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GMG

White Paper

INTRODUCTION TO GEOMETALLURGY

Abstract

Geometallurgy is an interdisciplinary approach that plays a pivotal role in any project's evaluation or proposed mining operation. It focuses on spatially characterizing the different material types or domains within a deposit, considering their impact on processing, mining performance, and environmental and closure aspects.

This white paper is an introduction to geometallurgy and is intended to be a reference for practitioners unfamiliar with aspects of the subject. The white paper is intended to provide an understanding of all geometallurgical elements into one document, using them to lay out a roadmap for future Global Mining Guidelines Group (GMG) geometallurgy guidelines.

This white paper includes a detailed definition of geometallurgy along with an overview of the key elements associated with the discipline, including:

- Common data reporting
- Representative sampling
- Geological characterization
- Metallurgical and environmental characterization
- Data consolidation and data quality assurance
- Model development
- Model evaluation
- Project optimization
- Reconciliation

CONTENTS

1. What is Geometallurgy?

Geometallurgy is an interdisciplinary practice that plays a pivotal role in any mining project evaluation or mining operation. It focuses on spatially characterizing different materials or domains within a deposit, considering their impact on processing and mining performance, as well as environmental and closure aspects. By integrating geological, mineralogical, mining, metallurgical, environmental, and economic parameters, geometallurgy aims to reduce technical and operational risk during project evaluation and production. Ultimately, the goal of geometallurgy is to maximize the economic value of an orebody by sufficiently characterizing different material types to inform predicted project and operational outcomes through a comprehensive understanding of the data generated.

1.1 Introduction

The growth of geometallurgy has been largely organic resulting in different levels of capability and maturity across the industry, limited development of industry-wide systems and guidelines, and limited opportunities for collaboration. However, the industry's resources and operating context are changing and becoming more available because of:

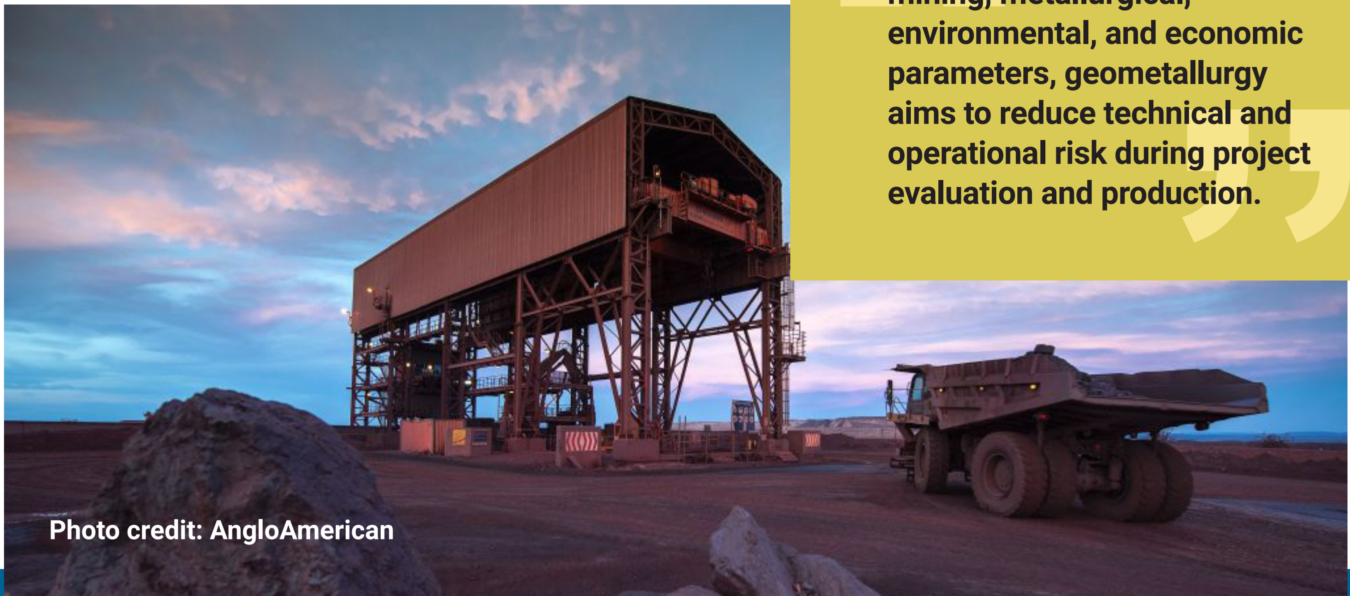
- An increased focus on data-driven technologies and systems to allow the ability to maintain productivity in the face of deeper, more complex orebodies, and realize the opportunities provided by AI.
- Greater focus on resource characterization to support future processing options.
- More focus on waste and tailings characterization to understand and manage closure costs and environmental impact, in line with increased community expectations.

1.2 Purpose

The purpose of this white paper is to provide a general overview of current geometallurgical practices in industry, intended for practitioners unfamiliar with aspects of geometallurgy.

This white paper, and future geometallurgy guidelines published, aim to advance the geometallurgy discipline through a structured approach by breaking the extensive field into manageable, focused guidelines (see Section 5 for a list of future guidelines). These guidelines will advance the industry by providing recommended best practices that have been agreed upon by experts in the field.

> **By integrating geological, mining, metallurgical, environmental, and economic parameters, geometallurgy aims to reduce technical and operational risk during project evaluation and production.**



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1.3 GMG's Geometallurgy Program Exclusions

The aim of this white paper, and future guidelines is to describe the geometallurgical concept and the activities that directly link geology and mineralogy to metallurgical performance. As such, the following areas will be excluded, while recognizing they can have direct impacts on the success of a geometallurgy program:

Geology	Topics that deal exclusively with geological studies, such as geological formation processes, mineral deposits, and tectonic processes, unless they directly influence metallurgical outcomes.
Mineralogy	While mineralogical analysis is crucial, studies that do not directly connect to processing performance, metallurgical response, concentrate specification, and tailings/waste rocks behaviour are out of scope.
Metallurgical Process Development	Development and optimization of metallurgical processes that do not involve variability due to geological considerations. The focus will remain on how geological factors impact metallurgical performance prediction and by extension overall plant design.
Mine Planning	Strategic planning and operational aspects of mining that do not directly affect or consider metallurgical performance.

The exclusion of these above areas ensures that these publications remain concentrated on the critical intersection of geology and metallurgy, providing clear, actionable insights for enhancing mineral, mining, and metallurgical processing based on geological data. This focused approach will help practitioners apply geometallurgical principles effectively without the dilution of discipline specific topics.

2. Background

The economic extraction of minerals required for the eventual production of raw material and useful finished goods begins with an understanding of the material to be mined, known as orebody knowledge. The tools, methodologies, and extent of work used to characterize an orebody have evolved over the past 20 years in concert with the advancement of the tools available for this work and the increasing mineralogical complexity of the deposits themselves.

Historical orebody characterization has consisted of extensive spatial drilling to obtain interval-based assay, geology, mineralogy, alteration, geotechnical and hydrogeological parameters, and rock quality information. This data is used to determine characteristics of the different geological material types (domains) and their respective mineralogical characteristics for resource estimation, and result in the selection of composite samples for subsequent metallurgical characterization testing. Metallurgical characteristics such as ore hardness, abrasion index, flotation or leach recovery, concentrate quality, or anode quality are a few of these parameters. Specific characterization testing is typically tailored to an individual project as determined by individuals experienced in the type of deposit and processes proposed.

To address the increasing geological, mineralogical, and metallurgical complexity of orebodies, this historical composite-based approach has advanced. It is now common practice to include specific sub-composites based on understood differences in materials, material properties, or metallurgical response as informed by early-stage test work. These sub-composites and their determined characteristics are important to informing plant design, potential planned design changes over the proposed life of mine, production performance over the life of mine, and economic predictions required to make appropriate business decisions.

The current common practice in industry also includes the use of a series of continuous intervals along a drill hole, referred to as variability samples, distributed across the proposed mining areas. These variability samples are intended to capture the differing response with respect to geological heterogeneity over the proposed life of mine to inform decision-making. The number of variability samples are intended to:

- Be proportional to the impact of the material on mining decision making from each identified domain and covering the compositional range of each domain, to ensure that characterization is sufficiently detailed in relation to the relative importance of the material over the proposed life of mine.
- Consider a higher sample density in the payback period for the proposed life of mine, to ensure this critical economic phase is sufficiently derisked.
- Cover a range of economic and marginal grade, as well as areas just outside of the pit shell available at the time of sampling, to ensure potential future changes to the mine plan and subsequent operational practice can be informed.

These variability samples are then processed through a wide set of characterization analyses and tests spanning a full range of discipline areas, developing a detailed and spatially attributed data set that is used in mining project development activities. It is important to note that sample selection, characterization and testing, and analysis is conducted in an iterative manner.

3. Activity-Based Workflow – First Iteration

Greenfield projects typically begins with the spatial drilling of a target location and the collection of drill core data, interval assays, and mineralogical information. The first characterization and analysis are typically conducted by geology and mineralogy specialists where the available data is used to develop geological models defining the project in terms of grade and impurities, and geology including lithologies, alteration, mineralization, and geotechnical features. Both numerical modelling and advanced data analytics techniques are used in some cases to refine these base geological models. The concept of activity-based workflow is used to describe both the sequential steps undertaken by different disciplines, combined with geometallurgy being an iterative process. In later stage iterations when mining and metallurgical characteristics are available, these advanced modelling and analytical techniques are used to help inform predictive outcomes for material types identified.

> **Geometallurgy is an evolving practice. There are no established geometallurgical standards for the collection, retention, and processing of data.**

There are three critical differentiations between historical orebody characterization and geometallurgical orebody characterization:

- The increased number of spatially discrete material characterization data points.
- The increased data available for each discrete material sample.
- The increased application of data analytics and advance modelling techniques that are possible with larger data sets.

It is important to note that geometallurgy is an evolving practice.
Several mining companies, universities, service providers, and industry organizations have established their own approaches to developing orebody knowledge under the umbrella term of geometallurgy. There are no established geometallurgical standards for the collection, retention, and processing of data that have received industry-wide acceptance.

A greenfield project typically includes the following major actions with respect to characterization testing and predictive modelling:

- Geological and mineralogical characterization of materials and the development of geological models defining the project in terms of grade and impurities, geology including lithology, alteration, mineralization among others, to inform block models, and geotechnical features.
- Mining specialists use the data provided by the geology, geochemistry, and mineralogy testing to inform mining sequencing and phasing, as well as overall mining area disturbance. This in turn assists in the development of initial planning for waste stockpiles, mine dewatering, and a further range of physical project considerations.
- Geometallurgical and metallurgical specialists use the data from geological, geochemical and mineralogical analysis, and mining activities to inform sample selection for material characterization related to key processing inputs, material process response testing, flowsheet development, and product material characterization testing. This information is subsequently used in process plant design, recovery predictions, product quality predictions, and to develop spatial geometallurgical models.
- Environmental specialists use information and samples from geological, geochemical and mineralogical analysis, mining and metallurgical activities to conduct material characterization tests for source control, waste streams, stockpiles, tailings materials, water quality, and a range of discipline specific predictive modelling activities. The information is also used to develop spatial geometallurgical models.

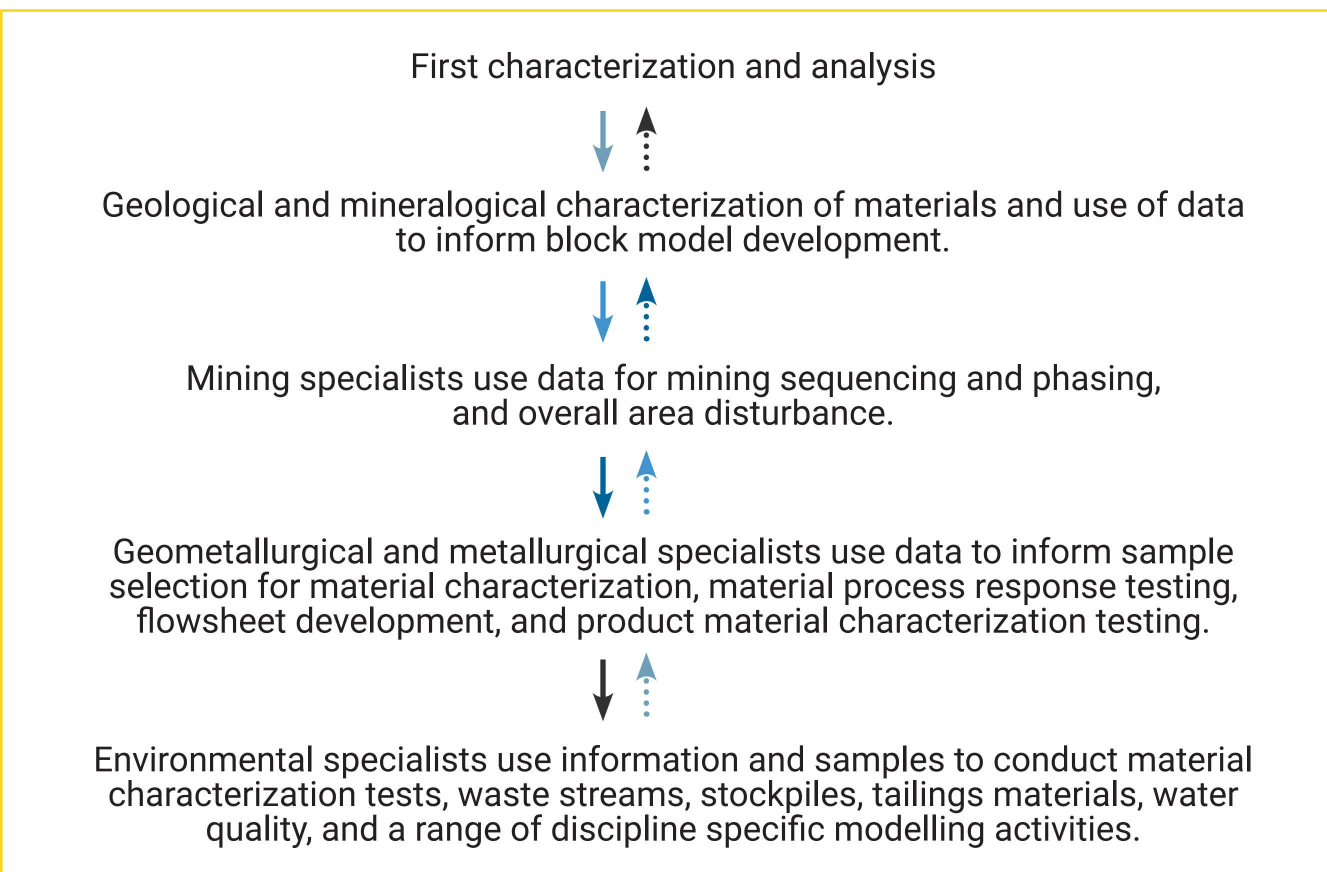

Figure 1. High-level overview of greenfield actions with respect to characterization testing and predictive modelling.

A thorough evaluation will utilize information from orebody characterization, grade and mitigating factors, mine design, metallurgical testing and product quality, and environmental characterization, to inform capital, revenue and operating costs for the project.

Experience shows that a successful geometallurgy program first requires the establishment of a cross-functional team to lead the project. This team has a mandate to meet regularly to discuss and evaluate developments from diverse perspectives and project stages including geology, mining, metallurgy, environmental, finance, and stakeholders, depending on the project. The geometallurgy program incorporates diverse data of variable scale, dimension, time horizon and significance. As such, the continuous communication of results are important for realistic projections, resource allocation and risk/opportunity identification as the operation progresses through various stages.

As key material characterization information and modelling results are obtained, they are proactively shared to promote project alignment. However, after the completion of work during the first iteration of a project by geology, geochemistry, mineralogy, mining, metallurgy, environmental, and marketing specialists, the overall project is brought together in a unified project configuration with the appropriate economic evaluations for business decisions to be made. This is generally part of an overall project optimization phase that can result in rework of individual components or individual discipline areas. Project optimization typically informs work planning for subsequent iteration stages in a geometallurgical program.

This optimization stage is often the point where preliminary spatial and predictive modelling is updated based on mining, metallurgical, environmental, marketing and economic information that only becomes available near the end of the stage. This critical exercise requires close coordination between disciplines.

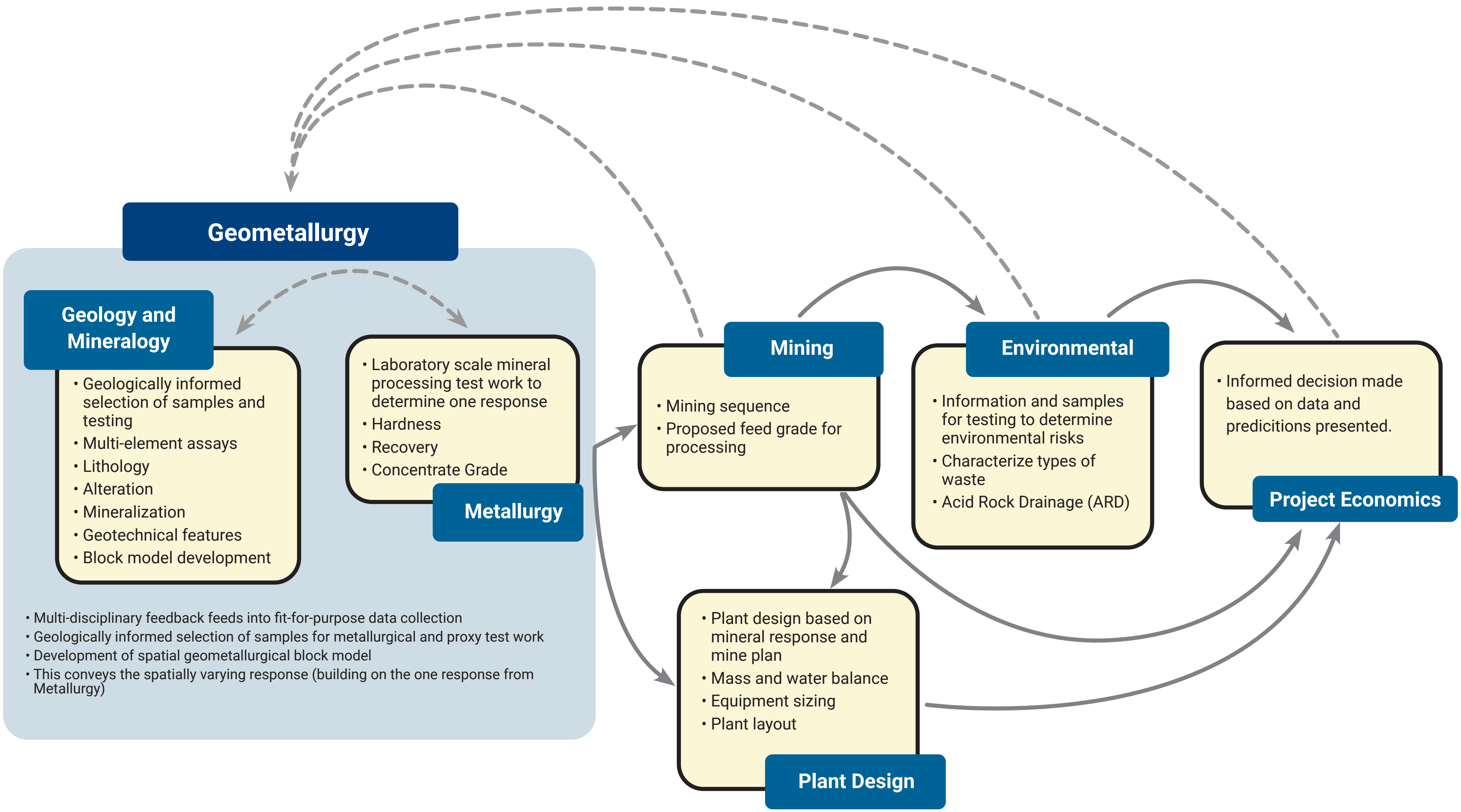

FIgure 2. Major steps involved with in a greenfield project with respect to characterization and predictive modelling.

Reconciliation represents the step where additional field drilling data, material characterization information, or operational data is systematically compared against the predictive models. This validation process ensures the models accurately reflect the behaviour of the orebody as the project progresses through study phases and to operations. Areas exhibiting poor reconciliation signal potential shortcomings in the models. These discrepancies and uncertainties can become apparent due to various factors, such as:

- Incomplete data
- Inherent variability stemming from complex deposits
- Unforeseen operational challenges
- Known and deliberate operational changes

In these cases, additional data collection or sampling becomes necessary. Reconciliation fosters an iterative process; therefore, if data does not fully support the original interpretations, the sampling, test work, and/or models should be revisited. When resolving the above uncertainties and increasing data density as projects progress from early-stage development to approval and execution, decisions generally form the basis for:

- Targeted drilling
- Data collection
- Material characterization
- Modelling

This can be applicable in subsequent iterations of the geometallurgical program.

This iterative approach for operational geometallurgy is illustrated in Figure 3:

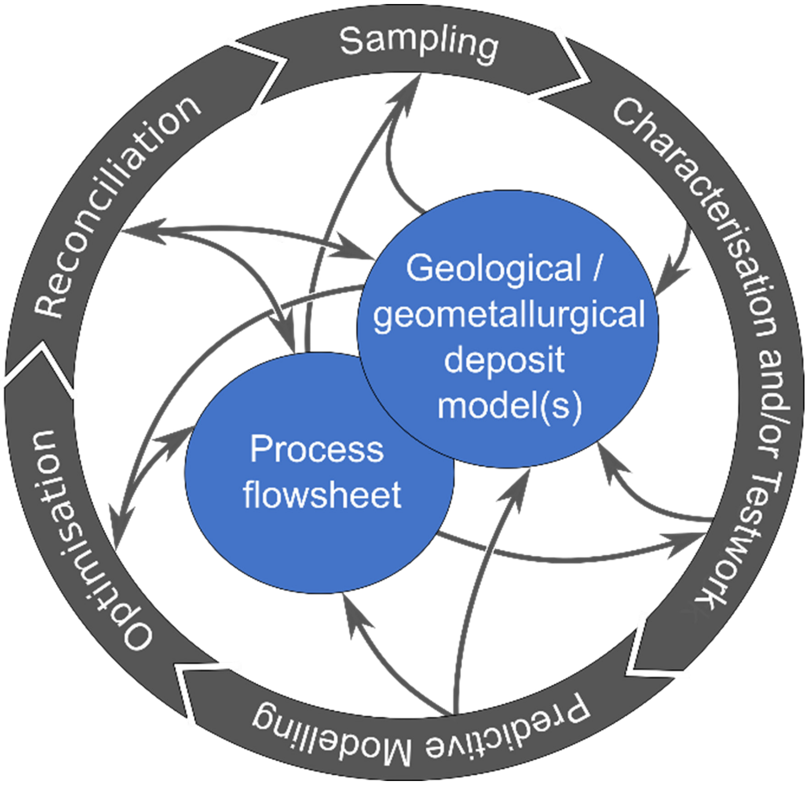

Figure 3. Iterative approach of a geometallurgy workflow with interactions between geological and metallurgical disciplines. Reproduced from Frenzel et al. (2023) with permission of Elements Magazine (Mineralogical Society of America).

4. Activity-Based Workflow – Subsequent Iteration/Brownfield

Once the first iteration stage of a geometallurgical program is complete, subsequent stage iterations are more readily informed by cross-discipline data. This is particularly true for data analytics and predictive modelling activities. At the beginning of the first iteration of a geometallurgical program, material classifications and predictive modelling are limited to geological types. Either at the end of the first iteration or in subsequent iterations, material characteristic or response characterization from other discipline areas can be incorporated into material type and predictive modelling (often considering a multi-typing approach for materials). For instance, one geological material type can represent multiple comminution response types as determined through testing. Similarly, flotation response domains can span multiple geological domains. This is also true of mining, environmental, product quality, and economic characterization and modelling.

In many cases, brownfield operations, expansion, or life extension projects have not undergone geometallurgical development. In these cases, significant historical production information can be used to develop spatial material characterization and models. Brownfield projects can typically be considered as subsequent iterations from a geometallurgical standpoint.

5. Specific Areas of Geometallurgical Guidance

Nine areas of geometallurgy are proposed as the subject areas for future GMG guidelines.

Note that individual companies can have internal specifications with respect to required data to be included in programs to achieve appropriate sanction. These requirements will vary by company, and it is the responsibility of practitioners to ensure that their requirements are met.

5.1 Representative Sampling

The objective of representative sampling is to obtain samples that will accurately represent the deposit in terms of physical, chemical, and mineralogical characteristics. Representative sampling should consider existing orebody knowledge and conform to the Theory of Sampling. The first iteration will generally incorporate available geological, metallurgical, and mineralogical data, if existent. Sampling methodologies, processing (such as sampling reduction, preparation, and transportation) and analytical methods (including analytical techniques and quality assurance and quality control) should be determined and can be limited by the available drillholes. At subsequent iterations, the sampling will be guided by the results of the first iteration which might have highlighted areas of less confidence, higher ore variability, or higher tonnage/volume as well as the follow-up type of testing. A dedicated geometallurgical drill program might be required to provide a larger number, mass, or spatially well distributed samples during the subsequent iterations.


Photo credit: AngloAmerican

5.2 Geological Characterization

The objective of the geological characterization is to ensure the samples collected are thoroughly described, both from a qualitative and quantitative point of view. Qualitative characterization includes lithology, alteration, and mineralization. Quantitative and semi-quantitative characterization includes geochemical, mineralogical, and geotechnical analyses and tests. The first iteration will depend on the overall deposit knowledge and geological concept at the time of sampling. This iteration is an opportunity to capture data that is normally not collected during routine logging and assaying. It can include specific geochemical analysis such as elemental speciation, deleterious elements, mineralogy using different methods, including hyperspectral data. The subsequent iteration analysis is guided by the results from the first iteration and other findings from orebody knowledge studies conducted on the deposit as well as metallurgical testing.

5.3 Metallurgical and Environmental Characterization

The primary purpose of this work is to develop throughput predictions, recovery and product quality predictions, a data set that is used for life of mine modelling, process design, assessing tailings and waste rock disposal methods, and identifying health and environmental risks related to the mine life and post closure. They include, but are not limited to air quality, water quality, water flows and volumes, and land usage. First iteration testing is dependent on sample availability. The scope of the test program is defined by geological and mineralogical characterization and likely limited to laboratory and bench-scale batch tests that may include comminution, flotation, leaching, dewatering, and ARD. Subsequent iteration testing is defined by results from first iteration testing and may include variability tests on individual samples, testing domain composite samples, locked cycle tests, pilot scale tests, and test programs to quantify byproduct values and quantify deleterious elements issues.

5.4 Common Data Reporting

A fundamental principle of geometallurgy is to test a higher volume of samples than has previously been sourced and to relate metallurgical response to ore properties. The large number of samples and tests typically results in large data sets that contain valuable data. Related disciplines in the mining value chain, such as geology and mining engineering, also manage large data sets; however, these disciplines have a wide range of commercial software applications tailored for their specific data types. There are no commercial applications specifically tailored to managing geometallurgical and mineralogical data, perhaps due to the lack of standardization in the reporting of geometallurgical and mineralogical test results which can create a barrier to the development and commercialization of data management applications.

5.5 Data Consolidation and Data Quality Assurance

Data consolidation takes valuable data and turns it into useful information for each iteration's analysis and testing. For this, the data (independent on the tool used for exploratory data analysis) should be validated via a data quality assurance program and subsequently evaluated by data analysis. At each iteration, the process should follow rigorous protocols and standardization, so the data can be traceable, appended, and used after each iteration.

5.6 Model Development

The first iteration will seek to identify deposit domains that will provide understanding of the metallurgical behaviours with respect to the geological parameters obtained during the characterization stage (geochemistry, mineralogy, geotechnical, etc.). The identity of these domains can be obtained with statistical and geostatistical modelling and modelling and analysis methods and models. Further sampling will be informed by the first iteration models. During the subsequent iterations, when a larger number of samples has been collected and tested, modelling and analysis methods can be developed to predict metallurgical responses throughout the deposit and further refine or modify the domains. It can also quantify uncertainties, populate to block models, and inform further sampling. Simulations can be applied to assess and manage geometallurgical uncertainty and incorporate nonlinear features. All of these models can be updated periodically with new samples.

5.7 Model Evaluation

The objective of the model evaluation stage is to obtain feedback as to whether the model honours the data. A model evaluation is done comparing the actual data with the predicted data using cross-validation methods that will assess the robustness of the model. Different types of geometallurgical models can require different metrics such as accuracy, precision, and truthfulness. A risk assessment should be conducted to assess overfitting, sample representativity and correlation significance. Because of the nature of a model, it will likely never be perfect; therefore, an uncertainty tolerance should be quantified. If the model performs poorly against actual data, more samples and/or a review of the domain in question may be required.

5.8 Project Optimization

With first and subsequent iterations, projects and processes might have the potential to be optimized. The combination of representative sampling and appropriate testing, along with the underlying understanding of geological drivers of performance, allows an orebody to be assessed under different mining and processing configurations. This can require specific geometallurgical sampling and testing to respond to specific questions. Because this stage is also dependent on financial, marketing, regulatory factors, and more, an overall assessment of the optimization potential should occur before embarking on project optimization.

5.9 Reconciliation

The purpose of reconciliation is to validate, calibrate, and ultimately improve the geometallurgical models and forecasts. The information obtained from reconciliation can provide fundamental indicators to an operation's performance and inform improvements in planning and operations. To assess the contribution of the geometallurgy model, a reconciliation process should be carried out at regular intervals. Geometallurgical reconciliation can be done at the mining stage and/or processing stage and can occur spatially and temporally. Geometallurgical reconciliation is a process designed to test the geometallurgy forecasts based on the actual material mined and processed. Geometallurgy performance predictions are compared to actual results for a given period.

Conclusion

Well-structured and appropriate geometallurgical programs play a crucial role in optimizing mining processes and ensuring projects are executed according to plan and budget. This is particularly relevant considering the increasing geological complexity of orebodies, cost pressures throughout the industry, and environmental, sustainability and governance goals. Whilst technology, industry, environmental circumstances, and material/ore types change, the fundamental ore properties do not. Thorough characterization of orebody variability, in relation to the mining processes affected by it, equips the company with the information needed for optimal decision making throughout life of mine – from exploration to mine closure, rehabilitation, and future use.

Pockets of geometallurgical excellence exist throughout the industry and the practice has demonstrated tangible value. However, the range in program designs, inputs and outputs can result in markedly differing efficacy levels across operations. Gathering best practices into several guidelines aims to provide professionals with a reference to inform tailored geometallurgical programs. This ranges from initial, first iteration workflows that broadly characterize geometallurgical variability in relation to known geological domains, to subsequent iterations that streamline data collection for optimal geometallurgical characterization and value-add.

Documenting the methods available to collect, store, interpret, and implement geometallurgical data, as well as the cross-disciplinary collaboration needed, aims to promote program success and the advancement of geometallurgy.

About Global Mining Guidelines Group

Global Mining Guidelines Group (GMG) is a network of representatives from mining companies, original equipment manufacturers (OEMs), original technology manufacturers (OTMs), research organizations and academics, consultants, regulators, and industry associations around the world who collaborate to tackle challenges facing our industry. GMG aims to accelerate the improvement of mining performance, safety, and sustainability by enabling the mining industry to collaborate and share expertise and lessons learned that result in the creation of guidelines and related documents, such as white papers like this one, that address common industry challenges.

Interested in participating or have feedback to share? GMG is an open platform, and everyone with interest and expertise in the subject matter covered can participate. Participants from GMG member companies have the opportunity to assume leadership roles. Please contact GMG at info@gmggroup.org for more information about participating or to provide feedback on this white paper.

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