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Geological Contributions to Geometallurgy: A Review

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Résumé de l'article

La géométallurgie est une science interdisciplinaire qui s'intéresse aux caractéristiques de la masse rocheuse qui influent de manière significative sur l'exploitation minière et le traitement du minerai. Les roches sont des mélanges composites complexes dont les éléments structurant de base sont des grains de minéraux. Les propriétés des minéraux, la façon dont ils sont liés entre eux, et de nombreux autres aspects de la texture des roches déterminent l'ensemble de la chaîne de valeur minière, de l'exploration à l'extraction à la transformation, à l'élimination des déchets et des résidus, jusqu'au raffinage et à la vente. La présente étude passe en revue les propriétés significatives de la roche (par ex. sa cohésion, sa composition, sa minéralogie, sa texture) en géométallurgie ainsi que des exemples de méthodes d'essai disponibles pour mesurer ou prédire ces propriétés. Les données géométallurgiques doivent être quantitatives et localisées spatialement afin qu'elles puissent être utilisées dans la modélisation 3D et la planification de la mine. Elles doivent également être peu couteuses afin d'être suffisamment nombreuses pour fournir une distribution d'échantillon statistiquement valide pour la modélisation spatiale. Une communication efficace entre les différents segments de la chaîne de valeur minière est impérative pour que les données soient produites et transférées sous une forme utilisable et que les duplications soient évitées. Le but ultime est d'avoir des modèles 3D qui montrent non seulement la qualité des éléments précieux (ou minéraux), mais aussi les propriétés de roche qui déterminent l'exploitation minière et le traitement du minerai, de sorte que les décisions concernant l'exploitation minière et le traitement du minerai peuvent être réalisées de façon holistique, c.-à-d. que l'impact des propriétés de roche sur tous les maillons de la chaîne des coûts du processus minier sont prises en compte. Les coûts d’amélioration des connaissances sur le gisement de minerai étant importants, il faut tenir compte de la courbe coûts-bénéfices lors de la planification du niveau d'investissement géométallurgique approprié pour le gisement considéré.

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SERIES

Economic Geology Models 3. Geological Contributions to Geometallurgy: A Review

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SUMMARY

Geometallurgy is a cross-disciplinary science that addresses the problem of teasing out the features of the rock mass that significantly influence mining and processing. Rocks are complex composite mixtures for which the basic building blocks are grains of minerals. The properties of the minerals, how they are bound together, and many other aspects of rock texture affect the entire mining value chain from exploration, through mining and processing, waste and tailings disposal, to refining and sales. This review presents rock properties (e.g. strength, composition, mineralogy, texture) significant in geometallurgy and examples of test methods available to measure or predict these properties.

Geometallurgical data need to be quantitative and spatially constrained so they can be used in 3D modelling and mine planning. They also need to be obtainable relatively cheaply in order to be abundant enough to provide a statistically valid sample distribution for spatial modelling. Strong communication between different departments along the mining value chain is imperative so that data are produced and transferred in a useable form and duplication is avoided. The ultimate aim is to have 3D models that not only show the grade of valuable elements (or minerals), but also include rock properties that may influence mining and processing, so that decisions concerning mining and processing can be made holistically, i.e. the impacts of rock properties on all the cost centres in the mining process are taken into account. There are significant costs to improving ore deposit knowledge and it is very important to consider the cost-benefit curve when planning the level of geometallurgical effort that is appropriate in individual deposits.

RÉSUMÉ

La géométallurgie est une science interdisciplinaire qui s'intéresse aux caractéristiques de la masse rocheuse qui influent de manière significative sur l'exploitation minière et le traitement du minerai. Les roches sont des mélanges composites complexes dont les éléments structurant de base sont des grains de minéraux. Les propriétés des minéraux, la façon dont ils sont liés entre eux, et de nombreux autres aspects de la texture des roches déterminent l'ensemble de la chaîne de valeur minière, de l'exploration à l'extraction à la transformation, à l'élimination des déchets et des résidus, jusqu'au raffinage et à la vente. La présente étude passe en revue les propriétés significatives de la roche (par ex. sa cohésion, sa composition, sa minéralogie, sa texture) en géométallurgie ainsi que des exemples de méthodes d'essai disponibles pour mesurer ou prédire ces propriétés. Les données géométallurgiques doivent être quantitatives et localisées spatialement afin qu'elles puissent être utilisées dans la modélisation 3D et la planification de la

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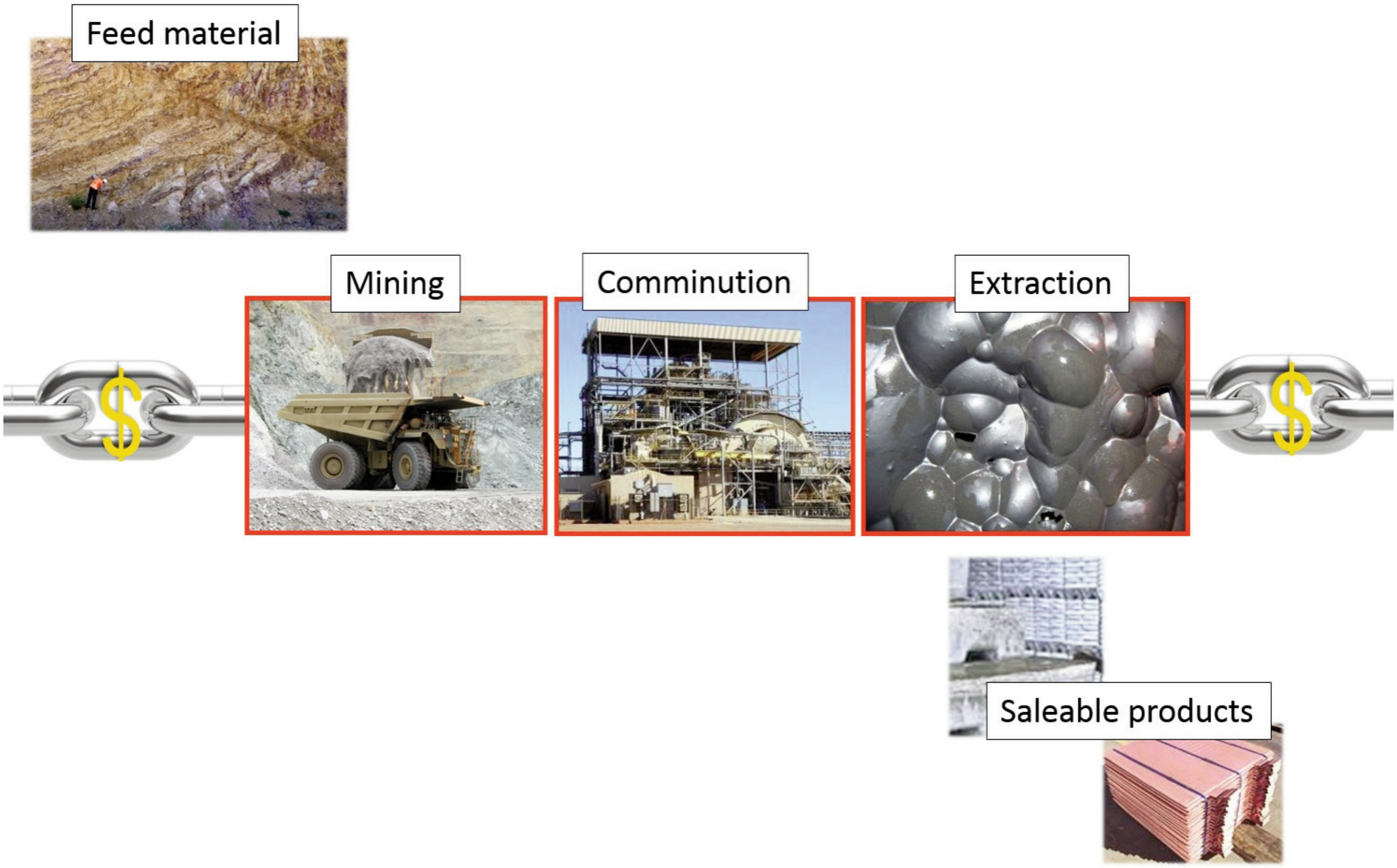

Figure 1. Example of the mining value chain (modified from Hunt and Berry 2015).

mine. Elles doivent également être peu couteuses afin d'être suffisamment nombreuses pour fournir une distribution d'échantillon statistiquement valide pour la modélisation spatiale. Une communication efficace entre les différents segments de la chaîne de valeur minière est impérative pour que les données soient produites et transférées sous une forme utilisable et que les duplications soient évitées. Le but ultime est d'avoir des modèles 3D qui montrent non seulement la qualité des éléments précieux (ou minéraux), mais aussi les propriétés de roche qui déterminent l'exploitation minière et le traitement du minerai, de sorte que les décisions concernant l'exploitation minière et le traitement du minerai peuvent être réalisées de façon holistique, c.-à-d. que l'impact des propriétés de roche sur tous les maillons de la chaîne des coûts du processus minier sont prises en compte. Les coûts d'amélioration des connaissances sur le gisement de minerai étant importants, il faut tenir compte de la courbe coûts-bénéfices lors de la planification du niveau d'investissement géométallurgique approprié pour le gisement considéré.

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INTRODUCTION

Geometallurgy is a team-based approach to documenting orebody variability in geology and mineralogy that affects the profitability of the mine (Fig. 1). Relevant performance parameters include comminution, (e.g. the transformation of ore, as transported to the mill, to mill feed by particle size reduction, through the use of crushing and grinding machines), metal recovery and environmental impact (e.g. Walters and Kojovic 2006; Walters 2011; Williams 2013). The aim is to generate a quantitative, spatially constrained database that can be integrated into 3D modelling and mine planning. It underpins a holistic approach to mine planning intended to optimize efficiency and profitability. Geometallurgy is also used to reduce the technical risk associated with new mine developments and/or the expansion of existing mines by reducing the difference between expected and actual mine performance in throughput, recovery, and value.

The ultimate aim is to value ore, not only on grade, but also on other factors, (e.g. throughput, recovery, tailings characteristics, product saleability, etc.) that better reflect the true value of each ore block. Geometallurgical data can also be used to compare prospects, in terms of real value, by taking into account processing parameters, such as hardness, (e.g. ease of crushing and grinding,) and mineralogy (e.g. minerals deleterious to processing, acid-producing minerals). It can be used during feasibility studies to assist with bulk sample selection and plant design for comminution (e.g. primary crushing followed by a semi-autogenous grinding (SAG) and ball-mill circuit with recycle crusher (SABC); three-stage crush, rod, and ball mill; or a crushing circuit including high-pressure grinding rolls (HPGR)), and processing options (e.g. gravity, flotation, and/or leaching). The data can also be used for optimizing long- and short-term block models, and mine scheduling (i.e. mine ore blocks in an order that produces the most value and least risk).

Geometallurgy is not new and has existed in various forms, (e.g. Mine to Mill) for at least 30 years (Holmgren and Marti 1984; McKee 2013). What is new, however, is the holistic view of the value chain and the strong team-based approach. It requires effective communication between what were traditionally information silos: isolated by specialization, business units, physical location, budgeting and management. Mine planning software has now been developed to make better use of the enhanced data that is becoming available (e.g. Carrasco et al. 2017).

We discuss the underlying character of rocks and then summarize typical rock and mineral factors that can affect the net present value of a deposit. The presentation is by no means exhaustive and the discussion is aimed at mine geologists. It emphasizes the most significant parameters that should/could be characterized based on drill core samples. The mine geologists' contribution to geometallurgy generally includes managing the mine database and deciding which small-scale geometallurgy proxies are relevant and practical. The geologists will probably work with the metallurgist to create models to predict metallurgical parameters from the available proxies. These models form the basis for 'transfer functions' (Deutsch 2013) that convert raw mine data into processing parameters suitable for geostatistical prediction across the ore reserves. This review only considers the applications of geometallurgy up to the hand over to the geostatistics group.

ROCK PROPERTIES

It is relatively common for geologists to be asked to provide large 'representative samples' of average ore. However, ore deposits are complex with different zones of ore and gangue mineralogy and alteration. Each deposit has many unique features and is unlikely to be controlled by a single set of rock parameters. The mine geologist has little basis on which to select 'average' ore, and the selection invariably leads to biased results in pilot mill testing. The mineral process engineers (metallurgists) respond, in general, by over-engineering the mill to cover the sampling error historically associated with this selection. The following section looks at aspects of this in terms of inhomogeneous breakage behaviour and how a better representative sample of the rock to be mined can be achieved.

In discussions of the rheology of rocks, it is common to assume they are a homogeneous isotropic medium that can be modelled by an appropriate simplified model (e.g. elastic-plastic, elastic-brittle models; Jaeger et al. 2007). Mining operates across a range of scales where the anisotropic, heterogeneous and granular properties of the rock are important and, in general, brittle behaviour is dominant over ductile response. At the scale of mine stability and blasting, the mining is strongly affected by faulting and joints and geotechnical specialists have long recorded this level of heterogeneity (Little 2011).

Table 1. Types of structural damage that reduce the strength of rocks.

Fault zones, gouge, and cataclasite
Jointing: regional sets, local jointing and micro joints
Micro-cracks: inter-grain and intra-grain fractures
Grain boundaries
Porosity

Quasi-brittle materials, such as rocks (Jiang et al. 2016), are also characterized by many other fine-scale structures (Table 1). They are composed of various minerals distributed in grains. Grain boundaries are weaker than the grains themselves. In addition, there are numerous randomly distributed micro-cracks and pores (Fig. 2) that contribute to the brittle response of rocks. In the crushing process, joints, micro-cracks, grain boundaries, and porosity are very important. The required energy for crushing changes dramatically as the

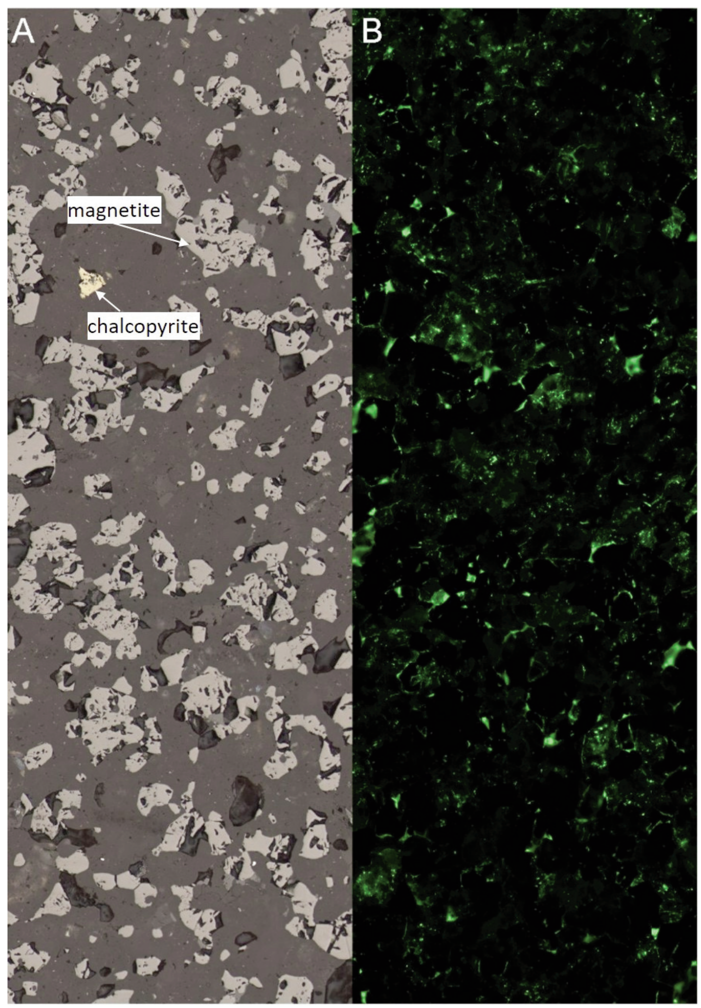


Figure 2. Microphotograph of iron oxide copper-gold (IOCG) ore. Field of view 0.9 mm wide. A. Reflected light image shows yellow chalcopyrite and slightly red-grey magnetite in a darker silicate gangue. B. Fluorescent light image shows doped resin decorating pores and microfractures.

Table 2. Examples of typical values that reflect mineral hardness.

	Mhos Hardness[1]	VHN(GPa)[2]	Fracture toughness[3]	Fracture toughness[4]	Cleavage[5]
hematite	6	10.29	20.8		parting
magnetite	6	7.25	12.9		none
pyrite	6–6.5	14.8	6.14		poor
quartz	7	12.1	5.35	1.5	none
plagioclase	6		5.48		perfect
K feldspar	6	6.9		1.1	perfect
chalcocite	2.5–3				none/sectile
bornite	3				none
chalcopyrite	3.5–4	1.83			poor/brittle
fluorite	4	2	3.2	0.89	perfect
calcite	3	1.49		0.39	perfect
barite	3–3.5		1.2		perfect
Comments	*Abrasion/C.S.*	*Tensile strength*	*Tensile strength*	*Tensile strength*	*in preferred direction*

Source: [1, 5]Hurlbut 1959; [2]VHN=Vickers Hardness: Whitney et al. 2007 and Broz et al. 2006; [3]Tromans and Meech 2002, 2004; [4]Whitney et al. 2007. C.S. = compressive strength

porosity and micro-fracture density increases (cf. Baud et al. 2014).

In blasting and crushing, rocks fail on the weakest zones with few mineral grains broken, and in many examples there is a low level of correlation of crushing energy with mineralogy (e.g. Schouwstra et al. 2013). Rocks with a coarse grain size are easier to crush than fine-grained rocks (Eberhardt et al. 1999). The uniaxial compressive strength of crystalline rocks is commonly much lower than expected from the strength of individual minerals. Noferesti and Rao (2011) argue this is due to the weak support for the grains and low interlocking factor.

During grinding, as size reduction continues, the particle size approaches the rock grain size and intra-grain fractures dominate over grain boundary fractures. During grinding the mineralogy is expected to be the major control on hardness. Typical values that reflect mineral hardness are shown in Table 2. In general, oxides, pyrite, quartz, and feldspar are hard, while sulphides, carbonates, sulphates, and phyllosilicates are soft. Martins (2016) reviewed the theoretical relationship between surface energy of a mineral, fracture toughness, and the Bond Ball work index. However, the response of real samples varies significantly from these predictions and the grinding response of variable mixtures of minerals can be even more difficult to predict (Ji et al. 2004; Tavares and Kallemback 2013; Csőke et al. 2013).

The toughest rocks are close to the mineralogical limit with grains tightly locked together and with low porosity and micro-fracture density. They have grinding hardness values (i.e. Bond Mill work indices, BMWi) that correlate at some level with the modal mineralogy. The grinding energy is not a simple linear function of the mineral abundance, but the mineral mode can be used as a proxy for BMWi in some deposits (e.g. Montoya et al. 2011; Hunt et al. 2013).

Sources of Geometallurgical Data

Geotechnical Logging

Geotechnical information is typically collected during the core logging process and includes rock quality designation (RQD), core recovery, and, in a few sites, geological strength index (GSI). RQD is an approximate measure of the degree of fracture (or jointing) in a rock mass and is measured as a percentage of the drill core in lengths of 10 cm or more (e.g. Deere 1964; Deere and Deere 1988). Core recovery is generally calculated as a percentage of the core run. GSI extends the concept of RQD to include the shape of the fragments and is most relevant in areas of weak rocks (Marinos and Hoek 2000).

Conventional geotechnical logging of strata for stability purposes typically concentrates on major structures, such as faults, and smaller structures may be ignored. For the purposes of blast design, the measurement of smaller structures, such as joints, foliations, and bedding are important as they can control blast fragmentation (Badal 1995; Scott et al. 1996). Scan line mapping can be used to record the properties of all discontinuities that cross it (e.g. Villaescusa 1991). This is typically done on an exposed rock face, but could also be carried out on oriented drill core. Typical properties recorded for the discontinuities are: location of the discontinuity along the scanline; dip and dip direction; trace length; type of discontinuity; roughness of the discontinuity surface; type (e.g. another joint, intact rock); and angle (low, i.e. < 20°; high, i.e. > 20°) of termination. For a rock face, sixty points are considered adequate to define the characteristics of a joint set (Scott et al. 1996). This information can be used to estimate *in situ* block size distribution (e.g. Villaescusa 1991), which can then be compared with the fragment size distribution expected at the primary crusher to determine the amount of breakage required from the blasting. This data can also be used in slope and bench stability analysis (Scott et al. 1996). Methods to automate geotechnical logging are being developed (e.g. Harraden et al. 2016).

RQD data can, in addition, be a significant input parameter in estimating rock strength and overall comminution performance as the abundance of fractures can influence the crushability and grindability of rocks. Burger et al. (2006) show the extensive use of RQD data in helping to improve predictions of throughput at Batu Hijau.

Figure 3. Example of point load testing of drill core. (image from Kojovic 2008). Force applied to the rock is gradually increased until the rock fails. The peak pressure applied is shown on the gauge.

Rock Strength Testing

Tests of uniaxial compressive strength (UCS), tensile strength, Young's Modulus, and Poisson's ratio are typically used to obtain information about the strength of intact rock (e.g. ISRM 1981; Napier-Munn et al. 1999). Lower cost tests that provide proxies for unconfined UCS include point load testing (PLT), sonic velocity, and rebound hardness (Verwaal and Mulder 1993; Meulenkamp and Grima 1999; Rusnak and Mark 2000; Sousa et al. 2005; Chang et al. 2006; Keeney et al. 2011; Momeni et al. 2015).

Point load testing (PLT) is relatively easy to carry out and can be done routinely on drill core (Fig. 3). PLT yields a strength index, referred to as *Is*, and is typically used in drill-and-blast and geotechnical fields as a quick and simple method to predict tensile and compressive strength (e.g. Broch and Franklin 1972; Brook 1985; Butenuth 1997). The point load index is also a useful guide to comminution behaviour. For example, at the Batu Hijau copper–gold porphyry in Indonesia, a large data base of PLT results were used, in combination with RQD data, to define hardness domains for the deposit. These domains were used in blasting (Fig. 4; Burger et al. 2006). They were also used to more accurately predict mill throughput.

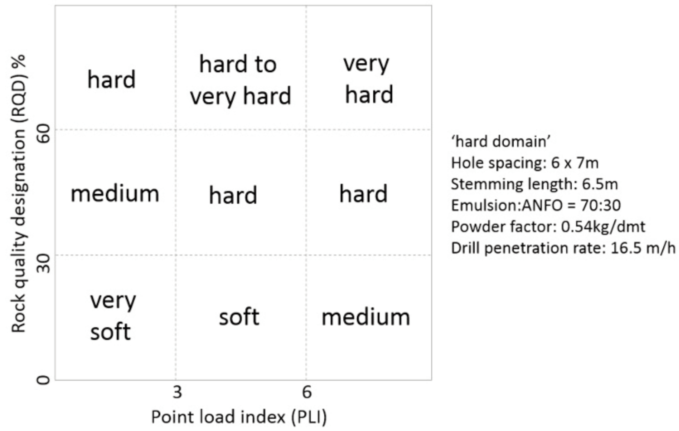


Figure 4. Left: point load index (PLI) versus RQD diagram developed for Batu-Hijau. Use of the diagram allows rocks to be divided into different strength domains each of which requires different drill-and-blast parameters. Right: example of drill-and-blast parameters developed for the 'hard domain'. ANFO = ammonium nitrate - fuel oil. Modified from Burger et al. (2006).

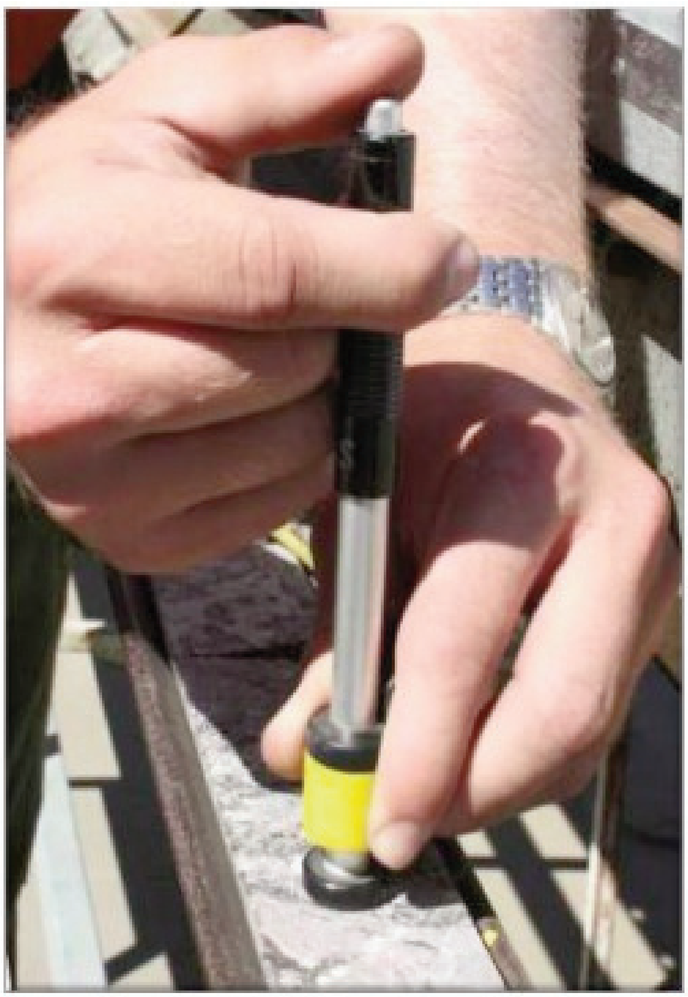
Dynamic values of Young's Modulus and Poisson's ratio of a large rock volume *in situ*, can be obtained by seismic techniques in which the velocities of compression (*Vp*) and shear (*Vs*) waves are determined. In order to determine the elastic constants, the density of the rock must also be known (e.g. Scott et al. 1996). Similar information can also be collected from drill core using hand held (e.g. sonic velocity tester, Fig. 5) or bench-scale (semi) automated petrophysical techniques (e.g. Geotek logger, Fig. 5; Vatandoost et al. 2008; Hunt and Berry 2015).

Rock strength information can also be obtained from rebound hardness measurements collected on drill core (Fig. 6). This data is easy and quick to collect allowing almost continuous downhole measurements to be obtained. The device impacts under spring force with known energy and then rebounds; the hardness value is calculated from the ratio of impact and rebound speeds (Proceq: https://www.proceq.com/compare/equotip-portable-hardness-testing/). Keeney et al. (2011) and Montoya et al. (2011) demonstrate that rebound hardness data can be used in modelling rock strength parameters that relate to crushing and grinding.

The point load index, sonic velocity, and rebound hardness largely correlate with impact (i.e. crushing) hardness (e.g. Burger et al. 2006; Vatandoost and Fullagar 2009). Point load test data can be used to predict about 50% of impact hardness of the material (Fig. 7). Sonic velocity has a similar correlation with impact hardness (Fig. 7b). The average rebound hardness value is less useful, but the 20% percentile of the measured range is a better predictor of impact hardness (Fig. 7d). For the range of deposits included in the AMRA P843A database, the correlation of these parameters with impact hardness is better on individual deposits than on the global database.

Grinding hardness, typically determined via Bond work index (BWI) testing, does not show a global correlation to UCS (Doll et al. no date). Similarly, there is no general correlation of point load, rebound hardness or sonic velocity with BWI (Fig. 8). However, these low cost tests along with bulk

Figure 5. Left: example of hand-held measurement of drill core sonic velocity. Right: example of a Geotek multi-sensor core logger used for collecting petrophysical measurements (e.g. gamma density, *p*-wave velocity, resistivity, magnetic susceptibility, etc.) from drill core.



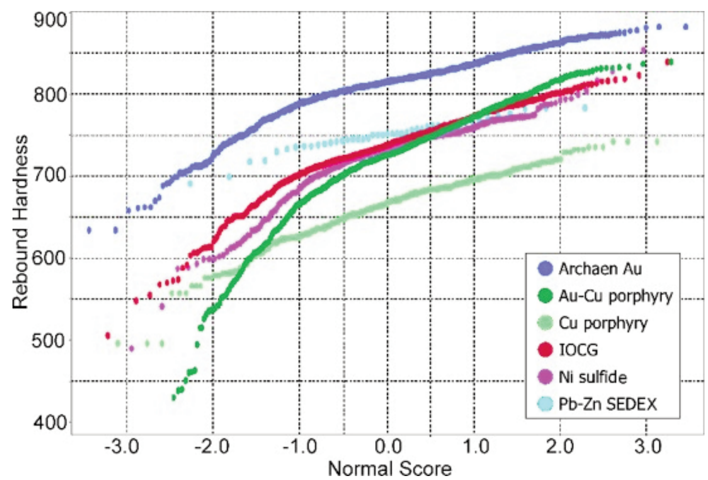


Figure 6. Left: example of collecting rebound hardness data from drill core. In this case the device being used is an Equotip (Proceq: https://www.proceq.com/compare/equotip-portable-hardness-testing/). Right: Rebound hardness results from the AMIRA P843A database. 1500 m of drill core was measured at ~2 cm spacing for each deposit. Possible hardness values are 0 to 1000. IOGC = iron oxide-copper-gold ore.

mineralogy may act as weak proxies for grinding hardness in individual deposits (e.g. Keeney et al. 2011; Montoya et al. 2011). Better geometallurgical tests for grinding hardness are cut down Bond Work Index tests, such as the SPI (SAG Power Index), simplified Bond test (e.g. Kojovic and Walters 2012a), or by high-energy impact breakage such as the JKRBT Wi (JK Rotary Breakage Tester; Walters and Kojovic 2013).

In order to collect the large amount of data required so that results can be used as inputs for geometallurgical domain development and modelling, rock strength tests for geometallurgy need to be: rapid, low cost, relevant to comminution performance and rock texture, able to be used on a small sample size (i.e. drill core), and reproducible (precise). The aim is for comparative testing rather than highly accurate testing. Examples of geometallurgical tests suitable for large-scale rollout (i.e. 1000's of tests) across a deposit include: rebound hardness (e.g. Equotip), petrophysics (e.g. sonic velocity), and rock quality designation (RQD). Table 3 lists some of the common tests that can be carried out on drill core and their approximate cost

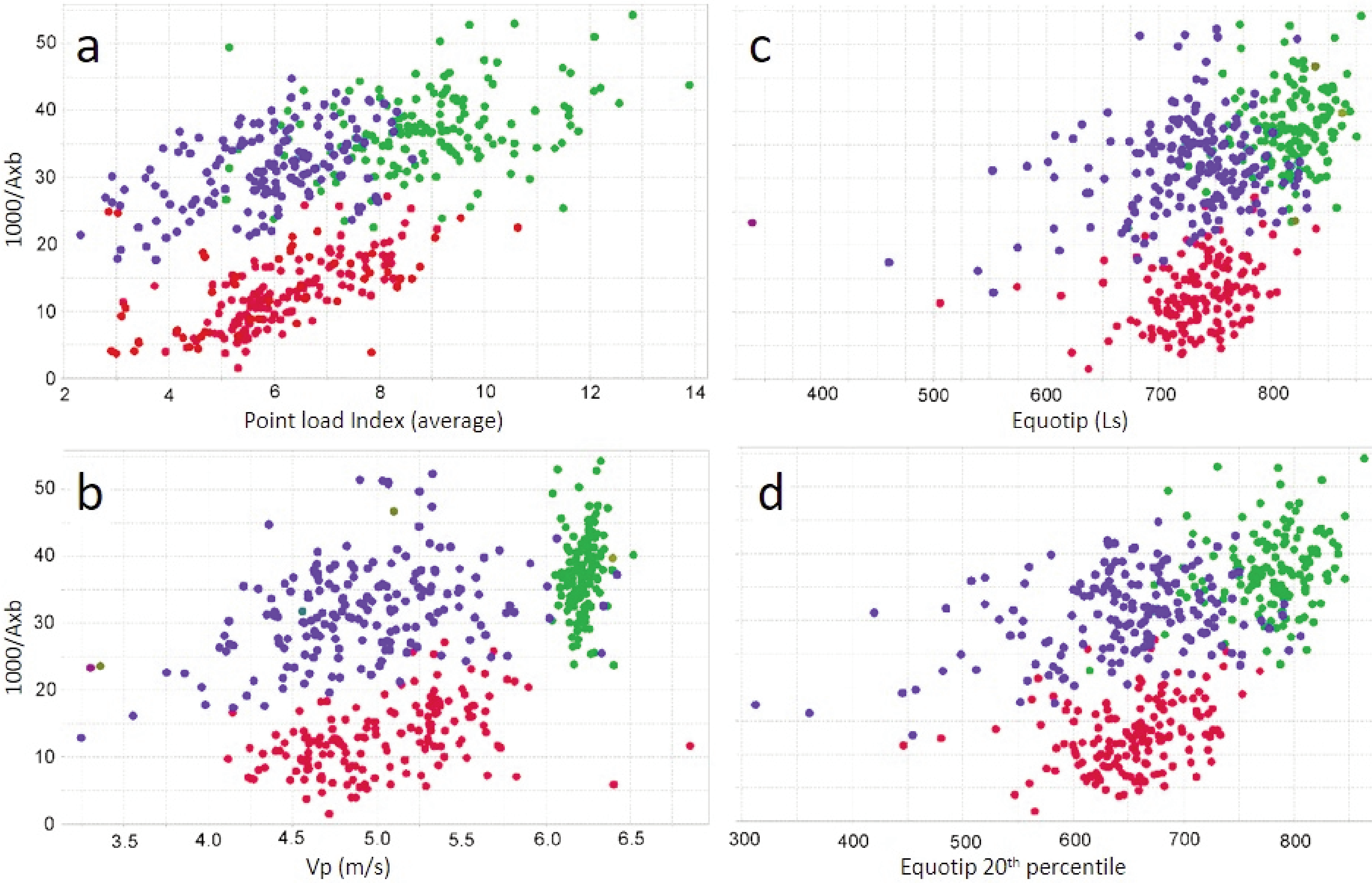


Figure 7. Comparison of small scale tests with inverse of Axb (JKMRC index for impact hardness) for a range of deposits in the AMIRA P843A database. *Vp* is compressional seismic velocity. Equotip (i.e. rebound hardness) results reported using Leeb hardness value (Ls; Proceq: https://www.proceq.com/compare/equotip-portable-hardness-testing/) and 20th percentile of 100 individual Equotip readings over 2 m intervals. Each colour represents a different deposit style: red = iron oxide copper-gold ore (IOCG), green = porphyry Cu, blue = Archean Au.

along with issues to be considered. Measurement while drilling (MWD) techniques have the potential to be a major source of data, but adjusting for drill-rig variability remains problematic (Mwanga et al. 2015).

Harbort et al. (2013) discuss comminution test that can be used to domain an ore body. The classic metallurgy tests such as JK drop-weight test and JK rotary breakage test are used to measure impact hardness and require more than 50 kg of sample. The grinding energy requirement is provided by Bond Ball and Rod Mill tests that require at least 10 kg of material and are expensive. Typically, less than 100 of these tests will be carried out on a mine.

There are other tests that, although not suitable for rollout across an entire deposit because of cost and sample requirements, can be used for variability testing (i.e. 100's of tests). These tests are generally cut-down versions of bankable tests. A summary of the cut down tests is provided by Verret et al. (2011) and Mwanga et al. (2015).

Chemical and Mineralogical Composition

Most drill core (at least in mineralized areas) is analyzed for elemental chemical content. Generally, drill core is divided into analysis intervals (e.g. 1m, 2m, 5m), split or cut in half, and one half sent for analysis. Results can include metal content (e.g. Cu, Pb, Zn, Au, Ag, Fe) and rock-forming elements (e.g. Si, K, Na, Ca). In terms of rock strength, an analysis method that involves complete digestion of the sample and provides information on rock-forming elements is most useful, for example four-acid digest with ICP-MS analysis (e.g. ALS: http://www.alsglobal.com/). Even better is full XRF analysis including loss on ignition (LOI) and SiO_2.

The abundance of constituent minerals (i.e. bulk or modal mineralogy in %) is not typically determined for routine assay samples of drill core. However, it is a key parameter in predicting performance characteristics in a mineral processing circuit, particularly in terms of geometallurgy. Modal mineralogy can be determined at relatively low cost using (semi-) quantitative X-ray diffraction (QXRD), as advances in instrumentation and application software have improved XRD throughput by an order of magnitude and analysis is now routine (e.g. Berry et al. 2011). The QXRD method is most applicable to major (i.e. rock forming) minerals and has limited application to minerals at low abundance. The nominal detection limit is 0.5%.

Bulk mineralogy can also be determined at low cost via calculation of mineralogy from chemical assay data (e.g. Berry et al. 2011). This method depends on the unique composition of

Figure 8. Comparison of small scale tests with Bond Work index (BMWi) for a range of deposits in the AMIRA P843A database. *Vp* is compressional seismic velocity. Equotip (i.e. rebound hardness) results reported by Leeb hardness value (Ls; Proceq: https://www.proceq.com/compare/equotip-portable-hardness-testing/) and 20th percentile of 100 individual Equotip readings over 2 m intervals. Each colour represents a different deposit style as in Figure 7.

Table 3. Examples of small-scale tests for rock strength.

Test	Example	Example of speed	Example of cost	Comments
Fracture frequency	RQD	slow		Generally already routinely done for geotechnical issues.
Rock appearance	Core description			Method exists to correlate with unconfined compressive strength.
Petrophysics	Sonic velocity; Density	50 m of drill core /hour	~ $5 per m	Best done on whole core.
Point Load	PLT	slow	~ $50 per test	Slow, destructive.
Rebound hardness	Equotip	30 m of drill core /hour; measurements every 2 cm	~ $5 per m	Best done on whole core. Core needs to be stable.

each mineral and problems can arise if the mineral compositions are ambiguous (e.g. solid solution series, polymorphic minerals, compositions not independent in assay space). However, it can be more accurate than QXRD when the correct minerals and mineral compositions are used.

If chemical assay data and QXRD results are available for all samples, the two datasets can be combined using weighted least squares methods to take advantage of the strengths of each technique when calculating modal mineralogy (e.g. Berry et al. 2011). In this case, estimates of high abundance minerals are controlled by QXRD measurements and low abundance minerals by chemical assay data. In a similar way spectral data (e.g. short wave IR (SWIR), thermal IR (TIR)), collected using hyperspectral scanners (e.g. Terraspec, Hylogger, Corescan, Geospectral, Specim, etc.) can provide less precise estimates of the abundance of some minerals and this can be combined with assays.

APPLICATIONS OF GEOMETALLURGY

Mine Stability

The availability of a comprehensive geological model is fundamental to any slope design (Hoek et al. 2000) and geological mapping techniques to classify rocks and to define the orientation and frequency of large- and small-scale discontinuities are essential in rock mechanics studies (Hustrulid et al. 2000). Hydrothermal processes that cause extensive alteration of the rock can significantly impact rock strength and discontinuities compared to surrounding less-altered rock. For example, studies at Chuquicamata have shown that potassic alteration has the least impact on rock strength, chloritic alteration has a significant impact, and sericitic alteration a major impact (Kazulovic personal communication in Hoek et al. 2000). Thus, a detailed map showing alteration type and intensity is also important for mine stability purposes. These should be continually updated as new information becomes available.

Data collected typically includes: information on structures and fabrics in the rocks, detailed core logs, images, and rock strength information. Connected to this are various forms of rock-mass classification including: rock quality designation (RQD), rock mass rating (RMR), geological strength index (GSI), and Q index (Barton et al. 1974; Hoek et al. 2000; Marinos and Hoek 2000; Barton 2006). The success of slope-stability analysis depends upon the level of understanding of the characteristics of the geological structure throughout the deposit (e.g. Nicholas and Sims 2000). The geological attributes that are most critical include: orientation, length, spacing, overlaps, and shear strength of faults and joints. Orientation and spacing of structures can be measured from surface exposures or oriented drill core. Structure length and overlap are best measured from surface exposures. Shear-strength data for structures can be obtained from surface exposures or from drill core samples. The strength that usually controls the behaviour of a fault is the strength of the material that is the weakest and comprises at least 20% of the fault zone (Nicholas and Sims 2000). It is important, particularly in open pits, to compare structural observations from diamond drill core (and underground exposures) to those from surface mapping to differentiate between natural fractures and those induced by blast damage to avoid underestimating the strength of the rock mass (Hoek et al. 2000).

The use of structural and strength data allows a deposit to be divided into ‘engineering rock types’ that are defined by intact rock and fracture shear strength. These may or may not match geological (i.e. lithological, alteration) boundaries. For example, at Grasberg, protolith, alteration type, RQD, and relative depth were used to differentiate engineering rock types (Nicholas and Sims 2000).

Blasting

Blasting is the dominant method used for large-scale rock breakage in all but the weakest rocks and the goal is to convert an *in situ* rock mass into a muck-pile of an appropriate fragment size distribution (i.e. avoiding excess fines or oversize fragments) and of a suitable shape and looseness to suit available excavation and transport equipment (e.g. Scott et al. 1996). The properties of the intact rock and any discontinuities play a role in determining the amount of explosive energy needed to achieve the required breakage.

In terms of blasting, important rock mass information (e.g. Scott et al. 1996) is that related to strength properties (compressive, tensile, and shear strength), mechanical properties (Young’s Modulus and Poisson’s ratio), absorption properties (ability to transmit or absorb blast energy), structural properties (faults, jointing, bedding, foliation, cleavage and small scale fractures), and comminution properties (ease of crushing, grinding). To be incorporated into blast design, these properties must be measured or estimated in a quantified, consistent, and systematic manner.

Faults, jointing, bedding, foliation, cleavage, and small-scale fractures all affect the blasting behaviour (Little 2011). For example, discontinuities that are favourably oriented with respect to a blast hole will be preferentially extended by the shock wave produced during blasting. The surfaces of pre-existing fractures can act as surfaces for reflection and refraction of shock waves. Layered material introduces zones of different impedance and additional boundaries for shock wave interactions and attenuation. Interconnected structures may allow the early escape of explosion gases. The presence of a large number of fractures reduces the effort required to achieve fragmentation and the absence of discontinuities makes blasting more predictable. However, the presence of fractures spaced at the desired blasting spacing distance or the presence of strong rocks in a weaker matrix can lead to fragmentation problems. Horizontal planes of weakness or vertical planes parallel to the (pit) face are generally favourable to blasting (e.g. Badal 1995; Scott et al. 1996). Less predictable results can be achieved with dipping discontinuities.

Comminution: Crushing and Grinding

Crushing and grinding of ore is used to partially liberate valuable minerals prior to separation in a mineral processing circuit. The way ore breaks is controlled by the properties of particles making up the ore, properties of minerals making up the grains and by the texture of the ore. Grain size, porosity, micro-fracture density, and modal mineralogy are considered to be the important characteristics that influence rock breakage (e.g. Malvik 1988; Petruk 2000).

During crushing and grinding, the main processes involved in grain size reduction are extension, abrasion, and compression, as illustrated in Figure 9. Failure can occur by tensile failure across the particle in unconfined compression and this is the most efficient process for reducing grain size (e.g. Tromans and Meech 2004). This type of failure is dominant in crushing. Less efficient processes are local zones of very high compressive stress that exceed the compressive strength of the material and also attrition during abrasion of particles.

Rocks fail on the weakest zones and rock elastic properties (e.g. Young’s Modulus) are important in the propagation of

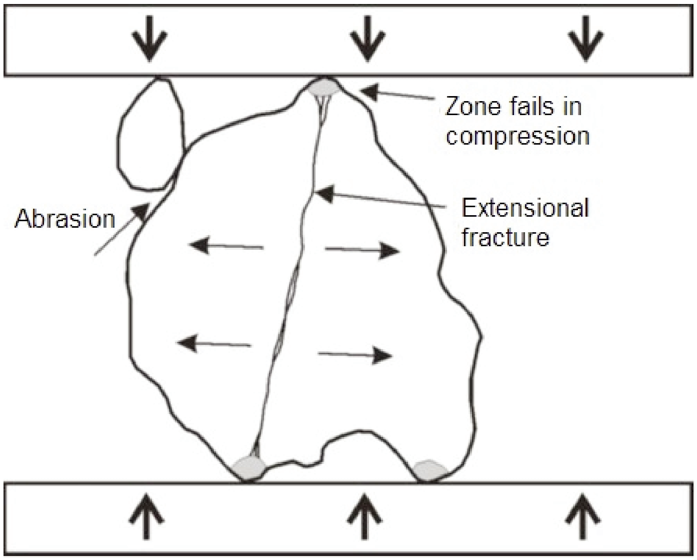


Figure 9. Three main processes in grain size reduction (after Wills and Napier-Munn 2006).

stress through the particles to the weakest point. Non-random breakage (Marino et al. 2016) may enhance the liberation properties that influence the behaviour of particles in the ensuing separation process(es). For example, breakage that exposes more of a valuable mineral at the particle surface may result in a significant improvement in the efficiency of separation processes that exploit surface properties (e.g. flotation) or provide access for fluids (e.g. leaching). Non-random breakage is more common when particle bed breakage devices are used (cf. Vizcarra et al. 2010; Runge et al. 2013).

Recovery

A number of mineral properties are used to liberate and recover valuable phases, for example, electrical properties (e.g. recovery of zircon, rutile, ilmenite from mineral sands), density (e.g. gravity separation of gold, cassiterite, scheelite), magnetic properties (e.g. magnetite, pyrrhotite). Surface characteristics of minerals can also be important, for example, in flotation of sulphide minerals (Shuey 1975; Pridmore and Shuey 1976; Lotter and Bradshaw 2010; Rabieh et al. 2016). Leaching is strongly dependent on permeability and reactivity of the ore (e.g. Ghorbani et al. 2011).

Rock factors affecting liberation and recovery include size, shape, and association (deportment) and composition of the mineral grains. If the average grain size of minerals is coarse enough it may be possible to estimate the abundance and mode of occurrence of some minerals during drill core logging. This can be particularly important for valuable metal-bearing sulphides and pyrite. For example, Figure 10 illustrates some visually logged drill core attributes from a copper porphyry deposit. The occurrence of sulphides as disseminated or massive can affect their processing potential, generally in terms of liberation and estimations of required grind size to attain liberation. Massive sulphides can typically be liberated from host rocks at coarser grain sizes than finely disseminated sulphides. Mesotextures (e.g. massive, banded) identified in drill core can be of assistance in estimating metallurgical recoveries as demonstrated by Bojcevski (1998) for the George Fisher Ag–Pb–Zn deposit. Bojcevski (1998) shows that ores containing larger proportions of massive galena and massive galena–sphalerite generally have greater lead recoveries. This is due in part, as expected, to the higher lead content, but is also influenced by coarser grain size of massive galena. This results in increased galena liberation at the target grind size, along with less iron sulphide content that makes the separation process simpler.

Grain size is a key factor in the liberation of valuable minerals, but the definition of grain size must reflect the complexity of the grain shapes and the grain size distribution (Fig. 11). Easily liberated textures typically have a high average grain size as estimated by a volume weighted averaging process, such as phase specific surface area (Sutherland 2007). Ease of liberation can also be estimated by the use of simulated fragmentation where an image of a sample is divided into square domains (i.e. pseudo fragments) at a size close to final grind size. The level of apparent locked grains in these simulated fragments can then be measured (e.g. Hunt et al. 2011).

Grain association is expected to affect liberation. If easily floated minerals (e.g. pyrite and chalcopyrite) are closely associated, this improves recovery of the valuable component (Tungpalan et al. 2015). It is commonly observed that gold in silicates is more easily liberated than gold in pyrite (e.g. Zhou et al. 2004), although it is not certain this is due to association as there is also a grain size effect. Other examples of association control on liberation are hard to find.

In recovery models, especially for flotation, it is commonly expected that recovery will be a function of grade (e.g. Splane et al. 1982; Corrasco et al. 2008). At high grade the recovery percentage is fairly consistent, while at very low grade it falls to zero. For some deposits this non-linear shape can be matched to a simple model that has a small proportion of the valuable metal as non-recoverable in any sample.

$$\text{Recoverable } X = a^* (\text{total } X) - b \qquad \text{(Eq. 1)}$$

where a is the proportion of X recovered at high grade and b is a fixed amount of X that can never be recovered. A model such as this gives rise to the equation:

$$\text{Recovery \%} = 100^* (a - b/(\text{total } X)) \qquad \text{(Eq. 2)}$$

An example of the fit of this curve shape to small-scale batch flotation test data is shown as the red line on Figure 12. However, in many deposits the recovery is limited by other factors and a more complex relationship is observed (e.g. Sciortino et al. 2013).

It may also be expected that grain size is related to recovery; however, there are very few examples where a recovery-relevant estimate of the grain size distribution of the valuable mineral has been measured and is available for comparison (e.g. Hunt et al. 2011). Where the grain size has been measured, the recovery factor correlates better with grain size than it does with grade (Fig. 12). Producing a suitable grain size proxy remains difficult, however, and recovery proxies are largely

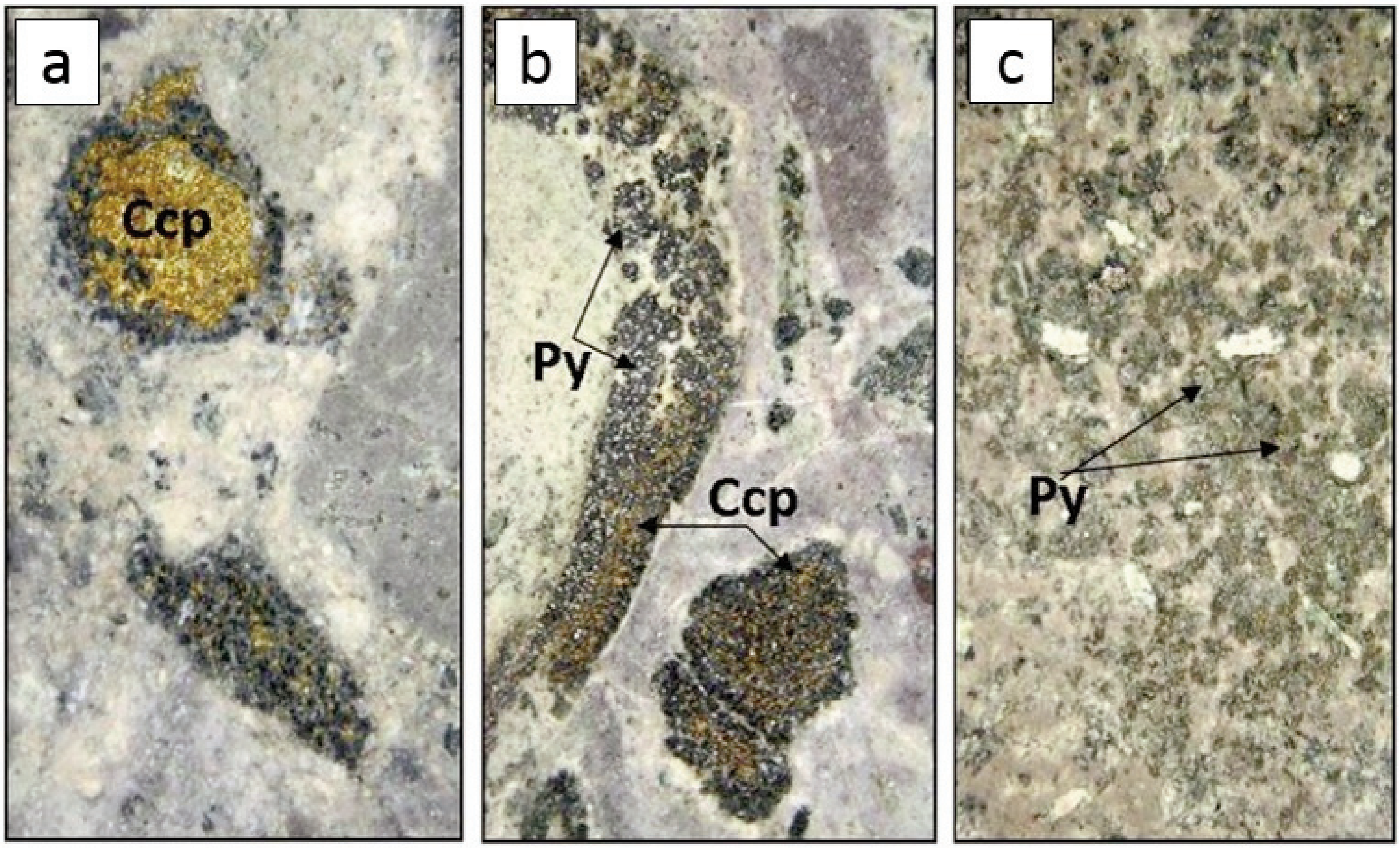


Figure 10. Examples of visually estimated chalcopyrite: pyrite ratios in drill core from a copper porphyry. a) 100:1, b) 60:40, and c) 0:100. Each image is of NQ drill core (NQ: ~48 mm diameter, inside core). Ccp = chalcopyrite, Py = pyrite. Modified from Bonnici (2012).

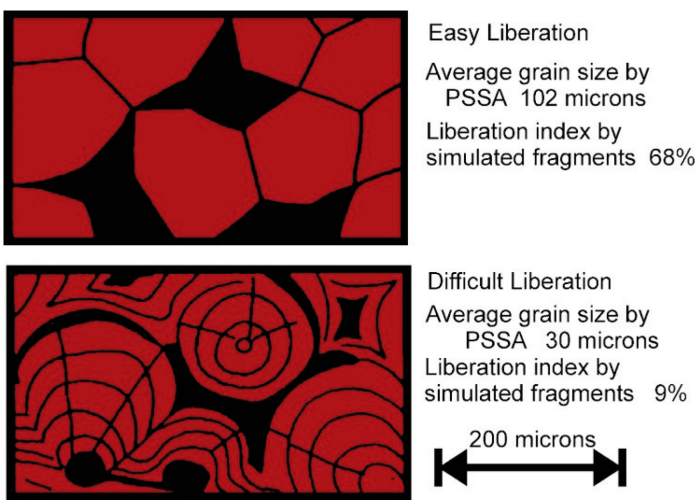


Figure 11. Grain size and liberation. Examples of textures for easy and difficult liberation redrawn from Craig and Vaughan (1981). Estimate of grain size of valuable phase (red) by phase specific surface area (PSSA). The images are also ranked in terms of percentage of simulated fragments (Hunt et al. 2011) that are 100% liberated at a fragment size of 20 microns.

limited to those from cut down tests whether for flotation (e.g. Chauhan et al. 2013; Runge et al. 2013) or leaching (Greet et al. 2015).

Lotter et al. (2016) provide a review of the flotation characteristics of copper sulphide minerals and point out the difficulties of floating different copper minerals with each having individual flotation characteristics. These authors also point out the added difficulties that occur if pyrite is present in sulphide ores, due to its natural tendency to float quickly and easily. In addition, if arsenic is present in the copper and iron sulphides, this can alter the flotation characteristics. Thus, the degree of mineral association and liberation (i.e. textural associations) between these minerals can be a complicating factor during the extraction of valuable phases and should be documented early in the mining value chain through mineralogical characterization of drill core (e.g. through complete chemical analyses, optical and SEM-based mineralogy).

Complicating Factors

Gangue mineralogy can have significant direct impact on mineral processing. For example, talc and/or clay content can cause issues with pulp viscosity, entrainment and bubble 'clogging' in flotation (e.g. Farrokhpay et al. 2016). Carbonaceous material can make Au difficult to recover (e.g. Helm et al. 2009). The presence of deleterious elements (e.g. As, Bi, Cd, F, Hg) can reduce the value of concentrate or make it un-saleable (e.g. Goldie and Tredger 1991; Fountain 2013). Complex intergrowth textures can make it difficult to separate individual sul-

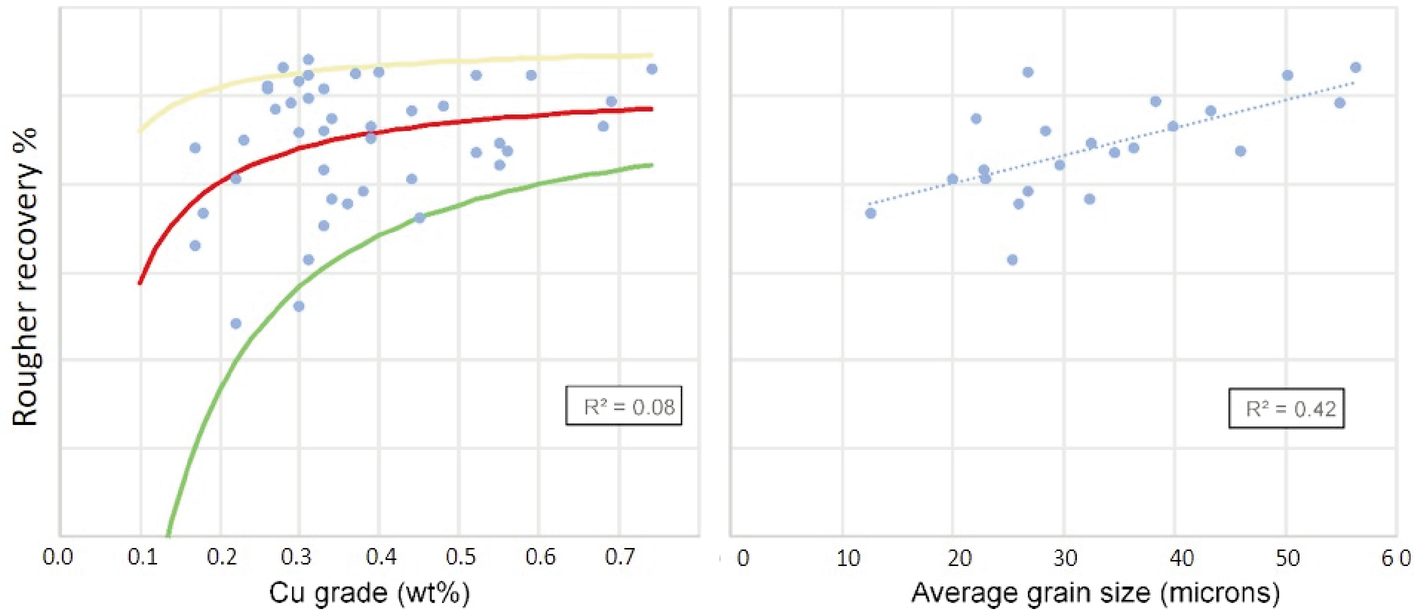


Figure 12. Recovery of Cu in a chalcopyrite dominated ore measured by small scale batch flotation and plotted against grade (left) and grain size of chalcopyrite (right). Best fit curve against grade is the red line (left graph). Yellow and green curves bound the distribution and reflect best and worst case grade recovery curves drawn using the equation form suggested in the text. Linear correlation coefficients (R^2) shown against grade and grain size.

Table 4. Examples of clay minerals and potential processing problems (cf. Cruz et al. 2013; Farrokhpay et al. 2016).

Clay mineral group	Common minerals	Type of clay	Swelling potential	Effect on viscosity and yield strength	Problematic amount (wt.%)
Smectite	Montmorillonite, nontronite, saponite, beidellite	Bentonite, swelling clay, attapulgite clay	High (extreme, especially for montmorillonite)	Moderate – high depending on wt.% clay	> 5 %
Kaolin	Kaolinite, dickite	Kaolin, china clay, tonsteins	Low	Moderate – high depending on wt.% clay	> 10–15 %
Illite	Illite, glauconite	K-bentonites	Low	Moderate – high depending on wt.% clay	1 to > 5 % depending on whether divalent cations are present
Interlayer clays	Illite – smectite		Low to moderate	Moderate – high	
Vermiculite		Zonolite	Moderate	Moderate	
Palygorskite	Palygorskite, sepolite	Fuller's earth, attapulgite clay	Low / none	Probably high (fibrous mineral)	Probably < 1 %

phide minerals and necessitate expensive fine grinding (e.g. Jankovic 2003). The presence of mineralogy with the potential for fast oxidation, or the presence of highly soluble minerals, can require special handling to minimize potential problems (e.g. Wills and Napier-Munn 2006).

Texture and Gangue Mineralogy

Several types of clays are known to cause problems with flotation and/or leaching as listed in Table 4. If test work indicates clays are likely to cause processing problems, then drill core can be routinely analyzed to determine the amount and type of clays present. This can be relatively easily and cheaply done using spectroscopy (e.g. SWIR) or semi-quantitative XRD (see Chemical and Mineralogical Composition section).

Disseminated versus massive textures of pyrite can be important in determining the acid rock drainage (ARD) potential of ore. Disseminated sulphides (i.e. low-sulphide-grade rocks) will likely have less exposed surfaces available for oxidation after size reduction steps (e.g. blasting or crushing), and thus less ability to produce acid (e.g. Parbhakar-Fox and Lottermoser 2017). The morphology of sulphides can also be important in production of ARD. For example, Weber et al. (2004) showed that euhedral pyrite is generally less reactive than framboidal forms. Galvanic effects can also affect the oxidation rate of pyrite if it is in contact with other sulphides, so it is also important to record this information (e.g. Parbhakar-Fox and Lottermoser 2017). In addition, the amount of acid formed, reaction rate, and resistance to oxidation vary between sulphide minerals and the reactivity is influenced by the Fe content of the sulphide mineral (e.g. Plumlee 1999; Lottermoser 2010). Generally, sulphides containing less Fe are less reactive.

The amount and composition of gangue minerals can also be important to ARD formation, as acid that is produced through oxidation of sulphides can be neutralized by reaction with gangue minerals (e.g. Parker 1999). The most effective neutralizing minerals are those containing calcium, magnesium, and manganese carbonate ($(Ca,Mg,Mn)CO_3$) (e.g. Parbhakar-Fox and Lottermoser 2017). Calcite is the most effective of these and, like the sulphides, reactivity of carbonates is affected by grain size and texture. Dissolution of some silicate minerals (e.g. olivine, serpentinite) and clays can aid in acid neutralizing; however, the rate of dissolution of silicates is typically much lower than that of carbonates, although this can be balanced by their greater abundance (e.g. Jambor et al. 2002). Chemical analysis can be used to help determine mineralogy (see below). Sulphur abundance correlates strongly with pyrite, and carbonate can be estimated if inorganic carbon (C) or loss on ignition is measured and these can be used to estimate the acid rock drainage potential (e.g. Berry et al. 2015).

Deleterious Elements

The presence of excess fluorine (>1000 ppm) in a metal concentrate can make it un-saleable (e.g. Fountain 2013). If fluorite, or other potentially fluorine-bearing minerals (e.g. biotite occurs commonly in porphyry copper deposits and can contain > 1 wt.% F) are identified in drill core, samples can be further analyzed to determine if processing problems are likely to occur. If fluorine is identified as a possible problem, then F analysis can be included in routine analysis of drill core.

Other commonly problematic elements are As, Hg, Sb, and Bi (Fountain 2013). The zinc sulphide sphalerite (ZnS) can contain significant amounts of Fe, which in addition to reducing the Zn content of the concentrate, is also detrimental to the rate of sphalerite flotation and hence its recovery (Boulton et al. 2005). The presence of other additional metals in a concentrate (e.g. Pb, Zn in Cu concentrate; Cd in Zn concentrate) can add or detract from the value (e.g. Goldie and Tredger 1991).

Like clays and F-bearing minerals, the presence of carbonaceous material can also detrimentally affect mineral processing, particularly leaching and flotation (e.g. Goodall et al. 2005). Again, C is not typically part of a routine geochemical analysis but if carbonaceous material is identified in drill core then, C analysis (or at least LOI) can be routinely included in chemical analyses.

Grain Size Distribution

Different minerals in an ore will grind to a different grain size distribution during comminution. Sulphide minerals (e.g. chalcopyrite, sphalerite, galena, nickel sulphides) often are finer grained after breakage than their host rock. This aspect of preferential grinding (Runge et al. 2013) can sometimes be exploited to increase the grade of mill feed streams by screening out low-grade (i.e. non-vein) particles. This tendency is being explored by the CRC ORE group in their 'grade engineering®' work (e.g. Carrasco et al. 2017), where they are designing innovative coarse separation technologies and modified circuits (CRC ORE: https://www.crcore.org.au/). In an example from a gold operation, belt cut material was screened into three sizes (+50 mm, 50–19 mm, -19 mm) and the grade engineering approach demonstrated: 1) 64% of the feed mass contains Au grades well below economic cut-off, and 2) 88% of the Au is contained in 36% of the mass in 'particles' below 19 mm. This provided the operation owners with information to make processing decisions about whether or not it is economic to process the +19 mm material through a comminution plant or should it go, as is, to leaching. The approach can also be used to recover higher grade material from feed streams destined for dump leach and re-direct them to mill feed.

GEOMETALLURGICAL MODELLING

Geometallurgical modelling is carried out to provide information about deposit variability in terms of processing performance throughout the mining value chain. Unless the deposit is homogeneous, this typically involves the identification of geometallurgical domains with models developed for each domain. Quantitative, spatially constrained data collected from drill core logging and analysis can potentially be used as inputs to geometallurgical models. This typically includes conventional data, such as assay results, but can also include modal mineralogy and data from small-scale geometallurgical tests (e.g. Table 3) that provide proxies for geometallurgical parameters.

Strong proxies allow models to be built that are fundamentally sound and can, in some cases, work as a global model. For example, the relationship between RBT lite (Kojovic and Walters 2012b) and crushing hardness is robust and will work across a large range of rock types. However, many of the parameters available for modelling processing response are weak proxies that do not represent a direct measurement of the target parameter, but correlate with it inside a discrete domain. In these cases, the model will improve if the variability of the model domain is relatively small. Thus it is common to domain the orebody based on some parameter(s) and model each domain separately. The domains can be spatial, geochemical, and/or mineralogical. Batu Hijau (Burger et al. 2006) is an example where using average values for a number of domains solved the modelling problem. Other examples of geometallurgy models based on domains are described in Montoya et al. (2011), Keeney et al. (2011), Harbort et al. (2013), Hunt et al. (2013), and Hunt and Berry (2015).

Most geometallurgy modelling problems have the possibility to include a large number of weak proxies and it is important to simplify models as much as possible. Many model building programs fail if too many weak proxies are included in the calculation as they model the individual samples rather than trends in the data.

When considering how good a model is, it is important to remember that the samples are not typically independent.

Many parameters are highly correlated and the training set does not come from a compositional space that covers all of the n-dimensional space, which the measured parameters can span. It is usual to select only one of each class of highly correlated parameters (Stone and Brooks 1990). Ordinary least-squares methods of modelling are numerically unstable and will play off highly correlated parameters to minimize the error in a way that models the training set, but ignores real trends in the data. Singular value decomposition is more stable (Press et al. 1986). Some papers have found partial least-squares methods suitable for this problem (e.g. Wells and Chia 2011), although these can make understanding the underlying driver of the solution difficult.

Standard statistical tests of goodness of fit may fail and it is good practice to keep a separate test data set. Measurement of error using cross validation can be used to identify unstable relationships (Witten and Frank 2005). The acceptable level of accuracy of the model will depend on the purpose of the model, the parameter(s) being modelled, and the sensitivity of the production chain. For example, a model that is able to estimate BWI values to ± 20% may be acceptable depending on the sensitivity of the comminution circuit, whereas a model that can predict fluorine content to ± 10% is not likely to be acceptable. It is also necessary to keep in mind the accuracy of the parameter that is being modelled. For example, reproducibility tests for the Bond test (BMWi) showed variances of up to 13% and a series of round-robin testing between commercial laboratories showed up to 9% variation (e.g. Kaya et al. 2002; Harbort et al. 2013). A model that reduces the difference between actual and predicted mill performance by 50% will be relatively easy to produce and will be sufficient in many cases. More accurate predictions will come at a rapidly escalating cost.

Parameters and estimates determined in geometallurgical modelling generally transition to geostatistical modelling at the point where transfer functions can be introduced that convert raw mine data into processing parameters (e.g. determining throughput from A*b and BWi values using software such as JKSimMet). However, care must always be taken to make sure that the relationships from small-scale samples match bulk sample testing. Blending in the mining process means that small samples test a wider range of compositions than will ever be seen in a mill. Indicated recovery problems in small-scale samples may result from these extreme compositions. For example, the results reported by Hunt et al. (2011) reflect the very high mica content of some small-scale samples and are not suitable for prediction of mill performance. The results do, however, indicate the importance of a blend model for the mill that includes more than just grade.

CONCLUSIONS

Geometallurgy is an applied cross-disciplinary area. The most important contribution that geologists make to this field is in defining the spatial variability of the deposit in parameters relevant to mine performance. Propagating geometallurgical attributes into a resource model requires a large supporting data set depending on the variability and variography of the processing performance indicator of interest: throughput, recovery, acid drainage, etc. A key aim of this paper is to review the options available to generate a representative geometallurgical database at a mine. Once the data has been produced there are two further stages required: multivariate modelling to integrate and visualize the geometallurgical data, and integration of the models into the mine plan which starts with geostatistics.

It is very important to continually cross-check modelling and to continue sampling throughout the mine life. The weak proxies typically used in geometallurgical models can only be used for interpolation. As mining extends and new parts of the mine open up there is always the potential for ores to be included in the ore reserves that lie outside the original training set. You can only relax when the mine is closed!

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REFERENCES

Badal, R., 1995, Rock blasting with discontinuities: International Book Traders, New Delhi, India, 200 p.

Barton N., 2006, Rock quality, seismic velocity, attenuation and anisotropy: Taylor and Francis, 756 p., https://doi.org/10.1201/9780203964453.

Barton, N., Lien, R., and Lunde, J., 1974, Engineering classification of rock masses for the design of tunnel support: Rock Mechanics and Rock Engineering, v. 6, p. 189–236, https://doi.org/10.1007/BF01239496.

Baud, P., Wong T-f., and Zhu W., 2014, Effects of porosity and crack density on the compressive strength of rocks: International Journal of Rock Mechanics and Mining Sciences, v. 67, p. 202–211, https://doi.org/10.1016/j.ijrmms.2013.08.031.

Berry, R., Hunt, J., and McKnight, S., 2011, Estimating mineralogy in bulk samples: First AusIMM Geometallurgy Conference 2011, Proceedings, p. 153–156.

Berry, R., Hunt, J., Parbhakar-Fox, A., and Lottermoser, B., 2015, Prediction of acid rock drainage (ARD) from calculated mineralogy: The International Conference on Acid Rock Drainage (ICARD) 2015, 17 p.

Bojcevski, D., 1998, Metallurgical characterisation of George Fisher ore textures and implications for ore processing: Mine to Mill Proceedings, p. 29–41.

Bonnici, N., 2012, The mineralogical and textural characteristics of copper-gold deposits linked to mineral processing attributes: Unpublished PhD thesis, University of Tasmania, AU, 255 p.

Boulton, A., Fornasiero, D., and Ralston, J., 2005, Effect of iron content in sphalerite on flotation: Minerals Engineering, v. 18, p. 1120–1122, https://doi.org/10.1016/j.mineng.2005.03.008.

Broch, E., and Franklin, J.A., 1972, The point-load strength test: International Journal of Rock Mechanics and Minerals Sciences and Geomechanics Abstracts, v. 9, p. 669–676, https://doi.org/10.1016/0148-9062(72)90030-7.

Brook, N., 1985, The equivalent core diameter method of size and shape correction in point load testing: International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts, v. 22, p. 61–70, https://doi.org/10.1016/0148-9062(85)92328-9.

Broz, M.E., Cook, R.F., and Whitney, D.L., 2006, Microhardness, toughness, and modulus of Mohs scale minerals: American Mineralogist, v. 91, p. 135–142, https://doi.org/10.2138/am.2006.1844.

Burger, B., McCaffery, K., Jankovic, A., Valery, W., and McGaffin, I., 2006, Batu Hijau Model for throughput forecast, mining and milling optimisation and expansion studies: Society for Mining, Metallurgy, and Exploration (SME), 2006 Conference, St. Louis, USA, 21 p. Available from http://www.metso.com/search-page/#/search/Batu%20hijau.

Butenuth, C., 1997, Comparison of tensile strength values of rocks determined by point load and direct tension tests: Rock Mechanics and Rock Engineering, v. 30, p. 65–72, https://doi.org/10.1007/BF01020114.

Carrasco, C., Keeney L., Napier-Munn, T.J., and Bode, P., 2017, Unlocking additional value by optimising comminution strategies to process Grade Engineering® streams: Minerals Engineering, v. 103–104, p. 2–10, https://doi.org/10.1016/j.mineng.2016.07.020.
Chang Chandong, Zoback, M.D., and Khaksar, A., 2006, Empirical relations between rock strength and physical properties in sedimentary rocks: Journal of Petroleum Science and Engineering, v. 51, 223–237, https://doi.org/10.1016/j.petrol.2006.01.003.
Chauhan, M., Napier-Munn, T., Keeney, L., and Bradshaw, D.J., 2013, Progress in developing a geometallurgy flotation indicator: Second AUSIMM International Geometallurgy Conference, p. 201–206.
Corrasco, P., Chiles, J.-P., and Seguret, S., 2008, Additivity, metallurgical recovery, and grade: 8th International Geostatistics Congress, December 2008, Santiago, Chile, 10 p.
Craig, J., and Vaughan, D., 1981, Ore microscopy and ore petrography, 2nd edition: Wiley and sons Inc., New York, 434 p.
Cruz, N., Peng, Y., Farrokhpay, S., and Bradshaw, D., 2013, Interactions of clay minerals in copper–gold flotation: Part 1 – Rheological properties of clay mineral suspensions in the presence of flotation reagents: Minerals Engineering, v. 50–51, p. 30–37, https://doi.org/10.1016/j.mineng.2013.06.003.
Csőke, B., Rácz, A., and Mucsi, G., 2013, Determination of the Bond work index of binary mixtures by different methods: International Journal of Mineral Processing, v. 123, p. 78–86, https://doi.org/10.1016/j.minpro.2013.05.004.
Deere, D., 1964, Technical description of rock cores for engineering purposes: Rock Mechanics and Engineering Geology, v. 1, p. 16–22.
Deere, D.U., and Deere, D.W., 1988, The rock quality designation (RQD) index in practice, *in* Kirkaldie, L., *ed.,* Rock Classification Systems for Engineering Purposes: American Society for Testing and Materials, ASTM STP 984, p. 91–101.
Deutsch, C., 2013, Geostatistical modelling of geometallurgical variables – Problems and solutions: Second AUSIMM International Geometallurgy Conference, Proceedings, p. 7–15.
Doll, A., Barratt, D., and Wood, K., (no date), Comparison of UCS to Bond Work Indices: Alex G Doll Consulting Ltd, Logan Lake, BC, 10 p. Accessed 2016 from: https://www.sagmilling.com/articles.
Eberhardt, E., Stimpson, B., and Stead, D., 1999, Effects of grain size on the initiation and propagation thresholds of stress-induced brittle fractures: Rock Mechanics and Rock Engineering, v. 32, p. 81–99, https://doi.org/10.1007/s006030050026.
Fountain, C., 2013, The whys and wherefores of penalty elements in copper concentrates: Metallurgical Plant Design and Operating Strategies (MetPlant 2013), 15–17 July 2013, Perth WA, p. 502–518.
Farrokhpay, S., Ndlovu, B., and Bradshaw, D., 2016, Behaviour of swelling clays versus non-swelling clays in flotation: Minerals Engineering, v. 96–97, p. 59–66, https://doi.org/10.1016/j.mineng.2016.04.011.
Goldie, R., and Tredger, P., 1991, Net smelter return models and their use in the exploration, evaluation and exploitation of polymetallic deposits: Geoscience Canada, v. 18, p. 159–171.
Goodall, W.R., Leatham, J.D., and Scales, P.J., 2005, A new method for determination of preg-robbing in gold ores: Minerals Engineering, v. 18, p. 1135–1141, https://doi.org/10.1016/j.mineng.2005.05.014.
Ghorbani, Y., Becker, M., Mainza, A., Franzidis, J.-P., and Petersen, J., 2011, Large particle effects in chemical/biochemical heap leach processes – A review: Minerals Engineering, v. 24, p. 1172–1184, https://doi.org/10.1016/j.mineng.2011.04.002.
Greet, C., Lazamanana, A., and Small, G., 2015, Bottle rolls versus stirred beaker leach testing – which is best?: The Australasian Institute of Mining and Metallurgy, Melbourne, Proceedings MetPlant 2015, p. 188–196.
Harraden, C. L., Berry, R., and Lett, J., 2016, Proposed Methodology for Utilising Automated Core Logging Technology to Extract Geotechnical Index Parameters: Third AusIMM International Geometallurgy Conference 2016, Proceedings, p. 119–124.
Harbort, G., Lam, K., and Sola, C., 2013, The use of geometallurgy to estimate comminution parameters within porphyry copper deposits: Second AusIMM International Geometallurgy Conference 2013, Proceedings, p. 217–230.
Helm, M., Vaughan, J., Staunton, W.P., and Avraamides, J., 2009, An investigation of the carbonaceous component of preg-robbing gold ores: The Southern African Institute of Mining and Metallurgy, World Gold Conference 2009, p. 139–144.
Hoek, E., Rippere, K., and Stacey, P., 2000, Large-scale slope designs – A review of the state of the art in slope stability in surface mining *in* Hustrulid, W.A., McCarter, M.K., and Van Zyl, D., *eds.,* Slope Stability in Surface Mining, 2000 SME, Littleton, CO, USA, p. 3–10.
Holmgren, D., and Marti, G., 1984, Applied microscopy and metallurgical forecasting at Los Bronces mine, Chile: International Congress on Applied Mineralogy (ICAM) in the mineral industry, Annual Meeting 1984, Proceedings, p. 407–419.
Hunt, J., and Berry, R., 2015, Estimating comminution indices from mine data: ESCC Conference 2015, Proceedings of the 14th European Symposium on Comminution and Classification, p. 270 –274.
Hunt, J., Berry, R., and Bradshaw, D., 2011, Characterising liberation and flotation potential using image analysis, simulated fragmentation and small scale flotation: First AusIMM International Geometallurgy Conference 2011, Proceedings, p. 331–333.
Hunt, J., Kojovic, T., and Berry, R., 2013, Estimating comminution indices from ore mineralogy, chemistry and drill core logging: Second AusIMM International Geometallurgy Conference 2013, Proceedings, p. 173–176.
Hurlbut, C., 1959, Dana's manual of mineralogy, 17th edition: Wiley and Sons, New York, 609 p.
Hustrulid, W.A., McCarter, M.K., and Van Zyl, D., *editors,* 2000, Slope Stability in Surface Mining: 2000 Society for Mining, Metallurgy, and Exploration (SME), 440 p.
ISRM. International Society for Rock Mechanics, 1981, International Society for Rock Mechanics suggested methods for rock characterization, testing and monitoring: Pergamon Press, 50 p.
Jaeger, J.C., Cook, N.G.W., and Zimmerman, R.W., 2007, Fundamentals of rock mechanics, 4th edition: Blackwell Publishing, Malden, USA, 475 p.
Jambor, J., Dutrizac, J., Groat, L., and Raudsepp, M., 2002, Static tests of neutralization potentials of silicate and aluminosilicate minerals: Environmental Geology, v. 43, p. 1–17, https://doi.org/10.1007/s00254-002-0615-y.
Jankovic, A., 2003, Variables affecting the fine grinding of minerals using stirred mills: Minerals Engineering, v. 16, p. 337–345, https://doi.org/10.1016/S0892-6875(03)00007-4.
Ji Shaocheng, Wang Qin, Xia Bin, and Marcotte, D., 2004, Mechanical properties of multiphase materials and rocks: a phenomenological approach using generalized means: Journal of Structural Geology, v. 26, p. 1377–1390, https://doi.org/10.1016/j.jsg.2003.12.004.
Jiang H., Li Q.M., Zhou Y.D., Zhang C.H., Chi C.J., and Tang X.W., 2016, Effects of spatial correlation property of microstructure on the pulverising performance of rock prisms: Minerals Engineering, v. 90, p. 96–104, https://doi.org/10.1016/j.mineng.2016.03.013.
Kaya, E., Fletcher, P., and Thompson, P., 2002, Reproducibility of Bond work index with different standard ball mills: Society for Mining, Metallurgy, and Exploration, SME Annual meeting, p. 140–142.
Keeney, L., Walters, S., and Kojovic, T., 2011, Geometallurgical mapping and modelling of comminution performance at the Cadia East porphyry deposit: First AusIMM International Geometallurgy Conference 2011, Proceedings, p. 73–83.
Kojovic, T., 2008, Overview of comminution tests for ore characterisation: AMIRA International P843 GeM project, Technical Report-1, p. 1–26.
Kojovic, T., and Walters, P., 2012a, Development of the JK Bond Ball Lite test (JK BBL) (Abstract): GECAMIN, Geomet 2012 Conference, Abstracts, p. 48–49.
Kojovic, T., and Walters, P., 2012b, Managing your geomet ore characterization needs with the JKRBT: Proceedings of the GEOMET2012 International Seminar on Geometallurgy, Santiago, Chile, 1–3 December 2012, p. 46–47.
Little, T.N., 2011, Geological controls on drilling and blasting operations: EXPLO Conference, Melbourne November 2011, p. 63–77.
Lotter, N.O., and Bradshaw, D.J., 2010, The formulation and use of mixed collectors in sulphide flotation: Minerals Engineering, v. 23, p. 945–951, https://doi.org/10.1016/j.mineng.2010.03.011.
Lotter, N.O., Bradshaw, D.J., and Barnes, A.R., 2016, Classification of the major copper sulphides into semiconductor types, and associated flotation characteristics: Minerals Engineering, v. 96–97, p. 177–184, https://doi.org/10.1016/j.mineng.2016.05.016.
Lottermoser, B., 2010, Mine wastes: Characterization, treatment and environmental impacts, 3rd edition: Springer, Berlin, 400 p., https://doi.org/10.1007/978-3-642-12419-8.
Malvik, T., 1988, Relations between mineralogical texture and comminution characteristics for rocks and ores: International Mineral Processing Congress, v. xvi, p. 257–270.
Marino, R.A., Evans, C.L., and Manlapig, E., 2016, Definition of random and non-random breakage in mineral liberation – A review: Minerals Engineering, v. 94, p. 51–60, https://doi.org/10.1016/j.mineng.2016.05.005.
Marinos, P., and Hoek, E., 2000, GSI: a geologically friendly tool for rock mass strength estimation: Proceedings of the GeoEng2000, International Conference on Geotechnical and Geological Engineering, Melbourne, AU, Technomic publishers, Lancaster, p. 1422–1446.
Martins, S., 2016, Size–energy relationship in comminution, incorporating scaling laws and heat: International Journal of Mineral Processing, v. 153, p. 29–43, https://doi.org/10.1016/j.minpro.2016.05.020.

McKee, D., 2013, Understanding mine to mill: The Cooperative Research Centre for Optimising Resource Extraction, Brisbane, AU, 96 p. Available from: https://911metallurgist.com/C/What-is-mine-to-mill.pdf.
Meulenkamp, F., and Grima, M. A., 1999, Application of neural networks for the prediction of the unconfined compressive strength (UCS) from Equotip hardness: International Journal of Rock Mechanics and Mining Sciences, v. 36, p. 29–39, https://doi.org/10.1016/S0148-9062(98)00173-9.
Momeni, E., Nazir, R., Armaghani, D.J., Amin, M.F.M., and Mohamad, E.T., 2015, Prediction of unconfined compressive strength of rocks: A review paper: Jurnal Teknologi, v. 77, p. 43–50, https://doi.org/10.11113/jt.v77.6393.
Montoya, P., Keeney, L., Jahoda, R., Hunt, J., Berry, R., Drews, U., and Chamberlain, V., 2011, Geometallurgical modelling techniques applicable to pre-feasibility projects: La Colosa case study: First AusIMM International Geometallurgy Conference 2011, Proceedings, p. 103–111.
Mwanga, A., Rosenkrantz, J., and Lamberg, P., 2015, Testing of ore comminution behavior in the geometallurgical context—A review: Minerals, v. 5, p. 276–297, https://doi.org/10.3390/min5020276.
Napier-Munn, T.J., Morrell, S., Morrison, R.D., and Kojovic, T., 1999, Mineral comminution circuits: their operation and optimisation: Julius Kruttschnitt Mineral Research Centre, University of Queensland, JKMRC Monograph Series in Mining and Mineral Processing, v.2, 413 p.
Nicholas, D.E., and Sims, D.B., 2000, Collecting and using geologic structure data for slope design, *in* Hustrulid, W.A., McCarter, M.K., and Van Zyl, D.J.A., *eds.*, Slope stability in surface mining: Society for Mining, Metallurgy, and Exploration, p. 11–26.
Noferesti, H., and Rao, K.S., 2011, Role of crystal interlocking on the strength of brittle rocks: Rock Mechanics and Rock Engineering, v. 44, p. 221–230, https://doi.org/10.1007/s00603-010-0094-5.
Parbhakar-Fox, A., and Lottermoser, B., 2017, Principles of sulphide oxidation and acid rock drainage, *in* Lottermoser, B., *ed.*, Environmental indicators in metal mining: Springer International Publishing, Switzerland, p. 15–34.
Parker, G., 1999, A critical review of acid generation resulting from sulphide oxidation: processes, treatment and control: Australian Minerals Energy Environmental Foundation, Melbourne, AU, v. 11, p. 1–182.
Plumlee, G., 1999, The environmental geology of mineral deposits, *in* Plumlee, G., and Logsdon, D., *eds.*, The environmental geochemistry of mineral deposits part A: processes, techniques and health issues: Reviews in Economic Geology, v. 6A, p. 71–116.
Petruk, W., 2000, Applied mineralogy in the mining industry: Elsevier Science, BV, Amsterdam, 500 p.
Press, W.H., Flannery, B.P., Teukolsky, S.A., and Vetterling, W.T., 1986, Numerical Recipes: The Art of Scientific Computing: Cambridge University Press, Cambridge, UK, 818 p.
Pridmore, D., and Shuey, R., 1976, Electrical resistivity of galena, pyrite, and chalcopyrite: American Mineralogist, v. 61, p. 248–259.
Rabieh, A., Albijanic, B., and Eksteen, J.J., 2016, A review of the effects of grinding media and chemical conditions on the flotation of pyrite in refractory gold operations: Minerals Engineering, v. 94, p. 21–28, https://doi.org/10.1016/j.mineng.2016.04.012.
Runge, K.C., Tabosa, E., and Jankovic, A., 2013, Particle size distribution effects that should be considered when performing flotation geometallurgical testing: Second AUSIMM International Geometallurgy Conference 2013, p. 335–344.
Rusnak, J., and Mark, C., 2000, Using the point load test to determine the uniaxial compressive strength of coal measure rock: 19th Ground Control Conference in Mining, West Virginia University, p. 362–371.
Schouwstra, R., De Vaux, D., Muzondo, T., and Prins, C., 2013, A Geometallurgical Approach at Anglo American Platinum's Mogalakwena Operation: Second AUSIMM International Geometallurgy Conference 2013, p. 85–92.
Sciortino, M., Muinonen, J., Korczak, J., and St-Jean, A., 2013, Geometallurgical modelling of the Dumont deposit: Second AUSIMM International Geometallurgy Conference 2013, p. 101– 103.
Scott, A., Cocker, A., Djordjevic, N., Higgins, M., La Rosa, D., Sarma, K., and Wedmaier, R., 1996, Open pit blast design: analysis and optimisation: Julius Kruttschnitt Mineral Research Centre, University of Queensland, JKMRC Monograph Series in Mining and Mineral Processing, v. 1, 342 p.
Shuey, R., 1975, Semiconducting ore minerals: Elsevier, Amsterdam, 500 p.
Sousa, L.M.O., Suárez del Rio, L.M., Calleja, L., Ruiz de Argandoña, V.G., and Rodriguez Rey, A., 2005, Influence of microfractures and porosity on the physico-mechanical properties and weathering of ornamental granites: Engineering Geology, v. 77, p. 153–168, https://doi.org/10.1016/j.enggeo.2004.10.001.
Splane, M., Browner, S.J., and Dohm, C.E., 1982, The effect of head grade on recovery efficiency in a gold-reduction plant: Journal of the South African Institute of Mining and Metallurgy, p. 6–11.
Stone, M., and Brooks, R. J., 1990, Continuum Regression: Cross-Validated Sequentially Constructed Prediction Embracing Ordinary Least Squares, Partial Least Squares and Principal Components Regression: Journal of the Royal Statistical Society, Series B (Methodological), v. 52, p. 237–269.
Sutherland, D., 2007, Estimation of grain size using automated mineralogy: Minerals Engineering, v. 20, p. 452–460, https://doi.org/10.1016/j.mineng.2006.12.011.
Tavares, L.M., and Kallembach, R.D.C., 2013, Grindability of binary ore blends in ball mills: Minerals Engineering, v. 41, p. 115–120, https://doi.org/10.1016/j.mineng.2012.11.001.
Tromans, D., and Meech, J.A., 2002, Fracture toughness and surface energies of minerals: theoretical estimates for oxides, sulphides, silicates and halides: Minerals Engineering, v. 15, p. 1027–1041, https://doi.org/10.1016/S0892-6875(02)00213-3.
Tromans, D., and Meech, J.A., 2004, Fracture toughness and surface energies of covalent minerals: Theoretical estimates: Minerals Engineering, v. 17, p. 1–15, https://doi.org/10.1016/j.mineng.2003.09.006.
Tungpalan, K., Wightman, E., and Manlapig, E., 2015, Relating mineralogical and textural characteristics to flotation behaviour: Minerals Engineering. V. 82, p. 136–140, https://doi.org/10.1016/j.mineng.2015.02.005.
Vatandoost, A., and Fullagar, P., 2009, Characterisation of ore crushability using petrophysical properties: 7th International Mining Geology Conference, AusIMM, Perth, p. 119–124.
Vatandoost, A., Fullagar, P., and Roach, M., 2008, Automated multi-sensor petrophysical core logging: Exploration Geophysics, v. 39, p. 181–188, https://doi.org/10.1071/EG08020.
Verret, F.O., Chiasson, G., and Mcken, A., 2011, SAG mill testing - an overview of the test procedures available to characterize ore grindability: SGS Mineral Services Technical paper 2011–08, 10 p.
Verwaal, W., and Mulder, A., 1993, Estimating rock strength with the equotip hardness tester: International Journal of Rock Mechanics and Mining Science and Geomechanics Abstracts, v. 30, p. 659–662, https://doi.org/10.1016/0148-9062(93)91226-9.
Villaescusa, E., 1991, A three dimensional model of rock jointing: Unpublished PhD thesis, University of Queensland, Australia, 100 p.
Vizcarra, T.G., Wightman, E.M., Johnson, N.W., and Manlapig, E.V., 2010, The effect of breakage mechanism on the mineral liberation properties of sulphide ores: Minerals Engineering, v. 23, p. 374–382, https://doi.org/10.1016/j.mineng.2009.11.012.
Walters, S., 2011, Integrated industry relevant research initiatives to support geometallurgical mapping and modelling: AusIMM Geometallurgy Conference 2011, Proceedings, p. 273–278.
Walters, S., and Kojovic, T., 2006, Geometallurgical mapping and mine modelling (GeM) – the way of the future: SAG Conference 2006, Proceedings, p. 411–425.
Walters, P., and Kojovic T., 2013, Prediction of grind response from high energy RBT products: AMIRA P843A GeM111 report, 23 p.
Weber, P.A., Thomas, J.E., Skinner, W.M., and Smart, R.St.C., 2004, Improved acid neutralisation capacity assessment of iron carbonates by titration and theoretical calculation: Applied Geochemistry, v. 19, p. 687–694, https://doi.org/10.1016/j.apgeochem.2003.09.002.
Wells, M.A., and Chia, J., 2011, Ni laterite mineralogy and chemistry – A New Approach to Quantification: First AusIMM International Geometallurgy Conference 2011, p. 187–196.
Whitney, D.L., Broz, M., and Cook, R.F., 2007, Hardness, toughness, and modulus of some common metamorphic minerals: American Mineralogist, v. 92, p. 281–288, https://doi.org/10.2138/am.2007.2212.
Williams, S., 2013, A historical perspective of the application and success of geometallurgical methodologies: Second AusIMM international Geometallurgy Conference 2013, Proceedings, p. 37–47.
Wills, B., and Napier-Munn, T., 2006, Mineral processing technology: Butterworth-Heinemann, 456 p.
Witten, I.H., and Frank, E., 2005, Data Mining: Practical Machine Learning Tools and Techniques, 2nd edition: Morgan Kaufman, 525 p.
Zhou J., Jago, B., and Martin, C., 2004, Establishing the process mineralogy of gold ores: SGS Minerals Technical Bulletin 2004–03, 16 p.

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