THE RECOVERY OF METALS FROM THE STORA SAHAVAARA AND HANNUKAINEN IRON OXIDE COPPER GOLD (IOCG) RESOURCES

DOMINIQUE LASCELLES, ANDRÉ MCKEN AND GUILLAUME CHIASSON (SGS MINERALS SERVICES, LAKEFIELD, CANADA), PAUL MARSDEN AND LAWRENCE HOOEY (NORTHLAND RESOURCES INC, CANADA) AND ALAN DIXON AND KARL HOUSELEY (CORUS CONSULTING UK)

ABSTRACT

The Stora Sahavaara and Hannukainen iron ore resources are located near the borders of Sweden and Finland. These deposits are categorized as Iron Oxide Copper Gold (IOCG) type, which typically contain magnetite with varying amounts of sulphides which are commonly, though not always, associated with copper, gold and potentially other metals.

In the case of the Stora Sahavaara resource the iron ore mineralization occurs as magnetite, which can be readily recovered by conventional low-intensity magnetic separation. The presence of significant amounts of magnetic pyrrhotite and its deportment to the magnetic concentrate created some challenges and had to be dealt with through reverse sulphide flotation. In the case of Hannukainen the presence of recoverable gold, copper and other potential metals also contributed to the project complexity and challenges.

This paper summarises the extensive bench and pilot-scale work performed on both deposits and the repercussions on the project's technical feasibility. The testwork included detailed mineralogical characterization, combining microprobe analyses, traditional optical microscopy and QEMSCAN techniques, as well as beneficiation and hydrometallurgical testing. The testwork was supported by significant variability testing, in which geo-metallurgical relationships were developed from mineralogical and chemical head assays.

INTRODUCTION

Iron Oxide Copper Gold (IOCG) deposits are identified by the occurrence of copper-gold sulphide mineralization with large concentrations of iron oxide minerals, mainly magnetite and hematite, as opposed to iron sulphides. These deposits are generally made up of more than 20% iron oxides [Corriveau, 2005]. Some well-known IOCG deposits are the high-Cu Olympic Dam deposit located in Australia, the low-Ti and low-Cu/Au Kiruna deposit located in Sweden, and the high-Ti and magnetite-rich Phalaborwa (Palabora) deposit located in South Africa. Typically, the magnetite in these deposits is easily recovered by low-intensity magnetic separation (LIMS) but any magnetic pyrrhotite present in the ore will also be recovered and concentrated. High sulphur grades in the iron concentrate have been known to delay the oxidation of magnetite to hematite, to increase the FeO content and to decrease the compression strength [Cline and René Rosas, 1975]. Additionally, today's strict environmental regulations suggest that sulphur capture and removal systems would be required for any pelletizing plant that would treat the high sulphur concentrate. A flowsheet for the flotation of iron sulphide from iron ore at Marcona in the 1970's required large amounts of potassium amyl xanthate and copper sulphate as activator [Cline and René Rosas, 1975].

This paper summarises preliminary flowsheet development for two IOCG deposits (Stora Sahavaara and Hannukainen) owned by Northland Resources Inc. Located in Sweden, only 150km from the Kiruna deposit, the Stora Sahavaara (Stora) deposit has a measured resource estimate of 77.1Mt at 43.3%Fe and 0.080%Cu with an additional indicated 44.6Mt at 43.2%Fe and 0.076%Cu. Located in Finland, the Hannukainen property has measured resources of 53.1Mt at 35.6%Fe, 0.25%Cu, and 0.12g/tAu (with an additional indicated resource of 31.5Mt at 32.9%Fe, 0.11%Cu, and 0.04g/tAu) in five deposits; Laurinoja, Kuervaara, Lauku, Vuopio, and Kivivuopio. The Laurinoja deposit makes up 70% of the measured Fe resource (35.4Mt at 37.6%Fe, 0.32%Cu, and 0.17g/tAu). The Laurinoja and Kuervaara deposits were mined as open pit during the 1980s through magnetic separation followed by flotation; producing magnetite and chalcopyrite concentrates [Mining Magazine, 1982].

METHODOLOGY

An initial two drill holes from the Stora Sahavaara deposit were submitted for flowsheet development. Selected intervals from these two drill holes were combined to give two composite samples representative of the hanging wall and the main orebody. Selected interval samples were also submitted for Davis tube and QEMSCAN characterisation for use in the development of geometallurgical relationships. Bulk samples representative of a cross-sectional sample of the hanging wall, the main orebody, and the footwall were submitted later for piloting. Additional samples (2nd and 3rd samples) representing other parts of the deposits were supplied later to assess variability.

In parallel, twin drill core samples from the Laurinoja deposit, 7009A and 7009B, were submitted for Hannukainen flowsheet development. All intervals from the 7009B drill core were combined to prepare the 7009B composite. Selected intervals were also submitted to Davis tube and QEMSCAN characterisation and eventually combined to prepare five grade variability composites.

SAMPLE CHARACTERIZATION

Each sample was submitted for Whole Rock Analysis (WRA), Cu, Au, and S assays, Satmagan determination of magnetic content, and Davis tube determination of Fe recovery. Selected samples (Davis tube feed and/or products) were submitted for Quantitative Evaluation of Materials by SCANning Electron Microscopy (QEMSCAN). Additionally, selected magnetite, pyrrhotite, and pyrite grains (plus tochilinite/valleriite for Stora) were submitted for microprobe analysis to quantify metal contents and impurities. The sample characterization results were compared in order to establish recovery relationships, where present.

BENCH-SCALE TESTWORK

For both deposits, the following bench-scale testwork was carried out as part of flowsheet development:

- Grindability testwork leading to grinding circuit design
- Coarse cobbing / primary Low-intensity Magnetic Separation (LIMS) to investigate coarse gangue rejection
- Secondary LIMS testing to evaluate the effect of grind size on concentrate quality
- Flotation testwork for the rejection of S from the magnetic concentrate through reverse flotation of pyrrhotite

In addition to the testwork outlined above, several flowsheets were investigated for the flotation recovery of Cu and Au from the Hannukainen deposit.

PILOT PLANT TESTWORK

A bulk sample from the Stora Sahavaara deposit was processed through a pilot plant, testing all aspects of the proposed flowsheet (Figure 1). The main purpose of the pilot plant, aside from flowsheet confirmation, was to produce sufficient amounts of magnetite concentrate for pelletizing testing. The first stage of the pilot plant, i.e. primary grinding with either High-Pressure Grinding Rolls (HPGR), Fully Autogenous Grinding (FAG), or Semi-Autogenous Grinding (SAG) followed by coarse wet cobbing, was conducted at a feed rate of approximately 1000 to 1500 kg/hr. The magnetic concentrate was then reground in a ball mill prior to three stages of LIMS. The

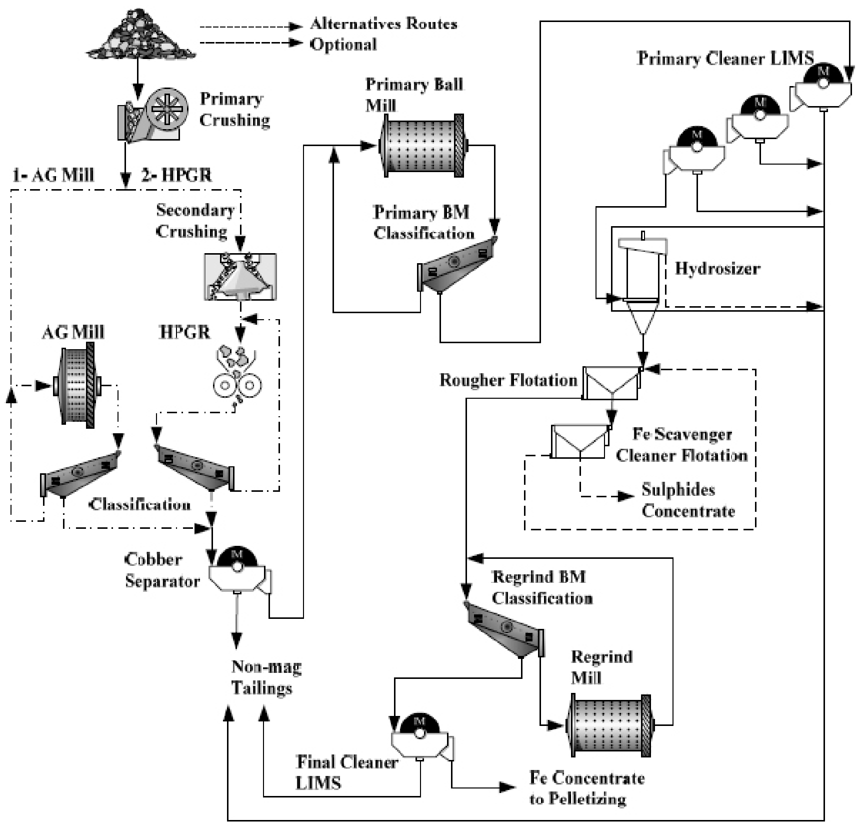

Figure 1: Recommended Beneficiation Flowsheet for Stora Sahavaara

LIMS concentrate was then fed to the flotation circuit. The flotation sinks (Fe concentrate) were reground to a K80 of 35-40µm, in order to achieve the required Blaine surface area, prior to a final LIMS cleaning stage. The flowsheet produces three products: an Fe concentrate, a non-magnetic tailings, and a sulphide tailings.

VARIABILITY TESTING

Selected interval samples were also submitted for Davis tube and QEMSCAN characterisation for use in the development of geometallurgical relationships. The objective was to develop simple relationships for use in the resource model from head analyses (assay or QEMSCAN). Most of the variability testing work focussed on predicting the LIMS concentrate grade and recovery. Variability in flotation performance was also touched; particularly for the Hannukainen deposit which includes two flotation circuits.

RESULTS AND DISCUSSION

STORA SAHAVAARA

Sample Characterization

A summary of the head assays and the grindability data obtained for the five Stora composites is presented in Table 1. Iron content, as determined by WRA, ranged from 36.7% in the 2nd Sample to 46.8% in the Main composite. Magnetite content, as measured by Satmagan, was lowest in the 2nd Sample and highest in the 3rd Sample. Microprobe analyses of magnetite grains indicated a high degree of variation in MgO content, explaining the lower than anticipated Satmagan values. It was also established that the Fe in the Stora ore is primarily present as magnetite (~95%), with small amounts in pyrite, pyrrhotite and gangue minerals. Low-grade copper mineralization is present, though primarily through unfavourable minerals from the valleriite/tochilinite group which have low beneficiation potential (only 5% Cu from microprobe analyses).

Flowsheet Development

The Marcona flowsheet was used as a starting point for processing the

Table 1: Assay and Grindability Summary of the Stora Sahavaara Head Samples

MINERAL ABUNDANCE	MAIN*	HANGING WALL
Fe-Oxides	66.2	65.3
Apatite	0.15	0.07
Tochlinite/ Valleriite	0.81	0.12
Chalcopyrite	0.02	0.03
Pyrite	1.2	1.2
Pyrrhotite	4.3	0.8
Serpentine	13.6	19.8
Olivine	6.3	6.2
Amphiboles	2.2	2.4
Fe Desitribution		
Fe-Oxides	90	95
Pyrite	1.1	1.2
Pyrrhotite	4.8	0.9
Gangue	3.2	3
S Distribution		
Tochlinite/ Valleriite	9.1	3
Chalcopyrite	0.4	1
Pyrite	29	63
Pyrrhotite	61	32
Cu Distribution		
Tochlinite/ Valleriite	90	65
Chalcopyrite	8	34

* +20 microns only

ASSAY	2ND SAMPLE	3RD SAMPLE	MAIN	HANGING WALL	BULK SAMPLE 2
SiO_2 %	19.8	12.8	10.4	14.7	12.4
Fe_2O_3 %	52.5	65.9	65.4	60.1	63.5
MgO %	16.9	13	15.7	16.9	15
S %	2.55	2.4	2.56	0.83	2.19
Cu %	0.062	0.086	0.15	0.044	0.081
Au g/t	0.07	<0.02	0.03	<0.02	0.11
Fe %	36.7	46.1	46.8	43.2	44.4
Fe_3O_4 % (satmagan)	43.1	56.5	49	52.4	52.4
Grindability					
A	64.5	69.7	61.7		64.8
b	1.16	1.23	1.08		1.49
A x b	74.8	85.7	66.7		96.8
ta			0.83		0.86
SPI (min)			59.7	41.5	42.2
MacP. Thr. Rate (kg/h)			17.2		23.9
AWI (kWh/t)			10.4		7.7
CWI (kWh/t)			7.3		6.3
RWI (kWh/t)	10.2	7.9	9.6		8.6
BWI (kWh/t)	16.9	16.6	16.3	17	18.8
BWI on mags (kWh/t)			16.9	17.9	17.4
AI (g)			0.094	0.121	0.108
HPGR power (kWh/t)	1.66	1.7	1.5		1.36

Stora Sahavaara ore. Coarse cobbing testwork showed only slight weight rejection with minimal Fe losses. The grind requirements for the secondary LIMS stage was investigated through Davis tube tests at different grind sizes as presented in Figure 2. Both SiO_2 and MgO are impacted by grind size.

As suggested by Cline and René Rosas (1975), the flotation of pyrrhotite (Po) from magnetite (Mt) required massive amounts of collector and sulphuric acid, especially with a much lower target S grade (0.05% in this case versus 0.3% in the case of Marcona). The role of $CuSO_4$ was not confirmed at this point. Additional laboratory testwork identified that a grind size of 80% passing 90µm and a solids density of 50% by weight (equivalent to 35% by volume) were optimum for the selective flotation of Po.

Pilot Plant Testwork

The laboratory flowsheet was tested at pilot scale. The cumulative net power requirements to grind the ore from 114mm to 78µm for each of the three primary grind/cobber circuits are compared in Table 2. The SAG mill option was the lowest at 10.3 kWh/t, while the HPGR option was the highest at 12.6 kWh/t. The FAG milling option required 11.3 kWh/t. This was slightly higher than the SAG option, but the additional energy costs would be offset by the saving in steel balls.

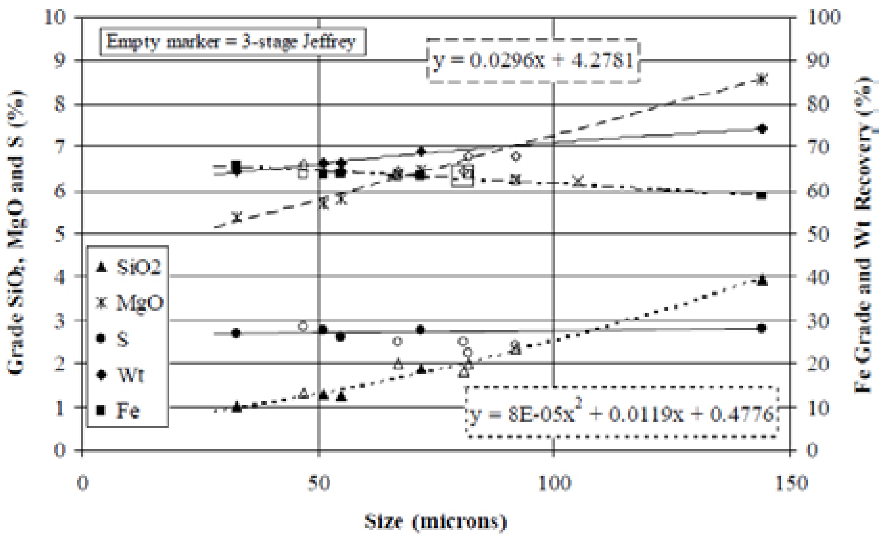

Figure 2: Effect of Grind on LIMS Concentrate Quality for the Main Sample

Variability Testing

The effect of variable feed on the final concentrate was investigated with the 2nd and 3rd samples at laboratory scale. The final LIMS concentrates achieved with each sample are compared in Table 3. Final concentrate grades and recoveries were dependant on both feed Fe grade and MgO impurities in the concentrate magnetite.

Geometallurgical Relationships

A number of predictive linear and non-linear geometallurgical models were developed for the three Stora ore samples to forecast various parameters of interest in the reserve model from head characterisation (assays and QEMSCAN). These models were developed using the results of the Davis tube tests yet the relationships strictly used head data. The overall actual versus predicted values for the models proposed are presented in Figure 3.

Table 3: Stora Sahavaara Final LIMS Summary

SAMPLE	FINAL LIMS CONC.								
	WT %	K_{80} µM	BLAINE CM²/G	GRADE, %				RECOVERY, %	
				FE	SIO²	MGO	S	SAT	FE
Bulk Sample #2	52.5	37	1743	67.6	0.93	4.44	0.06	88.5	81.6
2nd Sample	41.1	40		70.8	0.4	3	0.05	94.3	79.5
3rd Sample	54.9	41		70.2	0.28	2.32	0.01	90	83.7

Table 2: Stora Sahaavara Pilot Plant Grinding Summary

PRIMARY	AG/HPGR PERFORMANCE				BALL MILL PERFORMANCE			PRIM. AND SEC. GRINDING		REGRIND MILL PERFORMANCE		OVERALL	
GRINDING	FEED KG/H	F_{80} MIN	NET POWER KWH/T[1]	K_{80} µM	FEED KG/H	NET POWER KWH/T[1]	K_{80} µM	NET POWER KWH/T[1]	WIO KWH/T	NET POWER KWH/T[1]	K_{80} µM	NET POWER KWH/T[1]	WIO KWH/T
HPGR	1474	8.95	1.96	1427	500	10.6	78	12.6	11.6	8.1	32	20.7	12
FAG	1222	114	5.04	246	447	6.2	78	11.3	10.2	8.1	32	19.4	11.2
SAG	2600	114	3.81	502	486	6.4	78	10.3	9.3	8.1	32	18.4	10.6

[1]Based on crude (HPGR or AG mill feed)

A fairly good model for weight and recoverable Fe could be developed from the Fe assay only, indicating a consistency in the variation of recoverable Fe throughout the tested samples, but the inclusion of QEMSCAN (QS) Fe Oxide assay improved the relationship and is more likely to apply to the entire deposit.
The model for S grade relies on the pyrrhotite (Po) assay determination with QS and can vary significantly with the ratio of monoclinic (magnetic) to hexagonal (non-magnetic) Po which seems to be geographically-related. More work is required in this area.
The model for SiO_2 was based on head grade and the associations in the feed as measured by QS.

The current model was performed at constant grind and does not predict the effect of varying grind, which will affect the SiO_2 content. Size-by-size analyses characterisation would be required to bring the model to this higher level.

The MgO model was initially the least reliable because the MgO impurities in the magnetite matrix are highly variable and unpredictable, and the MgO content will also be strongly affected by grind. The inclusion of microprobe analyses in the model largely improved predictability, and could therefore be used to refine the model. More work may also be required in this area.

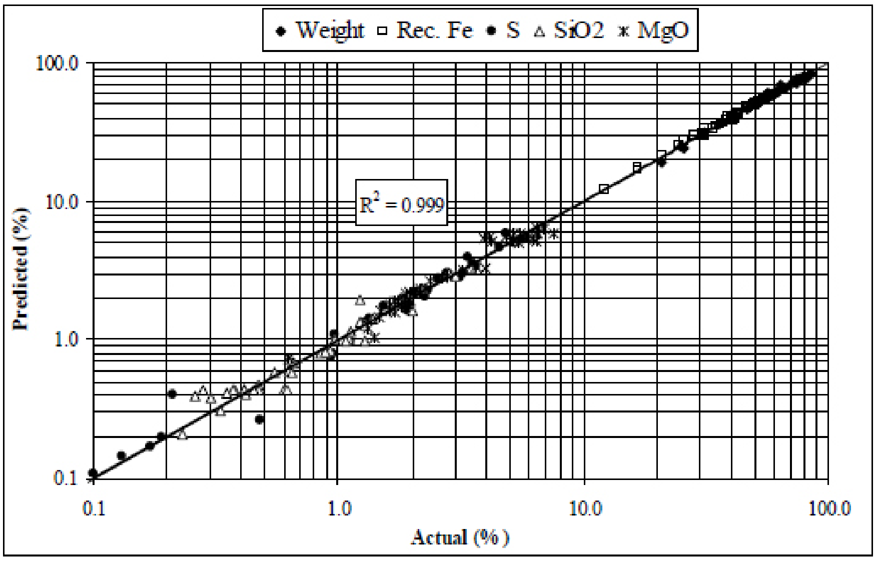

Figure 3: Actual vs. Predicted Values from the Various Models

Table 4: Hannukainen 7009B Composite Characterisation Summary

MINERAL ABUNDANCE	HANNUKAINEN	ASSAY	HANNUKAINEN
Fe-Oxides	48.4	SiO_2 %	28.2
Pyrite	2.29	Al_2O_3 %	4.2
Pyrrhotite	3.22	Fe_2O_3 %	50.3
Chalcopyrite	0.77	MgO %	4.46
Quartz	2.18	S %	2.71
Feldspar	6.93	Cu %	0.26
Pyroxene	21.7	Au g/t	0.21
Amphiboles	9.19	Fe %	35.2
Mica/Clays	2.4	Fe_3O_4 % (Satmagan)	38.7
Fe Distribution		Grindability	
Fe-Oxides	89.6	A	75.6
Pyrite	3.1	b	1.45
Pyrrhotite	5.23	A x b	110
Chalcopyrite	0.6	ta	0.64
Gnague	1.44	SPI (min)	60.6
S Distribution		MacP. Thr. Rate (kg/h)	19.7
Pyrite	46.5	AWI (kWh/t)	9.2
Pyrrhotite	44.9	CWI (kWh/t)	7.57
Chalcopyrite	8.2	RWI (kWh/t)	7.36
Cu Distribution		BWI (kWh/t)	18.2
Chalcopyrite	100	AI (g)	0.304

HANNUKAINEN

Sample Characterization

A summary of the mineralogy, head assays, and the grindability data for the Hannukainen 7009B composite is presented in Table 4. Most of the Fe (~90%) is present as magnetite, pyrite and pyrrhotite and essentially all copper occurs as chalcopyrite.

Flowsheet Development

Coarse cobbing, to reject coarse gangue, was tested with a dry magnetic drum. The tests resulted in significant weight rejection (30.0 to 34.6%) at high recoveries (98.0 to 98.9%), indicating a good level of gangue liberation at coarse size. The coarse cobbing option was abandoned, however, due to the high copper and gold losses to the cobber tails.

Three beneficiation flowsheets were investigated. Flowsheet #1 was the

Table 5: Overall Metallurgical Balances for Flowsheets #1 and #3

FLOWSHEET / REAGENT DOSAGES	PRODUCTS	WEIGHT %	ASSAYS, %, G/T							% DISTRIBUTION			
			Fe	S	Cu	Au	SiO_2	Al_2O_3	MgO	Fe	S	Cu	Au
Flowsheet #1	Fe Concentrate	30.6	70.6	0.01	0.003	0.02	0.94	0.35	0.33	63.7	0.1	0.4	4.8
706g/t Ca(OH)2	Cu Concentrate	0.61	34.6	37.7	27.1	4.28				0.6	9.3	71.2	20.5
12g/t PEX, 7.5g/t 3418A	Py Concentrate	2.15	40.1	39.7	1.33	1.46				2.5	34.5	12.3	24.7
180g/t PAX	Po Concentrate	5.46	61.4	23.3	0.43	0.29				9.9	51.4	10.1	12.5
2.5g/t CMC	Low 'S' Tail	61.2	12.9	0.19	0.022	0.078				23.2	4.7	5.9	37.6
20g/t MIBC	Head (calc)	100	33.9	2.47	0.23	0.13				100	100	100	100
Flowsheet #3	Fe Concentrate	31.5	70.6	0.05	0.002	0.02	0.98	0.39	0.35	67.8	0.6	0.2	4.3
1275g/t Ca(OH)2	Cu Concentrate	0.91	32.6	28.7	26.2	7.66				0.9	10.5	92.2	48
25g/t PEX, 17.5g/t 3418A	Py Concentrate	3.04	39.7	35.3	0.33	0.74				3.7	43.3	3.9	15.4
180g/t PAX	Po Concentrate	4.69	63.3	22.6	0.05	0.11				9	42.7	0.9	3.5
5g/tCMC	Low 'S' Tail	59.8	10.2	0.12	0.012	0.07				18.6	2.9	2.8	28.7
33g/tMIBC	Head (calc)	100	32.9	2.48	0.26	0.15				100	100	100	100

same as that used to process the Laurinoja and Kuervaara deposits in the 1980's, i.e. magnetic separation, followed by flotation of a Cu concentrate from the non-magnetic tails and Po flotation from the magnetic concentrate. Flowsheet #2 floated Cp and Po sequentially from the whole ore prior to magnetic separation on the flotation tails. Finally, Flowsheet #3 involved the flotation of Cp to produce a Cu concentrate followed by magnetic separation of the Cu flotation tails and Po flotation from the magnetic concentrate. Flowsheet #2 was abandoned because of the large flotation capacity required. Flowsheets #1 and #3, tested as locked cycle tests, are compared in Table 5. Both flowsheets performed similarly in terms of Fe concentrate grade and recovery but flowsheet #3 (Figure 4) was selected as it showed higher Cu and Au recoveries.

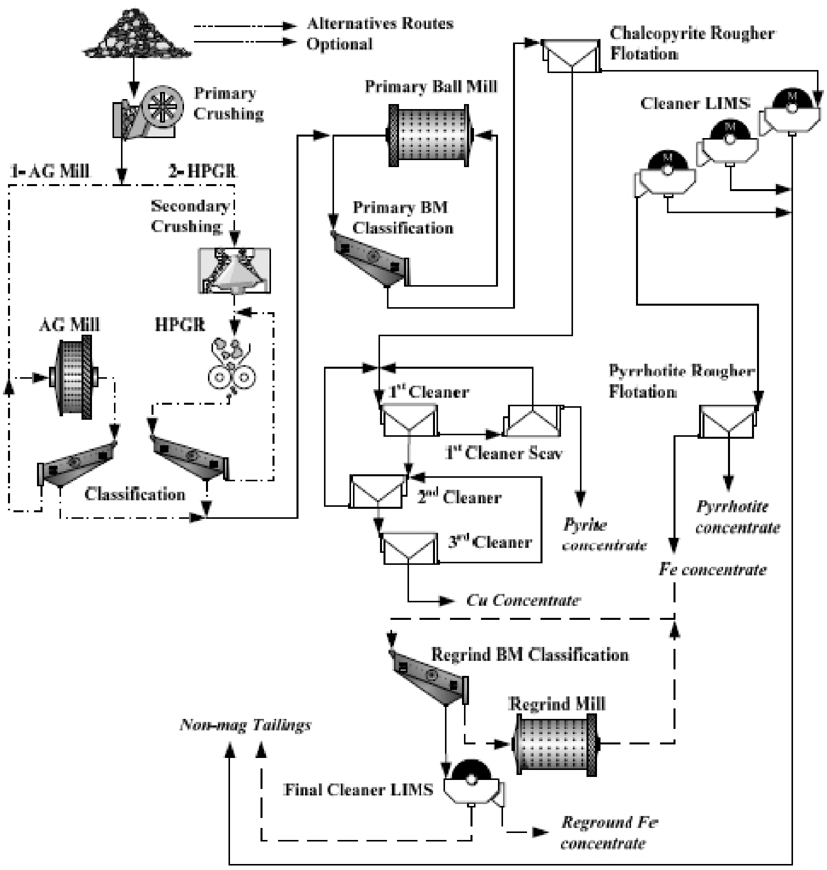

Figure 4: Recommended Beneficiation Flowsheet for Hannukainen

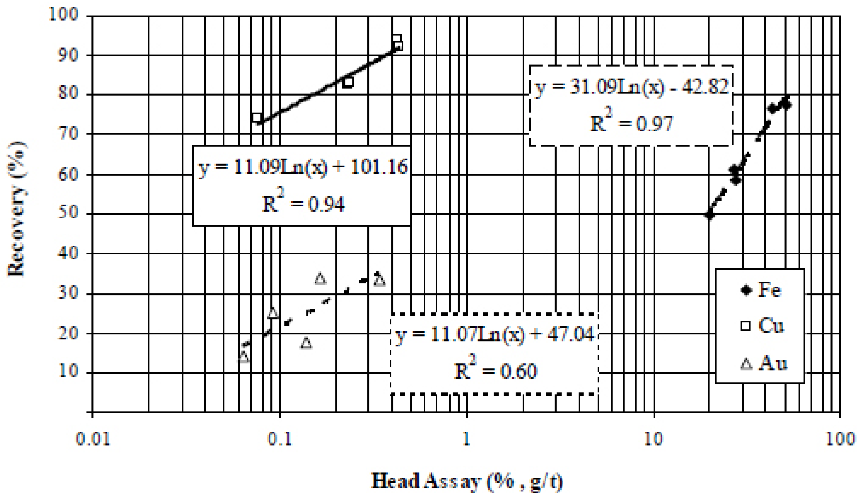

Figure 5: Effect of Feed Grade Variability on Recovery Added

Variability Testing

A key factor in flowsheet selection is the ability to produce a saleable Cu concentrate at reasonable recoveries. Five composites spanning a range of head Cu, Au, Fe, and S grades were processed using flowsheet #3. All samples tested achieved saleable Cu concentrate grades. The effect of head grade variability on Fe, Cu, and Au recovery is presented in Figure 5. As expected, a decrease in head grade resulted in a decrease in recovery. Iron appears to be the most impacted by head grade but this is likely due to a different magnetic to non-magnetic Fe ratio at lower Fe head grades.

Added Value Recovery

Initially, it was proposed that the high-S products produced by both flowsheets could possibly be converted by pressure oxidation into sulphuric acid (for use in the flotation circuit as pH modifier), and iron oxides that would be blended with the Fe concentrate to maximise Fe recovery.

The pyrrhotite concentrate from the Stora Sahavaara process and the pyrrhotite and pyrite concentrates from the Hannukainen process contain significant Cu and Au (Table 6) which could be extracted through pressure oxidation followed by appropriate recovery methods (e.g. precipitation, solvent extraction or cyanidation). It was established that high Cu extraction rates (>98%) could be obtained on the pyrite concentrates through POX. Further work is being performed in this area.

Table 6: Summary of Iron Sulphide Concentrate Assays

SAMPLE	GRADE, %, G/T				
	Cu	Fe	Au	S^{2-}	S(t)
Stora Po Conc	0.08	60.8	0.06	16.4	16.4
Hannukainen Po Conc	0.15	62	0.14		24.2
Hannukainen Py Conc	0.3	39	0.63	34.1	37.3

CONCLUSIONS

The testwork conducted on the Stora Sahavaara and Hannukainen IOCG deposits highlighted the possibility of using head characterization tools including conventional analytical methods in conjunction with QEMSCAN, Satmagan determination of magnetic content, and Davis tube determination of Fe recovery to develop simple predictive models for the ores. The models presented for the Stora Sahavaara composites are a starting point for full geo-metallurgical characterization of that deposit.

The flowsheets developed for the two deposits show the importance of clearly identifying the value in the ore. The lack of Cu or Au in the Stora orebody allowed for the insertion of a coarse cobbing stage for weight rejection prior to the ball milling stage. The presence of Cu and Au value in the Hannukainen sample, on the other hand, made coarse cobbing impractical. The recovery of sulphuric acid and/or Cu and Au through pressure oxidation of the sulphide streams may bring added value to the process.

REFERENCES

Corriveau L. (2005). "Iron oxide copper gold (±Ag ±Nb, ±P ±REE ±U) deposits: a Canadian perspective". http://gsc.nrcan.gc.ca/mindep/synth_dep/iocg/index_e.php. Geological Survey of Canada. [1]

Cline W.A. & C. René Rosas (1975). "How Marcona floats iron sulphides from magnetite pellet feed concentrate". World Mining, March, pp. 48-52. [2]

(1982). "Rautuvaara and Hannukainen Mines". Mining Magazine, August, Vol. 147, No. 2, pp. 101-111. [3]

CONTACT INFORMATION

Email us at minerals@sgs.com

WWW.SGS.COM/MINERALS