

# Beyond Geometallurgy – Gaining Competitive Advantage by Exploiting the Broad View of Geometallurgy

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## ABSTRACT

A cross-discipline approach combining geology, metallurgy and mine planning, geometallurgy is seen as the next logical advance in improving the design and operation of mining businesses. This rapidly evolving field is focused on realising the value that has often been lost in the chasms between the aforementioned technical silos. When successful, the geometallurgical approach promises the ability to tailor mining and mineral processing development and operational options more closely to the characteristics of the resource with resulting lower costs (both capital and operating), improved recoveries and fewer project failures.

As with any technological (or managerial) change, there will be side effects from the success of the geometallurgical approach that will impact areas beyond obvious linkages between geology and processing. Some of these effects have the potential to be beneficial to the resource industry and society in general. Beyond the basic geometallurgical promise of closer alignment between processing design/strategy and the multivariate 3D spatial characteristics of the mineralisation, this paper discusses the broader implications and ramifications of the emergent geometallurgical approach:

- enhancing exploration and discovery;
- improving project development success;
- achieving sustainability in an industry working with non-renewable resources;
- in a world of increasingly hard won license to operate, improving the management of potentially harmful by-products and waste materials (with knock on effects for proactive management of closure issues);
- smarter approaches to energy management and thus optimisation of projects with respect to carbon footprint; and
- potential to re-value assets and thus realise a strategic advantage in the area of acquisitions, divestments, mergers and take overs.

The authors strongly believe that companies that actively engage with the above issues (and ensure that technical efforts in the area of geometallurgy are not isolated from the larger value chain activities of the firm) will be able to exploit the opportunities that consequentially arise. These early adopters will gain first mover advantages. Firms taking the broad view of geometallurgy will have an opportunity to maximise stakeholder value and win greater success than their less insightful competitors.

## INTRODUCTION

Over the last 20 to 30 years the Australian and international mineral resource industry has metamorphosed from a dying industry that was seen as 'old technology' to now be the mainstay of the Australian economy; an industry that strives for new ways to improve productivity and profitability. Much of the change (in reality as well as perception) has been driven by internal and external factors such as the world economy,

emerging needs of developing nations (eg China, India), decreasing numbers (and size/grade) of new discoveries and increasing mining/metallurgical challenges posed by the deposits we have. In the face of these challenges the industry has been forced to renew itself.

While technological change has been detrimental to other industries (eg newspaper publishers, record stores, wired

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telecommunications; The Street, 2011), the mining industry has been reinvigorated by technology. In the authors' opinion the emerging area of geometallurgy (Dunham and Vann, 2007; Walters, 2009; Walters and Kokovic, 2006) is one example of invigoration by technological and research innovation. In this paper we take a broad view of geometallurgy which encompasses all those rock properties of resource and other mined materials which impact (positively or negatively) on the final value of the saleable product, concentrate or metal. This not only includes those properties of rocks impacting mineral processing efficiencies, but also properties of mined materials which impact other value steps such as, for example, blasting, transportation and disposal of tailings and waste materials.

## CURRENT FOCUS IN GEOMETALLURGY – AND POSSIBLE TRENDS

Geometallurgy has so far evolved in the technical sphere, mainly by collaborations of geologists and metallurgists. Consequently, in many cases the business dimensions and value have not been incorporated (Vann *et al.*, 2011) and a broad view of the implications of geometallurgy has been given less attention.

The historical and current efforts on geometallurgy have been focused on improved sampling and measurement of geometallurgical properties or appropriate proxies. This work has been driven by professional and academic geologists and metallurgical engineers. It is notable that mine planning engineers (who are critical in the value delivery of geometallurgy through changed planning approaches) and other disciplines such as environmental engineering, exploration geoscience and finance have so far been at the margins, or absent.

The basic ideas behind geometallurgy are not new nor are they particularly innovative. Historically however, application of geometallurgical approaches has been limited by data, computing power and, to some extent, industry trends to greater technical specialisation. Recent progress in geometallurgy has been driven by:

- Rapid advances in measurement and analytical technologies (Walters, 2009). This has resulted in increased ability (cheaper and faster) to more accurately and precisely measure rock properties, on smaller and smaller volumes of rock.
- Exponential improvement in computing power and capabilities to deploy these tools and techniques – and build operational modelling and simulation tools to process the results and change project decisions (Vann *et al.*, 2011).
- The emergence of mineral resource professionals who can effectively act as 'boundary spanners' between the diverse disciplines involved in geometallurgy. These individuals have a broad business and technical vocabulary and are not constrained to technical silos. They have a 'whole of value chain' view of the implications of geometallurgy.

We are thus now arriving at a critical change in our ability to analyse rock and processing properties and turn these data into meaningful information that can be used to maximise the total value of our mineral resources.

To date geometallurgy has focused on realising the value potential of integrating the deep technical specialties of geology, metallurgy and to a lesser degree mining engineering. Through increased knowledge and understanding of the

interactions of rock properties and extractive technologies, mining and mineral processing strategies can be more closely tailored to the characteristics of the resource with resulting lower costs (both capital and operating), improved recoveries and fewer failures. This is the geometallurgy value proposition. As with all technical or organisational change, the significant technology and management changes arising from implementing geometallurgical practices to seek this value proposition will spawn side effects. The technological gains yielding from research efforts and industrial experience in geometallurgy *sensu stricto* (ie prediction of processing performance in resource models) will have much broader benefits to the industry – and communities – than simply improving processing efficiencies. The attention of those developing geometallurgy thus far has been on improving processing efficiencies and this has included consideration of energy efficiencies as a means to cost reduction and increased value realisation (Walters, 2009).

In this paper we argue that a rigorous re-assessment of the current and future state of geometallurgy is essential to formulate a broader geometallurgical vision that builds on the beneficial consequences of the core value propositions. Beyond the basic geometallurgical promise of a closer alignment between processing design/strategy and the multivariate 3D spatial characteristics of the mineralisation what other impacts might arise? How can firms exploit these side effects for competitive advantage? Just as importantly, can geometallurgy become one of the key foundations for improving industry sustainability, maximising total stakeholder value and improving public perception of the industry?

This paper is not intended to be comprehensive or to spell out detailed pathways; our objective is to be provocative and to initiate a broader discussion of the context of geometallurgy. We will attempt to show that consideration of the broader context and implications of geometallurgy may well yield financial and social gains that are as large (or larger) than the pursuit of the core propositions of this emergent field. The authors argue that a continuing narrow focus on geometallurgy will miss some major opportunities. More than this, there is a risk that narrow focus on geometallurgy will damage the core efforts, because recognition and exploitation of the broader implications will feedback into the core effort by demonstrating larger value increase from these efforts. It is often the case that narrow technical efforts spawn much broader value propositions<sup>6</sup> and it is important that both researchers and industry be cognisant of this in the case of geometallurgy.

As an aside, the broad definition we have adopted here for geometallurgy clearly goes well beyond the narrow original connection of 'metallurgy' to 'geology'. However, the reality is that we are stuck with this word ('all-the-properties-of-rocks-that-impact-on-ultimate-value-ology' is a bit of a mouthful!). We recognise that the word geometallurgy is increasingly being used in the broad context proposed in this paper. This parallels use of the expression 'orebody knowledge' – which most mining industry professionals and managers now understand applies to marginal and waste materials as well as 'ore' (*sensu stricto*).

## SUSTAINABILITY

Orebodies are not renewable resources. Once mineralisation has been mined and metal produced we cannot go back and

6. The classic example is NASA space research which has had huge pay-offs in computing, cryogenics, insulation, aircraft propulsion and lightweight materials (see Greenberg and Hertzfeld, 1992).



## New orebodies from old mineralisation

An orebody is an occurrence of mineralisation from which it is economically viable to extract metals under a given set of economic and technical assumptions.

New orebodies are increasingly hard to find. The combination of time, economic development (ie, increased demand) and improved exploration science and technologies means that most (if not all) of the world's large, 'sticking out of the ground' orebodies have already been discovered: if it is obvious we already know about it. It is also a general feature of progressive exploration maturity that larger orebodies are often located earlier in the history of a given exploration terrane (Hronsky and Groves, 2008; Guj *et al.*, 2011). New significant discoveries thus tend to occur at depth and under the cover of unmineralised rocks. From an exploration perspective, the deeper the mineralisation is – in general – the harder it is to detect. Similarly from an economic perspective, the deeper the mineralisation is, the higher the mining cost and greater the technical challenges associated with mining.

Since the advent of modern exploration practices and techniques, exploration geoscientists have identified many significant occurrences of mineralisation that have been assessed as uneconomic and remain un-mined as a consequence. The assessment of economic viability is complicated and involves economic and technical analysis under a defined set of assumptions. Geometallurgy plays a key role in answering the economic/uneconomic question; however, it can also fundamentally shift the boundary between economic and uneconomic mineralisation through improved geological, mining and metallurgical performance. This shift, achieved through orebody knowledge and integrated technical practices, means that it may now be possible to mine and treat mineralisation previously thought to be uneconomic, thus making new orebodies from old mineralisation. From an exploration geoscientist's perspective, geometallurgy may thus be a powerful tool to 'find' new orebodies.

The resource industry has experience with these types of fundamental shifts in economics driven by technical advancement. For example the development of CIP/CIL technology in the 1970s and 1980s caused a dramatic shift in world gold production. Well known, but low-grade, gold occurrences in Western Australia changed from uneconomic mineralisation to one of the country's major sources of gold production, dramatically increasing Australia in the ranks of world gold producers. Similar technology innovations and shifts in mineral economics have occurred in the metallurgy of other commodities (eg copper – SX/EW; nickel – HPAL; mineral sands – synthetic rutile); as well as in mining technology (eg trackless vehicles vs tracked; open pit optimisation).

We believe that geometallurgy holds similar promise as a technical advancement that could transform some uneconomic deposits into viable operations. Mineralisation that has already been discovered could change from uneconomic to economic with the successful application of geometallurgical principles. For example, sophisticated management of scheduling based on 3D geometallurgical rock property models could materially reduce total energy consumption costs (and carbon footprint). The benefit may not only be in direct change to the processing rate or cost structure: by reducing uncertainty in contribution from future production, the total project risk can be reduced, and thus impact on risk to an extent where project funding costs can be materially altered. These impacts may shift some projects from negative to positive net present value (NPV) status, especially if they are large, long life assets forecast

to operate at low margin. Increasingly, large gains in of inventory are yielded by brownfields expansions, and the role of geometallurgy here is very powerful.

Another example of transformation of currently uneconomic operations to viability could be in the impact of geometallurgical models on the resultant scheduling of the deposit. By this, we mean the broadest definition of schedule, that is, not only the sequence of mining blocks, but also the impacts of stockpiling and blending strategies *in conjunction* with a given mining sequence. Stockpiling and blending strategies that take into account non-grade rock properties could enable different choices in processing technology, or processing strategy (campaign milling or use of parallel processing circuits). If the gain in NPV by some of these alternatives is sufficient, viability could be achieved. Opportunities for this type of transformation exist in known deposits such as the low-grade nickel sulfide mineralisation in the Canadian provinces of British Columbia (the Turnagain Nickel Project; Wells *et al.*, 2010) and Quebec (the Dumont Nickel Project; RNC, 2011). In both of these cases low-grade nickel mineralisation was discovered in the 1950s. It is only now, after changes in the technical and economic environment that they are capable of being developed.

Compared to the long lead times and high cost of exploration, the relatively low cost and relatively short lead times associated with applying geometallurgy to current subeconomic occurrences is a valuable space to 'explore' for new orebodies. Using geometallurgy to understand and spatially characterise properties such as rock mass strength, mineralogy, texture, and metal department in an effective way could well represent the next major technological advance and corporate competitive advantage.

In some cases assessment of mineralisation using the full tool kit of geometallurgy (including scenario analysis, see Vann *et al.*, 2011) may better demonstrate that the mineralisation really is uneconomic allowing the project to be divested or preventing a project that is destined to fail from ever being developed. Early focus on geometallurgy during exploration phase could also impact on economics, by allowing the realisation that an ore system or type of system will *not* be economic. This would increase confidence in the decision to 'walk away'. This is very important in terms of adding value to stakeholders: think of the value destruction in recent years for various nickel laterites.

The mining press is littered with references to 'one of the world's largest undeveloped copper/nickel/gold ... deposit'. Many very large, low-grade deposits have been known for decades but have still to be demonstrated to be the basis of economic mining operations. The systematic application of the geometallurgical tool kit will be an important strategy for firms interested in advancing decisions (positive or negative) on such properties. In this sense, geometallurgy enables re-valuation of acquisitions and divestments and we return to this topic later in our paper.

## Improved exploration strategies

If geometallurgy can change old mineralisation into new orebodies, can it help us find new (undiscovered) mineralisation and orebodies? Successful mineral exploration depends on well developed genetic models and comprehensive knowledge of existing deposits which can be used to target new, equivalent deposit styles (Hronsky and Groves, 2008). Geological theories about the formation and concentration of economically important elements drive exploration practices. The better the predictive power of a targeting theory, the more likely we are to make a discovery.

One of the core components of geometallurgy is a dramatic increase in orebody knowledge and understanding. The spatial mapping of attributes such as mineralogy, hardness and texture is central to the geometallurgical approach. While geometallurgy uses this data to improve operational efficiencies and design, the same data can be used by explorationists to enhance genetic mineralisation models and thus targeting. Improved spatial understanding of mineralogy, texture and other primary geological characteristics could directly lead to improved genetic models and better understanding of vectors towards mineralisation. For example linkage of geochemistry and geochemical ratios to underlying mineralogy has been applied increasingly in recent decades in understanding deposit paragenesis. Using vastly enhanced mineralogy (3D coverage, potentially for entire resource evaluation datasets) coming from new geometallurgical practices may give step-change improvements in knowledge of mineralisation paragenesis.

The mineralogical and other databases being accumulated for geometallurgical work can leverage the key aspect of understanding *paragenesis* of rock properties. Because the rocks in mineral deposits have invariably seen multiple events a pivotal question for exploration geoscientists is 'which events cause what changes to the rock mass, and which ones were the key controls on metal accumulation?' (McCuaig, personal communication) There is potential for the much denser 3D data coverage of geometallurgical projects to allow us to better spatially map those events that change rock properties of the orebody. This in turn can yield better answers regarding the time sequence of how the system got to its current 3D rock property state (McCuaig *et al*, 2010).

Spatially located mineralogical and other rock property data therefore has the potential to change paragenetic models and thus dramatically increase the exploration footprint for mineral deposits, making them easier to identify. Increasingly companies are exploring under deeper cover, so we are interested in largest possible scale footprints of the ore system. Some of the tools developed to generate quantitative mineralogical data for geometallurgy have undoubted leverage in mineral exploration, see for example Gunning *et al* (2009), who provide case studies for porphyry type and iron oxide Cu-Au as well as an REE deposit.

It is arguable that geometallurgy can actually help articulate the target geology of a deposit via a technical and economic definition of the required orebody type(s). This is a sort of reverse engineering, allowing the mineral exploration firm to say that the target orebodies (given technical constraints on their ultimate mining and processing) have certain characteristics, so then we will go hunt those. Penny *et al* (2004) give an example of such an approach for zinc deposits but did not incorporate geometallurgy in their formulation of the problem. Their approach to 'prospectivity rating' could be broadened to account to processing, environmental, energy and other sustainability issues discussed here, and this would add further power to the strategy they proposed.

Interestingly, current research efforts in exploration targeting and geometallurgy have limited overlaps, and in some cases may even be mutually exclusive. There is a scale dependency of processes which limits some of these overlaps. McCuaig *et al* (2010) note that conceptual targeting models change dramatically as a function of scale (broad regional scale - camp scale - deposit scale - shoot scale). They argue that

step changes in conceptual targeting models occur depending on whether we are in greenfields (terraces with little geological information and/or few or no existing deposits) or brownfields (well-mineralised and data-rich terraces). The immediate power of geometallurgical data sets will be greatest in brownfields camp/deposit settings, but we believe there are also longer-term implications for greenfields and regional scale exploration.

## IMPROVING PROJECT DEVELOPMENT SUCCESS

The project development pipeline generally proceeds through a number of phases which narrow the development options:

- a conceptual study phase, in which a wide range of possible alternatives for development are identified<sup>7</sup>;
- a prefeasibility phase, in which options are narrowed and one or more are selected for evaluation of investment;
- a feasibility phase, in which the project is given detailed scope, costs, schedule etc to a level sufficient to allow execution of the investment opportunity; and
- an execution phase, in which the project is built.

The flexibility to change decisions declines as this process advances through the above phases. By the time the feasibility stage arrives (and often during the prefeasibility phase), the core technology decisions around mining methods, materials handling and transport, extractive metallurgy, definition of final product (eg trade-off between selling a tightly specified concentrate or building a captive smelter) are more or less locked in. Since matching of technology and strategy to the characteristics of the orebody is a key determinant of success, and because the leverage is higher in the earlier phases, we propose that cognition of geometallurgical characteristics of the orebody at the earliest possible stage can generate improved project development decisions.

Accordingly, the concepts of geometallurgy should be communicated beyond the usual operational professionals (mine geologists, mining engineers and metallurgists) to exploration geoscientists in order that early stage mineralogical, textural and other data be collected to enable early consideration of processing options. This involves difficult tradeoffs, because at an early stage we do not know what the likely processing routes are, and we will need to collect a wide range of geometallurgical data at early stages to enable better decisions to be made.

In recent decades there have been numerous examples of operations that have failed or performed poorly because the selected mineral processing technology was not matched well to the deposit characteristics. The use of geometallurgical thinking throughout the project cycle, especially at early stages, will reduce the number of fundamental mismatches between technology, scale or operational strategy and the properties and characteristics of the mineral resource to be exploited. The role of inadequate metallurgical characterisation in project start-up underperformance is well documented (for example, McNulty, 2004). The use of non-spatial metallurgical testing to understand spatial and temporal project performance is problematic in itself and represents a risk to the 'modifying factors' in conversion of resources to reserves, at the very least. However, in a more geometallurgical framework, the sample selection strategies for mineralogical and metallurgical data impute clear risks to resultant resource estimates (Dominy *et al*, 2002).

7. This is where geometallurgical considerations early in exploration can be incredibly useful, as discussed in the previous section.

The other side of the coin is the potential for geomaterialurgy to allow us to get more rapidly (and more confidently) to the walking away decision. If a deposit will be marginal or does not align with the core competencies or strategy of the company – sell it off. This is a possible benefit of geomaterialurgy that people do not like to think of when selling the ‘benefits’, but is it a real benefit: loss averted equates to value protected!

## ACHIEVING SUSTAINABILITY IN AN INDUSTRY WORKING WITH NON-RENEWABLE RESOURCES

As previously defined, the vision of sustainability in mining is that mineral development needs to be commercially viable, done in a manner that is consistent with acceptable levels of environmental quality, and has acceptable social consequences (Eggert, 2007).

### Waste streams

A holistic view of geomaterialurgy requires that we consider not only the rock properties of ‘ore’ but also those of subeconomic and waste materials. In a world of increasingly hard won license to operate, improving the management of potentially harmful by-products and waste materials is vital.

The management of acid rock drainage (ARD) materials is a prime example (Johnson and Hallberg, 2005). In brief, ARD is the accelerated oxidation of sulfidic minerals resulting from the exposure of these minerals to both oxygen and water. Waste or ore materials at surface containing sulfide minerals are thus sources of acid drainage waters that can have severely adverse environmental impacts. Geomaterialurgical studies of mineralisation generate the type of data vital to determination of acid generating potential and buffering potential (mineralogy and texture in particular) and thus to determining strategies and costs of ARD management processes.

Johnson and Hallberg (2005) identify a range of management strategies, and note that (as is usual in risk management) prevention is the best strategy. Preventing generation of rock mixes that result in acid water generation may require blending of mineral waste materials, encapsulation of materials, solidification of tailings and use of various chemical strategies (such as the application of anionic surfactants). Such prevention (or ‘source control’) strategies are preferable to approaches which manage the migration of acidic waters that have already been generated, both on efficacy and efficiency grounds. In each case, source control strategies require detailed understanding of the mineralogical, chemical and physical properties of the mineral wastes. Properly conceived geomaterialurgical investigations will generate data of the kind required. Furthermore, geomaterialurgical data will give the spatial context and information enabling us to understand likely variability of key rock properties, which is essential to design and implement efficient management strategies and policies. Currently, ARD studies tend to be based on ‘old school’ metallurgical testing and do not incorporate spatial modelling or the fundamental rock property drivers behind the ARD problem. If spatial approaches are used to build predictive 3D models for ARD they are often simplistic and entirely chemical; ie estimate sulfur and use that to predict acid generation. When evaluating the potential of the rock mass to either form acid or neutralise acid formation, we must understand the basic chemical processes and the linkages to mineralogy and texture. Not all sulfide minerals (or even different forms of the same mineral; eg pyrite) generate acid at the same rate under the same conditions. The acid generation

or neutralisation capacity of the rock mass is dependant on mineral species, mineral texture, rock texture, fragmentation and crack propagation, dustability, and rock composition (both chemical and mineralogical). All of these properties are fundamental to geomaterialurgy and therefore we can use geomaterialurgy to improve our ability to manage ARD issues. Integration of geomaterialurgy efforts with ARD modelling lends a spatial context to ARD studies. Consideration of the spatial distribution of acid forming or acid neutralising capacity may dramatically change the mining sequence and project economics.

Another aspect of waste management is the management of biologically toxic components of mineralisation, tailings and waste materials that may impact environmental quality. Organic-metal and organic-waste interactions are key areas that require research in geomaterialurgy, for example. The future of biological and nanotechnology pathways for *in situ* metal extraction also needs to be aligned with the geomaterialurgical paradigm. The potentially enormous scale of environmental costs in mining projects implies that strategies that affect these costs are an important determinant of a firm’s competitive position (Christmann, 2000).

Cleaner production (CP) is a preventive strategy to minimise the impact of production and products on the environment (Fresner, 1998). It is an important approach which is centred on the idea that organisations transform to more sustainable operations by changing their approaches, for example, from:

- ‘throughput economics’ to ‘material flow management’,
- ‘waste of materials’ to ‘productivity of materials’,
- ‘waste of energy’ to ‘energy efficiency’, and
- ‘end of pipeline environmental management’ to ‘Preventative (whole of value chain) environmental management’.

Hilson (2003) examines the concepts of CP and pollution prevention in the mining context and Hilson and Murck (2001) give examples, including ARD and cyanide pollution, from the North American gold mining industry. Mineral deposits are such that their locations are fixed, so management cannot determine the locations of mine sites. Furthermore, mineral deposits remaining to be discovered are either in remote areas or in areas with competing land use (agricultural, environmental – such as parks and reserves – or even competing urban uses); consequentially mining companies now frequently conduct operations in particularly ecologically or environmentally sensitive areas. CP, pollution prevention, and related environmental management concepts involve various strategies such as waste minimisation, toxic waste reduction, etc.

Geomaterialurgical approaches are focussed on mineralogical and textural aspects of the rocks comprising the resource and its environs. Such data and knowledge can facilitate design of better materials handling systems and proactive pollution minimisation measures for mining and processing operations. Specifically, the use of improved scheduling based on specific rock properties to more effectively and efficiently separate waste from valuable materials and better predict and management the generation of harmful materials (eg arsenic bearing ores or materials containing dangerous fibrous minerals).

Finally, the improved understanding of mineralogy and other rock properties that allow better management of waste streams and deleterious components of both value and waste material flows during operation will also drive improved, proactive and predictive management of closure issues. It is quite conceivable that better and proactive strategies for

closure could save billions of dollars in the case of large, long-life assets and those involved in closure planning should be communicating with the teams working on geometallurgy as a matter of course.

## Energy management and carbon footprint

The area of energy management and carbon footprint is already in the focus of those working in geometallurgy (Walters, 2009). However we believe that the developments in this area are not communicating broadly to those beyond the geological and metallurgical communities and that this is clearly one of the ‘broad’ issues warranting inclusion in a synoptic paper like this.

About 30 million people work in large-scale mining operations and their associated mineral processing operations. This represents approximately one per cent of the world’s workforce (Azapagic, 2004). The largest portion of this industry, in terms of energy consumption, is related to metals.

Groenenberg *et al* (2005) have estimated that compound growth in demand for basic metal inputs developing countries will run at average rates between 3.5 per cent and 5.2 per cent *world wide* through to 2020. Current (and planned) growth in mining production for all major commodities is unprecedented.

Energy consumption of the mining industry will also track this trend. The consequences for metals prices as a result of ‘peak oil’ (Bentley, 2002) and at the same time mandated costing of carbon emissions, will be dramatic. The inexorable trend towards ‘clean production’ and sustainability (of which reduced energy requirements is a key component), dictates that mining companies will need to accelerate their efforts in the immediate future for reasons other than economics (although all will be eventually translated into economic terms!).

The mining industry is extremely energy intensive. To illustrate this, statistics from Chile – the world’s largest copper producer – show that about 30 per cent of total electricity in that country is consumed by copper mining, processing, smelting and refining activities (Pimentel, 2004). Of this total, half is consumed by the mineral processing part of the value chain, mostly by electric motors driving crushing and grinding circuits (ECEE, 1999).

Electricity consumption at Codelco’s Chuquicamata operation, one of the World’s largest copper mines, is estimated to be >2200 GWh per year, with more than 97 per cent from coal-fired power (UNFCC, 2007). Current CO<sub>2</sub> emissions related to Chuquicamata’s electricity consumption is about three million metric tons per year (UNFCC, 2007). Well over half of the energy used at Chuquicamata (61 per cent) is in mineral processing (ECEE, 1999).

Similarly, in Australia, the electricity consumption for comminution alone in the minerals industry is equivalent to the entire residential sector (Alan Bye, CRC Ore, personal communication).

‘Geometallurgical variables’ drive energy costs in a fundamental way, including, for example:

- The ‘scaling’ of a mill (ie the design throughput capacity in tonnes/hour) is a decision that impacts heavily on the energy economics of a project. Larger mills are more expensive and consume more energy but also generate more revenue, faster (thus better NPV). Understanding the orebody processing characteristics *as a function of time* is thus critical. Optimisation of the trade-off between size and cost is a difficult and complex decision, and could be

greatly aided by robust spatial models of geometallurgical properties.

- Arguably, the single most important decision impacting on both energy consumption and value (NPV) is the sequencing of the material mined and delivered for processing. In a conventional semi-autogenous (SAG) milling circuit the power consumption of hard ores can be 4-5 times higher than for soft ores (Dagbert and Bennett, 2006; Preece, 2006). Therefore the scheduling of materials on the basis of their energy consumption per unit of metal recovered represents a fundamental change in the traditional approach to mine planning.
- The optimisation of mining designs on the basis of maps that represent ‘energy consumption per unit of metal recovered’ rather than grade of ore (which is a poor proxy of delivered value). The objective is to use these maps to sequence and blend ore in ways that smooth the power required to process the ore (ie yields a reduction in the variability of power consumption) whilst still producing the same quantity of metal or product per unit time. This allows for better power factor management, reduced stress on large items of capital equipment and reduces spikes of maximum demand. These impacts will not only reduce the cost of power consumed but will, over the life of the operation, materially improve the energy efficiency of the project as a whole.

In summary, ‘traditional’ non-geometallurgical reserve models (ie grades and tonnes) and associated scheduling do not allow optimisation of projects from the viewpoint of energy consumption. The importance of characterising the metallurgical response in order to generate properly optimised, more energy efficient projects will rapidly increase. Driving factors will include: metallurgically complex deposits; escalating energy costs; lower grade deposits, and larger-scale mining (big pits, block caves). Overall sustainability performance of companies will be further spotlighted as cost of carbon is incorporated into the global economy via carbon taxes or cap-and-trade schemes. Scheduling and planning that is driven by geometallurgical resource models may allow significant cost and environmental benefits to companies.

## IMPROVING ASSET VALUATION

Geometallurgy also conveys potential to re-value mineral resource assets and thus constitutes a strategic advantage in the area of acquisitions, divestments, mergers and take overs.

For example, the ability to determine that innovative mining, scheduling, blending, or processing strategies could reduce costs sufficiently to materially impact project economics could allow a firm to recognise value in an asset on the market that is not recognised by competitors. This could be advantageous both for a bidder and a vendor of properties. In the case of bidders, the ideas espoused in this paper earlier about the ability of geometallurgical approaches to ‘make new orebodies out of old mineralisation’ have clear valuation implications. In the case of a vendor, the ability to demonstrate improved viability using a geometallurgical approach could boost the asking price of assets.

## CONCLUSIONS

While it is true that the issues of sustainability are not ignored in current efforts on geometallurgy (both in the research community and industry) we believe that increased urgency is required to make it clear that geometallurgy goes far beyond the linkage of orebody properties to processing performance. The very name ‘geometallurgy’ – although we are stuck with it – disguises the power and scope of the approach.

We believe that a broad view of geometallurgy, encompasses all activities that utilise improved understanding of rock properties of resource and other mined materials which impact (positively or negatively) on the final value of the saleable product, concentrate or metal, and hence project value. Relevant properties do not only include those that impact on mineral processing efficiency, but also properties of mined materials which impact other value-adding (or reducing) steps such as, for example, blasting, transportation and disposal of tailings and waste materials. Mining firms that take this broad and strategic view will open pathways to increased value for their stakeholders, including the communities within which they operate because geometallurgical programs can:

- enhance exploration efficiency by improving fundamental knowledge of mineralisation;
- potentially allow conversion of currently uneconomic deposits into viable economic operations;
- reduce the number of fundamental mismatches between technology, scale or operational strategy and the properties and characteristics of the mineral resource to be exploited;
- enhance project sustainability by facilitating design of better materials handling systems and proactive pollution minimisation measures for mining and processing operations;
- allow optimisation of projects from the viewpoint of energy consumption and carbon footprint; and
- conveys potential to re-value mineral resource assets and thus constitutes a strategic advantage in the area of acquisitions, divestments, mergers and take overs.

In summary, our argument is that geometallurgy is delivering and will increasingly deliver benefits well beyond its obvious scope. It is important for the continuing energy of this emergent field that these benefits be emphasised. Ongoing research and implementation efforts must be broad enough in conception to avoid collapse into a highly technical dialogue between experts about narrow aspects of processing performance and look forwards to the big pay-offs in many other areas.

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