Technical Paper

Mineral Processing

▲ The development of process mineralogy at Falconbridge Limited and application to the Raglan Mill

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ABSTRACT

Assessment of opportunities to improve mineral processing performance in existing concentrators and in describing undeveloped orebodies is key to improving the business case of a mining company. This assessment has traditionally been performed using the distinct and separate inputs from mineral processing and mineral science.

More recently, process mineralogy has been used to integrate these two disciplines. This trend has been driven by the need to develop and process more challenging ore deposits, and has been assisted by the availability of modern automated instruments. Together with the acquisition of a QemSCAN (quantitative evaluation of materials by scanning electron microscope) from CSIRO in Australia, and with the use of a supporting SEM with EDX/WDX capabilities and an XRD, the development of process mineralogy at Falconbridge commenced in 1997.

The sampling challenges in presenting a QemSCAN with representative sample material at the polished section level are significant, but have been effectively addressed. The full description of this aspect is beyond the scope of this paper.

Norman O. Lotter was born in Germiston, South Africa, and received his B.Sc. degree from the University of Natal in 1972, and his M.Eng. degree from the University of Cape Town in 1995. After working for Rio Tinto between 1972 and 1977 in an operations support role, he moved to Johannesburg Consolidated Investments Limited, where he worked for twenty years in the field of mineral processing, mostly in operations support. In this role, he developed and used sampling and quality control models for laboratory testing and plant-scale evaluation toward flowsheet optimization and reagent suite improvement. Most of his service with JCI was in Rustenburg Platinum Mines, now Amplats, where he managed the Divisional Metallurgical Laboratory at Rustenburg and provided technical support for the Merensky and UG2 concentrators. He joined Falconbridge Limited at Sudbury, Ontario, in 1997, where he is superintendent of the process mineralogy and materials science group in the Falconbridge Technology Centre. Mr. Lotter is a Fellow of the Institute of Mining and Metallurgy and of the South African Institute of Mining and Metallurgy.

Peter J. Whittaker received his B.Sc. (honours) in geology from Laurentian University in 1976, his M.Sc. from McMaster University in 1979, and his Ph.D. from Carleton University in 1983. His graduate degrees involved electron-probe microanalysis of silicate, sulphide, and PGM mineralogy related to the petrogenesis of the Port Coldwell layered alkaline intrusive complex in Ontario and to podiform chromitites in the Cache Creek Group serpentinized peridotites throughout central British Columbia. Following graduate work, he was employed by the Mineral Deposits Section of the Ontario Geological Survey and was involved in studies on chromite mineralization in Ontario and on shear zone related alteration mineralogy of gold deposits. Before joining Falconbridge Ltd. in 1991 as chief mineralogist, he spent three years with Noramco Explorations leading their PGM exploration program.

Lori Kormos received a B.Sc in geology from the University of Toronto in 1988. She joined Falconbridge Limited that same year and spent the next ten years in exploration geology and mine geology. In 1999 she joined the process mineralogy department where she currently holds the position of program mineralogist. The main focus of her work is the interpretation and reporting of QemSCAN data.

Johannes S. Stickling received his B.Eng. (metallurgy) at the University of Pretoria in 1983. He worked for Johannesburg Consolidated Investments Limited in both the Gold and Uranium, and Platinum Divisions, between 1985 and 1999. During this time, he worked extensively in mineral processing production operations, and saw the commissioning of three concentrators into production. These were the Potgietersrust Platinum mine concentrator, and the expansions of the Amandelbult and Atok concentrators. In 1994, he moved to the Divisional Metallurgical Laboratory, at Rustenburg, where he led a plant survey team in flowsheet auditing for Qem*SEM and other diagnostic analysis. In 1999, he moved to Falconbridge Limited in Sudbury, Ontario, where he was appointed senior metallurgist in process mineralogy at the Falconbridge Technology Centre. In mid 2001, he was transferred to the Sudbury Smelter Business Unit to work as senior metallurgist in the converter aisle operations. Mr Stickling is a member of the South African Institute of Mining and Metallurgy.

Gregory J. Wilkie obtained his B.App.Sci. and M.App.Sci. degrees from the Royal Melbourne Institute of Technology in Australia in 1983 and 1991, respectively. His research career started in 1985 when he joined the Qem*SEM team in the CSIRO Division of Mineral and Process Engineering. During this time, he worked on various research and development projects that delivered robust process mineralogy technologies to the Australian and International Mining Industries. These projects have ranged from instrument and application development, to business development and marketing of the Qem*SEM technology in Australia, Africa, and North America. Since 1998, he has resided in North America and been on secondment duties to Falconbridge and Phelps Dodge where he has assisted in the development and training of their new process mineralogy teams.

It is shown that, by use of this approach, the set nature of an orebody can be best exploited with selected flowsheet changes in a concentrator which address the generic characteristics of the orebody. In this way, the flowsheet provides a process that more effectively fits the mineral processing requirements of the ore. This leads to clear and tangible improvements in grade and recovery.

Introduction

Process mineralogy is a relatively new field and is used to a greater or lesser degree in all disciplines where materials are processed. Major advances have been made in this field in the last three decades, particularly in the sector concerned with mineral processing (Petruk, 2000). Henley (1983) reviewed this sector of process mineralogy and showed that it involves the integration of mineral processing and mineralogy. In this review, a flowsheet starting from orebody exploration through to optimization of plant operation was proposed. This flowsheet had the objective of developing a predictive process mineralogy model for the particular orebody and concentrator in question. Early inputs from mineralogy that describe the bulk mineral assemblage, possible liberation size ranges, possible problematic minerals and textures were shared with the mineral processing engineers. The latter would develop a flowsheet partly based on this information, and partly on laboratory and pilot plant testing. After commissioning of the plant, an optimization program was pursued for second and subsequent iterations of this study. These iterations extended beyond new samples of drill core and into samples taken from the operating plant. These samples were studied by the two disciplines to identify flowsheet limitations.

Various mineral science techniques were used to acquire the necessary information and these include X-ray diffraction (XRD), electron probe micro-analysis (EPMA), scanning electron microscopy (SEM) and classical optical microscopy and ore petrography with point counting. At the time of writing, the reviewer (Henley, 1983) noted the initial applications of QemSCAN, and suggested a size-by-size structure for mineralogical analyses to be in keeping with Trahar's models (Trahar, 1981). Some discussion was offered on the relative errors of point counting. Henley's review, however, did not address the issue of representative sampling, nor did it discuss the achievement of desired confidence levels for the predictive models.

In the merging of the two disciplines, the prime objective is to develop an integrated system that quantitatively describes the flowsheet in terms of actual mineral behaviour. This approach is enhanced by a size-by-size structure applied to each process sample. The requirements of this objective are demanding and involve re-training personnel in a new work culture and methodology for process studies. At Falconbridge Limited, this has taken approximately two years to complete.

Historical Review

The connection between mineralogy and metallurgical performance in a plant was recognized long ago (Petruk, 1976; Petruk and Hughson, 1977; Cabri, 1981; Petruk and Schnarr, 1981; Peyerl, 1983) as was the need to provide diagnostic sampling techniques of a plant (Restarick, 1976) and to improve the statistical reliability of mineralogical and process measurements (Henley, 1983; Lotter, 1995a). From all of this work, two main points were clear. First, there is a generic connection between the geology of the orebody and the way in which the minerals that make up that orebody behave in the mineral processing flowsheet. And second, that the confidence level of the analysis is often overlooked but has a significant impact on the content and value of that analysis.

The measured and desired confidence level of this work is important. Earlier experiences in South Africa have demonstrated that an unqualified standard of sampling and sample preparation negates any use of information from QemSCAN, because the mineral balances do not close and because there is no proof of trueness.

Diagnostic Plant Sampling

Mineral processing engineers commonly use plant surveys in order to sample and evaluate an operational concentrator in detail. Although the structure varies considerably from engineer to engineer, all pursue the desirable state of trueness in the sampling, which is solid ground upon which to claim that the interpretations of the plant survey are valid and reliable.

Commonly, a flowsheet is functionally described, showing the logical flow of streams in sequence. A list of streams to be sampled is prepared. A team samples the plant during its normal operation according to the list of specified samples. The sampled streams are often also checked for solids and water flow as necessary inputs to mass balancing. After dewatering, the samples are used for various purposes such as overall chemical analysis, or size-by-size analysis.

The duration of such survey sampling varies. Commonly, a survey samples the plant operation across a few hours. One of the earlier references to this approach described an audit of the Broken Hill South concentrator, Australia (Cameron et al., 1971). This project used a sampling duration of four hours with sample increments taken every 20 minutes. The samples were sized, and a size-by-size performance model developed for lead and zinc. The authors stated that unambiguous conclusions had been derived from the approach. A subsequent reference to the subject of concentrator surveying described the structure and procedure in logical detail (Restarick, 1976). In this practical work, the importance of proper planning, preparation, and execution of steady state campaign for metallurgical plants was emphasized.

The general rules emanating from this work were:

- construction of the actual flowsheet by physical inspection during the planning phase of the survey;
- a survey duration of at least four times the residence time of the process to be surveyed;
- no shift change at the time of the survey;
- the total number of 'cuts' for any stream should be between 20 and 50 to reduce the effect of any faulty cut;
- restricting, stopping or diverting all minor or continuous flows, such as floor washings (spillage);
- the selection of personnel for the sampling should consider adequate and relevant training and expertise; and
- diligent attention must be paid to the integrity and labelling of each sample bucket, including the recording of net mass before sampling.

The specification of sample cutters was described in detail. In particular, reference to Taggart's rule of the cutter gap being at least four times the size of the largest particle in the stream, was noted. Further, the slot length had to be at least five centimetres longer than the maximum stream width relative to the direction of cut (Taggart, 1944). The author correctly concludes that care and attention to detail in the preparation and execution of a sampling campaign is essential to the attainment of accurate and significant data that would emanate from such sampling.

An example of diagnostic metallurgy based on a plant survey system for the Mount Lyell concentrator, Australia, was reported in 1977. This approach used a five-hour survey consisting of sample cuts every 30 minutes (Hartley et al., 1977). The mass balance was based on direct measurements of the fresh feed rate of dry ore to all primary grinding circuits. The flotation analysis used a cyclosized size-by-size format. The key conclusions were that recoverable chalcopyrite losses in tailings occurred as locks or middling particles, and

that the chief pyrite loss occurred as fines in the desliming cyclone overflows. These conclusions were first established by detailed size-by-size mineral recovery modelling, followed by more specific investigation of suspected streams.

Automated Mineral Analysis

Attempts to automate mineral analysis for increased particle statistics and to remove operator bias led to initiatives at Royal School of Mines (Jones, 1982), at BRGM (Barbery et al., 1979), at CSIRO (Grant et al., 1976), at CANMET (Petruk, 1976, 1988), at JK Centre (T. Napier-Munn, 2001, pers. comm.), at a few universities and at in-house facilities at some major mining companies including Falconbridge Limited (G. Springer, 1991, pers. comm.). Out of this pioneering work during the 1970s and 1980s, two approaches to automated mineral analysis evolved, and three commercially available systems were developed. The three systems are the QemSCAN developed at CSIRO, the MLA (mineral liberation analyzer) developed at JK Centre (T. Napier-Munn, 2001, pers. comm.), and the MP-SEM-IPS that was developed at CANMET (Lastra et al., 1998).

QemSCAN evolved using X-ray identification of minerals as its foundation, whereas, the MP-SEM-IPS and the MLA use backscatter electron (BSE) images to identify most minerals followed by X-ray spectra for identification of minerals that cannot be discriminated in the BSE image. Falconbridge elected to work with the QemSCAN approach and develop process mineralogy based on mineral identification and quantification based on characteristic X-ray spectra of minerals.

The history of the QemSCAN technology dates back to 1976 when Grant et al. (1976) proposed an automated scanning electron microscope (SEM) system to perform multiphase particle characterization. Prior to 1995, the technology was known as Qem*SEM. The original aim of the project was the rapid determination of composition, size and shape of fine particles from the backscattered electron intensity (BEI) and X-ray images produced by the SEM.

Evolution from prototype demonstration instrument through to complete integration of commercially available hardware and software continued through the next decade. By 1984, a commercial system featuring its trademark four detector X-ray analysis and control system was on the market. This generation was designed around the ISI scanning electron microscope product range, Tracor X-ray detector technology, and DEC Vax and Micro-Vax mini-computers. CSIRO hardware and software integrated these components into a powerful process mineralogy tool. This year also marked the introduction of the Qem*SEM Bureau to the Australian mining industry.

Continued development over the next decade through to 1995 resulted in the next major generation change. Significant advances in digital electron microscopy, light element X-ray analysis and PC computing allowed the Qem*SEM technology to leap into the world of digital acquisition and control. The new generation of QemSCAN systems was designed around the Leo product range of digital electron microscopes, Oxford Scientific product range of light element X-ray detectors, and fast-networked PC computers.

The effect of these advances was to make the system more amenable to use by mineralogists, and the system became more flexible with detection of light elements and the ensuing improvement in X-ray identification of gangue minerals. This now meant that orebody mineralogy could be detailed with respect to specific gangue minerals as well as the ore minerals. Windows software and Excel spreadsheets became the basis for processing and interpreting data. This has opened up the use of QemSCAN data to a wider user group.

Process Mineralogy at Falconbridge Limited

Process mineralogy at Falconbridge is based on an integrated approach that incorporates the mineral processing and mineral science disciplines. Mineral analysis depends on a high QemSCAN availability level (90%), and the sized samples measured by QemSCAN rely on representative process samples provided by process engineers. A statistical benchmark survey represents the beginning of process mineralogy (Lotter, 2001, unpubl.) at an operating plant.

The business value of such practice in Process Mineralogy with quality control is significant. A first prototype of this model, using statistics and quality control diagnostics, is in practice at Falconbridge Technology Centre, Sudbury, Ontario (Lotter and Whittaker, 1998). The sampling model is called statistical benchmark surveying. A schematic of the existing three-stage process mineralogy model for concentrators in operation is shown in Table 1.

In addition, quantitative analysis of the minerals present on a size-by-size basis further enhances understanding of the flowsheet limitations. This arrangement is set out as follows: representative samples; closed mass and value balance; further options considered; size-by-size mass and value analysis; and QemSCAN mineralogical analysis.

Predictive metallurgical models can also be developed for orebodies currently in production and for future orebodies through metallurgical testing of drill core. Sampling of this drill core is equally important in order to present representative samples for flotation bench scale testing and for QemSCAN.

The sampling system in use for the evaluation of current mining of an orebody is equally important in deriving reliable data for grade control and underground call factors (Lotter, 1995a, 1995b). Such sampling systems have to be developed from designed experimentation in which, for example, the minimum primary sample mass for a fundamental variance of 5% is established (Bartlett and Hawkins, 1987). In addition, the sampling rules for reliable sampling of a mill treating that mined ore have to reflect an equivalent fundamental variance.

It was shown that the sampling of a production mill was amenable to the spatial sampling rules for underground by use of a third parameter in Gy's 50 piece experiment (Lotter, 1995a, 1995b). This third parameter managed the effects of differential breakage in the ball mill feed. This enriched the finer fractions of crushed ball mill feed with metal values, and caused the minimum sample mass to be increased by some 176% above that of the standard 50-piece experiment.

This approach was used during the sampling and flotation testing of the major ore types found in the Onaping Depth deposit in the Sudbury basin. This reserve is targeted for replacement tonnage in the Sudbury Operations plans in the medium-term future.

Sample Preparation and Sizing

Entrainment mechanisms in flotation become very apparent at micron and submicron particle sizes. Because of this fine particle size, it is necessary to have all particles reporting to their appropriate size fractions, and to have all particles isolated from each

Table 1. Essential structure of Falconbridge process mineralogy flowsheet

Stage 1 Concentrator	Stage 2 Mineral Processing Laboratory	Stage 3 Mineral Science Laboratory
Background geology	Sample dewatering	Species Identification Program (SIP)
Sampling	Sample preparation	Polished section preparation
Mass measurement	Mass and value balance	QemSCAN measurements
Quality control	Chemical analysis	Reconciliation of chemical and QemSCAN assays
	Size fractionation	Interpretation of QemSCAN data
	Quality control	Building of process mineralogy model(s)

other so that no aggregates are measured. Care must be taken with initial sample collection during the statistical benchmark survey, or with flotation tests of drill core composite samples, to ensure that samples and their size fractions are both representative and have efficient deportment of particles to these size fractions.

The component of quality control in the planning, sampling, and sample preparation ahead of the polished section stage is critical to representativeness. It is imperative to realize that each polished section contains approximately one gram or less of sample. Interpretations and conclusions drawn from these samples must be scaleable back to the mass of the ore treated in the mineral process being studied. Through the typical eight to ten size fractions, which represent the total sample, approximately 10 g of sample must represent typical plant throughput. The latter may vary from 3000 to 80 000 t/d, hence the role of evaluation modelling is central to the achievement of reliable polished sections. Strategic evaluation of orebodies from drill core material for future processing adds another dimension of complexity to ensure consistency and appliance to the standard.

The scope of the sampling and preparation is usually from drill-core to mineral process products (including smelter products) in sulphide operations, and from drill-core to leach residues in the hydrometallurgical operations.

Initial Inspection of Samples

The sample preparation following the primary sampling activities must pay due regard to the need for sample integrity and grade group separation. The following features in particular are noted:

- During dewatering, preservation of all size groups in each sample must be maintained.
- The drying of the sample filter cakes follows specialized procedures, in order to minimize the formation of aggregate particles.
- The bagging and labelling of samples are of a high standard.
- The final dried samples are prepared according to procedures designed to minimize biasing effects due to different mineral densities and sizes.
- An analytical sub-sample is extracted from each individual sample, and the bulk of the sample is retained until the analysis is reported.
- The survey samples are then adjudicated on their trueness.

Treatment of Final Survey Samples

Three sub-samples are usually produced from each prepared final survey sample. The first is the QemSCAN sample, the second is a sample for chemical analysis, and the third subsample is the back-up sample.

A specialized procedure for the sizing of ore samples was designed whereby the fractions produced are of the high quality necessary for QemSCAN analysis. This theoretical overall sample grade must agree to within specifications of the original assayed sample grade. If not, the size separation is disqualified and the back-up sample is referred to for repeat size separation.

Accurate sizing is a critical step in the production of high-quality polished sections necessary for efficient and accurate mineralogical analysis of a sample using the QemSCAN technology. Poor sizing procedures can lead to several problems. An example is the displacement of ultrafines into coarser size fractions, which tends to bias the overall mineral distribution on a size-by-size basis. In cases such as these, identification of entrainment in the flotation process would be impaired. Poor sizing will also increase analysis times required to complete QemSCAN measurements and may compromise the accuracy of the mineralogical analysis.

The size fractions of the sample may now proceed to polished section preparation.

Fig. 1. Fractured and plucked edges on sulphides, mineral information can be lost. Scale bar = 50 µm's, X160.

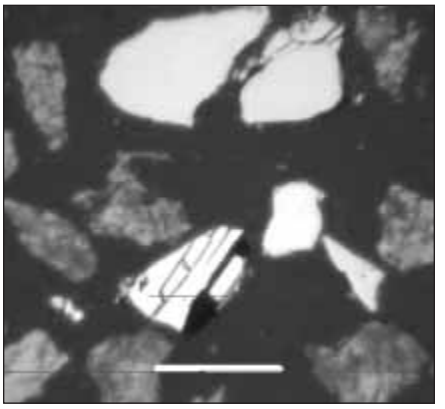
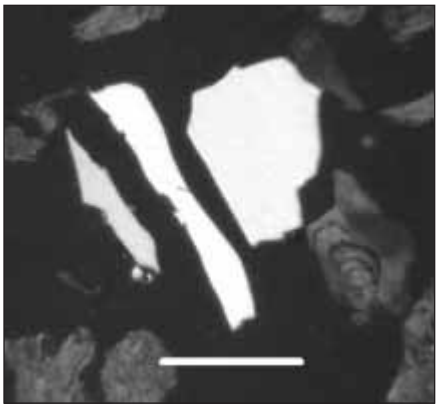


Fig. 2. Sulphides with clean edges, edge detail is preserved. Scale bar = 50 µm's, X160.



Polished Sections

Given the ability of QemSCAN to identify and quantify mineral information from 3 µm particles or 1 µm to 3 µm mineral features within mineral particles (e.g., pentlandite flames in pyrrhotite, or chalcocite rims on pyrite), it is necessary to accurately preserve these features in the polished section. In addition, it is also necessary to preserve the mineral proportions in each size fraction and avoid gravity segregation during mixing. A complete inventory of all mineral phases is required in order to get a true calculated assay from mineral abundances and their compositions.

Manual or interactive petrography, whether using a petrographic microscope or a SEM, allows the mineralogist to assess the condition of particles. To a limited degree, fractured particles and the potential of mineral plucking can be accounted for, and the quality of surfaces as shown in Figure 1 can be accepted. However, in the case of fully automated instruments such as QemSCAN, which are designed to produce quantitative mineralogy, such approximate surface preparation methodologies result in quantitative errors and erroneous conclusions. QemSCAN polished section preparation techniques have therefore been designed to reduce and/or eliminate these image artifacts (Fig. 2).

Preparation of polished sections is as much an art as it is a prescribed standard procedure. Once a solid procedure has been established that will produce "workable" polished sections, then it is time to begin experimenting to produce a finished high-quality surface.

Figures 1 and 2 show the difference that can be achieved. Different ore types and different process products, concentrates vs tailings, will have different polishing characteristics because of different mineralogy, thus techniques have to be fine-tuned for each different material.

Species Identification Program (SIP)

Accurate mineral identification is the key to quantitative image analysis as a process mineralogy tool. Development of a SIP that is capable of capturing a minimum of 99% of the mineral species in any given study is crucial to a successful reconciliation between chemical assays of the sample and calculated assays from QemSCAN mineralogy. In addition, mineral compositions must also be representative of subtle variations away from "textbook" compositions such as solid solution nickel in pyrrhotite. These compositional variations may be identified and quantified by classical WDX and EDX methods and used to update the QemSCAN SIP and composition tables.

Test specimens used in SIP development are obtained in advance of new ore or mill survey samples. This enables the collection of X-ray spectra and quantitative measurements, and allows the SIP code to be prepared ahead of the arrival of survey samples. Because of variations in mineralogy and texture, separate SIPs are often created for various ore classes such as porphyry copper deposits and volcanogenic massive sulphide deposits (VMS). These generic SIPs are stored in the software to be re-used when additional surveys or ore characterizations of similar material are requested.

Measurement Statistics

Before mineralogical data can be used for interpretation and evaluation of a plant operation, the measurements themselves must be evaluated to establish an appropriate level of confidence in them. Measurement statistics for each sample are reviewed to ensure that they represent the appropriate size fraction and valid liberation data has been collected. A set of quality assurance/quality control protocols are in place to capture abnormal measurement statistics, and support the ability to track through the sample history in order to resolve the problem.

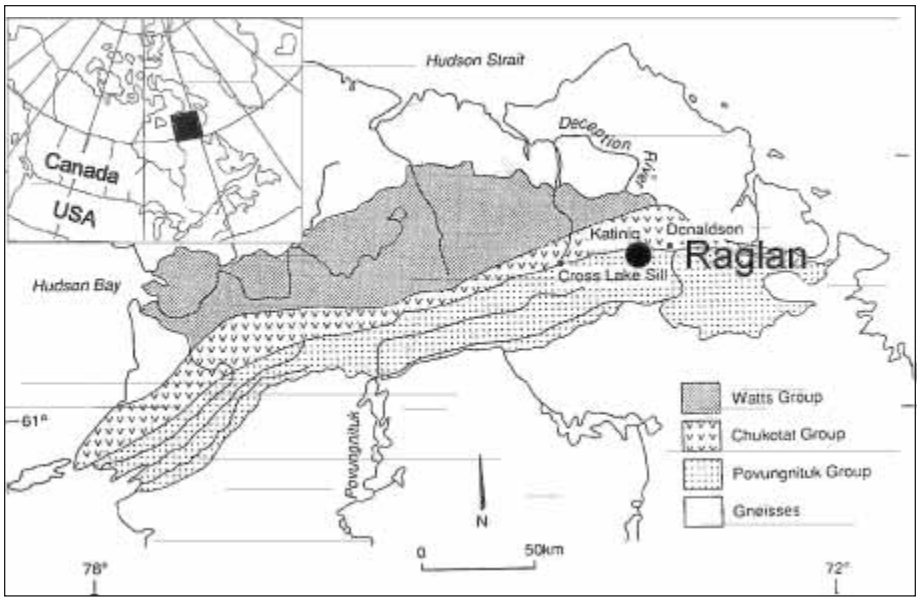
QemSCAN Operation

The precision and resolution at which QemSCAN conducts an analysis at each beam point has an holistic influence on the nature and design of the process mineralogy study. These influences include the design and implementation of the plant survey, the characterization of an orebody from drill core, and the use of mineralogical data for interpretation and process recommendations.

Mineral identifications are made based on characteristic peak height proportions for a given mineral. As the electron beam is stepped across rock fragments or liberated mineral fragments, a discrete mineral map is thus produced for each fragment. Spatial resolution is limited to around 0.5 microns in sulphide particles which limits the minimum particles for liberation measurements to around 3 microns. This corresponds to the cone size 6 fraction (CS6) produced by a cyclosizer. Consequently, complex and finely intergrown mineral textures can be mapped and their constituent phases quantified. The sub 3 micron, or CS7, cyclosizer fraction is only assayed and its mineralogy is estimated based on modal abundances from CS6.

The result of fine mineral particle resolution and accounting for a large range of boundary species (X-ray spectra acquired from the boundaries between minerals such as quartz and pyrite) is that a high-quality assay reconciliation between chemical and calculated QemSCAN assays can be expected. Assay reconciliation therefore acts as another level in the QemSCAN QA/QC protocols and provides the basis for independently assessing the value of both the quantitative mineralogy data as well as the conventional elemental data. When this level of assay reconciliation is achieved for each size fraction and product, then work can proceed with data interpretation. The final step is the provision of recommendations for changes in the process flowsheet to address metallurgical problems.

Fig. 3. Location map of the Raglan deposit, Ungava, northern Quebec (geology after St.Onge and Lucas, 1986).



QemSCAN Results and Interpretation

QemSCAN measurements provide size-by-size mineralogy and liberation data. Samples collected during mill surveys allow for the completion of a mineral mass balance that includes size-by-size recovery information by both mineral and liberation state. This becomes a very powerful diagnostic tool to evaluate individual streams within a mill and to make specific detailed recommendations for improvement. When the study involves ore characterization, invaluable process mineralogical information is obtained enabling the optimization of a flowsheet ahead of mining.

Application of Process Mineralogy to the Raglan Mill

The first application of process mineralogy at Falconbridge Limited involved a benchmark survey of the Raglan mill.

The Raglan Ni-Cu-PGE deposit is located in northern Quebec on the Ungava Peninsula (Fig. 3). The deposit is hosted by an alternating succession of thick komatiitic peridotite flows and sills of Archean age (Lesher et al., 1999) that are part of the Cape Smith Belt. The deposit has also been pervasively serpentinized and was then metamorphosed to regional greenschist facies (St. Onge and Lucas, 1986).

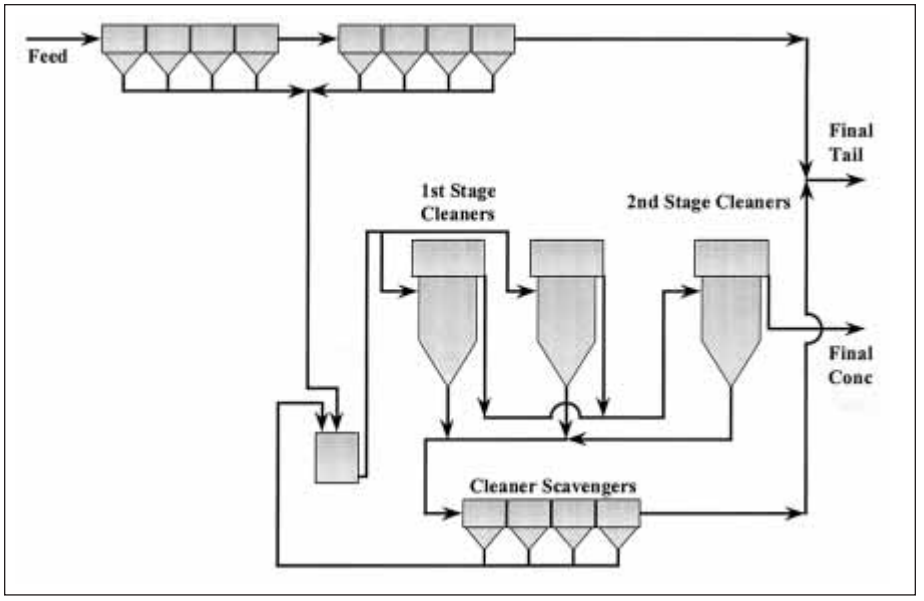
Mineralization occurs in a series of lenses that grade stratigraphically from massive sulphides at the base, upward into net-textured and, finally, disseminated sulphides. Post-serpentinization metamorphism has created complex replacement textures where sulphides have replaced silicates to define reverse net-textured sulphides (Dillon-Lietch et al., 1986). The result is a metallurgically challenging texture from which to separate ore sulphides. Comparisons have been made with the similar deposits of the Agnew-Wiluna greenstone belt in the Yilgarn block of Western Australia (Barnes and Barnes, 1990).

Falconbridge Limited staked claims in the area in 1969 and exploration activity proceeded in an intermittent fashion until the late 1980s. Falconbridge Limited acquired further property in the area and began development in 1995 with production underway in December of 1997 (Lesher et al., 1999).

After commissioning, plans were made for the first benchmark survey, which took place in June 1998. The objective was to provide baseline information on the commissioned circuit configuration and to identify potential areas for improvement in order to obtain optimum metallurgical performance. Figure 4 shows the original flowsheet configuration.

The main issue identified in the survey was a high circulating load in the cleaner

Fig. 4. Original Raglan flotation flowsheet.



scavenger circuit. QemSCAN results showed both the recirculating load and a significant proportion of the losses to the scavenger tailing were related to poorly liberated particles derived from the net-textured and disseminated ores.

The result of the poor liberation was low overall cleaner circuit recoveries. Figure 5 shows the size-by-size cleaner circuit recovery curves for the four major minerals at Raglan based on the total cleaner feed (rougher concentrate + cleaner-scavenger concentrate). The low recovery of pentlandite on an unsized basis (46%) is evident across all size fractions of the size recovery curve, with a maximum recovery of only 68% in the +7/-15 µm size fraction. Similarly, the recovery of chalcopyrite on an unsized basis is just 41%. The maximum recovery is 73% also in the +7/-15 µm size fraction. Both the pentlandite and chalcopyrite curves drop off dra-

Fig. 5. Size-by-size mineral recovery curve, cleaner circuit (based on overall cleaner feed-rougher concentrate and cleaner-scavenger concentrate).

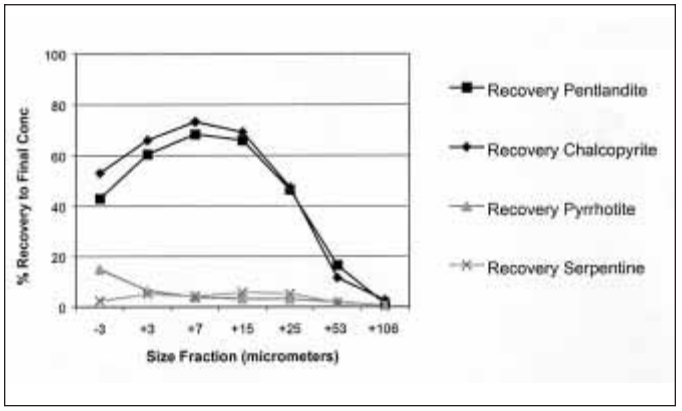


Fig. 6. Size-by-size pentlandite liberation in the cleaner scavenger tailing.

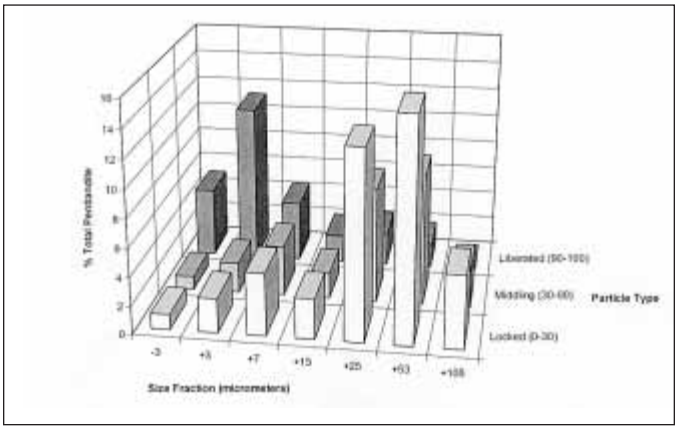


Fig. 7. QemSCAN particle map, primary column tail.

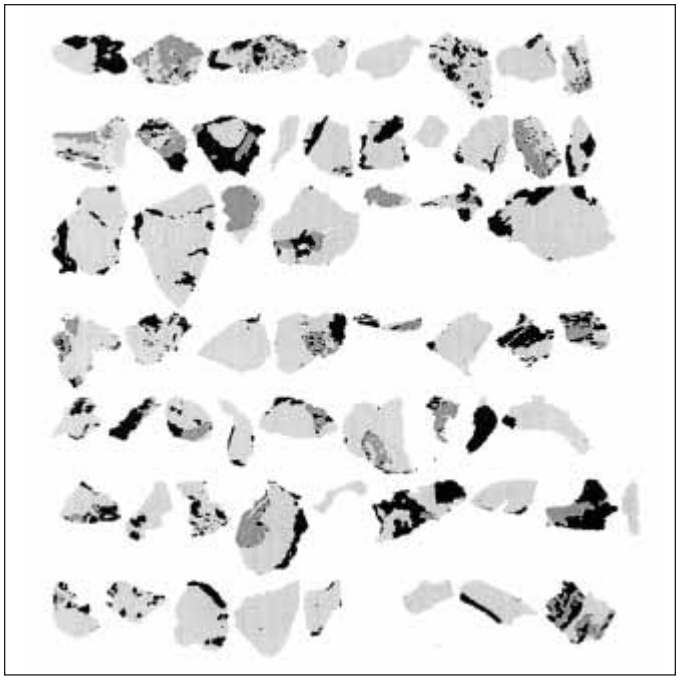


Fig. 8. QemSCAN particle map, scavenger concentrate.

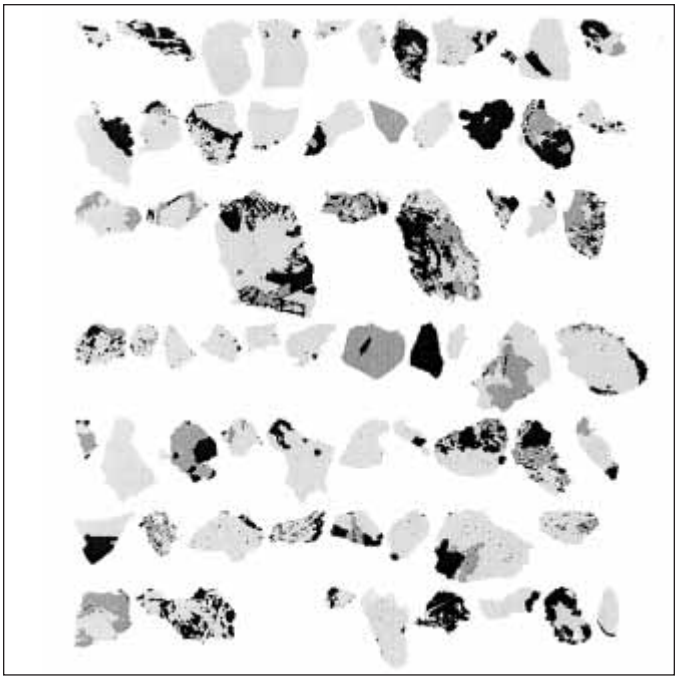


Fig. 9. Proposed flotation circuit configuration including regrind.

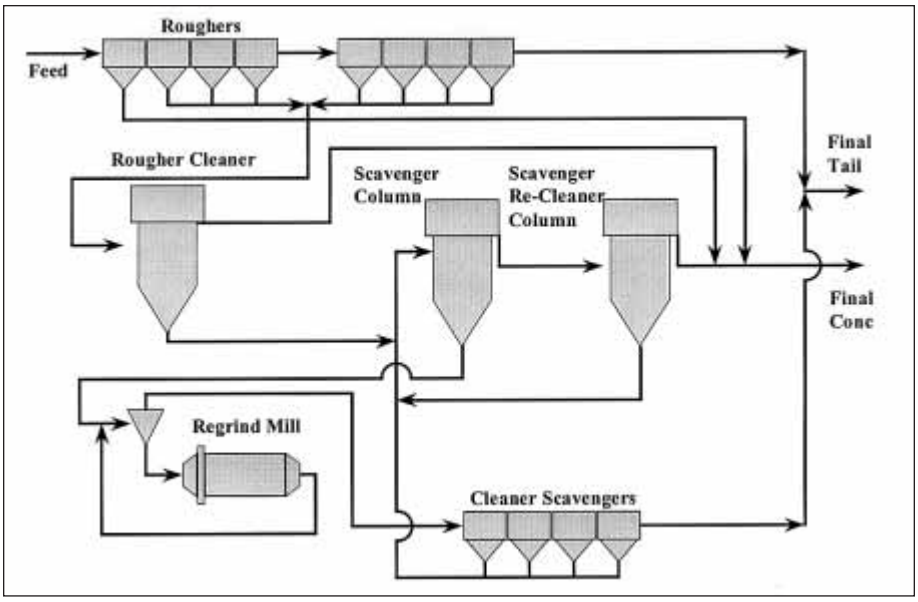
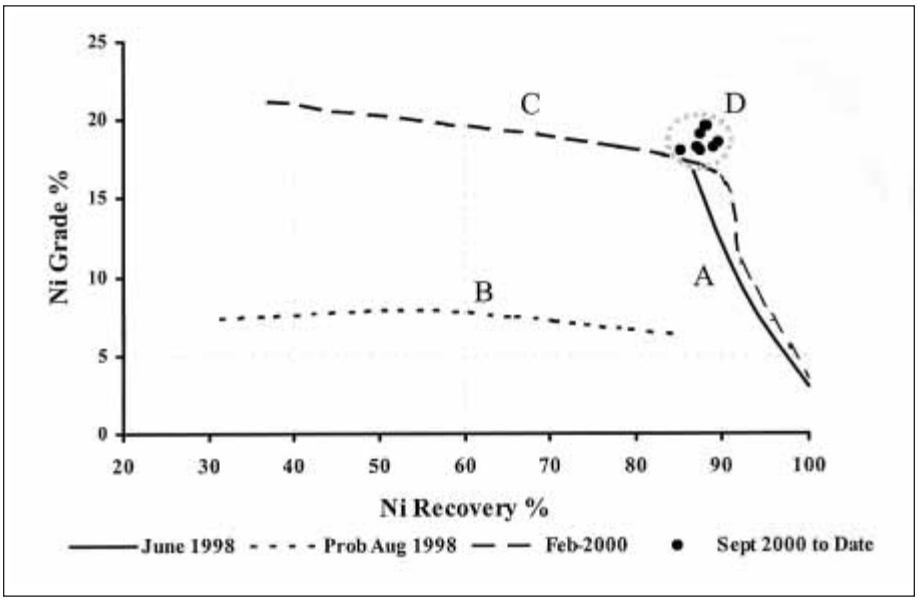


Fig. 10. Comparison of grade/recovery curves at the Raglan mill.



matically in the +25 µm size fractions, where the locking problem is most dominant. The other conclusion that can be drawn from Figure 5 is that cleaner circuit exhibits good selectivity with the pentlandite and chalcopyrite size recovery curves well-separated from the pyrrhotite and serpentine curves. Recoveries of pyrrhotite and serpentine are low, at 3.7% and 2.7%, respectively. However, the high rejection rate of the sulphide and non-sulphide gangue occurs at the expense of recoveries of the economic minerals. This is particularly true of the +25 µm size fractions where silicate/sulphide composite particles dominate the assemblage.

Figure 6 shows the size-by-size distribution of pentlandite by liberation state in the cleaner scavenger tailings. On an unsized basis, 26% of the pentlandite occurs as liberated particles, 29% as middling particles and 45% as locked particles. Locks and middling particles in the +25 µm size fractions account for 54% of the pentlandite losses in this stream.

Figures 7 and 8 are QemSCAN particle maps from the +106 µm size fractions of the primary column tailing and the scavenger concentrate, respectively. It must be noted that greater mineralogical detail is available but the requirements for black-and-white images in this paper precluded the use of full colour image presentation. The same types of particles that are rejected in the primary column tailing, due to their association with gangue, are picked up again in the scavenger concentrate, due to the presence of sulphides. Because there was no mechanism present in the commissioned circuit, to separate the economic sulphides from gangue in these complex middling and locked particles, a large circulating load was created.

Regrinding of the scavenger feed (primary column tailings) was recommended in order to:

- improve the liberation of pentlandite and chalcopyrite for cleaning;
- decrease the circulating load of coarse particles; and
- improve the selectivity between sulphide and gangue minerals through size reduction and gangue liberation.

The proposed circuit configuration including the regrind is shown in Figure 9.

Changes to the Raglan mill since the June 1998 survey include repiping the recleaner tailings to the head of the primary column cleaners, installing a rougher bypass straight to final concentrate, appropriate use of depressant, and commissioning a regrind in the cleaner scavenger circuit. Capital projects for the specification and construction of new metallurgical equipment are continuing at this time to address other recommendations to the flowsheet. Some of these changes have been discussed at the January 2001 CMP meeting (Langlois and Holmes, 2001).

The rougher concentrate bypass was implemented in June 1998 shortly after the first survey, and relocated the first rougher cell concentrate directly to final concentrate. This bypassed the cleaner circuit and took an increment of duty away from the cleaners, thus improving the retention time and removing the fast-floating species from the cleaners.

The recleaner tailings were relocated to match the first column feed stream in September 2000. This was done because the mineral compositions of the cleaner tailings and the recleaner tailings were very different and required separate treatment.

The implementation of appropriate gangue depressant dosage in the rougher float was completed in the fall of 1998 following laboratory-scale testwork at the Falconbridge Technology Centre. This work characterized the dosage curve for the depressant and defined an optimum dosage range. The grade/recovery performance of the problematic ore was significantly improved as a result. The key to this development was the identification of talc and chlorite by X-ray diffraction in samples of the problematic ore. The depressant selected and appropriately dosed to the rougher float effectively controlled the problematic flotation of these alteration minerals.

Regrinding of the cleaner tailings prior to scavenger flotation was implemented in September 2000 after a one-week pilot survey in February 2000. This study was conducted on problematic ore in order to

validate parts of the process mineralogy model, and to provide a prototype mass balance for design purposes.

The cumulative effect of these changes, from September 1998 to date, has resulted in a new grade/recovery curve for the mill. Where it is readily acknowledged that further performance opportunities exist, and which are being pursued, the concentrate grade and recovery have improved by several percent each. The various grade/recovery curves are shown in Figure 10. The June 1998 curve, labelled in Figure 10 as A, is the benchmark to which the others are compared. A problematic, talc-bearing ore milled during August of 1998 produced an inferior curve, shown as B. The February 2000 curve (C), also describes a problematic ore, although shows the benefit of the use of depressant and the temporary use of the regrind in the cleaner-scavenger circuit. Finally, the points marked as D are the initial data points from September 2000 onward, representing the period from which the on-line time of the regrind was significant and relatively stable.

The changes implemented to the Raglan flowsheet described above have had several impacts on operations performance and on the bottom line for Falconbridge. Involvement of operations personnel in the design and conduct of plant benchmark surveys has become a key part of the success of these studies and in gaining their support for future work. An appreciation of the predictive and analytical power of this approach is developing as a result.

Process mineralogy allows for a reliable approach to evaluating the efficiency of a plant-scale process. The continued growth of this discipline within Falconbridge Limited will focus not only on improvements to our concentrators throughout the world but also on development of other applications.

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