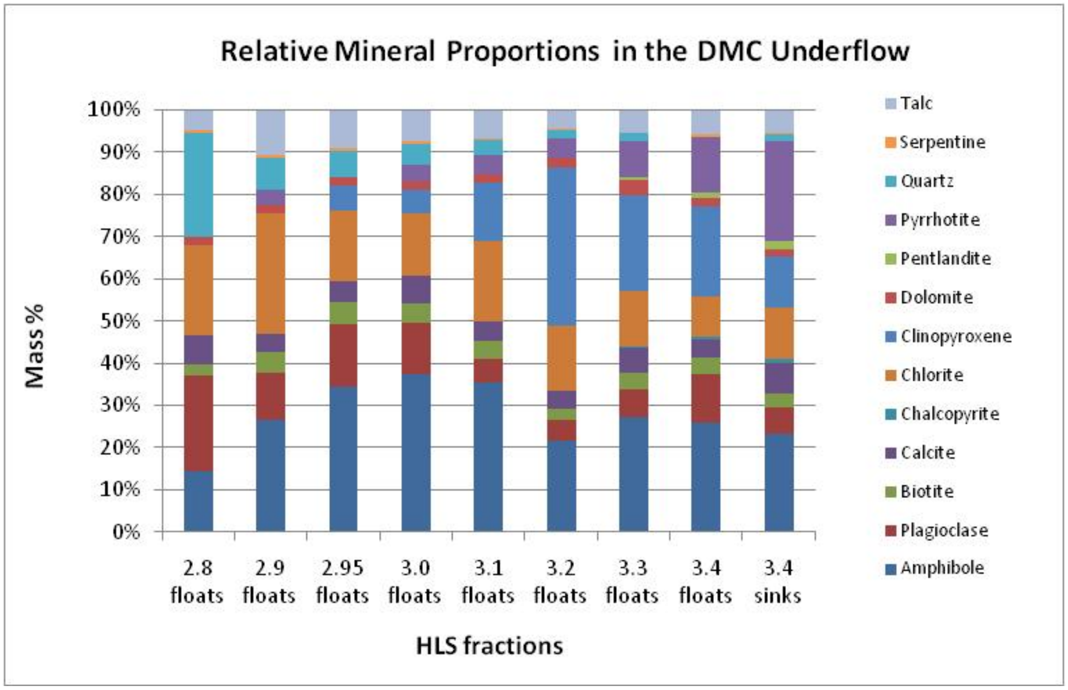

Figure 7 Relative proportions of minerals in the DMC underflow

5.2 Mineral textures

Petrographic examination of the MMZ samples showed that they are medium-grained and a variety of textures were observed. Cumulate textures are common and represented by rounded or euhedral olivine and pyroxene crystals as the cumulus minerals, usually with intercumulus plagioclase (Figure 8). In many of the samples studied, the original mafic igneous minerals have been altered to metamorphic minerals, mostly serpentine (chrysotile), talc, chlorite and actinolite (calcic amphibole). Alteration rims of serpentine can sometimes be seen surrounding olivine crystals in thin section. Amphibole in these samples is also found as uralite, a fine-grained alteration product of clinopyroxene, which maintains the form of the pyroxene crystal. Plagioclase is commonly altered to saussurite (fine-grained mass that may include clays, epidotes, chlorite, mica and calcite). In these cases the cumulate texture has been preserved by the alteration minerals.

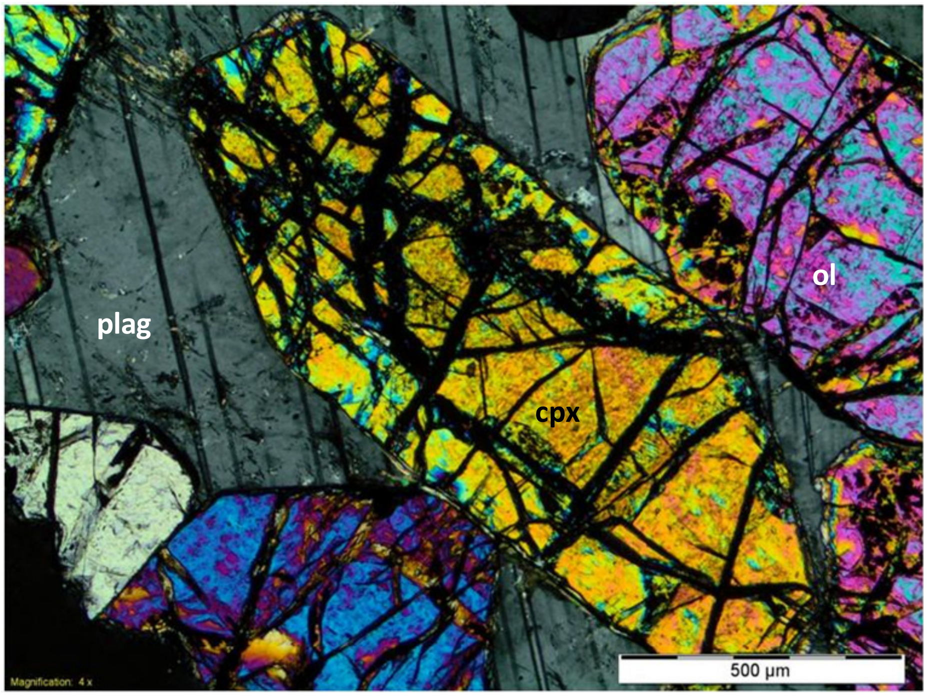

Figure 8 Clinopyroxene (cpx) and olivine (ol) crystals with intercumulus plagioclase (plag) at the edge of a particle; transmitted light, crossed polarised (DMC underflow, 3.1. floats)

The sulfide minerals in the MMZ ore occur as net-textured and disseminated sulfides. MMZ. Microscopically, the net-textured sulfides are generally seen to have formed interstitial to the cumulus minerals (Figure 9AError! Reference source not found.). Magnetite is commonly associated with the sulfides in this instance, especially at the contact with serpentine, where both magnetite and serpentine have formed by the alteration of olivine. Pentlandite, the Ni ore mineral occurs in two major forms throughout the samples, most commonly as granular aggregates and also as flame-like exsolution lamellae in pyrrhotite (Figures 9B and C). Some remobilisation of the sulfides is noted associated with deformation of the ore, occurring as disseminated sulfides (pyrrhotite, chalcopyrite) penetrating the cleavage planes of silicate minerals (e.g. actinolite, Figure 9D).

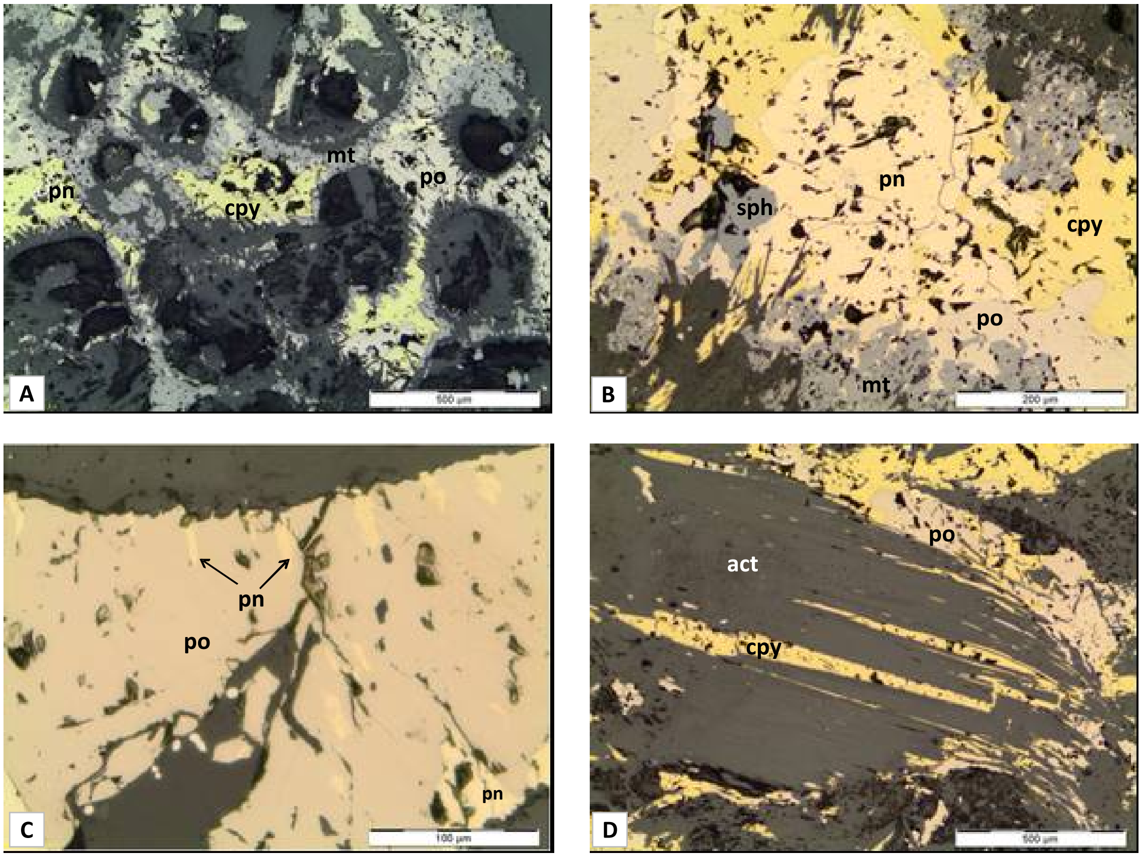

Figure 9 Sulfide mineral textures (reflected light, plane polarised) **A** Net-textured sulfides – chalcopyrite (cpy), pyrrhotite, (po), pentlandite (pn) and magnetite (mt) interstitial to serpentine (dark grey); **B** Granular pentlandite associated with chalcopyrite, pyrrhotite sphalerite (sph) and magnetite; **C** Pentlandite flames in pyrrhotite; **D** Chalcopyrite and pyrrhotite dissemination along actinolite (act) cleavage planes

5.3 Grain size and liberation characteristics

Grain sizes and liberation were qualitatively estimated by optical microscopy. Sulfide liberation is therefore described here as the area percent of total sulfides in a particle, as seen on a two dimensional surface. Chalcopyrite is also included as it is closely associated with pentlandite and pyrrhotite.

The grain size of pyrrhotite increases steadily from the lower to the higher density classes in both the DMC overflow and underflow. In the DMC overflow the average pyrrhotite grain size increases from approximately 70 µm in the HLS 2.7 floats to ~580 µm, which reported to the subsequent HLS 3.1 sinks fraction. The largest pyrrhotite grain found in the DMC underflow is ~1.6 mm, as observed in the subsequent HLS 3.1 floats fraction. In the DMC underflow pyrrhotite is generally larger than in the overflow per density class, reaching up to 4.6 mm in the 3.4 sinks fraction.

Pentlandite grain sizes also increase with higher density fractions but show a slightly erratic distribution compared to pyrrhotite. The grain size distribution generally depends on the

occurrence of the pentlandite in the sample. Flames are the more dominant occurrence in the lower density classes, where most of the sulfides are disseminated and the average size measured for pentlandite flames in the samples is 3x30 µm. Granular pentlandite reaches up to ~2 mm in size in the 3.4 HLS sinks fraction of the DMC underflow. Pentlandite is always associated with pyrrhotite in these samples. Similar grain size trends were observed with chalcopyrite and pyrite.

In general, an increase in sulfide grain sizes corresponds to a change in texture from disseminated to net-textured, which leads to increased liberation. Pyrrhotite is the strongest control on sulfide liberation and therefore Ni recovery, because of its abundance. Pentlandite is the main host of Ni in the ore and its successful pre-concentration depends on the recovery of pyrrhotite.

The DMC underflow shows poor liberation of sulfides in most density fractions except for the densest (3.1 sinks). The sulfides are generally locked in silicates (~ 10% liberated). The 3.1 sinks fraction contains particles with varying degrees of liberation from locked to completely liberated (100%). These particles were not recovered to the DMC underflow possibly because of their size. Most of the particles in this sample are < 2 mm in size and approach the particle size range at which the efficiency of the DMS is poor.

The total sulfide liberation in the DMC underflow is much higher than in the overflow, except at the lowest density classes where all the sulfides are completely locked in gangue. Most of the particles found in the lighter fractions of the DMC underflow are elongate in shape. The sulfide minerals are most commonly associated with the original minerals of the ultramafic rock – pyroxene, olivine and their alteration products (usually serpentine and amphibole). There is also a strong sulfide association with magnetite in most samples. In the higher density classes, where sulfide liberation is generally in the middlings (30-80%) or liberated (80-100%), some sulfide-free silicate particles have still been recovered to the underflow due to their inherent density (> 3).

6. Discussion

The MMZ is made up of a variety of ultramafic rock types with abundant calc-silicate, dolomite, quartzite and granite xenoliths that contaminate the magma (Hulley, 2005). This results in a heterogeneous orebody in terms of structure, mineralogical composition, alteration and base metal grades, which affects the mining and processing of the ore. Previous DMS testwork on MMZ ore by Sibanyoni (2006) shows varying results in the grades and recoveries achieved for different parts of the orebody, with successful pre-concentration only achieved on samples with head grades greater than ~0.7% Ni. The bulk sample in this study produced a meaningful upgrade to 0.7% from an original Ni grade of 0.4% at a recovery of 87% to the flotation plant. The DMS feed used by Sibanyoni (2006) was crushed to 25 mm, which could be a possible reason for the differing results, as crushing to 12 mm might have increased the sulfide liberation. However, this is unlikely due to the sulfide grain sizes being on the micron-scale.

It is a combination of mineralogical factors that affect whether a particle will be recovered or not in a cyclone. Properties such as grain size, intergrowth textures and mineral associations contribute to the liberation of minerals, and determine the overall particle densities. In reality, a continuum of particle densities occur, resulting from a continuum in liberation states of the minerals. Particle properties can also affect the separation within a DMC, causing their misplacement. These factors are negligible with laboratory HLS.

Metamorphism has affected the lower harzburgite unit, and is shown by the presence of albite, chlorite, actinolite, serpentine and talc. These minerals originate from a primary mineral assemblage of olivine, pyroxene and Ca-rich plagioclase and indicate relatively low temperature-pressure conditions of regional metamorphism (greenschist to lower amphibolite facies; Yardley, 1989). The major types of alteration observed (saussuritisation, serpentinisation, uralitisation and talc-carbonate alteration) are also characteristic of low grade metamorphism. Host rock alteration may affect density separation as the densities of these alteration products are generally lower than those of the ferromagnesian minerals of the original ultramafic rocks.

Nickel mineral liberation depends strongly on the sulfide textures, with net-textured sulfides being easier to liberate than disseminated sulfides. Pyrrhotite is the most abundant and generally largest sulfide mineral in the rock. Pentlandite, the main Ni host, therefore largely depends on its association with pyrrhotite and is recovered as composite pyrrhotite – pentlandite particles. In terms of gangue minerals, the sulfides are generally associated with original igneous minerals pyroxene and olivine or their replacement minerals such as serpentine, talc and amphibole. They are rarely found attached to quartz and calcite.

7. Conclusions

- DMS testwork on Nkomati MMZ ore produced a Ni upgrade of 0.7% from a head grade of 0.4%, with a total Ni recovery of 87%.
- The key mineralogical factor controlling the separation is the texture of the sulfides. As the proportions of net-textured sulfides increase relative to disseminated sulfides, their grain sizes and therefore sulfide liberation increase, and particles with a high degree of liberation should be recovered to the underflow. The change in pentlandite occurrence from flame-like lamellae in pyrrhotite to granular pentlandite also corresponds to this change in texture and grain size.
- Pentlandite is always associated with pyrrhotite, which is the largest and most abundant sulfide mineral in the MMZ. Pentlandite recovery therefore depends on its association with pyrrhotite.
- The characterisation of the DMC overflow and underflow show that the proportions of silicate minerals differ in the different products due to their density characteristics. The sulfides are mostly associated with the denser silicates and original igneous minerals such as clinopyroxene and altered olivine.
- Apart from average particle density, factors such as shape and size may also have an influence on density separation. This has been identified an area for further investigation using automated mineralogy (e.g. QEMSCAN, MLA) where the liberation and association of the different minerals can be quantified.

8. Acknowledgements

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