Domaining in Mineral Resource Estimation: A Stock-Take of 2019 Common Practice

René Sterk[1], Koos de Jong[1], Greg Partington[2], Sebastian Kerkvliet[1], Mathijs van de Ven[1]

[1] RSC Consulting Ltd, Level 2, 109 Princes Street, Dunedin 9016, New Zealand
[2] Kenex, PO Box 775, Dongara, Western Australia, 6525

ABSTRACT

Resource blocks estimated within a particular domain should only be informed by sample points from within that domain. If this fundamental principle of mineral resource estimation is not adhered to it may severely compromise the quality of the final resource estimate. Nonetheless, the repeated reminder of resource downgrades or even complete project devaluations as the consequence of poor domaining practice suggests that this principle is still not well-entrenched in industry practice. As many practitioners have warned and as documented in books, course materials and online blogs over the years: geology is important.

It is good practice to base domains primarily on geological information derived from geological logging of drill core or chips, underpinned by an understanding of the structural geometry of the ore body and a well-understood genetic model of mineralisation. However, a sound statistical analysis of geochemical data that are accurate and precise is also required to evaluate the domains. Multi-element geochemistry from laboratory or portable XRF instruments combined with multivariate data analysis and machine-learning (ML), as well as core scanners and down-hole optical televiewers, and other recent technological advances are powerful tools that enable the proper delineation of domains. However, these tools are often underutilised as they require additional investment at a time in a project when their value can be hard to demonstrate.

Unfortunately, the use of geological information to create domains is the exception rather than the rule. Our review of mineral resource estimates published since 2017 suggests that more than half of all estimation-constraining wireframes are built using grade cut-offs and are not informed by any primary geological information such as lithology or alteration. While using a grade cut-off may seem perfectly logical to delineate domains when detailed geological information is not available, if not treated with caution, this can lead to poor domain integrity.

Books and courses on resource estimation clearly express the importance of domaining but offer few practical solutions or rules of thumb. There appears to be a lack of clear standards, a lack of a framework to distinguish good from bad domaining practice and there is a perpetuation of bad practice masked as common practice. Here we offer some recommendations to raise domaining standards across the industry and present a rules-based approach to improve domaining practices at the individual level.

Keywords:
domaining practice
resource estimation
modelling techniques
implicit modelling
grade-shell
boundary analysis

INTRODUCTION

For several decades, the mining and exploration industry has been warned about the detrimental effects of getting the geology wrong in mineral resource estimates (MRE). Popular authors in this space such as Coombes (2008), Parker (2004) and Stephenson & Vann (1999) have memorable one-liners on offer in their books to make it clear that we cannot afford to get this wrong. Others have devoted

* r.sterk@rscmme.com, +64 211 78 55 00

their professional careers to the process of domaining and take every opportunity to point out bad practice on social media or other platforms (e.g. Reid & Cowan, 2019). It seems that as an industry we do not need further warning. However, there are still peer-reviewed papers published where the main, and arguably foregone, conclusion is that "…better geological input leads to better and more realistic models" (Gutierrez & Ortiz, 2019, p. 6).

Over the last five years, 'big data' has changed the way we approach data acquisition from exploration programmes. With the availability of core scanners, portable XRF instruments mobile analytical facilities such as Lab-at-Rig™ (Hillis et al., 2014) and integrated sample photography solutions such as Imago™, to name a few, we now have more and better information than ever to constrain our domains using geological data. The introduction of 'implicit modelling' (Cowan et al., 2003) has probably been the most significant recent innovation in the geological modelling and domaining space and provides a fast alternative to traditional, more labour-intensive, 'explicit modelling'. All major software packages now provide implicit modelling functionality in some shape or form. The potential of Machine Learning (ML) in this context is also increasingly recognised (e.g. Oliver & Wilingham, 2016, Gazley et al., 2019, Webb et al., 2019, Whaanga et al., 2019) and the integration of this technique into the space of domaining is the topic of numerous recent peer-reviewed papers and presentations (e.g. Green et al., 2019; McManus et al., 2019, Wedge et al., 2019).

The combination of big data, machine learning and implicit modelling techniques should be the catalyst for a major step change in domaining practices. The days of creating domains purely based on grade due to a lack of any other data should be over. However, the mineral resource estimation discipline is sometimes labelled the most conservative in the general mining industry (Gleeson, 2015). For example, 98% of all 161 initial resource estimations publicised since January 2017 were estimated using a mix of inverse distance (ID) and ordinary kriging (OK) (opaxe, 2019), both 60-year old linear estimation techniques. Change in practice takes time and is not aided by the perpetual display in the public arena of poor or long-superseded domaining practices.

In this paper we present a review of current domaining practice by analysing the last three years of publicly-available MRE reports and identify trends in the definition of domains in MRE. Are new techniques being adopted? How were resource domains constrained and what data were used to create the three-dimensional (3-D) wireframes? What validation processes were followed? We present an insight in current practices and suggest what future domaining workflows may look like. We also propose an improved workflow to generate grade-shell boundaries.

WHY IS DOMAINING IMPORTANT?

The basic principles of the estimation techniques used to estimate the average grades of deposits rely on the rules of statistics. If we agree to use statistics to predict grades at unknown points (often practically represented as discretisation points that represent 'blocks'), based on the data surrounding it, then we must conclude that a model based on inference cannot predict an event that is not represented in the data itself. This leads to the requirement of stationarity within the domains in which we estimate, which is the most important underlying condition of any domains we build. As Dunham (2017) puts it: "we need to ensure the data in our domains are apples and apples, not apples and oranges while at the same time allowing for the possibility that those apples may actually be plums". Glacken & Snowden (2001, p. 190) state that "a geological domain represents an area or volume within which the characteristics of the mineralisation are more similar than outside the domain". Therefore, the practice of domaining can be summarised as the generation of 3-D shapes (often called wireframes, constraints or domains) in which we assume that the controls on mineralisation are monogenetic and within which the data have no trends and are comprised of a monomodal distribution.

Failure to generate domains that adhere to the principle of stationarity may lead to significant bias in block grades and hence to flawed estimates. Sometimes this is inevitable, such as in early-stage exploration projects where there is insufficient data about geological- and grade-continuity. In these circumstances, it is up to the competent person(s) reporting and classifying these estimates to be transparent and to carefully identify the inherent risks. However, even in advanced exploration projects where data

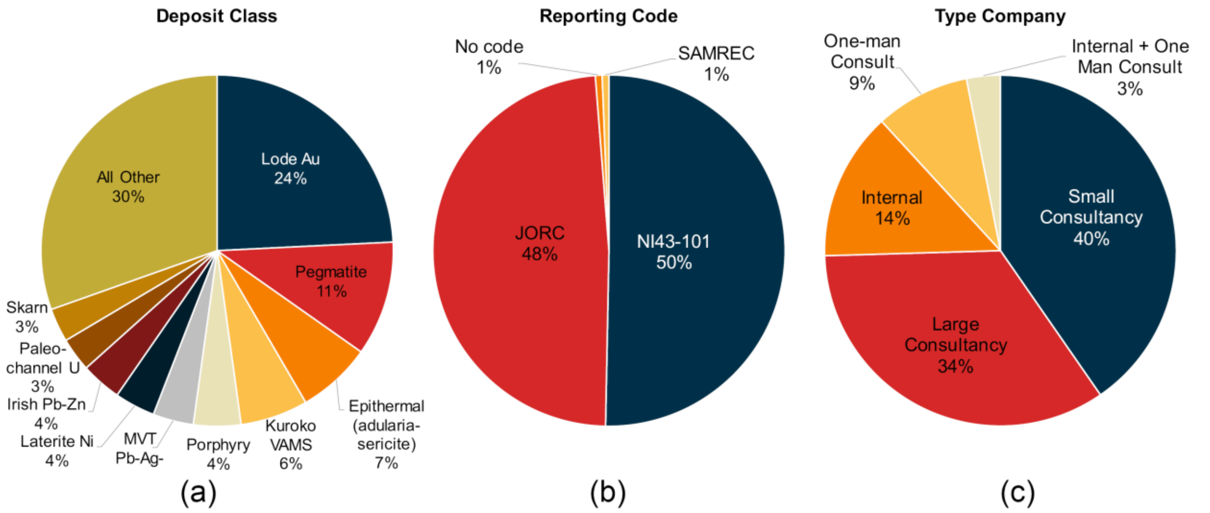

Figure 1 Statistics of the 161 MREs considered in this report showing all reports classed by: a) mineral deposit class; b) reporting code; and c) the type of company issuing the report.

are in abundance, there are too many examples of how a failure to create sound domains has led to substantial downgrades or project failures (e.g. Rubicon's *Phoenix* (Rubicon Minerals, 2016); Midway Gold's *Pan* (Midway Gold, 2015); Torex Gold's El Limón Guajes (Torex Gold, 2016); Golden Queen's *Soledad* (Golden Queen, 2015); Goldcorp's *Cochenour* (Koven, 2016); and Albidon's *Munali* (Albidon Minerals, 2013)).

REVIEW OF LAST THREE YEARS OF DOMAINING PRACTICE

To better understand the uptake of new techniques and to get a view of current domaining practices, we reviewed 161 public reports of mineral resource estimations announced to global markets since January 2017, available through www.opaxe.com. Only *initial* mineral resources (sometimes called 'maiden resources') were reviewed, as resource upgrades or updates typically build on existing domains and information from these reports is biased towards old techniques.

The 161 MREs were classified into 37 different mineral system classes using a customised classification based on the Geoscience Australia system (Geoscience Australia, 2019 and references therein), with the top-three most-reported classes being lode-gold (24%), pegmatite lithium (11%), and epithermal gold-silver (7%) (Figure 1a). A total of 81 reports (50%) cited compliance with NI43-101 and 78 (48%) with the JORC Code (2012) (Figure 1b). A

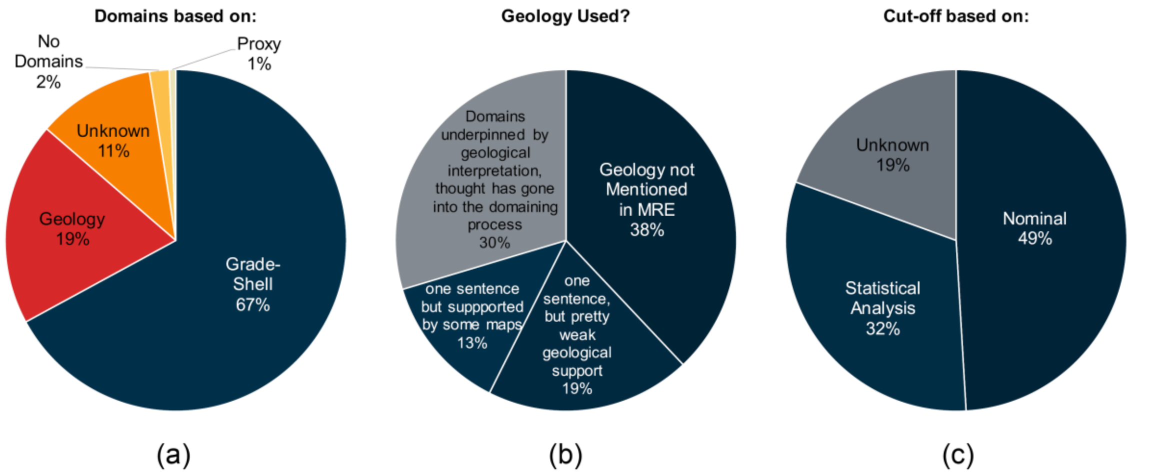

Figure 2 Statistics of the MRE reports showing a) the type of data used for constraining domains; b) a qualitative assessment of the degree to which geological information used in the estimates that used a grade-shell; and c) the type of information used to constrain the cut-off if a grade-shell was used for domaining. In c), 'nominal' captures all instances where cut-off grades were selected without statistical justification.

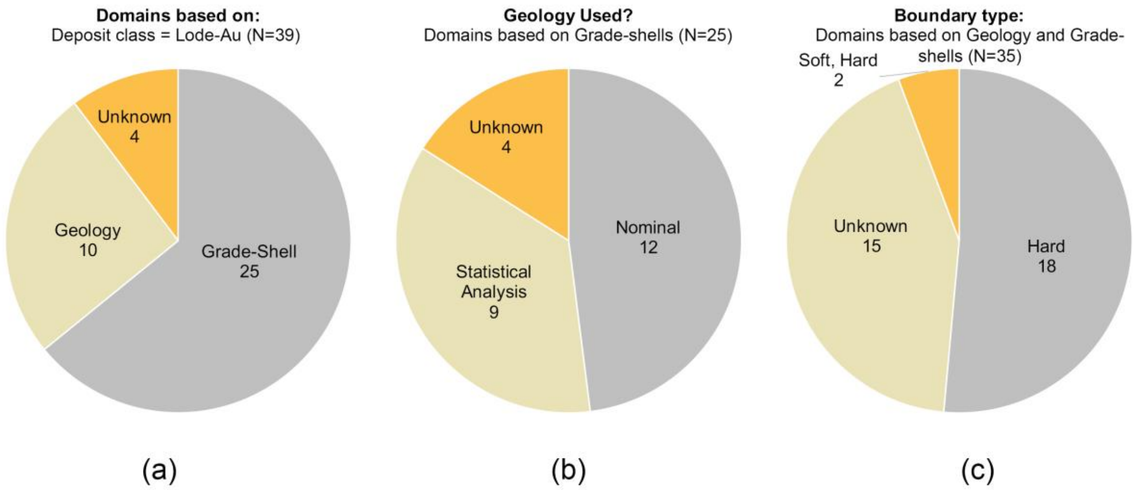

Figure 3 Statistics for the MRE reports of deposits classified as lode-Au (N=39), showing: a) the type of data used for constraining the domains; b) how cut-offs were determined for the models based on grade-shells; and c) the types of domain boundaries for the domains determined based on geology and grade-shells.

total of 40% of MREs were estimated by Competent/Qualified Persons working for small consultancies, 34% by Competent Persons working for large consultancies, and 9% by one-man consulting companies (Figure 1c). An additional 14% of MREs were carried out internally without involvement of external consultants, whereas 3% of MREs were reported internally with the estimation work done by consultants (Figure 1c).

Eighteen of the 161 reports did not document how domains were constrained. The lack of such information may constitute a breach of the various reporting codes that require this information to be included. Important information on geology and controls on mineralisation, deposit style are mandatory headers that are addressed under specific chapter numbers in NI43-101 and were therefore easy to extract. By contrast, for MREs reported in accordance with JORC, this information was comparatively more difficult to find or insufficiently documented. Based on the 161 reports reviewed here, such shortcomings in MRE reports are largely limited to the estimates carried out by small consultancies and internal resource staff; larger consultancies typically report this information sufficiently.

In 108 of the 161 MREs (67%), domains were constrained using grade-shells, based primarily or exclusively on a grade cut-off (Figure 2a). The cut-off grade was either applied to a single element (85%), or to a metal equivalent of more than one element (15% of reports, equivalents calculated based on metal prices at the time of reporting). For 38% of the MREs that constrained domains using grade-shells, no information was provided on the geological relevance of the resulting wireframes (i.e. no comment made on whether mineralisation was mapped properly and if the resource geometry reflected the geological interpretation) (Figure 2b). In 32% of MRE reports, some form of statistical analysis was discussed to justify the cut-off grade (Figure 2c). However, the majority of these discussions centred around the (subjective) appraisal of an inflection point on a cumulative probability grade graph and lacked statistical justification. For nearly half of the estimates using grade-shells (49%), no statistical analysis was carried out to justify the cut-off grade and grades were picked either nominally or by referring to “common practice”, or “analogous settings” (Figure 2c). For 20% of MRE reports it was unclear how the cut-off grade was determined. In 55% of all MRE reports, no comment was made on the nature of the contacts or boundaries (i.e. if they were ‘hard’ or ‘soft’). For the 100 MREs that were domained using grade-shells, 69% were modelled by explicit techniques, while 31% were modelled using implicit techniques.

The ability to rely on geological information to support domains may depend on deposit style. Building good domains in structurally complex gold deposits with various overprinting mineralisation events hosted in otherwise undifferentiated rocks may be more difficult than for instance in pegmatite-hosted deposits.

In a breakdown of domaining practices by style class, of the 39 projects classified as lode-Au deposits, which includes a mix of alteration-, lithology-,

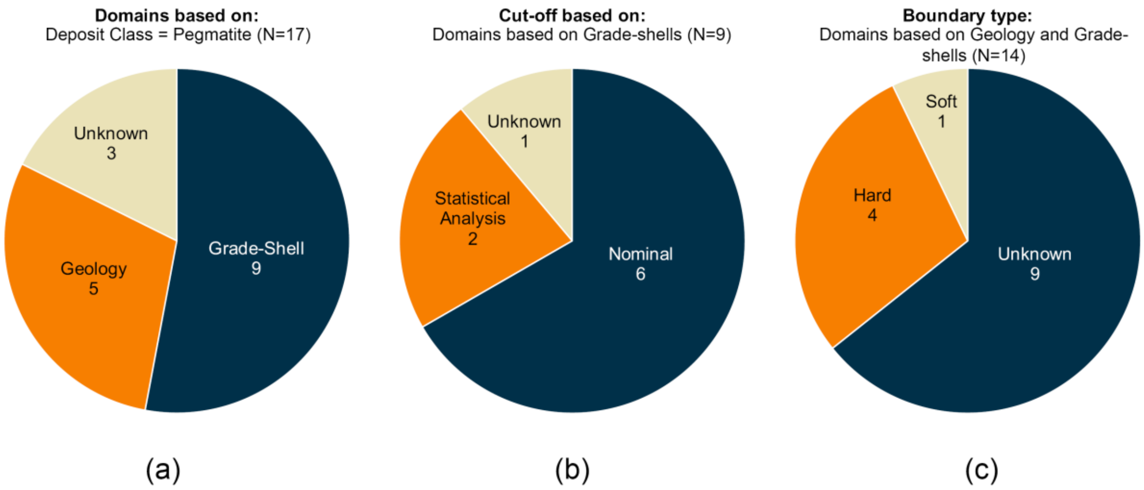

Figure 4 Statistics for the MRE reports of deposits classified as pegmatite (N=17), showing: a) the type of data used for constraining the domains; b) how cut-offs were determined for the models based on grade-shells; and c) the types of domain boundaries for the domains determined based on geology and grade-shells (if known).

vein-, and shear-hosted deposit types, 10 were domained based on geology and 25 were domained using grade-shells (Figure 3a). In the remaining four reports, domaining was not discussed or domains were not used. Of the 25 MREs domained using grade-shells, cut-off grades ranged from 0.05 g/t Au to 1.0 g/t Au. Five reports did not specify what cut-off grade was used. The majority of the estimates (60%) were based on cut-off grades for the grade-shells higher than 0.25 g/t Au. Nine reports supported the chosen cut-off grade with a statistical analysis (Figure 3b), generally an appraisal of the cumulative-probability grade plot. Of the 35 reports that were domained using either geology or grade-shells, 18 defined the ore-waste contacts as hard, two as a combination of soft and hard, and 15 did not report the nature of the contact (Figure 3c).

Of the 17 projects classified as pegmatite deposits, five were domained using geology and nine were domained using grade-shells (Figure 4a). Three reports provided insufficient information to understand what domaining approach had been applied. Of the nine MREs domained using grade-shells, cut-off grades ranged from 0.2% to 0.5% Li_2O. One report did not specify the cut-off grade. Two reports justified the chosen cut-off by a statistical analysis, generally an appraisal of the cumulative probability grade plot (Figure 4b). Four MRE reports determined a hard contact for the domain, while nine MRE reports did not describe the nature of the contact and one reported a soft/gradational boundary (Figure 4c). The data suggest that regardless of the more obvious geological contrast present in pegmatite-hosted deposits, grade-based domains are as common as they are in the more complex lode-gold deposits.

Of the 161 initial resource estimates, 67% were modelled with explicit techniques and 33% with implicit techniques. Additionally, 98% of MREs were estimated using a mix of inverse distance (20%) and ordinary kriging (78%) while 2% were estimated by Multi-Indicator Kriging. Machine learning was not discussed in any of the reports to have been used as a tool to generate or support domains. Only one report specifically referenced multi-element geochemistry and down-hole geophysical data as important proxies to support geology-driven domains. Generally, where grade-shells were used to constrain domains, this was done so without reference to- or validation against geological observations or interpretations. For most reports, the geological justification of the domain-building process is limited to statements such as: “domains were generated using grade-shells, whilst still honouring the geology”.

DISCUSSION: BEST PRACTICE VS COMMON PRACTICE

The review of the last three years of initial MRE reports suggests that despite recent technological advancements and warnings about the importance of high-quality domaining, there is little unity in the approach to domain definition. In principle, one might

argue, this seems perfectly reasonable, as no two deposits are the same. Moreover, the public reporting codes we adopt put considerable faith and trust in the competence of the Competent Person and allow the estimator the freedom to apply their experience to the process of MRE. However, the clear lack of geology as a first-order driver for the domaining process, the lack of statistical validations for cut-off grades, the lack of contact or boundary analysis, the widespread use of unsubstantiated and often too-high grade-shell cut-offs, as well as the repeated reminders of high-profile resource downgrades due to poor domaining practice, suggest that warnings about the importance of geology have not yet lost their purpose.

At the root of the issue is a lack of best-practice examples, case studies and other educational material. The authors are not aware of any books on domaining, and popular consultant-driven MRE courses merely state that 'good domaining is important' without covering the practice in any detail. There is simply no standard; and thus there is no clear distinction to incoming practitioners between best practice and common practice. How practitioners apply domaining is to a large degree determined by who they learn from, which can lead to the perpetuation of bad practice. Over time, due to a lack of good education and an absence of regulation or control, bad practice turns into common practice. In addition, with the onset of user-friendly implicit modelling software with intuitive user interfaces that make it easier to create blobs from drill hole data, there is now a further deepening of the chasm (e.g. Reid & Cowan, 2019). At least with the explicit-modelling approach, someone had to show a new practitioner the functionality of the (hundreds of) different buttons and complex workflows to create the desired outcome and there was some knowledge transfer in the process. As an industry, we seem obsessed with our competent persons' freedom to make just about any technical decision as they see fit, with no system in place to call them to account.

IMPROVEMENTS TO DOMAINING PRACTICE

To improve the standard of domaining, we provide a number of high-level recommendations and suggestions, directed to the industry, as well as some easily implementable rules of good practice that practitioners can adopt in their daily domaining workflows.

High-Level Recommendations and Suggestions

1) The AusIMM and kindred groups that have "to set and maintain high professional standards for their members" as one of their key purposes should take ownership and generate an industry best practice standard, similar to the AusIMM's Monograph 30 on Mineral Resource Estimation, with specific focus on domaining practices.
2) Improve accountability for CPs carrying out sub-standard work.
3) Highlight, and make more accessible, examples of good practice as well as bad practice; for example, information services such as www.opaxe.com can play a role in providing practitioners with a centralised repository of technical information.
4) Software developers should take ownership and create educational material on how to best use their software; it is in their own interest for their software to be used consistent with best practice.
5) Course material provided by consultants and other 3rd parties should have a stronger focus on domaining best practice, rather than just the nuts and bolts of geostatistics.
6) Address the fundamental skill issue at deeper levels and create educational materials at entry-level for students and young professionals to learn about modelling, stationarity and including structural controls on mineralisation into models. Geological mapping skills are fundamental to building realistic resource models and should receive stronger emphasis in university programmes.

Rules for Good Domaining Practice

Rule #1: Use geological information as primary input for the domains, complemented by proxies for geology (such as geophysical, geochemical, petrophysical and photographic data)

Only 31 of the 161 MREs published since 2017 used geological parameters as the primary source for its domaining, and only one study had included proxies for geology. Paragenesis, plunge orientations, small-

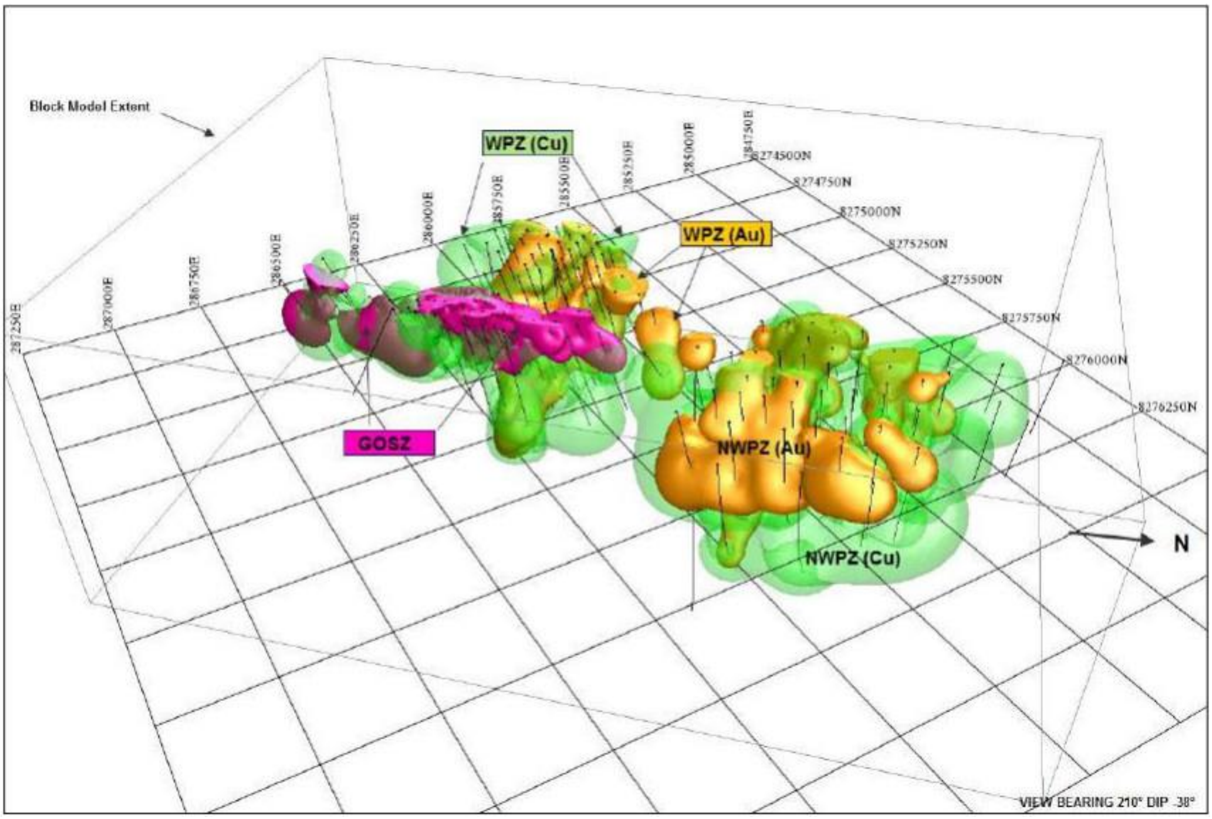

Figure 5 Example of an unrealistic 'blobby' model lacking any structural control. From: Reid, 2017

scale as well as deposit-scale structural architecture are critical ingredients to any resource estimation process. Invest in getting specialist advice on your deposit. Even deposits drilled via reverse circulation are no excuse for lack of structural data. Down-hole optical techniques have been available for several years and allow the same structural interpretations as from diamond core for only a few dollars per metre extra (Nielsen, 2017).

Proxies for geological information are a significantly underutilised resource that can provide important information on structure, mineralisation geometry and other relationships (e.g. King, 2019; Browning et al., 2019; Reid et al., 2019; Webb et al., 2019). For instance, multi-element geochemistry collected using portable XRF instruments provides elemental concentrations of typically around 25 elements. In combination with data reduction techniques such as principal component analysis, it is often possible to identify geochemical fingerprints of units with different geological characteristics (e.g. Gazley et al, 2015; Caciagli, 2015; Brauhart et al. 2016; Ordóñez-Calderón & Gelcich, 2018). Many of these units are often difficult to consistently log visually by geologists, who will inevitably introduce subjective bias in the logging, regardless of the quality assurance procedures in place. Following this, mapping of geological units will often allow interpretation of primary structural controls and constrain the geometries of mineralisation. Additionally, automatic core scanning facilities can now produce images where pixels can be classified to a 1 mm resolution. These classifications can be imported straight into modelling software where some (such as Seequent's Leapfrog™) allow immediate implicit modelling of each classification. Depending on the style of mineralisation this could also allow identification and implicit modelling of alteration minerals and zones, quickly and cost-efficiently.

Rule #2: Appreciate the difference between geological domains and estimation domains.

Regardless of Rule #1, it is important to note that estimation domains are not the same as geological domains. Domains based on primary geological data (e.g. "Lith1") often lack the resolution to separate different phases of mineralisation, leading to multimodal distributions or trends in the numerical data within a single geological domain. By contrast, models based exclusively on numerical data (e.g. grade-shells) often do not adequately represent reality either and in the hands of the inexperienced operator, often turn a deposit where mineralisation is controlled by various different structural trends into

a messy mix of 'blobs' (Figure 5). This is far from a representative model of the true geology and such models should never underpin any subsequent feasibility studies and are the result of widespread ignorance of how structural geological architecture plays a key role in the geometry of mineralisation (Cowan, 2017; Reid & Cowan, 2019).

Rule #3: Regard the process of domaining as an iterative process

Following Rule #2, geological and numerical data need to be reviewed together in order to end up with robust estimation domains. The domain building process is typically iterative and geological and numerical data are both used to build, validate and adjust any domains. Geology should always be the main control and the final model should represent as best as possible 'the rocks as they occur'.

Sound, iterative, workflows that integrate estimation domains with geological domains in sensible ways are part of the modern resource geologist's toolkit. The process of building domains, analysing the data within each domain, and then readjusting the domains, is critical to getting meaningful and representative estimates of mineral deposits.

Rule #4: Check for statistical stationarity

At the end of each iteration (Rule #3) there should always be a test of statistical stationarity. The issue of stationarity was only addressed in 2 of 161 reports. Although this may be a reporting issue (it was carried out but not reported), since statistical stationarity is critical to the integrity of the entire MRE process, it should be a standard procedure to include in any technical report. We recommend the simple grid-based variance review approach (Coombes, 2016), or similar, as a minimum requirement.

Rule #5: Treat grade-based domains appropriately

Grade-based domains may be perfectly acceptable if they have been created honouring the geology, their geometries have been verified against the structural data, and the statistics within the domains have been assessed for stationarity. However, there are too many estimates published where the domains have been established by economic parameters, or where

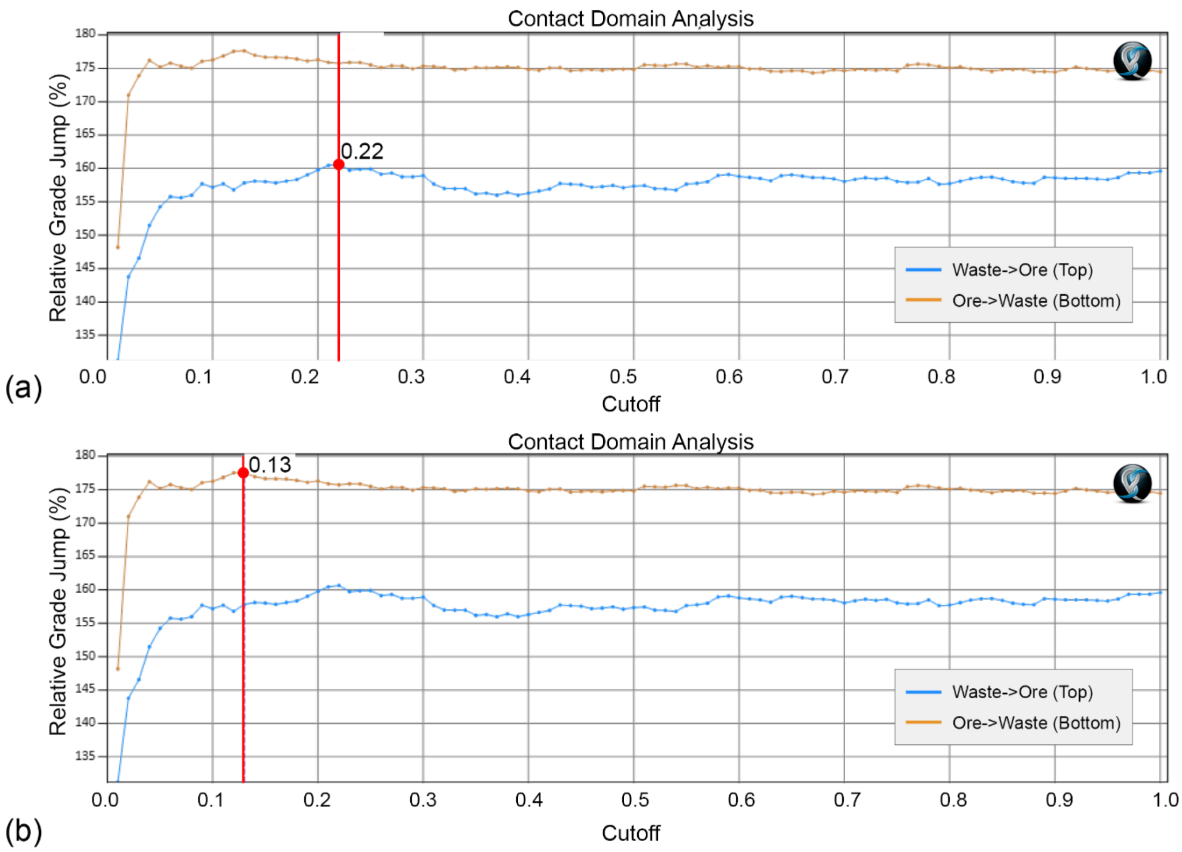

Figure 6 Phinar X-10 allows for testing of different cut-off grades by comparing the average grades of the first metre inside and the first metre outside the grade-shell. a) the maximum contrast for the waste-ore top boundary is found at a cut-off of 0.22 g/t Au; b) the maximum contrast for the ore-waste bottom boundary is found at a cut-off of 0.13 g/t Au.

a lack of understanding of implicit modelling techniques has resulted in short grade intervals being modelled into a surreal cluster of blobs (Figure 6, c.f. Reid & Cowan, 2019). The use of economic grade cut-offs or combined multi-element grade cut-offs based on element conversions (e.g. using a 'Au-equivalent' cut-off grade for an Au-Ag-Mo deposit) should *never* be used. The distribution of the element of interest within the stationary domain is simply not dependent on dollars or the market. Remember that if we agree to use statistics to predict grades at unknown points, based on the data surrounding it, then we must conclude that a model based on inference cannot predict an event that is not represented in the data itself, or with data that is curtailed by artificial grade cut-offs.

Take gold as an example: the average grade-shell cut-off used by practitioners in the last three years was 0.5 g/t Au. By effectively excluding material between 0.1 and 0.5 g/t Au from the MRE, the estimation is going to result in fewer tonnes at a higher grade. The practice of setting high grade cut-offs for resource grade-shells may be premeditatively, yet often unknowingly, used by practitioners to offset the well-known volume-variance effect (the observation that when mining the resource, lower tonnages and higher grades are achieved when the cut-off grade is lower than the resource mean grade). However, more realistic grade-tonnage curves are achieved by using far lower grade-shell cut-offs that appropriately mark the boundary of a mineralised domain and isolate a statistical population. The volume-variance effect can be dealt with afterwards through a process of variance correction (Rossi & Deutsch, 2013).

Grade cut-offs should be based on statistical evaluation of the difference between background concentration and enrichment and should be underpinned by geological evidence. A statistical evaluation could be a visual evaluation of an inflection point on a cumulative probability plot. However, a much more effective workflow is to review the maximum difference (expressed by the coefficient of variation) between the average grade of all first metres *outside* a zone of mineralisation and all the first metres *inside* a zone of mineralisation for a range of different cut-offs. The grade cut-off where this difference is largest presents the maximum geological contrast between waste and mineralisation and represents a geologically justifiable domain boundary. Effectively, this process is the same as looking at the maximum inflection point in a cumulative probability plot, but it has the important advantage that it is geospatially relevant and is not just based on a total average distribution curve. To the authors' knowledge, the only software currently providing this capability is Phinar X-10. In Pinar X-10, the user sets a maximum internal dilution and maximum consecutive dilution and the software creates unmineralised and mineralised intervals for a range of cut-off grades, specified by the user. The software also allows grade cap settings. It then calculates the average contrast between unmineralized and mineralised zones for each grade cut-off and visualises this in two graphs (Figure 6). The user can then select the maximum contrast and generate a contact analysis for that grade cut-off to check the nature of the contact (e.g. hard/abrupt or soft boundaries) (Figure 7).

Although the grade cut-off may not have a large impact on the grade-tonnage curve or the quality of the estimate, this must always be verified and the sensitivity of the model to different grade cut-offs should be reported in the public report. It is clear from this work that this rarely happens.

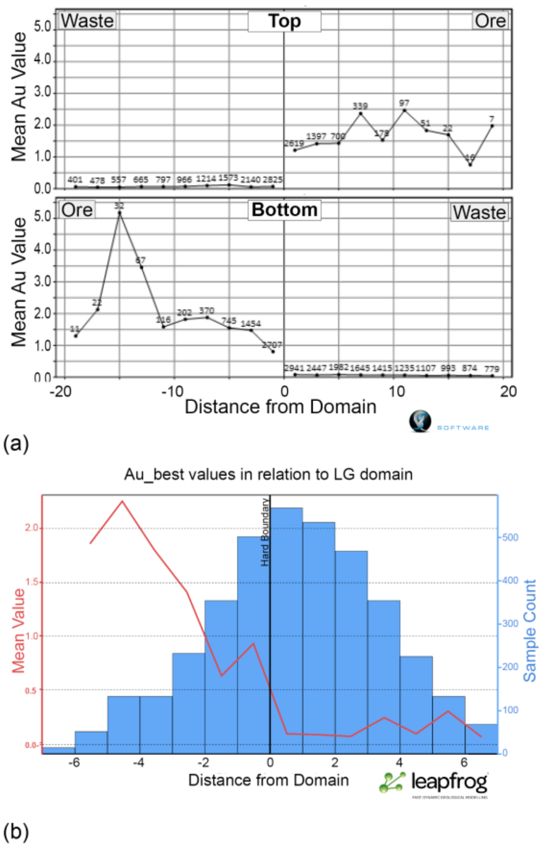

Figure 7 Domain boundary analysis carried out in a) Phinar X-10 and b) Leapfrog Edge.

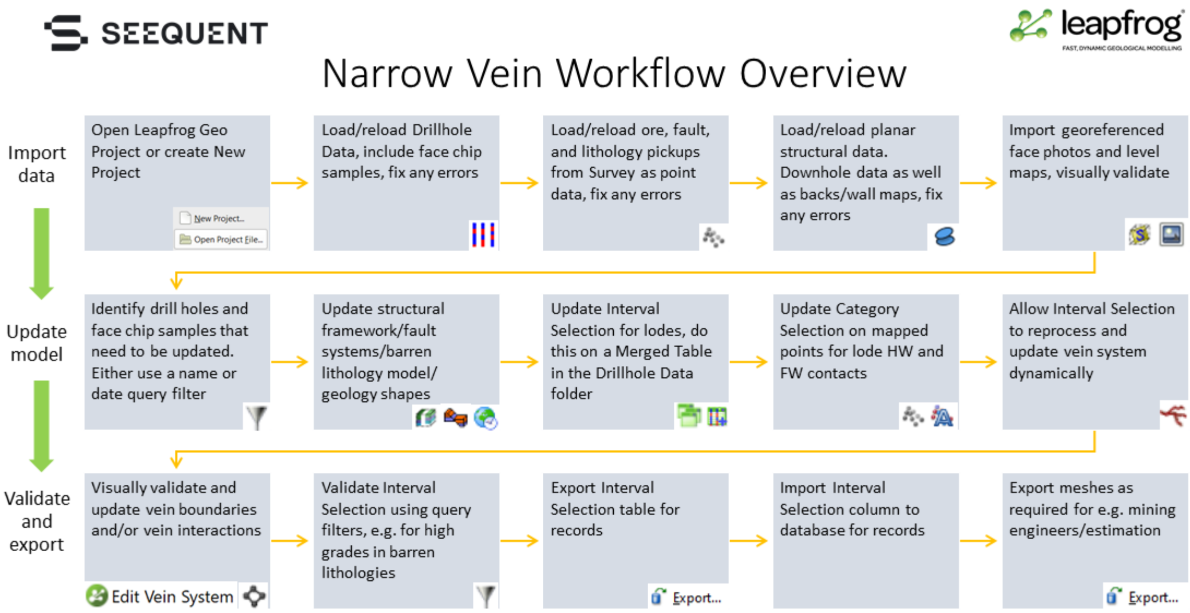

Figure 8 Narrow vein modelling workflow in Leapfrog Geo (Reid 2019, Pers. Comm.).

Rule #6: Carry out a boundary analysis.

Boundary analysis is an important tool to investigate whether ore-waste contacts are abrupt 'hard' or gradational 'soft' boundaries. This analysis not only provides important input for the estimation process but can also reveal important trends around the contact that could invalidate the supposition of stationarity in the domain.

Phinar X-10 software automatically creates contact plots once a grade cut-off with maximum contrast has been selected. Seequent's Leapfrog software automatically creates contact analysis plots once grade-shells have been generated and an estimation workflow has been added. The Leapfrog boundary analysis has the advantage that it is calculated perpendicular to the actual domain boundary.

Rule #7: Use implicit techniques where possible but use them wisely.

As an industry we need to come to terms with the fact that the benefits of implicit techniques outweigh their disadvantages (Gleeson, 2015). However, note that the boundary between implicit and explicit techniques has become fuzzy (Kentwell, 2019) and that many of the modern implicit workflows are heavily dependent on many explicit user settings. Most importantly, implicit modelling is superior in that it is much faster, and facilitates the sensitivity testing of different model assumptions. The ability to test different hypotheses simultaneously by running models on multiple computer processing cores, makes implicit modelling a powerful tool to resolve domaining and other sensitivity issues. Through advances in computer power and implicit modelling algorithms, this process can now be executed far more efficiently than it could 15 years ago, but an understanding of the software is important to avoid poor-quality outcomes.

For those working in a hard-boundary and narrow-vein environment who are still on the fence, Seequent's Leapfrog has excellent workflows that handle such deposits and honour the geology and create models far superior to those generated via explicit methods (Figure 8).

Rule #8: Report what you have done.

Our analysis suggests that important aspects of the MRE process are commonly not sufficiently documented. Common issues are:

1) a description of the controls on mineralisation is missing, or the geological model is absent, or only available in minimal format. This issue is more common in documents that state adherence to the JORC Code (2012);

2) the extent to which geological information was used in the generation of estimation domains is not discussed;

3) the rationale for the choice of cut-off grades for domains is not presented;

4) boundary conditions are not discussed, or plots are not presented; and

5) no discussion on the sensitivity to different geological models or domaining approach is presented.

Since project failures often stem from inadequate domaining at the MRE stage, the above information should always be transparently reported so that investors can appropriately ascertain the risk in the project.

CONCLUSIONS

The clear lack of geological input in the domaining process for MREs published since 2017 suggests that regardless of the doctrine that geology is important, the mining and exploration industry is not doing a very good job of adhering to its basic principles. Moreover, while having abandoned geology as a primary control on domains in the estimation process, it is clear that our collective approach to using grade-shells is flawed as well. At the root of this issue is a lack of good education and an absence of clear standards, a lack of framework in which good and bad domaining practices can be identified, and a perpetuation of bad practice masked as common practice.

REFERENCES

Albidon Minerals, 2012. Material Resource Downgrade [press release], Available from: <https://www.asx.com.au/asxpdf/20121108/pdf/42b25mlj3c41md.pdf> [Accessed: 11-11-2019].

Brauhart, C, Grunsky, E and Hageman, S, 2016. Magmato-hydrothermal space: A new metric for geochemical characterisation of metallic ore deposits, *Ore Geology Reviews*, 86(2017):867-895.

Browning, F, Clark, H, Ulrich, S and Clark, F, 2019. Developing the Geological Model for Sunrise Dam Gold Mine – Insights from Exploration to Mining presented to Mining Geology Conference, 25-26 November 2019, Perth, Australia.

Caciagli, N, 2015. Multielement Geochemical Modelling for Mine Planning: Case Study from an Epithermal Gold Deposit, *Proceedings International Workshop on Compositional Data Analysis* 2015, pp 45-61 (Springer: Cham, Switzerland).

Coombes, J, 2008. *The Art and Science of Resource Estimation: A Practical Guide for Geologists and Engineers* (Coombes Capability: Perth, Australia).

Coombes, J, 2016. *I'd Like to be OK with MIK, UC? A Critique of Mineral Resource Estimation Techniques*, 261 p (Coombes Capability: Perth, Australia).

Cowan, E, 2017. The fundamental reason why your geological models may be completely wrong [blogpost], Available from: <https://www.orefind.com/blog/orefind_blog/2017/10/23/the-fundamental-reason-why-your-geological-models-may-be-completely-wrong> [Accessed: 11-11-2019].

Cowan, E, Beatson, R, Ross, H, Fright, W, McLennan, T, Evans, T, Carr, J, Lane, R, Bright, D, Gillman, A, Oshust, P and Titley, M, 2003. Practical Implicit Geological Modelling, *Proceedings 5th International Mining Geology Conference* 2003, pp 89-99 (Australian Institute of Mining and Metallurgy: Carlton, Victoria).

Dunham, S, 2017. The Truth About Estimation #6 – The Domain Dilemma. [blogpost], Available from: <https://sd2.com.au/2017/11/28/the-truth-about-estimation-6-the-domain-dilemma/> [Accessed: 08-11-2019].

Gazley, M F, Collins, K S, Robertson, J, Hines, B R, Fisher, L A and McFarlane, A, 2015. Application of principal component analysis and cluster analysis to mineral exploration and mine geology, *Proceedings AusIMM New Zealand Branch Annual Conference* 2015, pp 131-139 (Australian Institute of Mining and Metallurgy: Dunedin, New Zealand).

Gazley, M F, Hood, S H and Sterk, R, 2019. Machine Learning and Resource Geology, presented to Mining Geology Conference, 25-26 November 2019, Perth, Australia.

Geoscience Australia, 2019. Mineral Deposits Mineral Systems and Mineralising Events [online], Available from: <https://www.ga.gov.au/scientific-topics/minerals/mineral-exploration/deposits-events> [Accessed: 12-11-2019].

Glacken, I and Snowden, D, 2001. Mineral Resource Estimation, in *Mineral Resource and Ore Reserve Estimation - The AusIMM Guide to Good Practice.* (ed: A Edwards), pp 189-198 (The Australasian Institute of Mining and Metallurgy: Melbourne, Australia).

Gleeson, P, 2015. "Is Implicit Modelling Reliable Enough For Use in Resource Domaining?" [blog-post], Available from: <https://www.seequent.com/is-implicit-modelling-reliable-enough-for-use-in-resource-domaining/> [Accessed: 11-11-2019].

Golden Queen, 2015. Golden Queen Mining Company Ltd. Provides Update on Resource Estimates, Reserve Estimates and Construction Progress at Soledad Mountain [press release], Available from: <https://www.goldenqueen.com/assets/docs/2015-02-10_NR.pdf> [Accessed: 11-11-2019].

Green, C, Sanderson, H, Carter, D and Sullivan, S, 2019. Deep Learning - A New Paradigm for Domain Modelling presented to Mining Geology Conference, 25-26 November 2019, Perth, Australia.

Gutierrez, R and Ortiz, J, 2019. Sequential Indicator Simulation with Locally Varying Anisotropy–Simulating Mineralized Units in a Porphyry Copper Deposit, *Journal of Mining Engineering and Research*, 1(1):1-7.

Hillis, R R, Giles, D, Van der Wielen, S E, Baensch, A, Cleverley, J S, Fabris, A, Halley, S W, Harris, B D, Hill, S H, Kanck, P A, Kepic, A, Soe, S P, Stewart, G and Uvarova, Y, 2014. Coiled Tubing Drilling and Real-Time Sensing - Enabling Prospecting Drilling in the 21st Century?, *Society of Economic Geologists Special Publication*, 18:243-259.

Joint Ore Reserves Committee of The Australasian Institute of Mining and Metallurgy Australian Institute of Geoscientists and Minerals Council of Australia, 2012. *Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves*. http://www.jorc.org.

Kentwell, D, 2019. Destroying the distinction between implicit and explicit geological modelling, presented to Mining Geology Conference, 25-26 November 2019, Perth, Australia.

King, A R, 2019. Applying Geophysics to Mining Geology Problems, presented to Mining Geology Conference, 25-26 November 2019, Perth, Australia.

Koven, P, 2016. Goldcorp Inc cuts dividend, lowers production guidance for next three years, *Financial Post, 25 February 2016, Available from: <https://business.financialpost.com/commodities/mining/goldcorp-inc-cuts-dividend-posts-bigger-quarterly-loss-on-us3-9-billion-charge>*.

McManus, S, Rahman, A, Horta, A and Coombes, J, 2019. Applied Bayesian Modeling for Assessment of Interpretation Uncertainty in Spatial Domains, presented to Applied Statistics and Policy Analysis Conference, 5-6 September, 2019, Wagga Wagga, Australia.

Midway Gold, 2015. Midway Gold Updates Pan Modelling [press release], Available from: <http://www.midwaygold.com/_resources/news/2015.05.11.pdf> [Accessed: 11-11-2019].

Nielsen, S H H and Franey, D, 2017. Downhole Logging in 3D Geology and Mineral Potential Modelling, presented to AusIMM NZ Branch Conference, 11-13 September 2017, Christchurch, New Zealand.

Oliver, S and Willingham, D, 2016. Maximise Orebody Value through the Automation of Resource Model Development Using Machine Learning, *Proceedings 3rd International Geometallurgy Conference 2016* 2016, pp 295-301 (Australian Institute of Mining and Metallurgy: Perth, Australia).

opaxe, 2019. Resource Reports Database [online], Available from: <www.opaxe.com> [Accessed: 11-09-2019].

Ordóñez-Calderón, J C and Gelcich, S, 2018. Machine learning strategies for classification and prediction of alteration facies: Examples from the Rosemont Cu-Mo-Ag skarn deposit, SE Tucson Arizona, *Journal of Geochemical Exploration*, 194:167-188.

Parker, H M, 2004. Harry M. Parker GAA Honorary Life Member [online], Available from: <http://www.gaa.org.au/pdf/GAA_Hon_Life_Member_harry_parker.pdf> [Accessed: 12-11-2019].

Reid, D, Harvey, G and Glasson, M, 2019. Regolith domain modelling using multivariate cluster analysis at Mt Thirsty Co-Ni Deposit presented to Mining Geology Conference, 25-26 November 2019, Perth, Australia.

Reid, R, 2017. Implicit Modelling disasters in the making – Part 1 [blogpost], Available from: <https://www.linkedin.com/pulse/implicit-modelling-disasters-making-part-1-ron-reid/> [Accessed: 22-11-2019].

Reid, R and Cowan, E, 2019. Toward Robust and Reliable Implicit Geological Models, presented to Mining Geology Conference, 25-26 November 2019, Perth, Australia.

Reid, Z, 2019. Narrow Vein Modelling Workflow Discussion, 18 November 2019.

Rossi, M E and Deutsch, C V, 2013. 7.3 Volume Variance Correction, in *Mineral Resource Estimation*, pp 122-128 (Springer Science & Business Media: Dordrecht, The Netherlands).

Rubicon Minerals, 2016. Underground Activities Temporarily Suspended at the Phoenix Gold Project; Rubicon to Enhance Its Geological Model and Develop an Implementation Plan [press release], Available from: <https://rubiconminerals.com/Investor-News/News/Press-release-details/2015/Underground-Activities-Temporarily-Suspended-at-the-Phoenix-Gold-Project-Rubicon-to-Enhance-Its-Geological-Model-and-Develop-an-Implementation-Plan/default.aspx> [Accessed: 11-11-2019].

Stephenson, P and Vann, J, 1999. Common Sense and Good Communication in Mineral Resource and Ore Reserve Estimation, *Proceedings Pacrim* 1999, pp 435-444 (Australian Institute of Mining and Metallurgy: Melbourne, Victoria).

Torex Gold Resources Inc., 2016. Torex Announces Q1 2016 Results And Updated Life Of Mine Plan [press release], Available from: <https://www.torexgold.com/news/torex-announces-q1-2016-results-and-updated-life-of-mine-plan> [Accessed: 24-11-2019].

Webb, L, Grujic, M and Truong, D T, 2019. The Application of Deep Learning to Extract Geological Information from Drill Core, presented to Mining Geology Conference, 25-26 November 2019, Perth, Australia.

Wedge, D, Hartley, O, McMickan, A, Green, T and Eun-Jung, H, 2019. Machine learning assisted geological interpretation of drillhole data: Examples from the Pilbara Region, Western Australia, *Ore Geology Reviews*, 114.

Whaanga, A, Vigor-Brown, W and Nowland, S, 2019. The implementation of photogrammetry and automated data analysis functions at the Waihi Underground Gold Mine presented to Mining Geology Conference, 25-26 November 2019, Perth, Australia.