Bergforsk

Mineral Supply – a Grand Challenge and Opportunity

Extended Abstracts

Bergforsk, May 5th, 2010

Luleå

MITU Swedish Mining Research

in co-operation with

Luleå Tekniska Universitet

VINNOVA

GEORANGE

in co-operation with

Investing in your future

European Union European Regional Development Fund

Bergforsk

Luleå, May 5th 2010

PREFACE

Future mineral supply is a grand challenge for the society at large. Competitive Swedish mining companies, the academia and leading global suppliers in Scandinavia have an excellent opportunity to respond to this challenge by developing methods for competitive and sustainable eco-efficient mining. The ongoing Strategic Mining Research Programme is an important keystone in the endeavors to build and maintain strong competence centres at Luleå University of Technology and to develop knowledge and results that later can be implemented for sustained competitiveness. The objectives of the programme can be summarised as follows:

- to reinforce the leading position in terms of technology and international competitiveness of the Swedish mining industry in selected strategic niches;
- to create strong education, research and innovation environments that make it possible to continue to develop and to hold a leading position in selected focus areas;
- to contribute to successful Swedish participation in international joint initiatives in the EU, but also increased collaboration with research for example in Australia, Finland, Canada, Poland, South Africa and the United States.

The compilation of Extended Abstracts from the ongoing projects within the Mining Research Programme provides a short insight of the work in progress. The printed version is in black and white; the full version will be available at www.bergforsk.se

Göran Bäckblom, editor
MD MITU/Bergforsk

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1 OVERVIEW OF THE MINING RESEARCH PROGRAMME

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In September 2006 the Swedish Government decided to commission VINNOVA to implement an "innovative and future-oriented mining research programme" in collaboration with the Geological Survey of Sweden (SGU) and the Swedish mining industry. The commitment is intended to strengthen the technology leading position and competitiveness of the Swedish Mining Industry and to strengthen future supply of skills and expertise. During the programme at least 100 million SEK is invested in the programme, of which the public part is 50 million SEK, and the Swedish mining industry finances at least as much.

1.1 Scope of the programme

The purpose of the programme is to reinforce the leading position in terms of technology and competitiveness of the Swedish mining industry in strategic niches and to create strong R&D environments with increased collaboration between industry, universities and institutes.

The mining research programme focuses on:

- Securing the supply of raw materials through exploration
- Improved competitiveness through development of production technology
- Increased knowledge in particle technology in mining industry processes
- Resource-efficient extraction of base metals
- Reduced environmental impact in mining operation

In addition, part of the programme budget was set aside annually especially for "innovative projects", which may span several areas or constitute more visionary research activities with great potential and containing radical ideas and innovative thinking.

1.2 Programme board

The programme is run by a programme board consisting of Ulf Marklund, Boliden, (chair), Göran Bäckblom, MITU, Seija Forsmo, LKAB, Ulla Grönlund, Länsstyrelsen Västerbotten, LKAB, Monika Hammarström, SKB, Marie Holmberg, Boliden, Ulf Holmgren, VINNOVA, Manfred Lindvall, Northland Resources, Per-Olof Samskog, LKAB (retired during 2009, replaced by Kent Tano, LKAB) and Lars Persson, SGU (adjunct). A program manager from VINNOVA, Lena Svendsen, is responsible for the operational management of the mining research program and reports to the programme board.

Following consultation with the programme board for the strategic mining programme, VINNOVA appointed independent, international scientific quality reviewers whose task was to assess the quality of the project proposals. The scientific quality reviewers had four meetings during 2007-2008, where incoming proposals were discussed (and assessed) and recommendations were made to the programme board. Based on this and discussions within the board, the programme board thereafter granted the projects that now are running. Most of the applications came from Luleå University of Technology, which has been identified by the industry as the centre for Swedish mining research.

1.3 Economy

A call for proposals opened in 2007 and closed in 2008. 13 projects have been granted, among them two smaller pre-studies. All projects have the requirement to have at least two companies involved. At the programme board meeting in November 2008 it was decided that the call should close. The remaining funds were set aside for programme conferences and evaluation.

The total budget of the projects is 101.8 million SEK. The financing of approved projects will be distributed according to Figure 1-1. The part funded via Vinnova comprises about 48 million SEK. In total (including university funding), the public part is about 50 %.

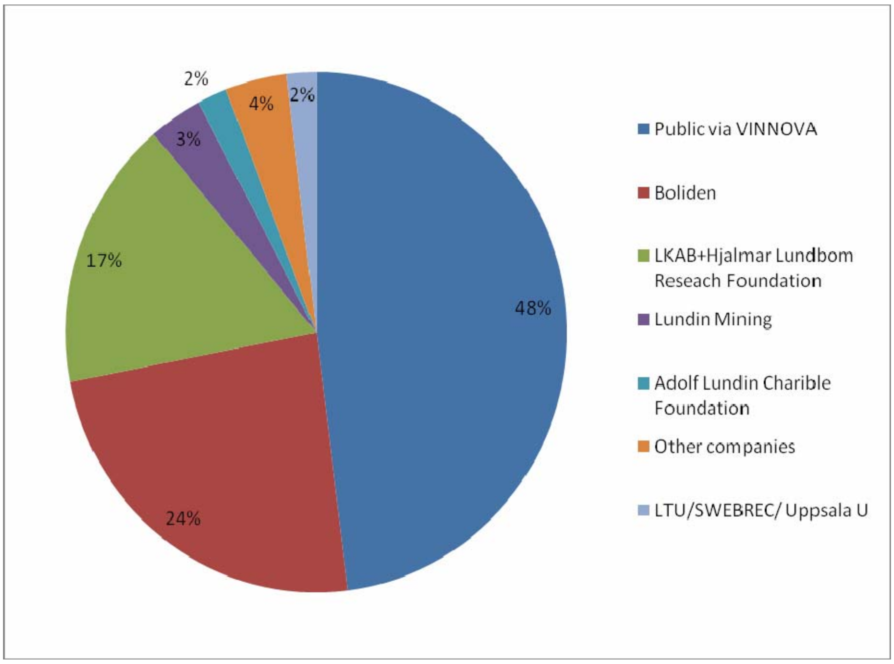

Figure 1-1. *Financing of projects.*

2 4-DIMENSIONAL GEOLOGICAL MODELING OF MINERAL BELTS

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Affiliations: [1]Luleå University of Technology [2]Boliden Mineral AB [3]Uppsala University [4]Geovista

The project aims at developing geological models that visualise the key spatial, geological, geophysical, geochemical and economic parameters of the western and central part of the Skellefte district, including the known ore deposits, in 3D and 4D. This is achieved by using detailed thematic geo-information gathered at scales from regional down to individual deposits. The distribution of geological units, structure and tectonics, and magnetic, gravity, seismic, electric and electromagnetic data are utilised to produce robust 3-dimensional models for the upper 3000 m of the Earth's crust in selected areas within the Skellefte district, combining the results from new high-resolution reflection seismic recordings, and other high-resolution geophysical measurements with results from new detailed structural mapping of the same areas. Data are modelled in the GoCad software platform to construct the 3D GIS models that are further interpreted in the 4th dimension with constraints from regional structures and tectonics.

2.1 Results

The project is subdivided into two main parts: 1) geological investigations and 2) geophysical measurements and interpretations. The first part is coordinated by LTU in close cooperation with Boliden. The aim of the field work is to derive a robust structural evolutionary model which can then be utilised in combination with the geophysical data to derive a 4D evolutionary model for the Skellefte district. In the second subproject, new high resolution seismic data are collected together with new electromagnetic data from the same areas. The seismic data are processed and, if feasible, migrated, then interpreted together with other geophysical information and information from the first subproject. A high resolution seismic profile is shown in Figure 2-3.

2.1.1 Geophysical interpretations

Inversion modelling of the gravity and magnetic data has now been done for a number of the profiles. However, the knowledge regarding the petrophysical properties of different rocks still needs to be improved. Thirty drill-holes have been logged and around 220 pieces of cores were sampled for different lithologies. Many of the holes intersect the major geological contacts and/or are located in the vicinity of the seismic and resistivity profiles (Figure 2-1). Petrophysical measurements on the first set of samples have been completed and will be used for further analysis and modelling, as soon as measurement of all other remaining samples is completed.

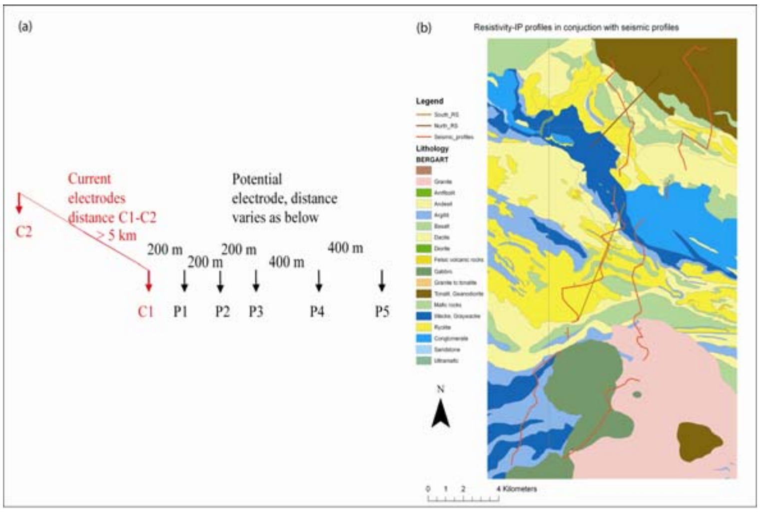

Figure 2-1. *(a) Pole-dipole array; (b) location of the resistivity and seismic profiles.*

The petrophysical results will be used to better understand the variation of the petrophysical properties of the different rock units in the area, and also as a reference during the geophysical inversion modelling.

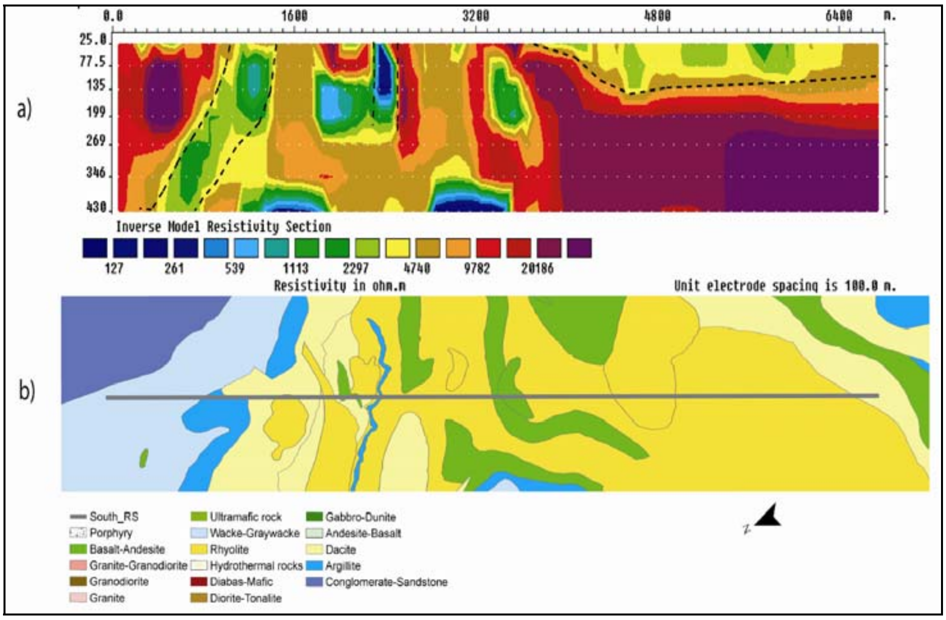

Figure 2-2 *(a) Inversion result from the southern resistivity/IP profile, the dashed lines indicate major geological contacts (b) the southern resistivity/IP profile overlain on the geological map.*

In November 2009, field work was carried out to measure the apparent resistivity and induced polarization of the shallow subsurface in the central Skellefte district. The field work was performed along two profiles with a total length of 12400 meters. The profiles were chosen to intersect the major geological contacts, and to interconnect the seismic lines. The pole-dipole method was used as a survey array and planned so that geological features with a thickness of >100 meters could be identified (Figure 2-2). The maximum depth of investigation for the array was 430 meters. The two resistivity profiles are now inverted and are in the process of interpretation together with the resistivity data from laboratory measurements (Figure 2-2). Testing different geological scenarios in 2D and 3D is executed to create a forward model of the resistivity profiles and to check how different geological scenarios will respond after the inversion.

To contribute to the 3D/4D geologic model of the Skellefte district, four new high resolution reflection seismic profiles have been acquired to date, two perpendicular profiles in the Kristineberg mining area and two nearly parallel profiles in the central part of the Skellefte District. The total length of these profiles is about 85 km. Figure 2-3 shows the stacked section of one of the profiles in the Kristineberg mining area which reveal a series of steeply dipping (M1 and C1) to sub-horizontal reflections (E1 and E2), some of which reach the surface (M1) and allow correlation with surface geology. Some of these reflections (e.g., M1) appear in direct connection with the main ore horizon in the Kristineberg mine, which extends down to a depth of about 2 km. Seismic reflection data has greatly improved our understanding of major geological structures hosting mineralization at depth and a framework along which other geophysical and geological data can be integrated.

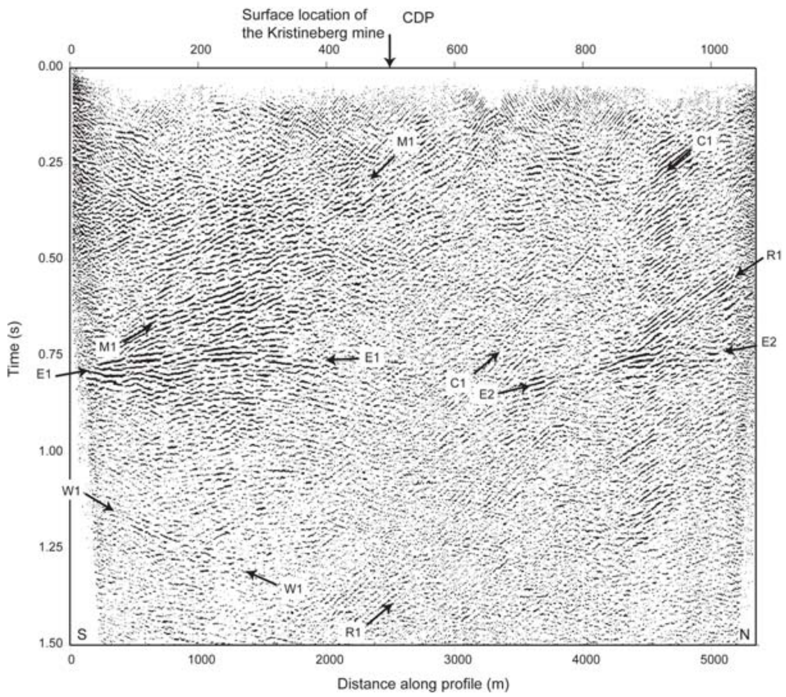

Figure 2-3 *Stacked section of one of the high resolution seismic reflection profiles in the Kristineberg mining area.*

In the western part of the Skellefte District electromagnetic data was recorded along the same profiles as the high resolution reflection seismics. The resistivity models obtained from that data show a good correlation with the imaged reflections (Figure 4). Further structural information and an approximate extension of the major geological units of the area can be extracted from the models. Moreover, the new models provide a better delineation of the conductive feature at depth (CI in Figure 2-4) associated to strong reflections in the seismic profiles and previously interpreted as a structural basement for the volcanic rocks.

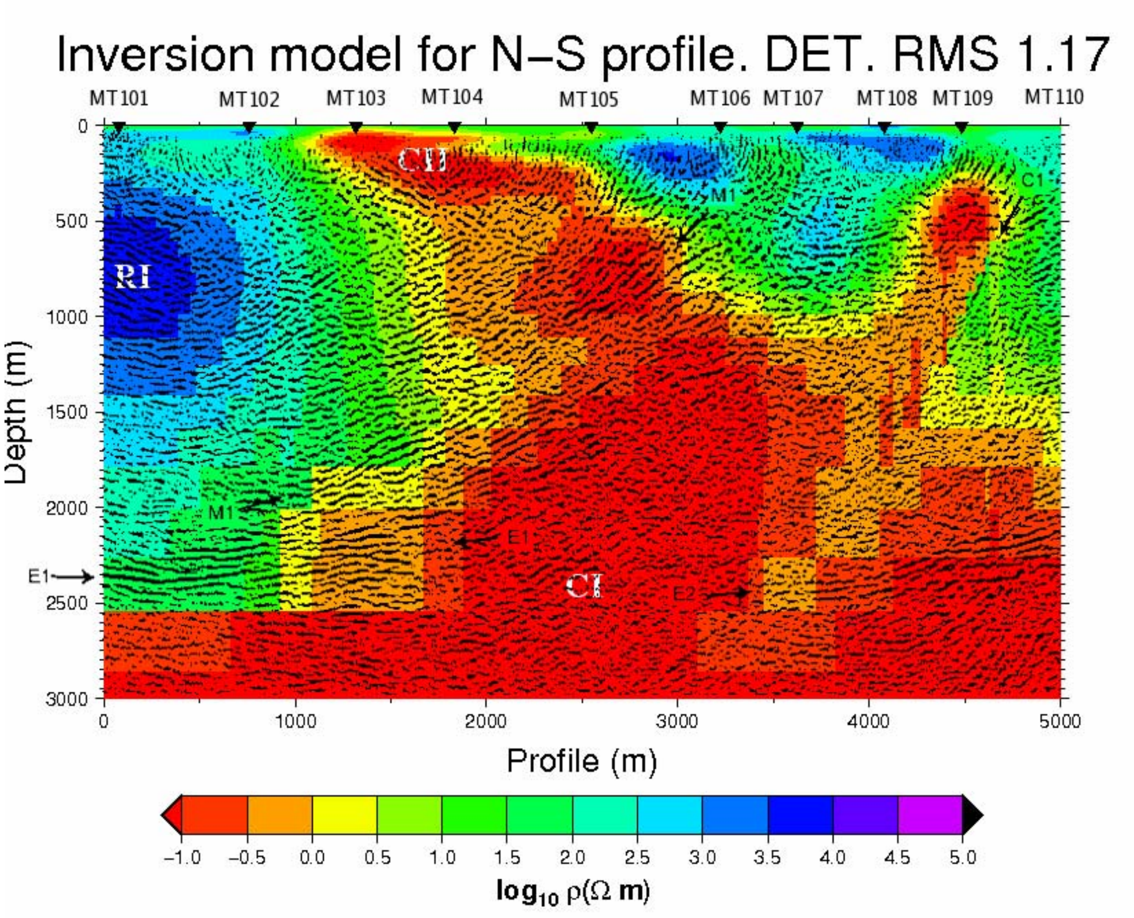

Figure 2-4: *Resistivity model for a North-South profile in the Krisitineberg area superimposed on the migrated seismic section from the same profile (Figure 2-3).*

2.1.2 Geological interpretations

The Kristineberg area in the western part of the Skellefte District forms the first focus area of the project. So far, the focus has been on providing reliable background geological data to enable construction of a solid 3D model of the area. These pre-3D modelling steps included studies on the orientation of the magnetic properties of rocks (AMS) and determination of their ages. The AMS studies indicate a two-phase crustal evolution, including early, reverse, dip-slip faulting that was overprinted by strike-slip shearing. The first, dip-slip deformation phase is also considered largely responsible for the structural geometry of the area, including the shape of the Kristineberg ore bodies.

The geochronology results are still preliminary, and will after processing, give further constraints on the timing of intrusive activity and ore-formation.

The second focus area of the project comprises the Central Skellefte District where structural mapping was carried out beginning in the area around the Vargfors basin. Detailed mapping of structures and stratigraphy resulted in a better understanding of the geological history. One part of the Vargfors basin was restored by unfolding and unfaulting each single fault (Figure 2-5). The restoration reveals the formation of fault bound compartments with varying internal structures and stratigraphy caused by the formation of a complex pattern of pre-sedimentary normal- and transfer faults. The primary geometry and different petrophysical properties of the lithologies control the later structural overprint. This modelling gives 3D voxel-models of start and end-stages of the deformation history and is the base for kinematic modelling in the area.

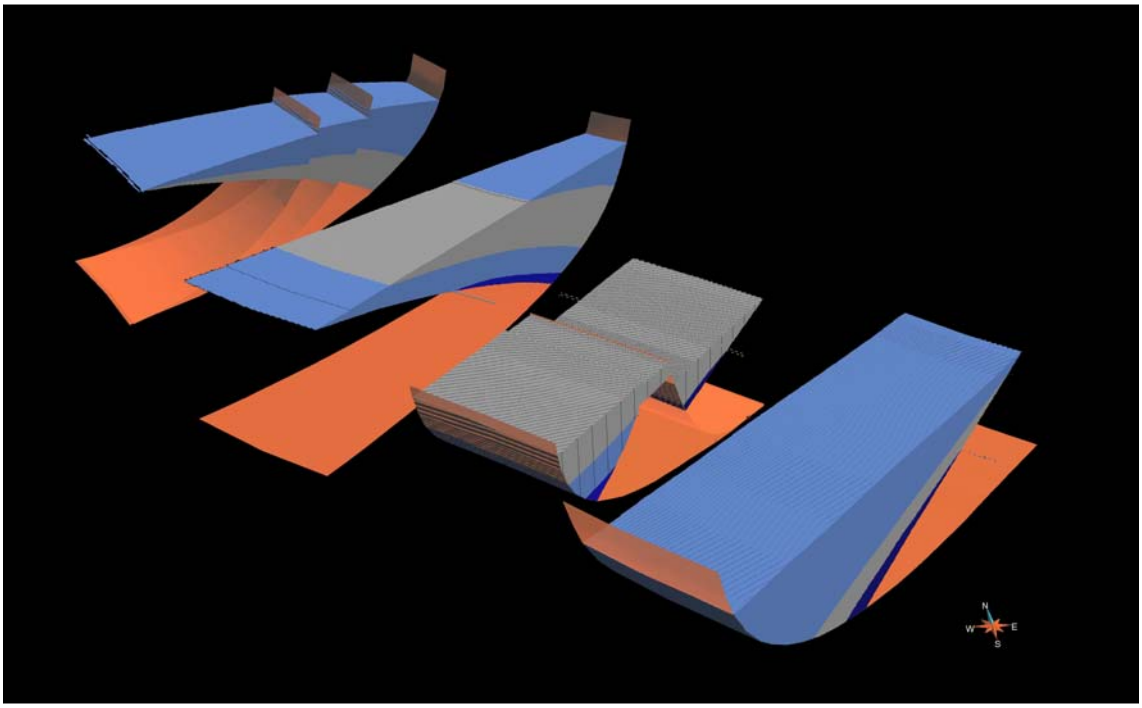

Figure 2-5: *Restored geometry of fault bound compartments within the Vargfors basin. Each compartment is separated from each other by transfer faults.*

2.2 Future work

The project will after this field season enter a new phase where all acquired data will be used to model the western and central Skellefte district in 3D. The first steps of modelling have been done for the Vargfors basin (Figure 2-5) as have the first trials to restore parts of the district with the software MOVE.

3 IMPROVED BLASTING RESULTS WITH PRECISE INITIATION

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Affiliation: Swebrec, Swedish Blasting Research Centre at LTU

3.1 Background and purpose of project

This project is a co-operation between LKAB, Boliden Mineral AB and Swebrec. Its industrial purpose is to achieve a better fragmentation, throw and other results in quarries and mines. There is also a scientific purpose, to identify the rock volumes within a blast were the shock wave interaction from neighbouring blast-holes may create additional damage, and thereby enhanced fragmentation, for varying detonation delay times.

Shock/stress waves in rock propagate with ca 5,000 m/s. Sub-meter precision in interaction requires sub-ms precision in blast-hole initiation. The new Electronic Programmable Delay (EPD) caps now on the market achieve this. Their effect in reduction of blast vibrations and contour damage is proven. Their effect on fragmentation is not thoroughly investigated and guidelines are not generally known.

Boliden has trialled EPD caps in the Aitik open pit mine, LKAB in the production ring blasting and drift driving. The Aitik mine is now entering a series of test blasts with EPD caps in 2010 with the purpose of improving primary mill throughput, which would substantially increase the production of concentrate.

To model blast fragmentation properly requires state-of-the-art computer codes with proper materials descriptions, both for the explosive behaviour and of the rock's response to pressures up to several GPa; including crushing and fracturing of the rock. The numerical models need to have a high resolution to achieve an acceptable description of the wave interaction and fragment formation, resulting in a considerable number of elements/nodes. The aim is to be able to run models with approximately 24 million elements with reasonable computation times on a computer cluster.

The project started in September 2008 with a unique fragmentation code which could calculate the fragment size distribution of a blast. Control and calibration runs against lab-scale tests and data from the literature showed however that the code did not to live up to its promises and our requirements. The project plan was revised and a new go-ahead was given in November 2009. It runs till the end of 2011. The present plan has the following tasks:

- Development of numerical methodology with a new code for shock wave interaction and damage evaluation.

- Numerical study of 3D shock wave interactions and damage in rock to support blasts at Aitik using EPD detonators and participation in Aitik blasts rounds.

- Numerical study of model scale tests of timing effects. These tests are performed by Swebrec as part of HLRC project Optimized blasting of SLC rounds.

- With successful studies, simulations for the optimisation of delay times with EPD detonators both in bench blasts at Aitik and in ring blasts at LKAB will be made.

Most of the spring of 2010 has been spent on the development of a numerical methodology using the ANSYS AUTODYN and LS-DYNA numerical codes.

3.2 Initial calibration runs

These simulations with Blo-Up version 2.04.07 were made on the mortar cylinders tested in Johansson's thesis work /2008/ and on bench blasting models, see Figure 3-1.

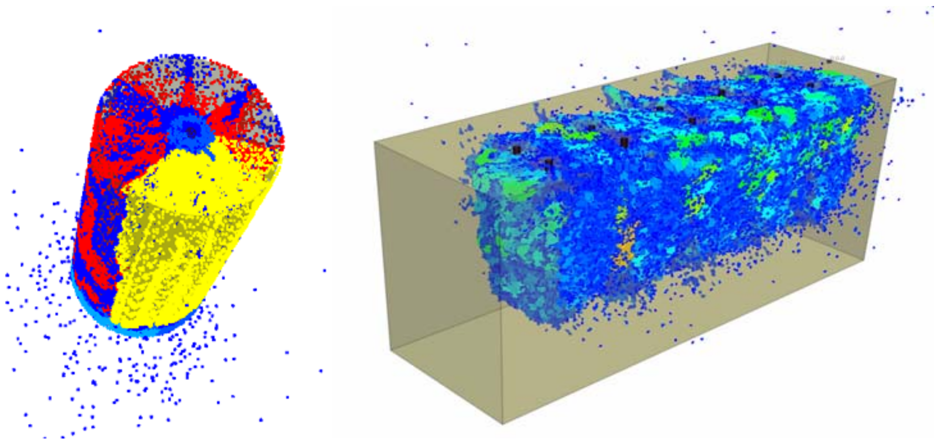

Figure 3-1: *Mortar cylinder model and bench blast model with shown fragments, these are colour coded according to their sizes.*

One of the major limitations with Blo-Up was that it only considers a pure tensile failure condition without any possibility to consider pressure dependent strength within the lattice formulation, which was introduced to obtain manageable run times. The lattice formulation doesn't calculate the three dimensional stress state within the rock, and thereby pressure dependent strength models can not be implemented. It is also considered very unlikely that the effect of the interaction of stress waves on fragmentation can be determined with this code. The reasons why these calibration runs gave unsatisfactory results are further elaborated by /Hansson ,2009/ and /Johansson & Ouchterlony, 2009/.

3.3 Development of new numerical methodology

The development of the new numerical methodology focus on evaluation of explicit FE methods to determine shock wave interactions and its effects on damage evolution within the rock. Two major concerns are the numerical stability of the used methodology and the computational speed (i.e. runtime for the models). Other important parts of the study are the evaluation of material models, element formulations, fluid structure interactions, boundary conditions, runtime for the simulations, pre-processing and post-processing capabilities.

A major concern regarding the evaluation of the numerical methodology is that the increased strength of rock at an increased pressure level needs to be considered within the simulations, i.e. pressure dependent strength and failure models needs to be used. Further, this requires the three dimensional stress state to be determined in the computational models. In comparison with the earlier performed Blo-Up simulations these later computational models therefore require increased computational resources.

One of the preliminary test models that are used for evaluation of the numerical methodology is a computational model with two boreholes. This model uses 16 million elements and is run on a PC workstation with two Xeon Quad core 2.67 GHz processors and 48 GB memory. In short the rock block is 1547 m³, the diameters of the boreholes are 311 mm and distance between boreholes is 8.5 m. The model element resolution is 40 to 50 mm. The runtime using LS-DYNA is 16 h for a 10 ms event with the use of the available eight processor cores for the workstation. Preliminary simulation results of the shockwave propagation and interaction are shown in Figure 3-2. The initiation delay between the two boreholes is 2.5 ms, and the figures show the pressure contours respectively 1.25 ms and 3.75 ms after initiation of the first borehole.

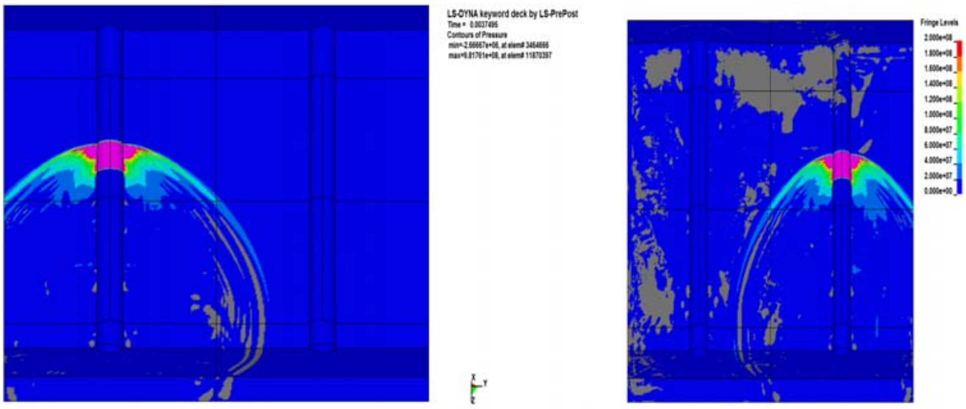

Figure 3-2: *Shock wave interaction with pressure shown for a test simulation with two boreholes. The negative pressure regions (= tension) in the model are shown in grey colour, and pressures above 200 MPa are shown in magenta. Scale in MPa.*

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Johansson, D. & Ouchterlony, F. 2009. Numerical simulations of a cylindrical blast model, preliminary tests with Blo-Up. Swebrec report 2009:U3.

4 ROCK SUPPORT SYSTEM IN INTERACTION WITH THE ROCK

Authors: E. Nordlund[1], D. Saiang[1], P. Zhang[1], M. Westblom[1], S. Shirzaegan[1], L. Malmgren[2], P-I. Marklund[3], D. Sandström[3], U. Nyberg[4]

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4.1 Background to project

Mining at greater depth implies increased stress magnitude which in turn increases the risk of instabilities in underground openings and leads to the occurrence of new phenomena. The design of rock support is based on the philosophy that the support should help the rock mass to carry its inherent loads. The load from the rock on the support depends on how the support deforms in relation to the rock as well as on the stiffness and load-bearing capacity of the rock support. The complexity of the rock mass behaviour and of the interaction between the rock mass and the rock support has had a great impact on the research carried out historically. Most of the research historically has therefore been focused on the performance of the support elements, e.g., shotcrete and bolts.).

The objective of this project is to improve the understanding of (i) the rock mass response and the rock support system performance and (ii) the interaction between the rock mass and the rock support system with increasing mining depth for squeezing as well as brittle and rock burst conditions. The objective for the mining companies is to reduce the number of production disturbances caused by poor or unforeseen rock conditions or rock mass response, thereby decreasing the risk for personnel injury and production losses. The results from this project will be used to (i) improve the ground control strategy, (ii) develop rock support systems for squeezing (large deformations) and rock burst conditions and (iii) develop robust design methods for rock support.

4.2 Project activities

4.2.1 General

Ground control problems related to deep mining can be grouped into two extremes: (i) hard rock and rock burst-prone ground and (ii) altered weak ore contact zones within a hard host rock mass. The project is therefore divided into two sub-projects: (i) burst-prone ground and (ii) soft and squeezing conditions, respectively. The main activities in the project are (i) Numerical analyses and (ii) Field studies. The first part of the project has focused on the preparation and planning of field monitoring programmes and field tests, as well as on preparatory numerical studies. The objective of the preparatory numerical analyses was to (i) help us to choose the right modelling approach in the rest of the project and to develop numerical modelling tools for the project. Examples of initial numerical studies are: (i) analysis of the effect of the uneveness of the rock surface on the shotcrete behaviour, (ii) the effect of uncertainties in the rock mass stiffness on the calculated deformations for soft and squeezing conditions, (iii) preliminary studies of wave propagation phenomena in the rock mass, The planning of field monitoring programmes and field tests can be summarized by the following activities: (i) development of a monitoring/damage mapping programme, (ii) investigation of instruments and techniques for detailed monitoring of the rock bolt and shotcrete performance, (iii) preparation of the dynamic large-scale field test of rock support systems. In the following details from two investigations will be presented.

4.2.2 Numerical studies

/Malmgren,2005/ showed, by 2D analyses, that the most important factor for the behaviour of the shotcrete and the shotcrete-rock interaction was the uneveness of the surface of a drift (walls and roof). While a smooth shotcrete layer behaved like an arch, a surface with the slightest uneveneness showed no arch action and local failures at apexes and depressions of the rock surface. Since the walls and roof of an underground opening is uneven in 3D, it is important to find out if it gives an effect on the shotcrete lining which is similar to that of a 2D uneveness or of a smooth surface. Therefore we analysed the laboratory tests carried out by /Chang, 1994/ using the 3D Distinct Element Code, 3DEC, see Figure 4-1. This study showed that it was a great difference in behaviour between a smooth surface and a surface with an uneveness. The 2D uneveness constitutes the worst case, but the 3D uneveness gives a similar behaviour of the shotcrete lining, see Figure 4-1.

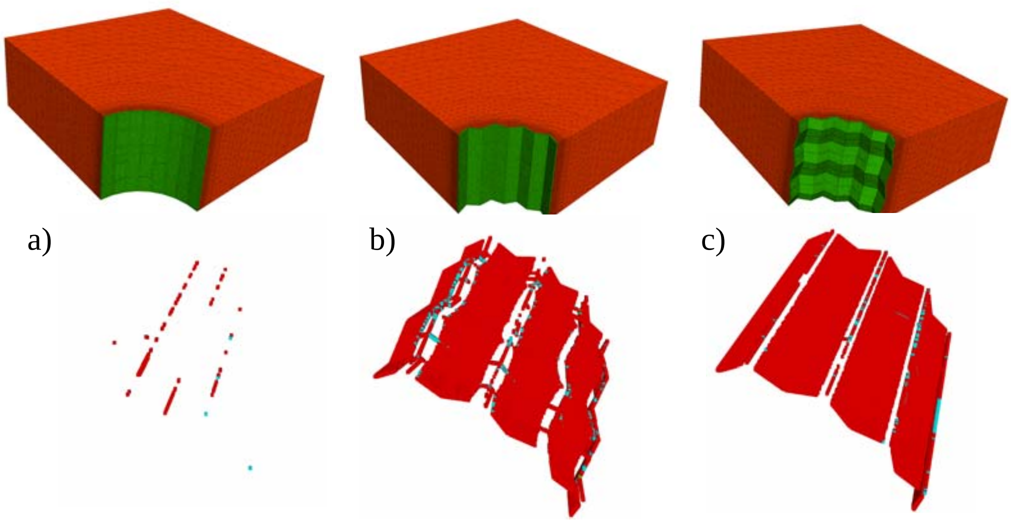

Figure 4-1. *The model and the areas with debonding between the shotcrete and the rock. a) Smooth, b) simply waved (2D) and c) Doubly waved (3D) rock surfaces.*

4.2.3 Field measurements and large-scale test

In the project two field measurement programmes will be carried out, one in the Kristineberg mine and the other in the Malmberget mine. The field test in the Kristineberg mine has already been done. The measurements were carried out in stope J10-3 and comprised 10 rounds. Rebars and D-bolts, respectively, were used in every other round i.e., 5 rounds with rebars and 5 rounds with D-bolts. The instrumentation consisted of 4 “high density” measurement profiles, 6 “low density” measurement profiles and 2 extensometer/convergence profiles (located between the high density D-bolt rounds and the rebar round), see Figure 4-2. Preliminary convergence results are shown in Figure 4-2.

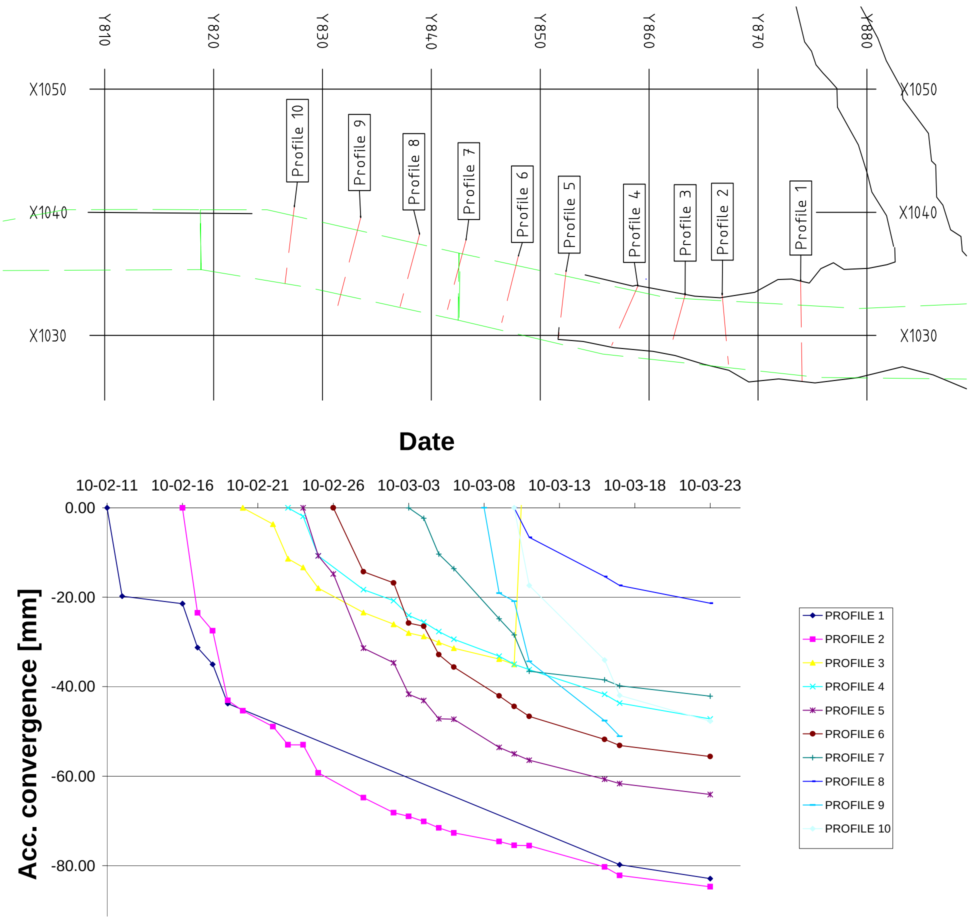

Figure 4-2. *a) Convergence measurement sections in the J10-3 stope in the Kristineberg mine, b) preliminary convergences.*

The field measurements in the Malmberget mine have been planned and the instruments will be installed during the autumn 2010. A large-scale dynamic test of rock support systems for burst prone ground will be carried out in the Kiirunavaara mine during the autumn 2010. The dynamic load will be generated by detonation of explosives. Each support system will be exposed to three different loads, represented by three different blast charges,

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5 MODELLING OF THE INTERACTION BETWEEN CHARGE AND LINING IN TUMBLING MILLS

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The comminution process in tumbling mills is complex and several parameters do significantly influence the effectiveness of the grinding operation. Many of these parameters are either difficult or laborious to measure. Grinding in tumbling mills is also an energy inefficient process; much of the energy is absorbed in low-impact contacts that do not break particles. An important point in optimising the process is to understand the charge motion within the mill. Both the breakage of ore particles, deflection of the lining and the wear of liners/ball media are closely linked to the charge motion. To include all phenomena that occur in a single numerical model is today not possible. However, some improvements of today's models can be identified, for example the structure of the mill (geometry and material composition) could be modelled with the finite element method (FEM). Coarse particles in the grinding medium could be modelled with the distinct element method (DEM) and the slurry can be modelled with some particle based continuum method e.g. smoothed particle hydrodynamics method (SPH). SPH has its strength in modelling free surface flow and very large deformations and is suitable for model fluid and granular flow. Each of these methods has its strength and weaknesses, but combined they may successfully model the main features of the grinding process.

5.1 Potential for the industry

The main scientific objective of this project is to combine element based methods like FEM together with particle based methods like DEM and SPH to a complete mill model. Such model should give a better understanding of the physical and mechanical behaviour of particulate material systems during grinding in a tumbling milling. This is very important in order to develop future high quality mineral products. The industrial benefits of the research will be improvements in mineral process plant performance through generic advances in knowledge and provision of engineering tools and methodologies. A numerical tool that captures some of the main features of the grinding process will be vital in the optimisation of the process and in product development. It should result in a better control of the grinding process and in improving the knowledge of the mechanical and physical behaviour of the whole comminution process.

5.2 Numerical modelling

DEM have been used in simulations of tumbling mill processes. A pure DEM model provides useful information on charge motion, collision forces, energy loss spectra and power consumption. This is important for improving the milling efficiency and gain more understanding of the process itself. For improved estimations of the complex nature of the milling process better and more physically precise models are desirable. For structural analysis the FEM is the most developed and used numerical method. The method originated from the need for solving complex elasticity and structural analysis problems in civil and aeronautical engineering. FEM is a numerical solution method based on continuum mechanics modelling, a constitutive relation for the actual material is described and the governing equations are solved. A variety of different constitutive models for a large number of materials are implemented in a modern finite element (FE) code.

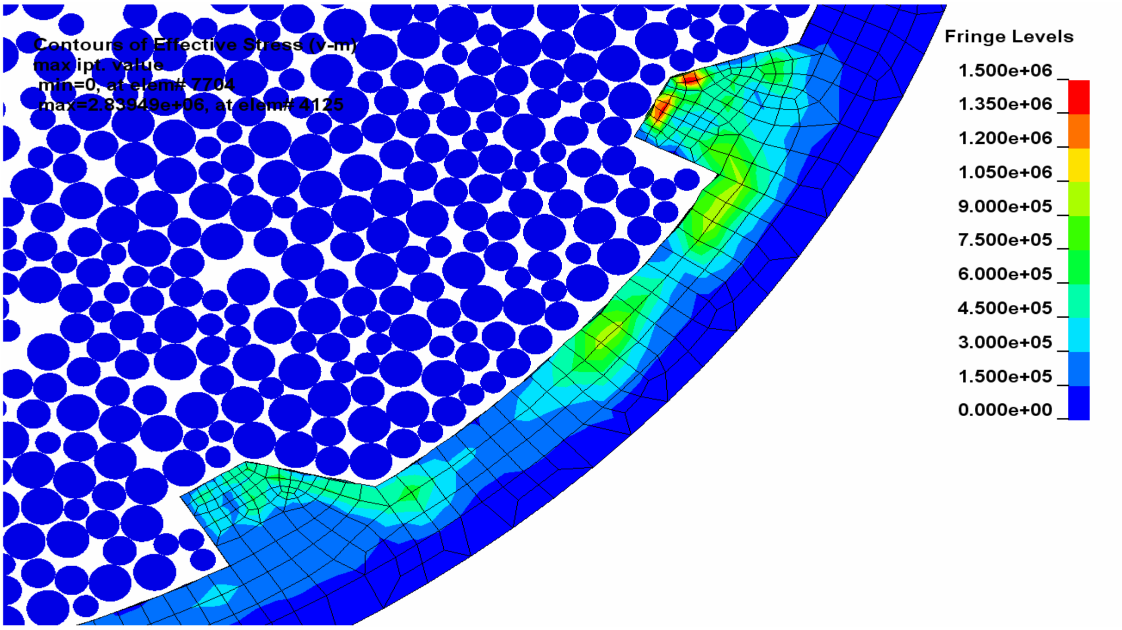

Figure 5-1. *A snapshot of the von Mises' stress field for a part of the mill model during its passage through the charge.*

Steps towards more physically correct numerical descriptions of mill systems are combined DEM-FEM models, see /Jonsén et al. ,2009/ and /Jonsén et al., 2010/. With a DEM-FEM model structural response and its influence of the charge motion can be studied on the whole mill. Mechanical response of the mill structure is predicted by constitutive models included in the FE formulation. It also, predicts forces travelling in the lining and by that the echoes from consecutive lifter-charge hits. This gives an opportunity to validate signals from on-shell sensor types. Bending of the flexible rubber lifter and the corresponding stress field during its passage in the ball charge is shown in Figure 5-1. The major difference between DEM only and DEM-FEM models is that the latter give a direct coupling between force, stress and displacement for the whole mill system.

In the next step towards more physically correct models the slurry will be included. The smoothed particle hydrodynamics method is a mesh-free, point-based method for modelling fluid flows. The method can be combined with FEM and should be suitable for modelling slurry. Today, the SPH is used in areas such as fluid mechanics and solid mechanics (for example; free surface flow, incompressible flow, compressible flow, high velocity impact, penetration problems and high explosive detonation over and under water). The main advantage with SPH is the ability to virtually reproduce free surfaces, which is known to be a difficult problem in CFD with the classical Euler approach. The SPH method is an adaptive Lagrangian method, which means that in every time step the field function approximations are performed based on the current local set of distributed points. The mesh free formulation and the adaptive nature of the SPH method result in a method that handles extremely large deformations.

5.3 Validation

Validations of the numerical result are very important in the project. To ensure accurate behaviour of the models each step in the development has to be validated against experimental data. Experimental studies of Continuous Charge Measurement system (CCM) are exploited to validate the combined numerical models and to determine the material parameters. The industrial partners provide data to the models and initially data from pilot mill measurements has been used for the initial calibrations of the DEM-FEM model. In addition, the test work on pebble charges in the same pilot mill will provide data sets that will validate the accuracy of the combined numerical models.

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6 INCREASED PRODUCTION SYSTEMS EFFECTIVENESS THROUGH CONDITION MONITORING AND PROGNOSTICS

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6.1 Project goal

The project goal is to map maintenance data and develop theoretical modelling of wear and cracks in mining mills in order to produce suitable methods for the prognostics of optimum service intervals and for the possible increase of loads with increased productivity. An additional goal is to study, promote development, test and evaluate suitable measurement methods for the wear of liner material and cracks in machinery in order to increase the competence concerning measurements of reliable data for prognostics. The project started at 2008-08-04 and will end at 2012-08-04. The total budget is 9.9 million SEK

6.2 Methods

- Collecting and analyzing of relevant failure, wear, repair, maintenance and processing data that is useable for prognostics of optimum maintenance actions
- Testing and evaluation of relevant measurement equipments. Measurements of relevant parameters like crack length and wear of liners in mills
- Theoretical modelling of tools for prognostics of optimum maintenance intervals
- Comparisons of theory with real data and development of demonstrators for optimum maintenance intervals and actions

6.3 Results so far

Concerning the optimum change interval of liners in mills, as a first approach, the optimum change interval in the case of only one type of ore, has been developed. It was found that considerable savings can be done by means of relining at about 220 days instead of at 360 days as today, due to increase in efficiency and decrease of power consumption.

Concerning prediction of cracks in mills, a new method which is capable of wireless measurements of the cracks has been used for collecting crack data. The project contribute to the goal of the VINNOVA program by means of reinforcement of the leading position in terms of technology and international competitiveness of the

Swedish mining industry and by means of to create strong education, research and innovation environments . See also Figure 6-1 concerning optimum change interval of liners and Figure 6-2 concerning prediction of cracks in mills

Economic life (E) = *f* (Throughput, Grinding performance, Energy cost, Downtime cost, Replacement cost, Liner wear)

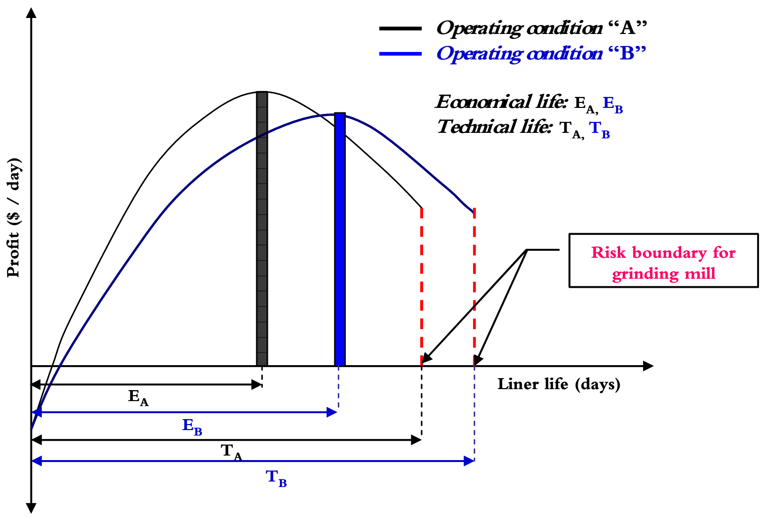

Figure 6-1. *Economic life estimation of mill liners based on operational and maintenance parameters*

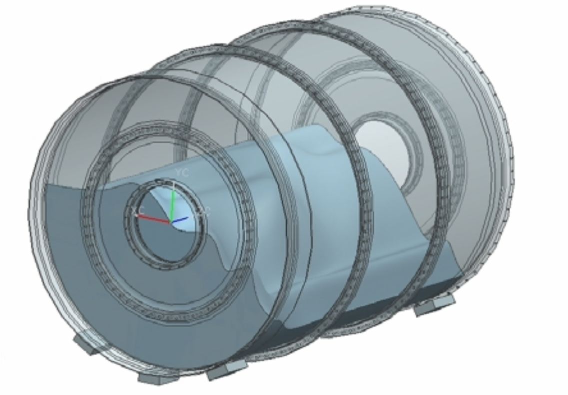

Figure 6-2. *Primary FEM modeling of mill for crack propagation analysis*

Publications so far:

1) A systematic evaluation of devices for measuring abrasive wear of mill liners, Proceedings of the 22nd International congress on Condition monitoring and diagnostic engineering management: COMADEM 2009, 9-11 June 2009, San Sebastian, Spain

2) Crack detection methods for Mining Mill Machinery, J. Nordström, A. Parida, R. Dandotiya and J. Lundberg (2009), Proceedings of 22nd International Congress of Condition Monitoring and Diagnostic Engineering management, June 09-11, Spain, pp.313-321

3) Mathematical model for optimum replacement interval of grinding mill liners", International Conference on Quality, Reliability and Infocom Technology: ICQRIT 2009, 18-20 December 2009, Delhi, India

4) Evaluation of abrasive wear measurement devices of mill liners, International Journal of Condition Monitoring and Diagnostics Management: COMADEM, Article accepted.

The first three publications will be found on the following link: http://www.ltu.se/staff/r/rajdan?l=en

6.4 Successes

Of special interests is the very strong economical output of the new, by the project suggested, replacement policy of the mill liners, since the economical savings are significant to a degree which has lead to the decision to keep the exact amount as a company secret. The results from the project have also been used as a catalyst and as an important data base for developing new improved measurement equipments by the involved companies by them selves. All together we think that this is a real research break trough concerning maintenance in the mining industry. This project has also been awarded a price regarding the final of the contest of "Stora Produktivitetspriset 2010" in Gothenburg 2010, arranged by Underhållsföretagen. See also http://www.ltu.se/d173/1.60116andhttp://www.alphagalileo.org/ViewItem.aspx?ItemId=71492&CultureCode=en

6.5 Industrial participants

Boliden Mineral AB is participating by means of continually supplying the project with personal help and with process data concerning mill efficiency, ore flow, power consumption, particle sizes, etc.

LKAB is participating by means of continually supplying the project with personal help concerning measurements and also in necessary stopping of production in order to make it possible to catch relevant data.

Metso Minerals is participating by means of continually supplying the project with measured data of the wear of liners

Ringhals AB is participating by means of supporting with knowledge concerning crack measurements

7 INTERACTIONS IN MULTI-COMPONENT MINERAL SYSTEMS

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7.1 Goals of Agricola Research Centre: Interactions in Multi-component Mineral Systems (ARC-MMS)

Understanding the interactions in multi-component mineral systems is of utmost importance for a deeper understanding of flotation, agglomeration, and environmental sustainability. Our goal is to underpin the state-of-the-art within sulphide flotation and agglomeration of iron oxides, opening a scientific-based gateway to future processing of these minerals. This will eventually imply new and more efficient industrial processes.

More specific goals of ARC-MMS program are: (i) to understand the effects of the major (Ca^{2+} and sulfate) and minor (e.g. reduced sulfoxyanions) species present in recycled process waters on sulphide mineral flotation at New Boliden and Lundin Mining; (ii) to explore the molecular scale approach in understanding of behaviour of dithiophosphate and xanthate collectors on sulphide surfaces; (iii) to determine three dimensional distributions of process water, air bubbles, residuals of flotation reagents and mineral particles in wet iron ore pellets produced at LKAB.

In long-term practical process-directed applications these goals are reformulated as following objectives:

Objective 1: To provide remedies to selectively regulate surface properties of sulphides, which are affected by recycled process water.

Objective 2: To utilize understanding of adsorption mechanisms of collectors in improving selectivity and recovery of the valuable sulphide minerals.

Objective 3: To supply a new type of 3-D data for water, air bubbles, flotation reagents and particles in wet iron ore pellets. To create remedies for controlling of air-bubble inclusions in iron oxide pellets, which affect their mechanical strength and other properties important in metallurgy.

7.2 Methods

In the proposed programme traditional indirect flotation, "wet" chemistry methods, potentiometric titrations, ATR-FTIR, solid-state NMR spectroscopy, Density Functional Theory (DFT), electron microscopy (cryo-SEM and TEM) and tomography are combined in an interactive and complementary fashion to extract information about interactions in multi-component mineral systems such as (i) complex zinc-copper-lead sulphide minerals and (ii) iron oxide pellets with fillers and binders.

7.3 Results

After two years of ARC-MMS activities, useful results were already obtained in all three subprojects of the program.

7.3.1 Recycling of process water and influence of its chemistry on sulphide flotation and flotation selectivity

The collector-mineral interaction in the presence of flotation effluent components by adsorption, zeta potential and spectroscopic measurements and the interaction/ adsorption of HSO_3^- on ZnS, $CuFeS_2$ and PbS in the absence and presence of the principal components present in the Boliden's process waters, Ca^{2+} and SO_4^{2-} ions, separately and combined at different concentration were studied to elucidate the principal effects of these species on flotation and separation efficiency of these minerals in the concentrates after flotation. /refs. 1-3, 2009-2010/. As an illustrative example of the progress in these studies, among other tasks influence of Ca^{2+} and SO_4^{2-} species in Hallimond flotation response of pure ZnS, PbS and $CuFeS_2$ minerals and complex sulphide ores from two mines owned by Boliden was thoroughly studied at both ambient and low temperatures using both tap water and process waters. Renström ores show general depression of all metals at lower temperature when both tap water and process water were used with a *ca* 5 % high recovery of PbS at 22°C when the process water was used ($[SO_4^{2-}]$ = 510 and $[Ca^{2+}]$ = 450 mg/l.) There was no clear effect of a lower temperature on Kristineberg ore when tap water was used, however, an additional activation of ZnS was obvious at 4-22°C when the process water was used (not shown).

Table 7-1 Recovery and Grade from flotation of Renström ore at different temperature using both tap water and process water (Concentrations of the principal species in the process water: $[SO_4^{2-}]$=510 and 360; $[Ca^{2+}]$=450 and 200 mg/l at 22 and 11°C, respectively)

Renström ore at different temperature

	Tapwater Recovery %	Tapwater Grade %		Processwater Recovery %	Processwater Grade %
			~22 °C		
Cu	88.30	2.08		89.69	1.74
Zn	73.68	22.50		68.01	25.85
Pb	82.37	6.30		87.49	5.48
			~11 °C		
Cu	83.81	1.56		84.94	1.31
Zn	67.76	19.07		69.88	18.10
Pb	75.44	4.46		77.95	4.08
			~4 °C		
Cu	83.39	1.42		83.54	1.73
Zn	68.18	17.15		68.58	20.05
Pb	75.58	3.69		75.09	5.20

7.3.2 Molecular scale approach towards behaviour of collectors on sulphide surfaces

DFT calculations on different dithiophosphate and xanthate species that may be formed in a flotation pulp and/or on a sulphide mineral surface during the flotation have been finalized. Structures of various species have been optimized and ^{31}P and ^{13}C chemical shift anisotropy (for NMR) and vibration frequencies (for FT-IR) of these species have been calculated. The latter values correlate very well with experimental data obtained by both ^{31}P and ^{13}C CP/MAS NMR and FT-IR spectroscopy. /refs. 4-10, 2008-2010/.

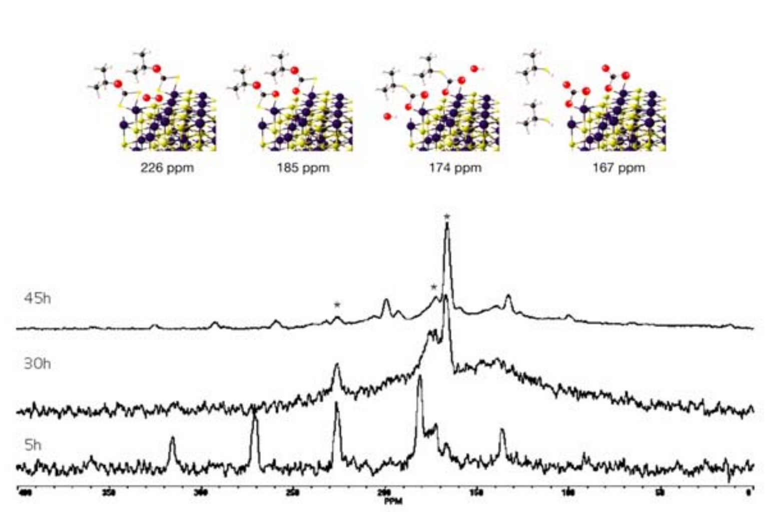

Figure 7-1. *Adsorption and decomposition of ^{13}C-enriched ethylxanthate on PbS (top: illustration of how the xanthate collector decomposes on the mineral surface; bottom: ^{13}C CP/MAS NMR spectra as a function of time. /ref. 9, 2010/.*

Currently, results of the DFT calculations and NMR experiments on various xanthate complexes are used to assign species formed on the surfaces of various sulphide minerals. /refs. 8-9, 2010/. Results show that the longer alkyl chains the more stable the xanthates are against decomposition. Short chain ethylxanthate is almost completely destroyed after 45 h, leaving only a hydrophilic carbonate ion on the surface. Comparing the relative intensities of the resonance signals of the different surface species, a reaction pathway for the degrading could be suggested (see Figure 7-1). Preliminary results show that decomposition of xanthates occurs faster on PbS compared with that on lead activated ZnS. This imposes that the adsorption mechanism of the collector is different: Activated ZnS leads to a loosely bound PbX_2 precipitate, which is not as much affected by surface reactions as xanthate adsorbed directly to a PbS surface. Copper activation of ZnS gives a different route of xanthate decomposition. Most of these conclusions were drawn from recent ^{13}C CP/MAS NMR measurements at LTU. DTP collectors seem to be more stable against decomposition. /ref. 10, 2010/.

7.3.3 Three-dimensional (3D) data for iron ore pellets

The aim of this subproject is to map the three-dimensional distribution of different constituents present in green iron ore pellets: iron ore particles, water, binder, and to study porosity using cryogenic scanning electron microscopy (cryo-SEM) to image iron ore pellets in the wet and dry states. *In this subproject it was shown that cryo-SEM provides microstructural information that has not been observed before, and it appears as an interesting technique to gain fundamental knowledge about balling processes in the future* (see Figure 7-2) /refs. 11-12, 2010/.

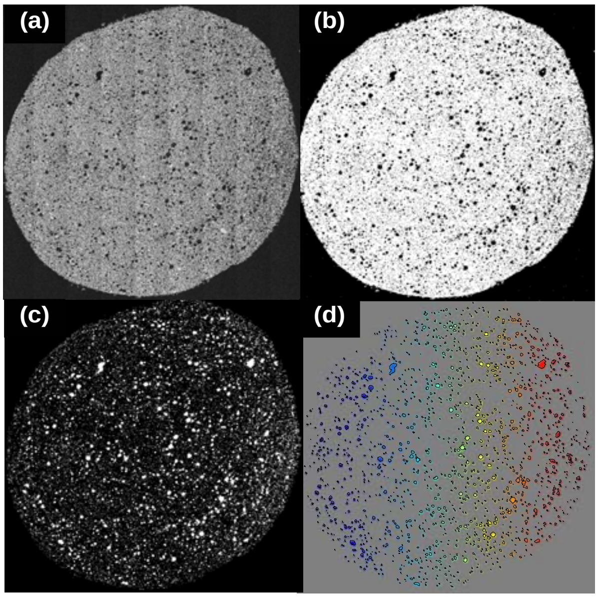

Figure 7-2 *Cross-section of an iron-oxide pellet after: assembling (a), binarization (b), morphological operations (c) and labelling of pores for statistical data extraction and analysis (d). /refs. 11-12, 2010/.*

Freshly balled iron pellets were frozen by immersion in liquid nitrogen. A fracture surface was produced by breaking *in vacuo* a thin slice previously obtained by polishing in liquid nitrogen to observe large cavities left by entrapped air bubbles by cryo-SEM. Polished cross-sections of epoxy embedded dry pellets were made to quantify these cavities by image analysis. Individual air bubbles were counted from the microstructure and its area, its equivalent diameter, major axis length and minor axis length, centrioid, eccentricity, etc. were measured utilizing Matlab image analysis toolbox.

Figure 7-3 shows size distribution of the large spherical cavities of the two series of pellet. It was found that the number of air bubbles is higher in pellet, in which iron oxide concentrate has been treated with the flotation reagent (ATRAC), compared to the pellet with the iron oxide feed that has not been treated by the flotation reagent. The smaller size bubbles are entrapped in enormous number in case of ATRAC pellets compared to non-ATRAC pellets. Air bubble size larger than 150 µm does not vary in the two series of pellets. *Therefore, by the first time it has been proven that the image analysis of polished pellet cross-sections can be used to determine the size distribution of the large spherical cavities inside pellets and might be employed as a method for quality control using high throughput mineral liberation software.* The data obtained in this subproject are important for LKAB and other mining companies working with pelletizing and agglomeration, since the complex arrangement of the different constituents of pellets determines mechanical strengths of both wet and dry pellets and subsequently the final porosity important in oxidation and reduction reactions in blast furnaces.

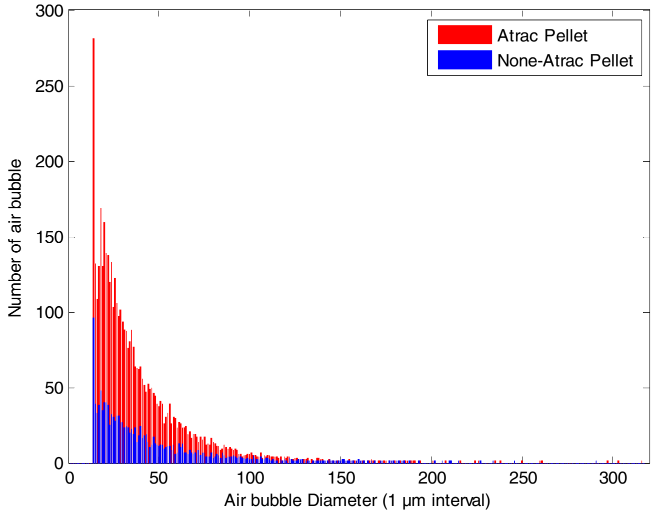

Figure 7-3. *Size distribution of the large spherical cavities inside a pellet prepared from iron-oxide concentrate processed with the flotation collector ATRAC (red) and without this reagent (blue). /refs. 11-12, 2010/.*

7.4 Partners of ARC-MMS and International Collaboration

ARC-MMS programme with a total budget of 13.52 Mkr (2008-2011) is financed by *VINNOVA's Strategic Mining Research Program* and co-financed by the Swedish leading mining companies and LTU. The following partners are involved in this program:

Luleå University of Technology: lead partner, which carries out all lab testing, spectroscopy, quantum-mechanical calculations, microscopy and tomography.

New Boliden AB: one of the core industrial partners, which co-finances all three subprojects (20.7%) and assists in sampling of process waters at flotation pulps and in the elemental analysis of samples.

LKAB: one of the core industrial partners, which co-finances subproject 3 (18.5%) and assists in production and testing of iron-oxide pellets (at R&D laboratory in Gällivare) before SEM and TEM tomography studies on the same pellets at LTU.

Lundin Mining: has provided financial support for the first 18 months in the subprojects 1 and 2 (6.8%). However, the company has terminated its participation in ARC-MMS from September 2009, because of the economical crisis and moving most of company's activities from Sweden to Canada during 2008-2009.

A fruitful collaboration with Kola Research Center (Russia) on purification of Boliden's process waters using a novel class of cheap and efficient sorbents, titanium-phosphates (TiP) and titanium-phosphate-silicates (TiPSi) produced from tailings of apatite ores, was engaged in 2009. Laboratory tests are complete and pilot testing of these sorbents is planned to carry out during 2010. There are already three patents on TiPSi in Russia and production of TiPSi from calcium-titanium-silicate ores and tailings in Sweden is also possible. Long-term collaboration with LaTrobe University, Bendigo, Australia and Ian Wark Research Institute, University of South Australia is also extended into current ARC-MMS projects.

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8 WISE PROCESS ROUTES FOR VARYING FEEDSTOCK IN BASE METAL EXTRACTION

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8.1 Background

Due to the increased demand of metals the mining companies now needs to give more attention to lower grade and complex ores. Complex types of mineralizations are common in Europe and in Sweden where they can be found both in the Skellefte field and in the mining area in Bergslagen /Lips, 2006/. Some of the Swedish deposits are very large and have been known for long times but have so far not been possible to mine economically with conventional techniques. The reason is, in addition to their complexity also the presence of impurities like arsenic, bismuth and antimony. Possibilities to process these types of deposits would greatly increase the Swedish ore reserves. Base metals are produced in coupled processes from both primary and secondary raw materials, where by-products from production of one metal are raw material for the production of another metal. Recycling of metals from "end of life" scrap and metal containing waste are a necessary part of the metal production. The increasing complexity of the materials entering the metal extraction plants requires an in-depth knowledge of metallurgical reactions, thermodynamics and kinetics to assure the quality of metal products, sulphur products, slag products as well as producing new value added products.

8.2 Research

The aim with the research program is to determine the consequences of changing raw material base, primary as well as secondary, on the metal extraction chain in respect to impurity removal, recovery of valuable side elements and introduction of secondary products to the production chain.

In-depth experimental studies, plant data and theoretical modelling contributes to an extended knowledge on how to extract minerals and metals with a sustainable and efficient use of resources. The whole process chain will be evaluated based on data from experimental results to consider the best process routes for complex materials. Based on the evaluation, tailor-made process routes will be proposed.

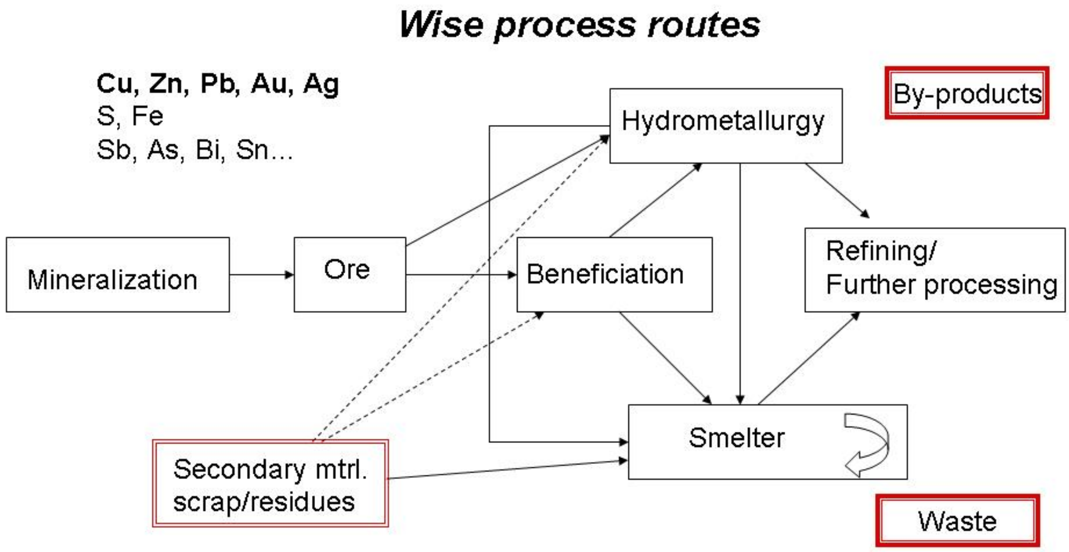

Figure 8-1. *A simplified schematic flow of possible routes for different types of materials are shown in the figure.*

Hydrometallurgical as well as pyrometallurgical treatment methods are studied within the project. The project is part in the Swedish research program “Strategiska gruvforskningsprogrammet” funded by VINNOVA and Industry. Participating industrial partners are the smelting and mining division of Boliden Mineral AB and LKAB. In addition Adolf H. Lundin Charitably Foundation is funding the project. The consortia cover all the important fields of base metals metallurgy as well as mineral processing.

8.3 Results

Hitherto, three Master thesis works have been completed within the program /Awe, 2008, Khatibi, 2008, Jonsén, 2010/. Within one of the Master thesis /Awe, 2008/, studies concerning leaching of Sb from complex sulfide concentrates were carried out. The results showed that alkaline sulfide leaching could be a feasible way to treat the concentrate for elimination of antimony. In the continuing work, extensive leaching tests of complex concentrate in laboratory scale equipment have been carried out. In addition, fundamental kinetics studies of the dissolution of a pure antimony mineral, tetrahedrite, has been carried out /Awe, 2010/. The results are so far promising and further studies are in progress. The aim with this part of the project is to test, (possibly in pilot scale), and optimize a complete hydrometallurgical step for leaching and extraction of antimony from complex concentrates. A combination of available thermodynamic data/models and plant data, complemented with measurement of thermodynamic data when needed will lead to a fundamental knowledge of smelter capacities for impurities and possibilities for recovery of valuable materials. Evaluation of thermodynamic databases and tools has shown that there is a lack of data in models that are available from commercial databases. Formulating appropriate models describing the systems relevant for smelting processes is under progress. The models will mainly be based on thermodynamic data from work reported in the literature. In cases where data are missing, experimental studies will provide necessary distribution data. Experimental work in laboratory scale to determine distribution of elements between phases in smelting units has been carried out /Khatibi, 2008/. Further work is carried out in lab scale to determine distribution coefficients for specific elements. Extensive sampling campaigns at different process units at Boliden Smelter have been carried out. The data from sampling have given valuable information concerning material flows at the smelter. The data are also used to model and predict distribution of elements at a smelting unit /Jonsén, 2010/.

8.4 Conclusions

The research work is carried out in close cooperation between industrial partners and the University, where part of the work is carried out at the industry, both collection of data as well as performance of experimental bench scale studies and characterization of materials. Preliminary results from shows that a hydrometallurgical treatment unit prior to smelting can be a feasible route to treat complex sulfide concentrates with a high content of Sb.

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9 TRACING GRANULAR PRODUCTS USING RFID

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Customers are constantly demanding a higher product quality with tighter specification limits for various product properties, and different customers have different needs. If the product properties of a batch were off specifications, it would be of great value if the batch could be tracked before delivery. Traceability and monitoring ability of a product is thus important for quality control, but difficult to achieve in continuous processes, common in process industries such as the mining industry. Benefits with traceability of granular products include possibilities for:

- Improved back-tracing of a delivered products;
- Production of products with customized properties within the same production line;
- Studies of product property deterioration during transport;
- Studies of flow induced segregation during transport; and
- Studies of product residence time and product mixing in the distribution chain.

This project studies how Radio Frequency IDentification (RFID) may improve traceability and can be used to monitor properties of granular products. The project aims to study how the performance of RFID systems in continuous granular flows may be improved and other application possibilities that the RFID technology brings.

9.1 Background to project and experimental aims

RFID is a wireless data capturing technique that normally is used for identification purposes. For identification purposes, the RFID transponder is attached to the object it shall identify. To monitor pellets flow, transponders with a casing shaped as pellets have been inserted into the flow; see Figure 9-1 a) and b).

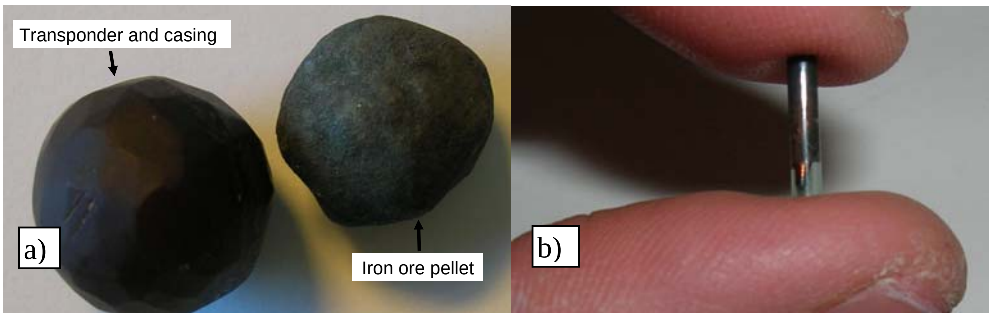

Figure 9-1 a) *An RFID transponder with a hematite and epoxy composite mixture as casing and an iron ore pellet, b). A 12 mm transponder without casing.*

A difficulty with the use of RFID to trace pellets has been that the transponder need to fit in a casing with the same shape and size as a pellets (12 mm were used). The small transponders have had low detection rates within the production plant settings. Higher detection rates are possible with larger transponders, but these transponders need larger casings; see Kvarnström & Vanhatalo (2010). A larger casing may prevent the transponder to flow as a regular pellet during transport, which also has been indicated by earlier results. The experiments described here have therefore had the purpose to study if casing density adjustments or different casing shapes may compensate for the increased size. We have also studied the use of multiple readers to increase the read rate of transponders, since the readability of the transponders is affected by the angle between the transponder antenna and the reader antenna.

The transponders seen in Figure 9-1 had a casing with the same density as the pellets, and these transponders were used as benchmark for the study (here called type A). In earlier experiments, we had noticed that larger transponders with a lower density casing gave residence times that were longer than the A type transponder. In this experiment, the larger transponder was therefore designed to have the same density (Type M) or a higher density (Type H) compared to the pellets. The transponders where dropped into the product flow at different occasions, with differing silo levels and production rate.

9.2 Experimental results

The experimental results show that an increase in casing density may compensate for the larger sizes of the 22 mm transponders. Figure 9-2 demonstrated the results of one experiment. The Type A did in this experiment behave similarly as Type H and M, with two outliers in experimental block 3.

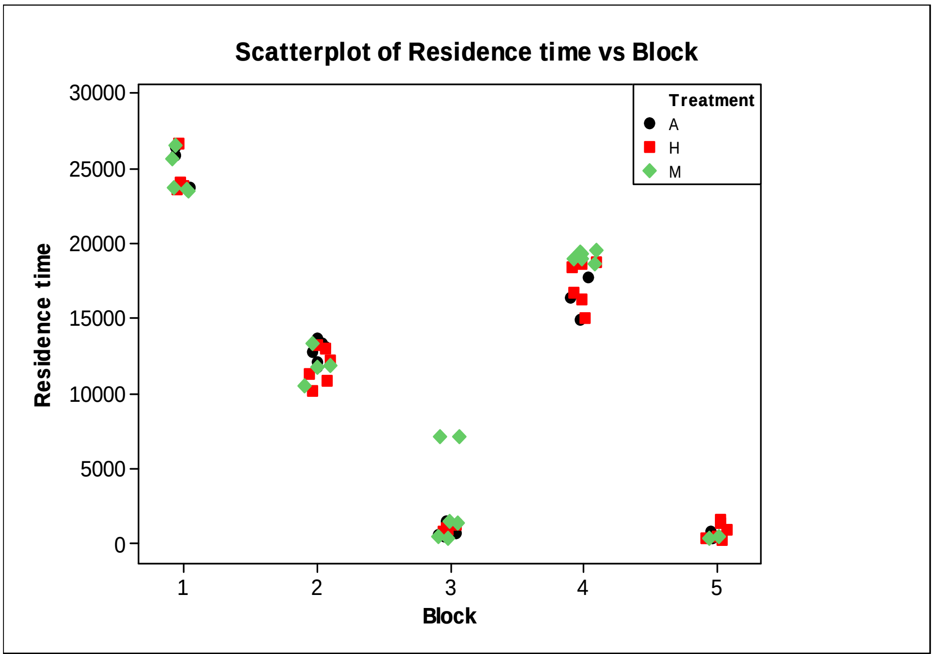

Figure 9-2. *Observed residence time for transponder within each experiment. Note that two transponders with treatment M within block 3 shows a deviating residence time.*

Two reader antennas also increased the read rate from 60% to 80%. The two readers did thus not prevent some of the transponders to pass the reader unnoticed, which may be compared to the overall read rate of 12% for 12 mm readers. The read rate for the 12 mm transponders did not increase by adding another reader.

9.3 Conclusions

We conclude that, within the limits of densities used here, it is possible to reach comparable residence times of large transponders, by adjusting the density of the casings. The different casing shapes tested did not affect the residence time. These results lead us to conclude that traceability may be reached even if larger transponders with casings larger than pellets is used, if the larger size is compensated through casing density.

9.4 Work in progress

RFID transponders can also be supplied with sensors monitoring physical properties such as pressure, vibrations, and temperature. Figure 9-3 shows a pressure sensor that may be connected to an RFID transponder. We aim to use these sensors to measure pellets pressure in the pellet beds.

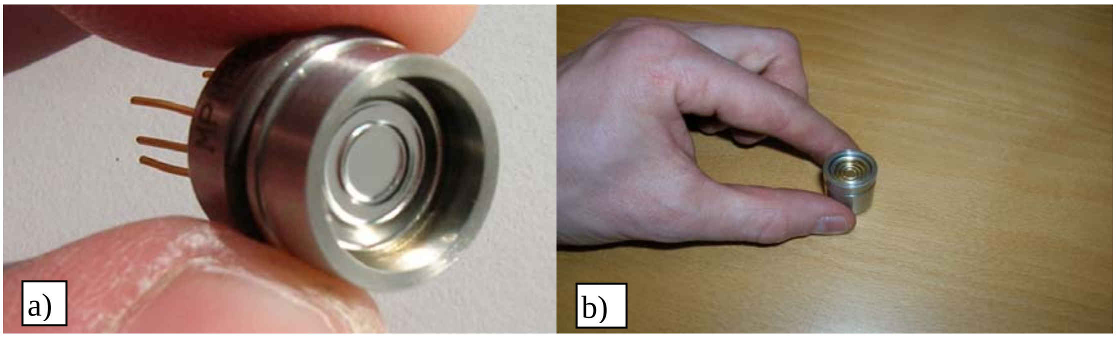

Figure 9-3 a) *A pressure sensor used for RFID pellet bed pressure measurements.* ***b)*** *Pressure sensor with protective casing**.***

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10 NITROGEN EFFLUENTS FROM MINE SITES – ENVIRONMENTAL EFFECTS AND REMOVAL OF NITROGEN IN RECIPIENTS

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In most mining regions in Sweden, natural total nitrogen concentrations (sum of concentrations of all species) are usually below 0.3 mg/L, which is the upper limit of low concentration suggested by the Swedish Environmental Protection Agency. In contrast, nitrogen concentrations in waters discharged from mine sites often greatly exceed the 5 mg/L suggested as the lower limit of extremely high concentrations. Ammonium nitrate-based explosives and sodium cyanide (NaCN) used in gold extraction are two major nitrogen sources at mine sites. As nitrogen is an essential nutrient in aquatic ecosystems, high levels of nitrate and/or ammonium may be associated with eutrophication of surface waters. This presentation provides an overview of a Swedish research programme addressing the discharge, transformation and attenuation of nitrogen in mining recipients /Frandsen et al., 2009/. The programme runs during the period 2008–2011, and is financed by The Swedish Governmental Agency for Innovation Systems (VINNOVA), the mining companies LKAB, Boliden Mineral AB and The Adolf H Lundin Charitable Foundation.

10.1 Main goals of the research programme

The main goals of the research programme are:

- To quantify the environmental significance of nitrogen effluents from the mining industry in relation to the natural load of nitrogen in streams and rivers. The knowledge gained will be used to address the question to what extent the status assessment of waters according to the EU Water Framework Directive is affected by the nitrogen load from mine sites.

- To improve the possibilities to reduce nitrogen discharge through efficient water management at mine sites (optimized conditions in clarification ponds and nitrogen removal in natural wetlands and/or constructed wetlands/barriers).

10.2 Methods

Fieldwork is carried out in two recipients receiving waters with high nitrogen concentrations from the Kiruna and Boliden mine sites in northern Sweden (Figure 10-1). Data from the two recipients includes regular monitoring data collected by LKAB and Boliden Mineral AB, as well as data collected within the VINNOVA project. At the two field sites, total nitrogen, ammonium, nitrite, nitrate, total phosphorus, phosphate, chlorophyll-a and main and trace elements are determined. Biogeochemical computer simulation models based on system dynamics modelling will be developed for the two studied recipient systems. At the Malmberget iron mine, a pilot-scale barrier for removal of nitrate through denitrification has been installed.

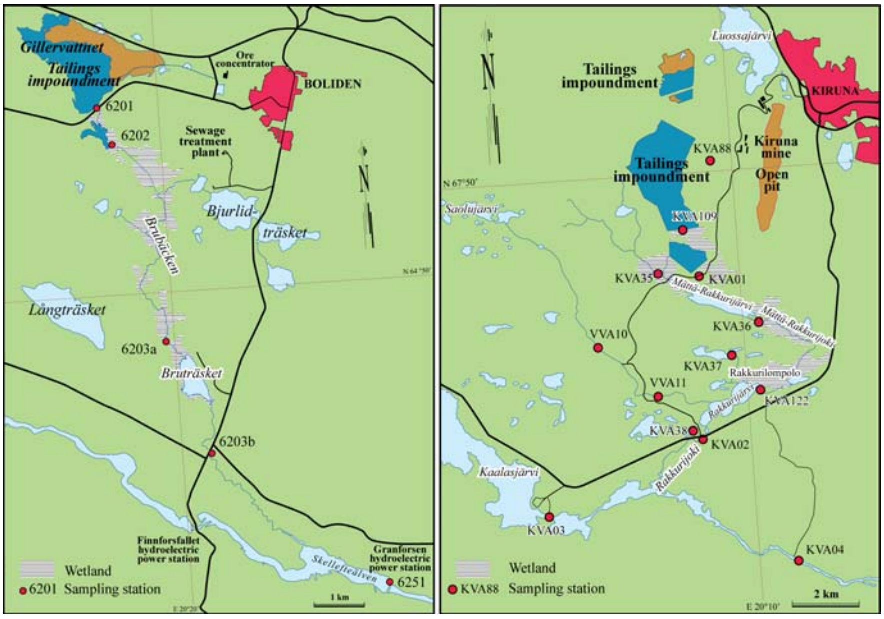

Figure 10-1. *Study areas at Boliden (left) and Kiruna (right)*

10.3 Results

Samples of water, sediments and plankton have been collected in the recipients at Boliden (Brubäcken) and Kiruna (Rakkurijoki) from April 2008 to October 2009 (in addition to regular monitoring data from the mining companies). The analytical data is of good quality, and clear seasonal trends are evident in both recipients. Development of a computer simulation model has been in progress since January 2009, with the aim of improving the understanding of nitrogen cycling in mine water recipients.

Preliminary model results from the Boliden site show good correlation between measured and simulated nitrogen concentrations /Siergieiev, 2009/. There are signs of eutrophication in the system, with an increased biomass of algae in lakes during summer. However, it is presently unclear whether nitrogen or phosphorus is growth limiting nutrient in the Brubäcken system.

Laboratory experiments show that denitrification can be initiated and maintained in mesocosms containing an organic substrate /Herbert and Björnström, 2009/. During 2010 the nitrate removal capacity for such a system will be investigated in the pilot-scale barrier at Malmberget.

10.4 Conclusions

System dynamics modelling suggests that 1) denitrification and 2) nitrogen uptake by aquatic plants followed by permenent nitrogen burial in lake sediments are the two main nitrogen sinks in the Brubäcken recipient /Siergieiev, 2009/. Ammonia volatilization probably also occurs, but appears to be of minor importance as a permanent nitrogen sink. Modelling of nitrogen transformation pathways will be performed also in Rakkurijoki, the mine water recipient at the Kiruna site.

Computer simulations based on the developed nitrogen transformation model will be useful as a decision support tool in the work towards reduced nitrogen effluents from mine sites.

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11 METAL ATTENUATION IN TAILINGS

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11.1 Goals

Oxidation of sulphide minerals in mine waste can result in extensive release of metals, which may escape the waste via groundwater discharge. However, the metals may also be attenuated by various processes in which metal ions are re-associated with the solid matter within the tailings. The main goals of the project are to identify the minerals in mining waste that are of significance for the attenuation in short and long term perspective of heavy metals released by oxidation of metal sulphides in mine waste, and to facilitate prediction of the quality of discharging ground water in a long term perspective by quantifying the metal retardation capacity of tailings of different composition.

11.2 Methods

The study comprises field sampling of tailings of different mineralogical composition and age, characterisation of the tailings chemical and mineralogical composition, structural investigations with respect to metals and quantification of the metal uptake capacity. The project also includes compilation of a spreadsheet model for metal retention in tailings considering chemical and mineralogical composition.

Tailings were in October and November 2008 sampled in Kristineberg, Aitik and Zinkgruvan using core drilling in which the tailings were captured within a PVC liner to avoid oxidation. Fresh tailings were sampled in the concentrator in Boliden. All samples are stored in freezer. The elemental composition of the tailings and pore-water has been analysed at ALS Scandinavia, Luleå. The elemental composition of individual mineral grains has been examined using a Scanning Electron Microscope equipped with a detector for energy dispersive X-ray analysis of the elemental composition of particles. A preliminary determination of the mineralogical composition has been made using X-ray Powder Diffraction. Supplementary mineralogical analysis using Mineral Liberation Analysis will be made during spring 2010 by GTK, Finland. The specific surface area, as well as the porosity, of the tailings has been analysed. The speciation of elements and the local structure on a molecular level of metal ions associated with tailings are investigated using X-ray Photoelectron Spectroscopy and synchrotron based Extended X-ray Absorption Fine Structure (EXAFS). The latter is being made at the synchrotron at MAX-lab, Lund. The metal uptake capacity is studied in batch uptake experiments and column experiments.

11.3 Results

11.3.1 Field sampling and sample characterisation

Table 11-1 Physicochemical data for tailings - selected elements

	Aitik	Boliden	Kristineberg	Zinkgruvan
Porosity (%)	30	35-40	35-40	28
BET area (m^2/g)	2.5	3.5		1
pH (pore water)	9.3	10.4	5.5	8.4
Main elements (%)				
SiO_2	58.2	22.2	37.4	61.4
Al_2O_3	16.5	5.5	13.1	12.0
Fe_2O_3	8.2	42.7	12.8	6.6
CaO	3.6	0.4	2.0	4.7
MgO	2.6	3.7	11.6	3.5
Minor elements (mg/kg)				
As	6	467	330	43.3
Cu	171	647	1 010	72.7
Pb	3	153	680	3 960
Zn	52	871	8 025	6 490
S	8 515	332 000	116 000	8 890

The metal uptake capacity has been studied for Cu, As, Zn and Cd in batch and column experiments. For copper the main problem has been to distinguish between adsorbed copper and precipitation of copper hydroxide. The copper removal from the solution is strongly correlated to pH. At pH > 5 copper was strongly removed from the solution. This coincides with the onset of precipitation of copper hydroxide at these total concentrations. To avoid precipitation of $Cu(OH)_2(s)$ in the experiments, pH was regulated by adding HCl to pH≈4.5. The amount of acid added for the different tailing also reflects the buffer capacity of the tailings.

Tailings from Zinkgruvan showed the highest acid neutralization capacity (Figure 11-1). Tailings from Aitik and Kristineberg were less efficient in neutralising acidity. The tailings from Kristineberg and Zinkgruvan showed almost the same capacity to adsorb copper. This was ca. 5 times higher than the uptake capacity of tailings from Aitik. The reason for the low adsorption capacity of the tailings from Aitik is likely to be the low content of sulphide minerals.

Batch and column experiments for arsenic performed at pH> 6 demonstrated that tailings from Kristineberg has the highest adsorption capacity and Aitik the lowest capacity to remove metals (Figure 11-2). The magnitude of arsenic removal from water by tailings from is the same as for copper, indicating that the arsenic and copper bind to the same type of binding sites on the mineral surfaces. However, for tailings from Zinkgruvan the adsorption of copper is twice as high compared to adsorption of arsenic, indicating that other mineral then sulphides may be involved. The important of sulphide rich tailings for arsenic attenuation is clearly illustrated in a column experiment where a sulphide rich tailing (Boliden) is compared to a sulphide poor tailing (Zinkgruvan).

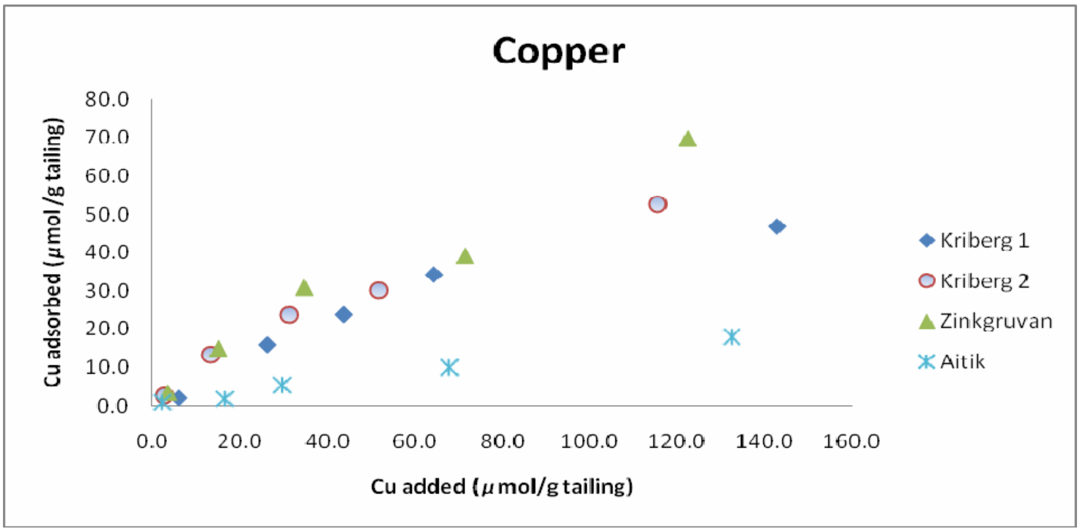

Figure 11-1. *Copper adsorption from aqueous solutions at pH 5 by tailings from Aitik, Zinkgruvan and Kristineberg. Results from batch uptake experiments.*

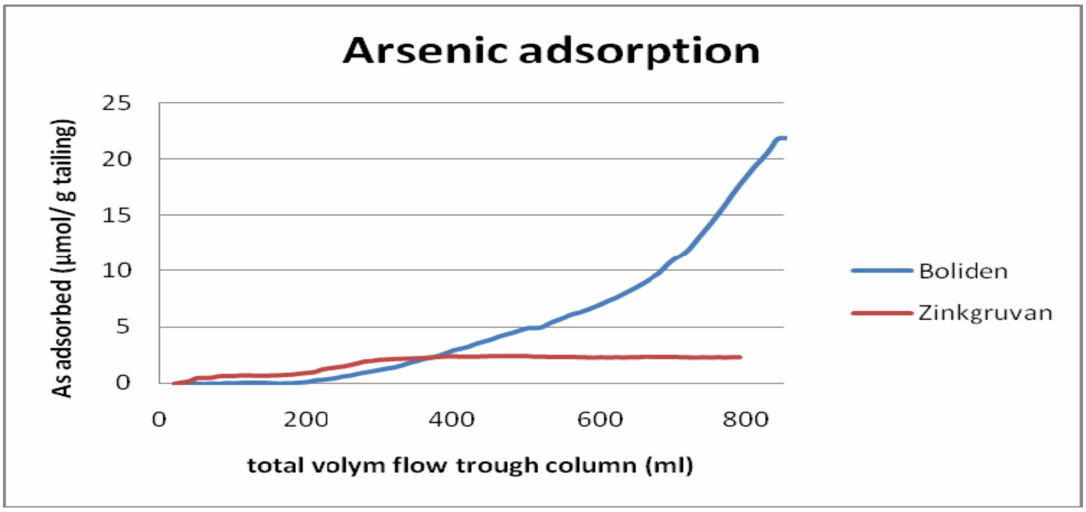

Figure 11-2. *Arsenic adsorption from aqueous solution at pH=8 by tailings from Boliden and Zinkgruvan. Results from column experiments (flow rate 1.8 ml/h).*

EXAFS analysis of copper speciation performed at MAX-lab, Lund showed that some $Cu(OH)_2$(s) was found despite the low pH of 5. Additional measurements

At Umeå University the following scientists are actively involved in the project: Associate Professor Lars Lövgren (project leader), PhD Tomas Hedlund, PhD Torbjörn Karlsson and PhD Andrey Shchukarev. Support is also provided by technical staff at the department. No publications have been released so far.

12 VIEWS ON MINING BY 2030 AND BEYOND

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The conceptual study "Mine of the Future" (MIFU) brings together major Swedish and Polish mining companies and several major global suppliers and the academia (Figure 12-1, left) to develop a common vision for future deep, underground mining.

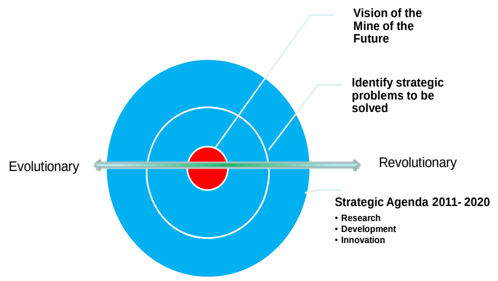

***Figure 12-1**. Left: Parties involved in the Mine-of-the-Future conceptual study March 2009-Dec 2010. Right: Major deliverables.*

The vision will be used to identify the most strategic issues that need to be addressed and solved in present mining operations to stay world class in production and in level with world class manufacturers in other sectors, and also to convey an image of the sector as innovative, interesting and sustainable. It is envisioned that the study will be used to prepare the framework for a Swedish national mining Strategic Research, Development and Innovation Agenda 2011 – 2020 (Figure 12-1, right).

Do we understand the current situation? Can we share a common vision among the Parties in the MIFU study? What strategic choices can we make? How will these choices influence challenges and need for preparation to meet the vision? The analogue picture (Figure 12-2) is outlining the work process.

The work is conducted in seven work packages with WP1 - Setting the Scene - already finished. Some general observations from the work so far are:

- The mining companies share a common thought that mining industry in the future should use continuous processes rather than batch processes (Figure 12-3, left)

- The suppliers requested that clear performance objectives were established to guide their future research, development and innovation work (Figure 12-3, right)

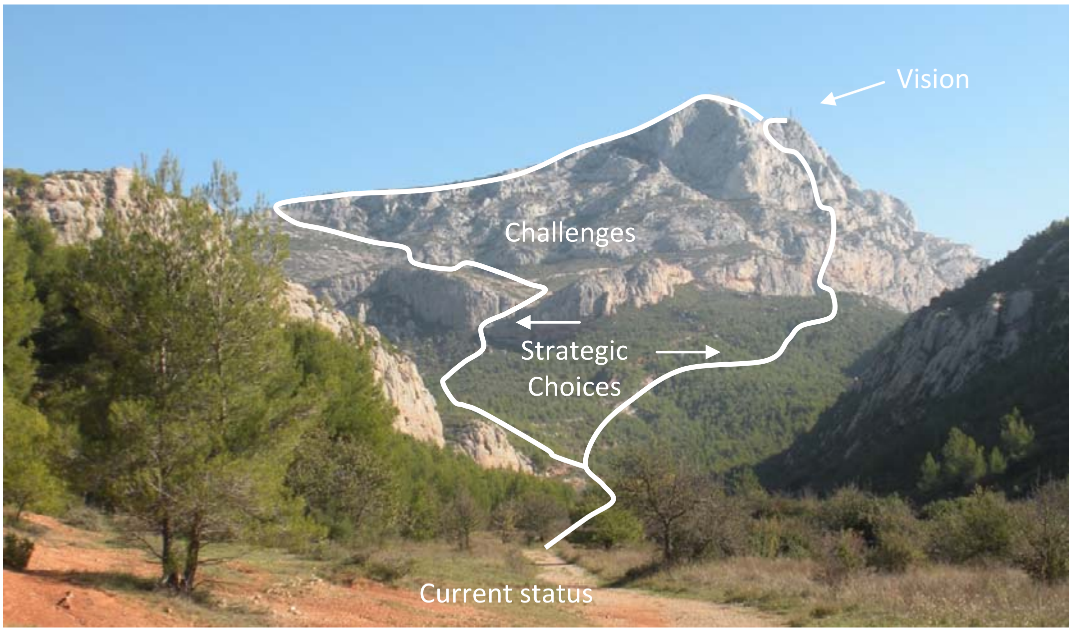

***Figure 12-2**. The MIFU project described by an analogy*

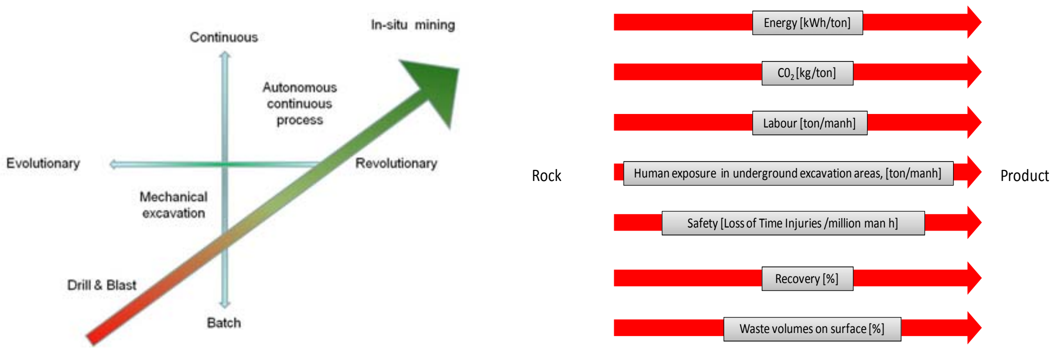

***Figure 12-3.** Left: Mining companies move in the direction of being a process industry. Right: Suppliers requested clear performance objectives. The project defined a set of performance factors. Baseline description and ideas to meet the targets are in progress*

In common there is a strong quest to make mining, safer, leaner and greener. The mining companies also share a strong interest to develop methods for resource characterisation necessary for efficient product and process control. One striking detail in common is also the wish to completely stop using diesel underground.

Work is in progress to define the current baseline at Boliden, KGHM and LKAB for the performance factors selected. The project has decided targets as shown in Figure 12-4. Work is in progress to define the actions necessary to meet these targets. While technology is considered being the main driver for long-term improvements, the work also honours the necessary adaptation of human and organisational skill. It is likely that the development of a generic technology like IT will create many opportunities to make the future production systems more efficient and reliable. In the MTO (Man-Technology- Organisation) perspective, it is especially difficult to assess how future

Figure 12-4. *MIFU has preliminary set performance targets as > 30 by 2030 as the basis for future work.*

Organisation, e.g. mine-supplier business relations will develop. Will the suppliers always track the performance of their equipment on-line to develop the most optimal design and preventive maintenance programme in a similar way as e.g. Rolls-Royce from their control room in Derby where Rolls-Royce continuously assesses the performance of 3,500 jet engines around the world? The data collected enables Rolls-Royce to predict when engines are more likely to fail, letting customers schedule engine changes efficiently. That means fewer emergency repairs and fewer unhappy passengers. The data are equally valuable to Rolls-Royce. Spotting problems early helps it to design and build more reliable engines or to modify existing ones.

The strong development of process control in combination with current trend of globalisation will likely impact future organisation as well as the requirements on human skill and knowledge. How to develop the future attractive workplace?

To develop a new image of the mining industry, the ongoing work to further develop safety, resource efficiency and greener mining need to be continued. The challenges and the changes are so large that a comprehensive international cooperation is needed both within and outside the industry in order to succeed /Abrahamsson et al., 2009/.

ACKNOWLEDGEMENT

This short abstract is prepared by the MIFU project group to share the work in progress. The final statements of the MIFU study may deviate from this presentation. The authors acknowledge important contributions from the MIFU parties.

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