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A Special Issue focused on Geometallurgy: Preface

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Abstract

Geometallurgy is an interdisciplinary field aimed at describing potential ore deposits in terms that mine planners and economists can use to design and run profitable mining operations. The major geological contribution to the field is defining the spatial variability of potential and active mining resources so that planning and scheduling can accurately predict the economic performance and environmental impact of mining in time to respond efficiently to variations in ore type. This information is needed at feasibility stage and throughout the mine life. We review the available literature on how geologists have contributed to these predictions in the past. There have been substantial advances in predicting comminution behavior. Prediction of recovery and environmental impacts are less advanced. This introductory paper provides a brief review of geometallurgy and a synopsis of the papers in the Special Issue, along with suggestions on future directions.

Introduction and Review of Geometallurgy

Introduction

Descriptions of case studies with a geometallurgy focus, particularly those that highlight links to geological variability, are not abundant in the published literature and much of what is available only appears as conference papers and abstracts with limited circulation. Modern mine planning requires much better ore deposit knowledge than was accepted last century and mine geologists are now required to generate new types of data for the metallurgists and engineers in addition to the grade control data that was the bread-and-butter of the last 50 years. This collection of papers presents a series of geometallurgy case studies including examples from North and South America, Australia and Europe that provide a snapshot of some of the data that will need to be routinely collected in the future.

This introductory paper provides a brief review of geometallurgy and a synopsis of the papers in the Special Issue, along with suggestions on future directions.

Review

Geometallurgy is an interdisciplinary field nominally covering the overlap between geology and extractive metallurgy. However, in practise it has grown to cover the interaction between geology, geostatistics, mining engineering and extractive metallurgy. With such a broad cross disciplinary ambit it requires a team-based approach. The geologists main contribution is documenting variability within the prospect/resource, including mineralogy, texture and structure, so that the metallurgical sampling program includes all significant ore types. Changes in the geological characteristics can affect the cost of comminution (i.e., crushing and grinding) and waste rock management, and the value extracted in the metal recovery processes (e.g., Walters and Kojovic, 2006; Walters, 2011; Williams, 2013; Hunt and Berry, 2017, Dominy et al., 2018a). The ultimate aim of geometallurgy is to produce a quantitative, spatially constrained database containing all the relevant mineral processing parameters for every part of the resource and surrounding waste rock. This data can be used to build a block model where each block in the mine plan is valued, not only on grade, but on a combination of all the relevant properties (e.g., throughput, recovery, tailings characteristics, product saleability etc.) that contribute to profitable mining.

Geometallurgy is an important tool in assessing technical risk associated with new mine developments or the expansion of existing mines. It can also be used to compare prospects during mineral exploration, not just in terms of grade, but also considering processing parameters that affect value, such as hardness (e.g., ease of crushing and grinding) and mineralogy (e.g., elemental occurrence, minerals deleterious to processing or acid producing minerals). It is used during feasibility to make sure the bulk samples selected for plant design (e.g., types of crushers and grinding mills) and testing mineral processing options (including flotation, leaching, and gravity and magnetic separation) are representative of the whole deposit. The data can also be used for optimising block models (long and short term) and mine scheduling to maximise value. This can be done by allowing mining methods to target more consistent plant feed and, if significant feed changes are identified, by informing the plant operators ahead of time of expected changes in feed characteristics.

Geometallurgy is not new and has existed in various forms for more than 50 years, under such names as mine site valuation and “mine to mill” (McKee, 2013). What is new, however, is the holistic view where geologists, mining engineers and metallurgists share the responsibility for profitable operation of the mine and communicate across the boundaries of what were traditional data silos (i.e., geologists, geostatisticians, mining engineers and metallurgists historically did not share a common technical language and received no training in their degree programs on what the other groups need to know to optimise a mining operation). Geometallurgy complements, but does not replace, existing approaches to design and optimization of mining and mineral processing options (Walters, 2015).

Geometallurgy: a brief history – The concept of geometallurgy has been around since the 1960s (e.g., McQuiston and Bechaud, 1968). It had strong supporters in various parts of the world. In Chile, Pedro Carrasco of CODELCO was a leading advocate for using a geometallurgical approach over many years (Beniscelli, 2011). At the Los Bronces porphyry copper deposit, Holmgren and Marti (1984) developed maps showing the distribution of ‘metallurgical types’ that were used to optimize the metallurgical process, predict concentrator results, and provide a tool to forecast copper production. In a notable study in Australia, Bojcevski (1998, 2004) demonstrated relationships between rock textures at the meso- and micro-scale, and metallurgical characteristics that could be used to optimise metal recovery at the George Fisher mine, Mount Isa, Australia. The Mine to Mill conference in 1998 (AusIMM, 1998) provided a snap shot of ideas and methodologies applied before the term 'geometallurgy' came into general use in the early 2000s (Williams and Richards, 2004)

There was a significant increase in geometallurgy research after 2005. This included the large industry sponsored geometallurgical mapping and mine modelling (GeM) projects (AMIRA P843, P843A/Australian Research Council funded project with scientists based in JKMRC and BRC, Brisbane; CODES, Hobart and CSIRO, Perth) designed to support and enhance emerging commercial and cultural trends towards more effective mine site integration and optimisation (Walters and Kojovic, 2006). They involved cross-discipline research collaboration between groups with expertise in economic geology, mining and mineral processing, mining geostatistics and optimisation, automated core logging, and hydrometallurgy research. For most of the groups in the GeM projects this was the first time they had collaborated on research projects outside their disciplinary "silos" despite a long history of research funded by the same industry sponsors and in some cases research on the same mining operations. Much of this information remains confidential but case study summaries have been published for Cadia East (Keeney et al., 2011) and La Colosa (Leichliter et al., 2011; Montoya et al., 2011). Publications relating to test and methodology development from these projects are listed in Table 1.

Table 1: Examples of geometallurgy testing-focused publications from the GeM projects.

Testing/methodology topic	Reference
Meso to micro-scale mineralogy	Bonnici et al., 2009; Hunt et al., 2009
Estimating mineralogy in bulk samples	Berry et al., 2011
Automated optical microscopy	Berry et al., 2008
Integrating optical and SEM-based microscopy	Hartner et al., 2011
Characterising liberation using image analysis and simulated fragmentation	Hunt et al., 2011a,b; Nguyen, 2013
Small-scale hydrometallurgical tests	Kuhar et al., 2011, 2013; Turner et al., 2013
Small-scale flotation tests	Chauhan et al., 2013
Small-scale comminution tests	Kojovic et al., 2010a,b; Kojovic and Walters, 2012
Petrophysical characterisation of comminution	Vatandoost et al., 2009
Environmental characterisation	Parbhakar-Fox et al., 2013
Integrating and modelling data	Keeney and Walters, 2009, 2011; Keeney et al., 2011; Hunt et al., 2013.

During this time geometallurgy focused research was also gaining ground at other institutions including Cambourne School of Mines (UK), COREM (Canada), University of Cape Town (South Africa) and Colorado School of Mines (USA). The first conference dedicated entirely to geometallurgy took place in 2011 and has been followed by many others (Australian Institute of Mining and Metallurgy (AusIMM): 3; Gecamin: 3; Institute of Materials, Minerals and Mining (IOM3): 2; South African Institute of Mining and Metallurgy (SAIMM): 1). The conferences led to a rapid increase in the availability of geometallurgy based papers and some recent examples are provided in Table 2. These include models used for geometallurgy data that vary from simple domaining (Burger et al. 2006) to decision trees (Lishchuk et al. 2019). Escobar and Jara (2012) describe challenges in the development of a geometallurgical model for oxide heap leaching. Papers that illustrate how geometallurgy can improve the net present value (NPV) of a deposit include Dunham et al. (2011), Bye (2011), Wolff et al. (2012), King and MacDonald (2016) and Lotter et al. (2018).

Table 2: Examples of geometallurgy-focused publications relevant to the geological community.

Type	Commodity	Mine	Reference	Target
Porphyry	Cu	Los Bronces	Rocha et al., 2012	comminution
		Cadia East	Keeney et al., 2011	comminution
		Collahuasi	Alruiz et al., 2009	comminution
		generic	Cropp et al., 2013	Cu recovery
		Northern Europe	Parbhakar-Fox et al., 2018	AMD
	Cu-Au	Batu Hijau	Burger et al., 2006	comminution
	Cu-Au-Mo	Cerro Corona	Baumgartner et al., 2016	Cu, Au recovery
	Cu-Au-Mo	Pebble	Gregory et al., 2013	Au deportment and recovery
	Au	La Colosa	Montoya et al., 2011; Leichliter et al., 2011	comminution, recovery
IOCG	Cu	Productura	Escolme et al., (2019); King and Macdonald (2016)	comminution
		Prominent Hill	Hunt et al., 2011a; Hunt et al., 2014	recovery
	Cu-U	Olympic Dam	Boisvert et al., 2013; Ehrig et al., 2015	comminution, recovery
Epithermal	Cu-Au	Chelopech	Rincon et al., 2019	comminution
	Au-Cu-Ag	Canahuire	Baumgartner et al., 2013	recovery, AMD
Mesothermal	Au	San Antonio	Dominy et al., 2018b	recovery, comminution
		Paracuta	Bhuiyan et al., 2019	comminution
Magmatic	Pt	Mogalakwena	Schowstra et al., 2013	comminution, recovery
VHMS	critical metals	Neves Corvo	Frenzel et al., 2018	critical metal deportment, recovery
U deposits	U	generic	Pownceby and Johnson 2014	recovery
Iron Ore	Fe	Mont-Wright	Pérez Barnuevo et al., 2018	comminution, concentrate grade
		Leveaniemi	Lishchuk et al., 2019	recovery
		Kings deposit	Vatandoost et al., 2013	concentrate quality
Industrial minerals	feldspar-nepheline	Nabbaren	Silva et al., 2018	recovery, concentrate grade

Current state of geometallurgy

Equipment and methods to collect data are continually being upgraded and new data handling protocols are being developed to rapidly and efficiently analyse and interpret the large amounts of data now being collected. In addition, the awareness that improved understanding of a geological resource can provide key information to link with processing performance etc. is also growing. Some recent examples are included in this Special Issue (Johnson et al. 2019; Escolme et al. 2019; Harraden et al., 2019). Others include McKinley et al. (2017) who describe how they incorporate near and shortwave infrared (NIR-SWIR) data into 3D models for the Kisladağ gold porphyry deposit in Turkey. Rifai et al. (2018) demonstrate the use of laser-induced breakdown spectroscopy (LIBS) for real-time geochemical applications on samples with complex mineralogy and varying surface topography. Developments are continuing in scanning electron microscope, energy dispersive X-ray-based (SEM-EDS) automated mineralogy (Graham et al., 2015: Hrstka et al., 2018).

Geometallurgy requires abundant data to create statistically valid spatial models and one way of obtaining such data is via small-scale proxy tests which, by design, use small sample size and are less expensive to perform than full scale metallurgical tests (e.g. (Kojovic et al., 2010a, b: Kojovic and Walters, 2012; Mwanga et al., 2015; Heiskari et al., 2019). While small scale tests for comminution are reaching a mature stage, small sample tests for recovery are still at a developmental stage especially in flotation (see references in Table 1).

Methods of analyzing and interpreting data continue to be developed and improved. Lishchuk et al. (2019) carried out a comparison of machine learning methods to determine if process data (mass pull, liberation, particle size, recovery) could be effectively incorporated into spatial models of geometallurgical parameters at the Leveäniemi iron ore mine in Sweden. The authors suggest tree methods perform better than regression methods in predicting non-additive variables such as recovery. El Haddad et al. (2019) describe new methodologies for analysis of laser-induced breakdown spectroscopy (LIBS) data. They used a multivariate curve resolution – alternating least squares (MCR-ALS) method for mineral identification and quantification and suggest the method could be scalable and used to gather automated mineralogy measurements in coarse rock streams. The new Handbook of Mathematical Geosciences contains a chapter on Predictive Geometallurgy (van den Boogart and Tolosana-Delgado, 2018) that discusses the state of the art but emphasises the need for new mathematical and computational developments to tackle problems arising from geometallurgical studies.

It is also evident that geometallurgy is now being used in areas outside metallic deposits, such as the bulk commodities exploited in the mining of industrial minerals (e.g., Ellefmo et al. 2019). Recently Silva et al. (2018) tested a range of methods for calculating the modal mineralogy of the Nabbaren nepheline syenite deposit, Norway, based on X-ray fluorescence (XRF) and X-ray diffraction (XRD) data by two different element-to-mineral conversion methods, one least squares-based and one regression-based.

Environmental parameters suitable for geometallurgy are now available (Parbhakar-Fox and Lottermoser 2015). Recent innovations are the use of core scanning technologies (including RGB, VNIR-SWIR) to determine geoenvironmental parameters (Cracknell et al., 2018; Parbhakar-Fox et al., 2018), using “calculated mineralogy” to estimate ARD (Berry et al., 2015) and the development of a more rapid biokinetic test for the characterisation of ARD potential (Opitz et al., 2016).

Synopsis of Papers Included in this Special Issue

The use of a geometallurgical approach to characterising variability within an ore body and its impacts on the mining value chain now has significant uptake and the increased use of the approach has led to upgrading of methods and equipment used to collect data. Johnson et al. (2019) discuss how near and shortwave infrared (NIR-SWIR) hyperspectral data collected from blast hole samples using an automated system can be used to characterise samples and predict recovery and throughput at the Phoenix Au-Cu porphyry-related skarn deposit, USA. The complex skarn mineralogy associated with ore grade mineralization poses significant challenges to blasting, mining, comminution, and process operations. The different host rocks are, in general, fine grained and similar in colour making them difficult to distinguish from one another in the field. Mill performance data plus hyperspectral data collected from mill samples were used to build predictive Au-Cu recovery, grade and throughput models. Blast hole data were then applied to models to calculated predicted recoveries and throughputs. These models showed excellent relationships to geologic features.

Harraden et al. (2019) describe the development of geometric models derived from laser profiling of oriented drill core to extract fracture locations, orientations and roughness from oriented drill core at the Cadia East Au-Cu porphyry deposit, Australia, during routine measurement of NIR-SWIR spectra using an automated system. The fracture orientation and spacing coupled with the mineralogy information on the joint surface collected with the NIR-SWIR spectrometers, is used to calculate the rock mass rating (RMR), and rock tunneling quality index (Q index). This data is required for geotechnical models and the automated method has the potential to produce enough data to provide robust statistical support for a spatially-defined geotechnical model in future mines.

Escolme et al. (2019) describe both qualitative and quantitative approaches to estimating bulk mineralogy from multi-element geochemical data for the Productura Cu-Au-Mo deposit, Chile. In the qualitative approach they used whole rock geochemical data plus dominant sulfide mineralogy from core logging in a combination of ternary and bivariate plots to provide a rapid and simple classification of dominant alteration assemblages. Geochemical data plus supplementary semi-quantitative X-ray diffraction (QXRD) data were used with linear programming to generate estimates for abundance of major mineral phases (calculated mineralogy) for drill core assay intervals. The results demonstrate that the amount of bulk mineralogy data available can be significantly increased via calculated mineralogy and used in a mining environment to map mineralogical variability.

Ellefmo et al. (2019) describe the key differences between the industrial minerals and metallic ore sectors in terms of their development and use of block models and optimization strategies using examples from the Norwegian mining industry. They discuss key levers for value creation in industrial mineral operations and the differences to those used in the mining of metallic ores along with the extent to which geometallurgy has been adopted. Pereira et al. (2019) use the Catalão I Nb deposit at the Chapadão phosphate mine, Brasil to examine the feasibility of recovering rare earth elements as a by-product. They characterised the mineralogy and chemistry of tailings plant streams and identified the stream with the greatest potential for recovery of REE without compromising the current Nb beneficiation process.

Geometallurgy – Future Directions

Developments to reduce energy usage in mining, particularly in size reduction (comminution) circuits, have led to the emergence of several innovative technologies (e.g., CAHM: conjugate anvil hammer mill, eHPCC: eccentric-high-pressure-centrifugal-comminution; e.g., Canada Mining Innovation Council, 2019; Impact Canada, 2019). Improved ore sorting and upgrading methodologies are emerging to reduce the amount of material requiring size reduction (Rutter, 2017). If these technologies become widely adopted, new methods will be required to predict which ore types are suitable for upgrading, and these methods must be incorporated into geometallurgical programs.

Other areas such as public acceptance and social licence to operate are increasingly important as the industry aspires to provide minerals and metals to society in an economically viable, environmentally responsible way that benefits all stakeholders (Bradshaw and Digby, 2018). It has also been acknowledged that it is unlikely that future mineral demand will be met by new discoveries and recycling (Ali et al., 2017), and that the focus on known 'complex' undeveloped sub-economic ore bodies will be renewed. The practice of geometallurgy will play a significant role in the ability to overcome many of the technical, environmental and socio-political challenges associated with these undeveloped "ore" bodies (e.g., Valenta et al., 2018).

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