Physicochem. Probl. Miner. Process. 50(1), 2014, 203−215

www.minproc.pwr.wroc.pl/journal/

Physicochemical Problems of Mineral Processing

ISSN 1643-1049 (print)
ISSN 2084-4735 (online)

Received June 10, 2013; reviewed; accepted July 17, 2013

UPGRADING VALUABLE MINERALIZATION AND REJECTING MAGNESIUM SILICATES BY PRE-CONCENTRATION OF MAFIC ORES

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Abstract: Amenability of mafic ores to pre-concentration was investigated with respect to ore mineralization characteristics. For the pre-concentration tests seven ores from various nickel-copper operations at Sudbury, Ontario were subjected to dense medium separation. Size assays of metal values, i.e. distribution of nickel and copper with respect to size fractions, were also determined. The ores were assessed in three categories of valuable mineralization as massive pure sulphides, coarse massive sulphide grains and disseminated sulphides. For ores with massive pure sulphides and coarse massive sulphide grains even a size classification based pre-concentration route could be sought since a clear trend of metal enrichment was identified towards finer fractions. Orebodies of similar mineralogy had similar responses to pre-concentration tests. The best results were for those ore bodies with a distinct differentiation between mineralization and gangue, i.e. the ores with massive pure sulphides, where nickel recoveries of 97% and mass rejections of 38-53% were achieved. Similar results were obtained for ores with coarse massive sulphides. For disseminated sulphide mineralogy relatively lower mass rejection was attained with acceptable recoveries of metals. Rejection of magnesium bearing gangue, such as talc, was identified as another benefit of pre-concentration. The extent of magnesium rejection occurred as a function of ore mineralogy. Clear distinction between valuable mineralization and gangue provided preferential magnesium rejection at high levels with no or minor metal losses.

Keywords: *mafic ores, pre-concentration, dense media separation, metallic sulphides, ore mineralogy*

Introduction

Pre-concentration is a beneficiation concept with the primary goal of early waste rejection, i.e. discarding barren rock from run-off-mine ore at coarse sizes prior to downstream processes. It is not a new concept and has been in practice since early 1900’s. Depending on the characteristics of the ore and scale of the process, pre-concentration can be accomplished using several methodologies ranging from simple techniques such as hand sorting and screening to conventional mineral separation

http://dx.doi.org/10.5277/ppmp140117

techniques such as dense medium separation (DMS) or highly advanced sorting technologies. As mentioned, it is a proven concept with practices for a wide range of ores and several large scale applications. Some of the successful applications include, pre-concentration of a Zn-sulphide ore at American Zinc Company (TN, USA), a native-Cu ore (Houghton, MI, USA), Pb-Zn sulphide ore at Mt.Isa (Australia), a Cu-sulphide ore at Copper Creek (AZ, USA), a Pb-Zn sulphide ore at Sullivan Mine (BC, Canada), a Ni-sulphide ore at Whistle Mine (Sudbury, ON, Canada). The South African Chamber of Mines also conducted and extensive researh programme for more than a decade (1978-1989) to identify the potential of underground pre-concentration for several deep gold mines (Miller, 1978; Lloyd, 1979; Munro, 1982; Fiedler et al., 1984; Lloyd et al., 1986; Vatcha et al., 2000). All these applications and previous research showed that application of pre-concentration, either at the surface or underground, would potentially lead to numerous benefits by realizing early waste rejection in the mining sequence. The most significant outcomes include (Schena et al, 1990; Salter and Wyatt, 1991; Feasby and Tremblay, 1995; Peters et al., 1999; Scoble et al., 2000; Klein et al., 2002; Klein et al., 2003; Bamber et al., 2006):

- savings in material handling and transportation costs by early rejection of waste
- savings in grinding and processing costs by removing siliceous and/or Mg bearing gangue.
- increased efficiency in downstream processes due to improved feed metallurgy
- extended mine-life due to lowered cut-off grade
- possibility to use bulk-mining methods due to higher toleration of dilution in the ROM ore
- higher mining rate without installing higher capacity processing facilities
- decrease in the amount of fine wastes and slime production after concentration processes
- possibility to use rejected waste as backfill material in U/G operations.

Effective pre-concentration therefore would improve the economics, efficiency and contribute to the environmental viability of the operation. In addition, pre-concentration has been reported to be particularly in favour of operations at extreme depths and/or on low grade ores (Hinde et al., 1986). In this respect it is envisioned to contribute to the sustainability of a vast number of metal mines in the globe constrained by increasing ore depth, decreasing ore grade, and environmental measures. This paper presents results from an extensive test programme aimed at identifying the amenability of ores from some of the major nickel-copper operations at Sudbury, Ontario, Canada. These operations commonly suffer from technical restrictions such as increasing ore depth, decreasing ore grade and increasing mining costs as well as environmental pressures. The impact of ore mineralogy on the liability of the ores to pre-concentration was assessed by interpreting the results in relation to the occurrence modes of nickel and copper bearing portions, using dense medium separation.

Materials and Methods

Seven different ores from the Craig, Fraser and Thayer Lindsley mines were grouped with respect to the distinctive mineralogical characteristics of metallic sulphides in the ores. The specific names and characteristics of these ores are presented in Table 1. In all the ores, the nickel and copper values exist in the form of metallic sulphides. It is also possible to classify the ores as contact and footwall with sub-groups based on their specific mineralogical characteristics (Bamber et al., 2006):

- Contact ores with coarse grained metallic sulphides; Craig LGBX, TL Zone 2,
- Contact ores with disseminated sulphides within the host rock; Craig 8112, Fraser Ni, TL Zone 1,
- Footwall ores of narrow-vein high grade stringers containing high copper grades mostly in the form of massive pure sulphides: Fraser Cu, TL Footwall.

Table 1. Summary of the ore characteristics

Ore	Head Grades		Grain Size (mm)	Description
	Ni (%)	Cu (%)		
Fraser Copper	0.61	10.94	No discrete grains	*Mineralization:* Massive pure sulphides *Gangue:* Very minimal visual fine grained sulphides
Thayer Lindsley Footwall	1.24	8.14	No discrete grains	*Mineralization:* Massive pure sulphides *Gangue:* No visible sulphides
Craig LGBX	2.28	0.33	> 1	*Mineralization:* Coarse grained massive sulphides *Gangue:* No visible sulphide
Thayer Lindsley Zone 2	1.35	0.75	< 1	*Mineralization:* Coarse grained massive sulphides *Gangue:* No visible sulphide
Craig 8112	1.11	0.48	< 0.5	*Mineralization:* Coarse disseminated sulphides *Gangue:* No visible sulphide
Fraser Nickel	0.74	0.38	<0.1	*Mineralization:* Coarse disseminated sulphides *Gangue:* Minimal visual fine grained sulphides
Thayer Lindsley Zone 1	0.69	0.41	< 1	*Mineralization:* Coarse disseminated sulphides *Gangue:* Minimal visual fine grained sulphides

Each sample was screened into size fractions based on a $\sqrt{2}$ series. The size fractions started from a top size of 254 mm. Dense medium separation tests were conducted using a laboratory type closed-circuit vessel setup. Due to the limitations of the laboratory type DMS vessel, each ore was crushed so as to have a top particle size of 75 mm. DMS tests were conducted using a laboratory type dense media vessel. Ferrosilicon was used to adjust the separation density and was circulated through the vessel in closed circuit. The separation density in the vessel was controlled using a Marcy scale. The concentrate and waste products were weighed and assayed for nickel, copper and magnesium.

Results and discussion

Size assays

The size-assay of the crushed ore allows to identify the metal distribution and liberation data with respect to particle size fractions. This also reveals the size classes potentially available for direct rejection and the optimum cut-size for discrimination between waste material and metal enriched fractions. The observation of specific size fractions with apparently high metal grades would even allow implementation of simple screening as a possible pre-concentration tool.

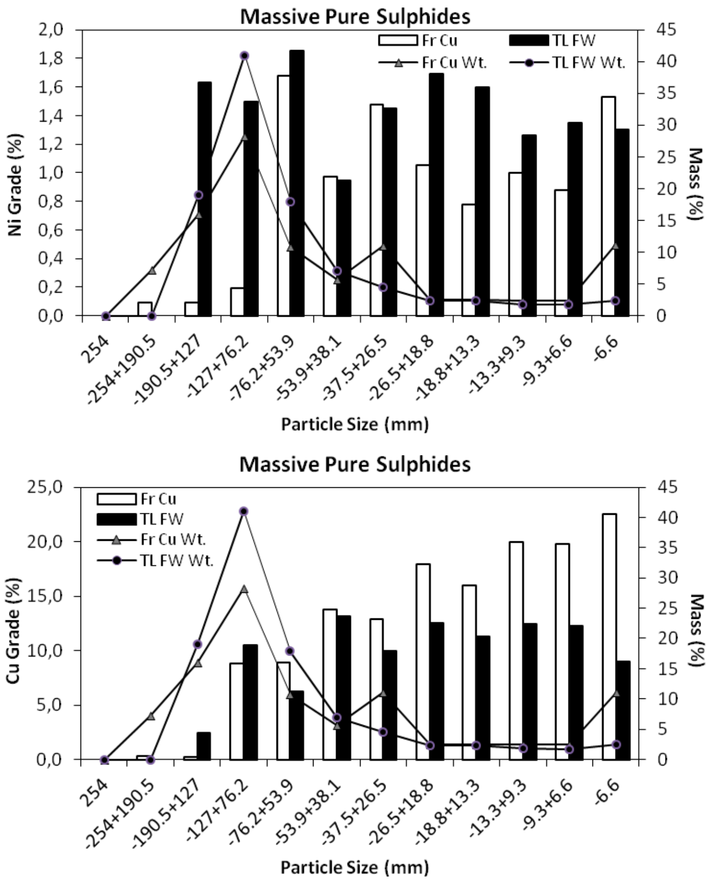


Fig. 1. Ni and Cu grade and size distribution for ores with massive pure sulphides

For the Fraser Copper and Thayer Lindsley Footwall ores, constituted of massive pure sulphide grains, nickel and copper enrichment towards finer fractions were seen. Higher grades at finer fractions were particularly clear for Fraser Cu (Fig. 1). The Ni grade in –53.9 mm fractions were higher than coarser sizes in Fraser Cu. Also for copper, significant enrichment was identified for –76.2 mm fractions and Cu grades exceeding 20% were recorded. For TL Footwall, +127 mm fraction had a low Cu grade. In view of the size-assay values for both metals and considering the mass distributions, fractions coarser than 76.2 mm could be directly discarded for Fraser Cu ore. This corresponds to a mass rejection of more than 50% prior to the downstream processes. Also, +127 mm fraction is practically barren rock for TL Footwall ore and could be scalped of as waste. With a Cu grade of higher than 30%, direct addition of –26.5 mm fractions of Fraser Cu to the final flotation concentrate could be suggested.

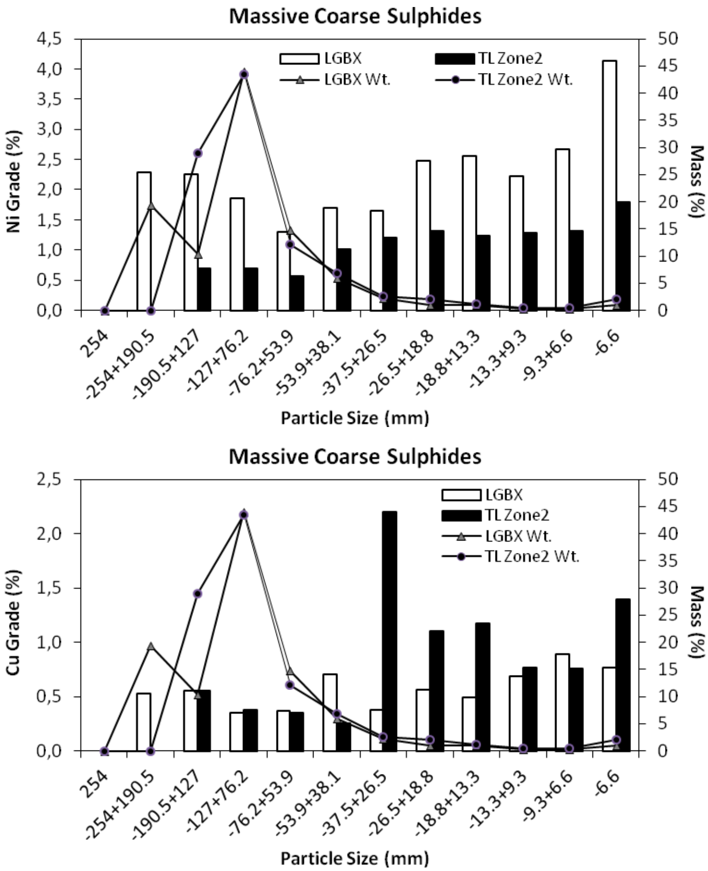


Fig. 2. Ni and Cu grade and size distribution for ores with massive coarse sulphides

For the LGBX and TL Zone 2 ores, characterized with massive coarse sulphide grains, Cu enrichment was seen for fractions finer than 37.5 mm. The Cu grades of the –37.5 mm fractions were particularly higher for TL Zone 2 ore (Fig. 2). For the same ore, there is a distinct increase in Ni grade in –53.9 mm fractions. Nickel assay in LGBX ore was more equally distributed across all size ranges except –6.6 mm fraction

(Fig. 2). Therefore a potential exists for rejection of coarser fractions of TL Zone 2 ore as waste, considering the delicate balance to recover both Ni and Cu values. Possible screening off +53.9 mm fractions corresponds to a huge mass rejection of around 85% where significant benefits would be expected.

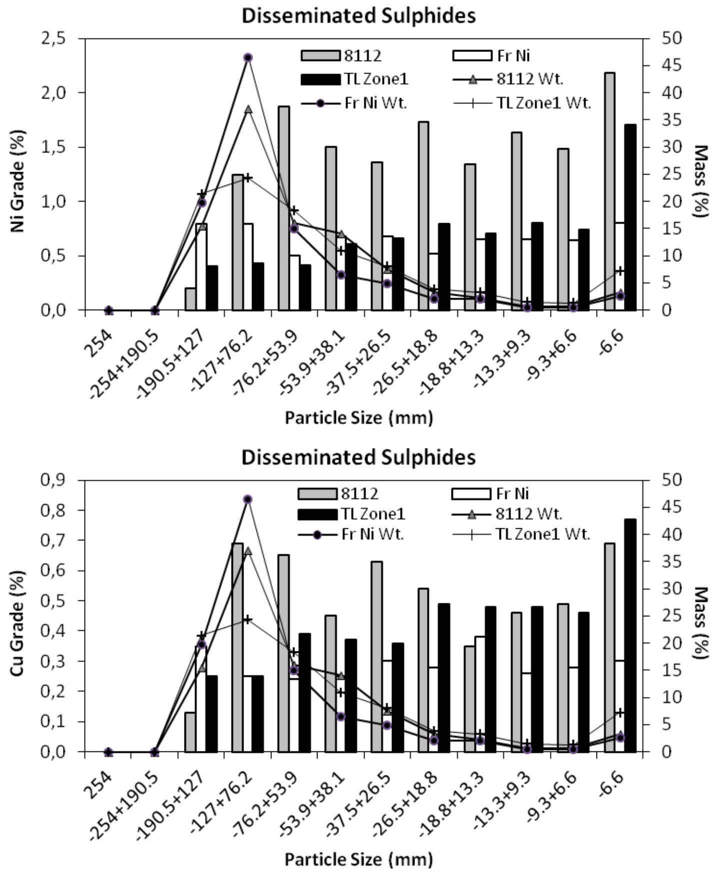


Fig. 3. Ni and Cu grade and size distribution for ores with disseminated sulphides

The ores with disseminated sulphides show relatively slight trend towards enriched fines (Fig. 3). Except -6.6 mm fraction, setting a distinct cut size is not likely particularly for Craig 8112 and Fraser Nickel ores. Only for TL Zone 1 ore, separation of +76.2 mm fractions would be sought, corresponding around 45% mass rejection with tolerable loss of metal values (Fig. 3).

The results illustrated that the ores with distinct metal sulphide mineralization provide a relatively higher trend towards enriched fines. Fraser Copper, a footwall ore with massive pure sulphides and TL Zone 2, a contact ore with massive coarse sulphide grains yielded the most promising results for size-based pre-concentration. With these ores great extent of mass rejection was revealed with minor metal losses. All other ores with massive pure or coarse massive sulphides also showed significant potential for size-based early waste rejection. The results for ores with dissemination of metal sulphides showed relatively limited possibility for a size-based pre-concentration.

It should also be noted that regardless of ore type and mineralogy, metal enrichment in the finest fractions (-9.3+6.6 mm and -6.6 mm) were common almost for all ores. This is normally associated with the liberation of softer sulphides being readily susceptible to breakage and attrition from the host rock. Therefore, for all ores, screening of these finest fractions for by-passing into the flotation concentrates would be suggested.

DMS tests

Tables 2-4 present the results of the DMS tests with respect to ore mineralization classes. For each ore the change in the separation performances as a function of specific gravity of separation are also shown. Considering the primary objectives of pre-concentration as maximum rejection of gangue mineralization with minimum loss of metal values, i.e. with the highest possible metal recoveries, the importance of comparing different levels of separation specific gravities could be clearly understood. The results of DMS study were apparently favorable for Fraser Cu and TL Footwall ores (Table 2). For Fraser Cu, separation at both 2.9 and 3.1 yielded significant rejection of barren rock with Ni and Cu recoveries over 95 % in the concentrate.

Table 2. DMS results for ores with massive pure sulphides

Ore	Feed Grade (%)		Sep. SG	Conc. Mass (%)	Mass Rejection (%)	Concentrate Grade (%)		Recovery (%)	
	Ni	Cu				Ni	Cu	Ni	Cu
Fraser Cu	0.41	10.48	2.7	91	9	0.48	11.47	99.67	99.47
			2.9	47	53	0.84	22.01	96.01	97.95
			3.1	44	56	0.95	23.39	95.14	97.61
TL Footwall	1.19	6.99	2.7	88	12	1.35	7.92	99.93	99.85
			2.9	63	37	1.83	10.79	97.67	97.89
			3.1	59	41	1.98	11.68	96.76	96.90
			3.35	45	55	2.10	11.92	80.01	77.15

Waste rejection was slightly higher at 3.1 with similar metal recoveries in the concentrate. For TL Footwall ore, starting from 2.9 acceptable results were achieved with improved separation and waste rejection towards higher separation densities. Separation at 3.1 provided the most effective pre-concentration with 41% waste rejection and Ni and Cu recoveries around 97%. Further increase of the separation density to 3.35 caused reductions in nickel and copper recoveries (Table 2).

For ores with coarse massive sulphide grains, DMS results were also promising. At 2.95, more than 30% of the feed could be discarded as waste with a concentrate of more than 97% Ni and 81% Cu recoveries. Mass rejection was further increased to around 50% by shifting the separation density to 3.1. At this level Ni recovery remained almost similar, but Cu recovery decreased by around 10%. For TL Zone 2, Ni and Cu recoveries exceeding 95% were achieved at 2.9, but only one quarter of the feed could be discarded. Increasing the separation density to 3.1 significantly enhanced waste rejection up to 43% with a high Ni (≈93%) and an acceptable Cu (≈ 88%) recovery in concentrate (Table 3).

Table 3. DMS results for coarse massive sulphides

Ore	Feed Grade (%)		Sep. SG	Conc. Mass (%)	Mass Rejection (%)	Concentrate Grade (%)		Recovery (%)	
	Ni	Cu				Ni	Cu	Ni	Cu
LGBX	2.46	0.31	2.8	84	16	2.90	0.34	98.84	92.55
			2.95	68	32	3.52	0.38	97.18	81.55
			3.1	51	49	4.65	0.44	95.65	71.14
TL Zone 2	1.29	0.86	2.7	97	3	1.33	0.88	99.90	99.75
			2.9	74	26	1.70	1.11	97.73	95.65
			3.1	57	43	2.11	1.33	92.78	87.78

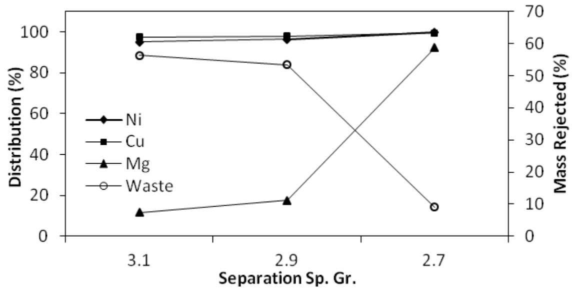
Table 4. DMS results for disseminated sulphides

Ore	Feed Grade (%)		Sep. SG	Conc. Mass (%)	Mass Rejection (%)	Concentrate Grade (%)		Recovery (%)	
	Ni	Cu				Ni	Cu	Ni	Cu
8112	1.12	0.51	2.8	94	6	1.17	0.54	98.88	98.79
			2.95	86	14	1.27	0.57	97.63	96.68
			3.1	47	53	2.12	0.93	89.39	85.41
Fraser Ni	0.68	0.41	2.7	99	1	0.68	0.40	99.87	99.87
			2.9	52	48	1.08	0.64	82.80	83.24
			3.1	21	79	1.49	0.87	45.43	45.62
TL Zone 1	0.69	0.39	2.7	99	1	0.69	0.39	99.98	99.90
			2.9	80	20	0.82	0.45	95.40	92.67
			3.1	46	54	1.23	0.63	81.21	73.77

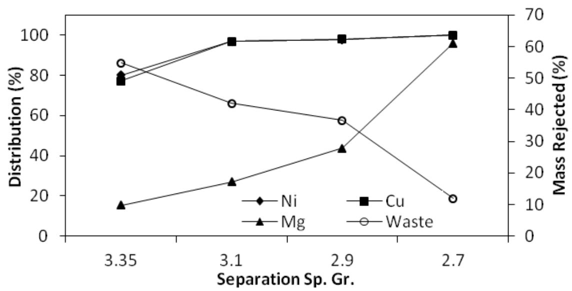
Although the separation results for the ores with disseminated sulphides can not be noted as unsatisfactory, the success of the process was relatively limited for these ores from the pre-concentration perspective. For 8112 and TL Zone 1, the nickel and copper recoveries exceeded 90% in the concentrate product when the separation was conducted at 2.95 and 2.9, respectively. However, at these separation densities mass rejection remained fairly low for both ores (Table 4). For 8112, pre-concentration could be justified at 3.1 with more than 50% mass rejection and Ni recovery close to 90% and

Cu recovery more than 85% in the concentrate. For TL Zone 1, separation at 3.1 could also yield significant mass rejection at 54%, but with lower Ni and Cu recoveries as 81.21 % and 73.77 %, respectively. At a separation density of 2.9, Fraser Ni provided similar results to TL Zone 1 in terms of mass rejection and metal recoveries. Further increase of separation density to 3.1 dramatically decreased Ni and Cu recoveries to 45% for Fraser Ni (Table 4).

Another benefit of DMS was recognized as reduced Mg in the concentrate products. The adverse effect of Mg bearing minerals and particularly talc is obvious in the flotation based beneficiation of metallic sulphides. Potential rejection of these minerals, therefore, corresponds to increased metallurgical performance in the downstream processes. The change of Mg and metal recoveries as a function of separation density was assessed and the results are presented in Figs 4–6.



Fraser Cu				
Sep SG	Mass Reject (%)	Mg Grade (%)		Mg Rec. (%)
		Feed	Conc.	
2.7	9		1.85	92.15
2.9	53	1.83	0.69	17.49
3.1	56		0.48	11.54

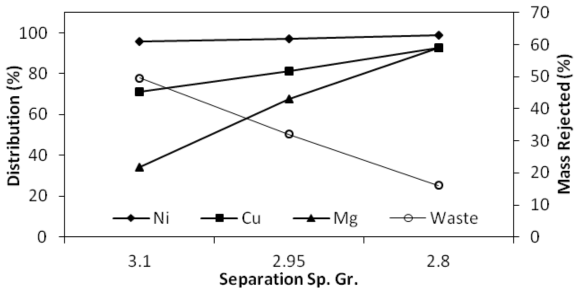


TL Footwall				
Sep SG	Mass Reject (%)	Mg Grade (%)		Mg Rec. (%)
		Feed	Conc.	
2.7	12		1.62	95.94
2.9	37		1.03	43.68
3.1	41	1.49	0.69	26.87
3.35	55		0.51	15.42

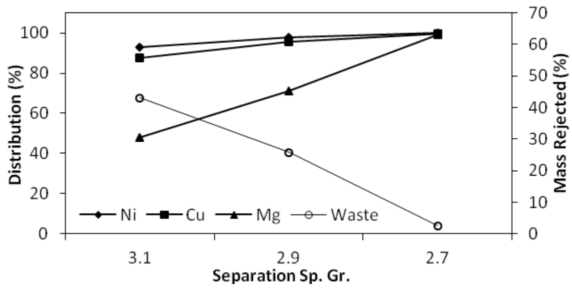
Fig. 4. Mg and metal recoveries for massive pure sulphide mineralogy

For the ores characterized with a massive pure sulphide mineralogy, a significant fraction of Mg was rejected at the optimum densities of separation, i.e. a concentrate product with high metal recoveries and low Mg content could be achieved at acceptable levels of waste rejection. For Fraser Cu, the concentrate product of 2.9 included only 17.49% of Mg from the feed while the Ni and Cu recoveries were over 96 %. Mg in the concentrate of 3.1 was as low as 11.54% and the metal recoveries were still high (Fig. 4). For Thayer Lindsley Footwall ore separation at 2.9 provided rejection of more than half of the Mg with the waste. The shift of separation density to 3.1 yielded even better results. The Mg recovery in the concentrate decreased to around 27% with almost no metal loss and increased extent of waste rejection (Fig. 4). Separation at 3.35 provided further reduction of Mg in the concentrate, but at the expense of decreases in Ni and Cu recoveries.

DMS also favored Mg rejection for Craig LGBX and Thayer Lindsley Zone 2 ores which were specified by coarse grained massive sulphides. With a separation at 2.95, around 68% of Mg could be discarded with the waste (Fig. 6). Mg rejection at 3.1 was twice as high (% 34.19) at an improved mass rejection of 49%. At both separation densities, nickel recoveries remained quite significant. For TL Zone 2, Mg rejection at 2.9 and 3.1 were relatively lower than LGBX (Fig. 5). However, separation at 3.1 provided optimum results in terms of all criterions considered for possible implementation of pre-concentration. At this separation density, the concentrate included 48% Mg with significant Ni and Cu recoveries and 43% of feed could be discarded (Fig. 5).



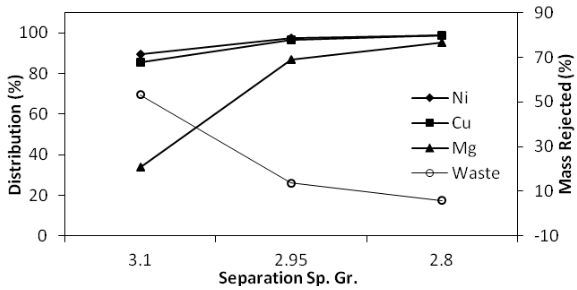
LGBX				
Sep SG	Mass Reject (%)	Mg Grade (%)		Mg Rec. (%)
		Feed	Conc.	
2.8	16		2.61	92.50
2.95	32	2.37	2.37	67.83
3.1	49		1.60	34.19



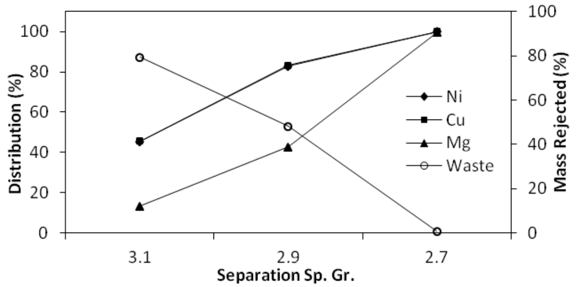
TL Zone 2				
Sep SG	Mass Reject (%)	Mg Grade (%)		Mg Rec. (%)
		Feed	Conc.	
2.7	3		3.81	99.26
2.9	26	3.74	3.58	71.14
3.1	43		3.16	48.18

Fig. 5. Mg and metal recoveries for ores with coarse sulphide grains

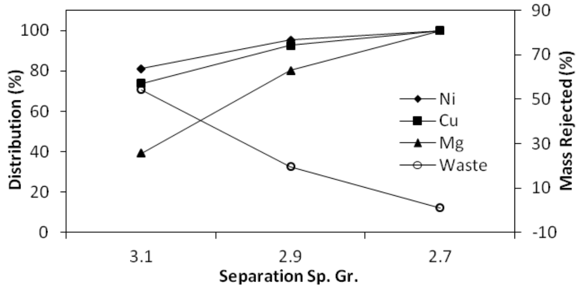
For the ores categorized with disseminated sulphide inclusions, the results were rather fluctuating. Overall, separation at the highest specific gravity (3.1) provided the highest Mg rejection for all three ores. It should also be noted that a shift of separation density from the mid-level to 3.1 dramatically increased the amount of waste discarded (Fig. 6). However, it is not likely that separation at 3.1 would be justified with respect to only Mg rejection as the metal recoveries remained fairly low at this specific gravity particularly for Fraser Nickel ore. With respect to all parameters considered for pre-concentration, Craig 8112 provided the most promising results with significant rejection of Mg and waste associated with acceptable levels of metal distributions in the concentrate at a separation specific gravity of 3.1 (Fig. 6).



8112				
Sep SG	Mass Reject (%)	Mg Grade (%)		Mg Rec. (%)
		Feed	Conc.	
2.8	6		5.73	95.29
2.95	14	5.66	5.71	86.89
3.1	53		4.11	33.94



Fraser Ni				
Sep SG	Mass Reject (%)	Mg Grade (%)		Mg Rec. (%)
		Feed	Conc.	
2.7	1		4.26	99.42
2.9	48	3.97	3.50	42.71
3.1	79		2.72	13.24



TL Zone 1				
Sep SG	Mass Reject(%)	Mg Grade (%)		Mg Rec. (%)
		Feed	Conc.	
2.7	1		6.22	99.94
2.9	20	6.22	6.20	80.21
3.1	54		5.34	39.28

Fig. 6. Mg and metal recoveries for ores with disseminated sulphides

An overall evaluation yielded that rejection of Mg bearing entities with the waste product was closely related with the mineralogy of the ores tested. In the ores with massive pure metallic sulphides, pre-concentration by DMS resulted in a distinct separation between high-density metal-rich entities and lower density Mg-including barren part. Enhanced Mg rejection, with a higher mass rejection as the specific gravity of separation was increased, confirms this observation. Further, slight changes in the metal distributions in the concentrates as a function of the specific gravity of separation reveals that a favorable liberation could be achieved in this type of mineralogy, i.e. metallic sulphides occurring as free entities with no or little association of Mg bearing minerals and gangue. This is an important indication directly pointing to the amenability of the ore to pre-concentration and potential for waste rejection prior to downstream processes. The same conclusions could be derived for the ores characterized with coarse massive sulphide grains, despite lower extent of Mg rejection with the waste. Significant liberation between the nickel and copper bearing sulphide grains and gangue would be possible. This provides a concentrate with favorable metal recovery, reduced Mg content at a justifiable level of mass rejection from the pre-concentration perspective. For the ores with the disseminated sulphides, a potential for early rejection of waste and specifically Mg bearing entities could still be sought, as revealed for the Craig 8112 ore. However, the amenability for pre-concentration for disseminated metallic sulphides mineralogy is relatively lower as the separation was not as distinct. An attempt to enhance mass rejection by increasing the specific gravity of separation could further increase rejection of gangue and Mg bearing entities, but resulted in subsequent loss of nickel and copper in the concentrate. This observation and lower effectiveness of pre-concentration was attributed to the disseminated form of metallic sulphides, obstructing a favorable liberation between the mineralized portions and gangue. Disseminated form of metallic sulphides would be anticipated to correspond to a higher degree of gangue associations with nickel and copper bearing sulphides.

Conclusions

All the ores tested in this study showed amenability to pre-concentration at varying levels. The effectiveness of pre-concentration, either size-based or by DMS, was linked to the occurrence modes of metallic and gangue portions. It was seen that ore mineralogy should be in favour of pre-concentration. Ores with massive pure sulphides and coarse sulphide grains, i.e. with clear differentiation between valuable mineralization and gangue, yielded an effective liberation of nickel and copper bearing entities and successful separation through DMS subsequently. Ores with disseminated form of metallic values provided relatively lower mass rejection and metal recoveries and being more sensitive to the specific gravity of separation. A potential for discarding Mg bearing minerals with early waste rejection was also identified. The significance of Mg-rejection was also related with ore mineralogy. Almost for all ores, Mg showed an apparently different separation curve from nickel and copper. Ores with distinctive metallic sulphides provided high levels of separation and a clear differentiation between valuable mineralization and gangue with Ni and/or Cu rich concentrates and Mg rich waste products. Overall, despite the variation of the performance of the ores tested, high metal recoveries with significant mass rejection could be realized through further refinement of the process.

References

BAMBER A.S., KLEIN B., SCOBLE M.J., 2006, *Integrated Mining and Processing of Massive Sulphide Ores, Proceedings*, 39th Ann7ual General Meeting of the Canadian Mineral Proc., Ottawa, 01/2006.

FEASBY D.G., TREMBLAY G.A., 1995, *Role of Mineral Processing in Reducing Environmental Liability of Mine Wastes*, Proceedings, 27th Annual CMP Meeting, Ottawa, 218–231.

FIEDLER K.J., MUNRO P.D., PEASE J.D., 1984. *Commissioning and operation of the 800 t/h heavy medium cyclone plant at Mount Isa Mines Limited*. Pro. Australasian Institute of Mining and Metallurgy, Darwin, Australia 1984. C41–C49.

HINDE A.L., FRANKENHAUSER R.M., KRAMERS C.P., 1986, *The Benefits of Reducing the Transport, Hoisting and Processing of Barren Rock in Witwatersrand Gold Mines*, Proceedings of the SAIMM International Conference on Gold, 333–343.

LLOYD P.J.D., *An Integrated Mining and Extraction System for Use on Witwatersrand Gold Mines*, Journal of the SAIMM, Vol. 79, January 1979.

KLEIN B., DUNBAR W.S., SCOBLE M., 2002, *Integrating Mining and Mineral Processing for Advanced Mining Systems*, CIM Bulletin, Vol. 95, No. 1057, 63–68.

KLEIN B., HALL R., SCOBLE M., MORIN M., 2003, *Total Systems Approach to Design for Underground Mine-Mill Integration*, CIM Bulletin, Vol. 97, No. 1067, 65–71.

LLOYD P.J.D., VAN DER WALT J., *Critical Issues in Gold Mining: An Independent View*, Proceedings of the International Conference on Gold, SAIMM, Johannesburg 1986.

MILLER V.R., NASH R.W., SCHWANEKE A.E., 1978. *Pre-concentration of Native Copper and Porphyry Copper Ores by Electronic Sorting*. Mining Engineering 1978:1194-1201.

MUNRO P.D., SCHACHE I.S., PARK W.G., WATSFORD R.M.S.,. 1982. *The Design, Construction, and Commissioning of a Heavy Medium Plant for Silver-Lead-Zinc Ore Treatment – Mount Isa Mines Limited*. XIV International Mineral Processing Congress. Toronto, 1982: 2–21.

PETERS O., SCOBLE M., SCHUMACHER T., 1999, *The technical and economic potential of mineral processing underground*. Annual General Meeting, Can. Inst. Min. Metall., Calgary, CD ROM.

SALTER J.D., WYATT N.P.G., 1991, Sorting in the Minerals Industry: Past, Present and Future, Minerals Engineering, Vol 4, No 7–11, 779–796, 1991.

SCHENA G.D., GOCHIN R. J., FERRARA G., 1990, *Pre-concentration by dense-medium separation – an economic evaluation*, Trans. Instsn. Min. Metall. (Sect. C: Mineral Process. Extr. Metall.), 99, January-April 1990, C21–C31.

SCOBLE M., KLEIN B., DUNBAR W.S., 2000, *Mining waste: Transforming mining systems for waste management*, 6th Int Conf on Environmental Issues and Mining Production, Calgary, 333–340.

VATCHA M.T., COCHRANE L.B., ROUSELL D.H., 2000, *Pre-concentration by magnetic sorting of Ni–Cu ore at Whistle mine, Sudbury, Canada*, Mineral Processing and Extractive Metallurgy, Volume 109, Number 3, 156–160 (5).