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THE GEOMETALLURGICAL FRAMEWORK. MALMBERGET AND MIKHEEVSKOYE CASE STUDIES

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Abstract: Geometallurgy is a growing area within a mineral processing industry. It brings together tasks of geologists and mineral processing engineers to do short and medium term production planning. However, it is also striving to deal with long term tasks such as changes in either production flow sheet or considering different scenarios.

This paper demonstrates capabilities of geometallurgy through two case studies from perspective of Minerals and Metallurgical Engineering division Lulea University of Technology. A classification system of geometallurgical usages and approaches was developed in order to describe a working framework.

A practical meaning of classification system was proved in two case studies: Mikheevskoye (Russia) and Malmberget (Sweden) projects. These case studies, where geometallurgy was applied in a rather systematic way, have shown the amount of work required for moving the project within the geometallurgical framework, which corresponds to shift of the projects location within the geometallurgical classification system.

Keywords: geometallurgy, classification, proxies, mineralogy, case study, Malmberget, Mikheevskoye

1. WHAT IS GEOMETALLURGY?

A classical approach to model a deposit is to derive metal grades from chemical assays and build a 3D block model that includes geology and metal grades. However, the complexity of ores and deposits is increasing over the years and a need for enhanced models has emerged. In recent years several authors have proposed different definitions, all based on the close interaction between geology, mineral properties and

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behaviour of a feed in metallurgical operations (McQuiston and Bechaud, 1968; Vann et al., 2011). While the approach in itself is not new, recent advances in automated mineralogy, data processing and comminution testing have made it feasible in practice (Lamberg and Lund, 2012; Schouwstra et al., 2013).

Geometallurgy is a multi-disciplinary science that aims at integrating geology, mineralogy, mineral processing and metallurgy to build a spatially-based model for production management that quantitatively predicts:

- quality of concentrates and tailings,
- metallurgical performance, like metallurgical recoveries and throughput,
- environmental impact such as fresh water usage for tons produced.

To achieve these goals, a unified framework is needed to guide the practical work needed.

2. GEOMETALLURGICAL USAGE AND APPROACHES CLASSIFICATION

The data structuring and data modelling in geometallurgy heavily depend on geometallurgical approach used in the mine and final purpose of geometallurgy. When developing a geometallurgical program, i.e. industrial application of geology, one should have clear vision how this information will be used. To benchmark different geometallurgical programs we have developed a two dimensional classification system. The first dimension of the classification system is the type of geometallurgical approach and the second dimension is the depth of usage of geometallurgy (Fig. 1).

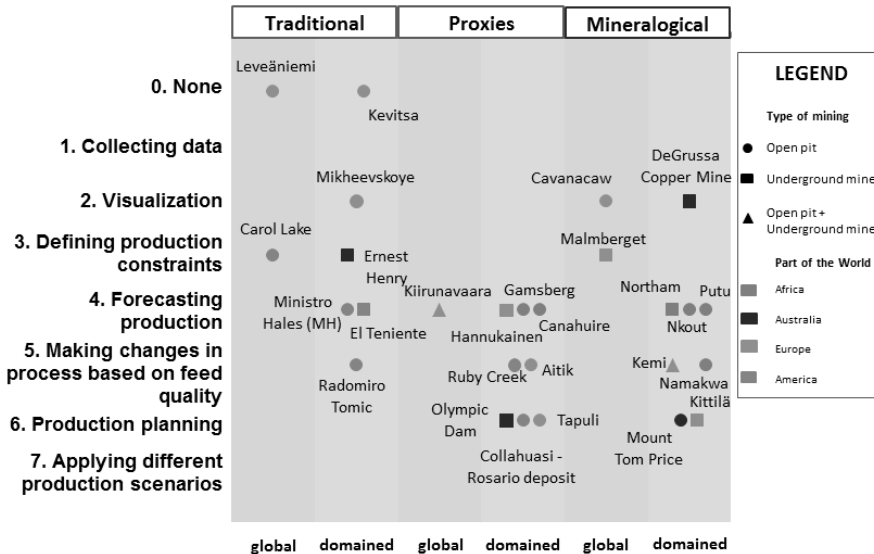


Fig. 1. Selected mines arranged in classification matrix

2.1. GEOMETALLURGY APPROACHES

The geometallurgical programs are divided in three approaches: traditional, proxies, mineralogical.

In **traditional approach** the metallurgical response of an ore in the mineral processing plant is calculated from the normal (chemical) assays using mathematical functions, which are often called as recovery functions. The functions are developed using variability testing and statistical analysis to define the correlation between the metallurgical response and feed properties (i.e. chemical composition).

Proxies approach uses geometallurgical tests for large number of samples. The geometallurgical test is a small scale test which indirectly measures the metallurgical response. Normally the geometallurgical test results must be converted with certain correction factors to give estimate on the metallurgical results of plant. Examples of geometallurgical tests are Davis tube (Niiranen and Böhm 2012), Minnovex crusher index test (Kosick et al., 2002).

Continuous and systematic collection of quantitative mineralogical information is the main characteristic of the **mineralogical approach** in geometallurgy. An example how mineralogy can bridge geological model to model of mineral processing plant (Figs. 1, 2) is work done by Lamberg (2011) and Lund (2013).

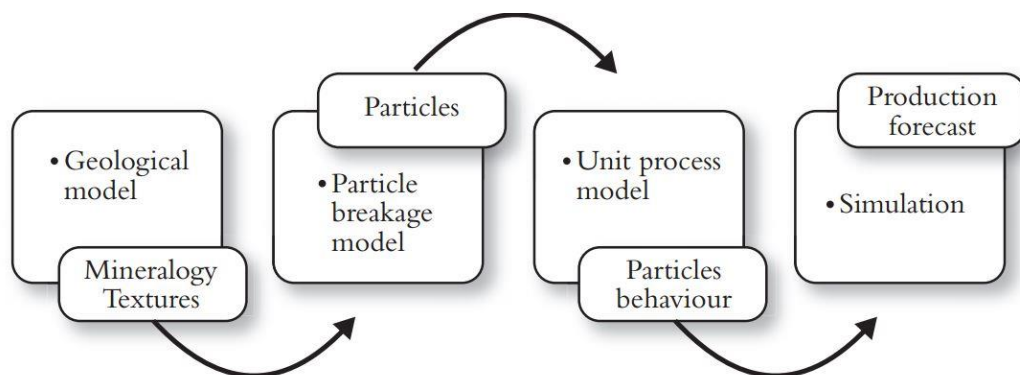


Fig. 2. Role of particles in proposed geometallurgical approach (Lamberg, 2011, modified)

2.2. GEOMETALLURGY USAGES

Depth of usage in geometallurgy means how the geometallurgical data is used in the mine:

0. None (neither usage nor collection of geometallurgical data);
1. Collecting data (geometallurgical data is collected but not used);
2. Visualizing data (the variation within the ore body);
3. Defining production constraints (for example, cut-off grade);

4. Forecast production;
5. Making changes in process based on feed quality (changes are made in the process beforehand with the knowledge of geometallurgy);
6. Production planning;
7. Applying different production scenarios (geometallurgical data is used to make large scale decision of the future; e.g. when to invest, what alternative technologies is selected etc.).

The deeper the level of geometallurgy is, the deeper integration and cooperation between involved parts of the mineral production chain (geology exploration and production, mining, processing, sales etc.) are.

3. CASE STUDIES

3.1. MIKHEEVSKOYE

The Mikheevskoye geometallurgical model was developed by Lishchuk (2014). The aim of the study was to find a way for improving performance of the mineral processing plant through the better understanding of the variation in the ore body and mine planning of Cu-porphyry deposits. The aim of the study was reached by including information on hydrothermal alteration zoning in geological block modelling and geometallurgical zonality in estimates on operational costs.

The Mikheevskoye deposit is located in Chelyabinsk region, Russian Federation on the territory of the Varna municipality on the border with Kartaly municipality. The ore reserves of the Mikheevsky deposit within the outlines of an initially planned open pit mine were approved by the State Commission for Mineral Reserves in July 2010 in an amount of 352 million tonnes (Mt) of categories A+B+C1+C2 (more about Russian resource and reserve categories could be found Henley, S., 2004) with an average copper content of 0.41% (Beloshapkov, 2012). Mikheevskoye could be considered as a greenfield project and commissioning was planned in 2013-2014.

The Mikheevskoye deposit demonstrates a typical alteration-mineralization zoning pattern for porphyry Cu deposits (Sillitoe, 2010). Zoning pattern forms a shape of a shell (Sillitoe, 1973). Alteration zones of Miheevskoye consist of the inner potassic and outer propylitic alteration zones. The zones of phyllic and argillic (clay rock) alteration are the part of the zonal pattern between the potassic and propylitic zones.

Copper mineralization occurs as chalcopyrite and bornite dissemination within the host lithology. Ore zones of the Mikheevskoye deposit have locally outlined, sometimes not well defined vertical mineral zonality (ore stratification) from the top to the bottom:

- The top layer consists of the shallow Cenozoic rocks (soil),
- Laterite zone (also known as supergene or oxidized zone - oxidized ore),
- Intermediate (oxidized/ cemented) zone - transitional (mouldy) ore,

- Hypogene (fresh) zone - sulphide (rocky) ore.

Initially, Mikheevskoye project did not have any geometallurgical model and the collected geological data had little use for mineral processing planning (level 0). Therefore, a project to develop a geometallurgical model was the set for the Mikheevskoye project. Two scenarios were evaluated for the project: the head grade based and geometallurgical based. The head grade scenario assumed that mine planning and feed quality would be forecasted based on ore metal grade. The geometallurgical based scenario assumed predictions based on geometallurgical domains. The geometallurgical domains were established for the ore zones which would behave homogeneously in the beneficiation process. The following objectives (Table 1) were formulated for the head grade scenario and geometallurgical program based on ideas developed in Lamberg, (2011).

Table 1. Objectives of the head grade and geometallurgical program scenarios

Head grade scenario	Geometallurgical program scenario
Investigation of feed quality needs of concentrator process (comminution and flotation departments usually have different needs)	
Collect up-to-date geological information about the deposit	
Conduct sampling campaign	
Collect up-to-date topographic data from surveying	
Model zonality of the ore body based on commodity grade	Model zonality of the ore body based on process behaviour of different ore types
Run open pit optimization	
Develop optional open pit design based on commodity grade	Develop optional open pit design based on ore zonality
Develop mining plan and extraction schedule	
Estimate cost efficiency of the proposed solution	

Application of the geometallurgical approach requires to link metallurgical and geological parameters. Williams and Richardson (2004) suggested using parameters listed in Table 2.

Table 2. Linkage between geological and metallurgical factors after Williams and Richardson (2004)

Geological/mineralogical factor	Ore property	Metallurgical output		
		Grinding	Flotation	Dewatering
Rock type	Hardness	X		
Ore assemblage	Solubility, hardness	X	X	X
Alteration	Clays, hardness	X		X
Faulting	Clays, oxidation		X	X
Metamorphism	Clays, hardness	X	X	X

Mineral processing flow sheet suggested that hardness, oxidation and presence of magnetite were the most crucial parameters for the process performance. Some permutation of these parameters resulted in 13 geometallurgical domains and are presented in Table 3.

Table 3. Geometallurgical domains suggested for Mikheevskoye mine

Cut-off 0.2% Cu	Hardness	Magnetite	Oxidation	Code
Outside	Not relevant			1
Inside	Hard			2
Inside	Hard		X	3
Inside	Hard	X		4
Inside	Hard	X	X	5
Inside	Very hard			6
Inside	Very hard		X	7
Inside	Very hard	X		8
Inside	Very hard	X	X	9
Inside	Extremely hard			10
Inside	Extremely hard		X	11
Inside	Extremely hard	X		12
Inside	Extremely hard	X	X	13

Two mining scenarios were calculated based on the metal grade and geometallurgical domains. The metal grade scenario assumed that the ore would be extracted by metal grade and the processing cost would be constant for each block. Geometallurgical domained approach assumed ore extraction by domains, which implies variable processing cost for different domains. Discretization of the mining schedule was done with one year frequency for the next five years.

Since the result of research was not used in production planning, this project was classified as visualization usage of geometallurgy (level 2, Fig. 1) and approach as traditional. It was also predicted that geometallurgical approach could potentially decrease the payback period for the project by 1.5 years and significantly increase the net present value.

3.2. CASE STUDY – MALMBERGET

Lund (2013) developed a geometallurgical framework established in three steps using the Malmberget iron ore deposit, northern Sweden, as a case study.

Malmberget deposit is a major iron ore source operated by LKAB located close to Gällivare in northern Norrbotten, Sweden. At the end of 2014, approximately 680 Mt of crude ore have been produced in open pits and underground workings and the reserves were estimated to 288 Mt with 42.1% Fe (LKAB, 2013).

The deposit consists of more than 20 sub-vertical ore bodies of hematite and magnetite occurring as massive lenses surrounded by an extensive brecciation. The origin is intensively debated and one of the prevailing theories is that the massive ore is formed as magmatic intrusions with the iron-enriched magma or high temperature hydro-thermal fluids circulation at 1.88-1.90 gigaannus (Geijer, 1930; Romer et al., 1994). The breccia (semi-massive) ore is suggested to have been formed by low-temperature hydro-thermal processes (Martinsson, 2004).

Lund (2013) showed that the reason behind the magnetite-hematite partition of the deposit might be oxidation of magnetite into hematite following an easterly to westerly direction.

The initial work focused on building the geological model in a geometallurgical context based on mineralogical characterization. This was done in several steps:

1. Ore characterization: gather chemical and mineralogical information on the ore and host rocks, as well as study their variations within the ore bodies
2. Quantification of mineralogy and textural information:
 - a. Use chemical assays and element to mineral conversion (EMC) to evaluate mineral grades.
 - b. Use optical microscopy and scanning electron microscopy (SEM) to evaluate the grain size (not particle size) of minerals. The association index (AI) and liberation data were used to build textural archetypes.
3. Definition of geometallurgical ore types (GEM-types): combine mineral grades and textural information to build GEM-types
4. Study comminution related to textural information: perform simple rock mechanics test and small-scale comminution tests to build a particle breakage model (establish liberation degree by size fraction). The particle breakage model follows the structure.
5. Test the applicability of the results using a metallurgical unit model: After converting un-sized modal composition to liberation distribution using textural archetypes (particle tracking algorithm based on Lamberg and Viana, (2007), a one-step dry magnetic separation (cobbing) was used.

Steps 1 to 3 yielded 6 different GEM-types for the Fabian and Prinzsköld ore bodies (Lund, 2013) and 5 textural archetypes. Step 4 gives an overall size distribution model, several lab-scale models linking mineralogy, comminution and limited liberation data, and provided classification into several grindability-liberation classes (Koch, 2013). Finally, Step 5 allowed validating the approach within a 2% error limit. These results validate the mineralogical approach to geometallurgy and indicate that, even with a limited number of samples and tests, it could be used to obtain geometallurgical parameters for the block model.

The approach in the Malmberget model is mineralogical and it enables production forecasting (level 4, Fid. 1).

3.3. DISCUSSION

Two case studies, Mikheevskoye and Malmberget, where geometallurgy was applied were reviewed in this paper. The purpose of these reviews was to show some capabilities and practical use of geometallurgy. Both case studies were initially at a low level of geometallurgy usage of. The low level of geometallurgy corresponded also to low predictability of production in these case studies.

The case studies demonstrate:

- With the right characterization and tests, even with limited samples, we can acquire quantitative information regarding the ore (hardness, modal mineralogy, grain size, degree of liberation and association index).
- Understanding on the behaviour of minerals and particles (of different sizes, modal mineralogy and textures in the beneficiation process is critical for creating reliable process model.
- Linking the information above enables to build a geometallurgical block model and use it as a production planning tool.

4. CONCLUSIONS

A modern mining industry faces new challenges which were not common several decades ago. Decreased ore grades, increased variability within ore body and highly fluctuating commodity prices have higher impact on the projects profitability and thus, require more accurate short and long term planning. One of the possible solutions for this is implementation of geometallurgy. Geometallurgy is instrument which allows connecting geological and mineral processing information for a predictive model to be used in short and medium term planning.

Geometallurgy has to cover all parts of mining production chain and take into account connections which exist between all production stages. Thus, more detailed and uniform descriptions of ore recourses, plant feed and process streams are required. Therefore, a two dimensional classification system of the geometallurgical approaches and usages was developed. This classification system was used to analyse typical geometallurgical data structure and applied over studied case studies. The practical use of this classification system becomes obvious when there is a need to either change geometallurgical approach (i.e., traditional, proxies, mineralogical) or go to the deeper level of the usage of geometallurgy. Information shown in Fig. 1 can also be used for benchmarking.

The potential impact of the geometallurgical program on production management was shown in two case studies: Mikheevskoye (Russian Federation) and Malmberget (Sweden). The result has proved to bring significant improvement in predictability of the feed quality and processing performance. For example, successful implementation of geometallurgical program in Mikheevskoye potentially decreases the payback peri-

od by 1.5 years. Both of these case studies were developed under the strong impact of research ideas and scientific approaches of the MiMeR (Mineral processing) division of the Lulea University of Technology (Sweden).

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