AEGC Australasian Exploration Geoscience Conference | Brisbane 2023

Recognising, qualifying, and managing uncertainty in mineral exploration data and resource estimates

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SUMMARY

Uncertainty is present in all aspects of mineral exploration, resource evaluation, feasibility studies and operations. It represents a key contributor to both technical and commercial risk facing projects that requires considered, systematic management. Multiple sources of uncertainty are present at all stages of resource project development, from the earliest stages of exploration to completion of bankable feasibility studies. These may be classified as:

1. Internal: largely technical in nature and frequently able to be managed and even quantified through quality assurance measures and parallel collection of confirmatory data; and,
2. External: frequently associated with critical issues affecting security of tenure, access to land and permitting of specific work, particularly when land disturbance or disruption of existing land use may result.

Bias, which is frequently an unintended consequence of a geoscientist's experience with comparable projects can also be a significant contributor to uncertainty.

Every mineral deposit should be considered unique to help ensure that it is evaluated on its merits. Importing practices applied to the evaluation of other deposits helps to ensure that the contribution and value of previous experience is maximised, but care must be taken not to adopt a recipe approach that may overlook significant features that combine to determine the deposit's potential and development options.

Opportunities for improved management of uncertainty exist in cross-pollination and adaption of techniques and experience between the minerals and oil and gas sectors. Mineral resource projects progress through a series of stages, each of which have distinct sources of uncertainty that become more diverse as projects mature.

Maintenance of a project audit trail is essential. Transitioning from spreadsheets and file notes to a structured, curated and accessible set of records has benefits for any project and is supported by developments in cloud computing communications and information processing technologies.

Key words: exploration, mining, resources, uncertainty, geostatistics

INTRODUCTION

Uncertainty is present in all aspects of mineral exploration, resource evaluation, feasibility studies and operations. It represents a key contributor to both technical and commercial risk faced by projects that requires considered, systematic management through:

- Recognising sources of uncertainty and taking specifically targeted actions to characterise, mitigate or even eliminate them.
- Understanding the impacts of risks affecting specific aspects of projects.
- Examining how uncertainty affecting one aspect of a project may contribute to further increase uncertainty in another. This is particularly true of uncertainty affecting data which become embedded in interpretations on which further decisions affecting assessments of a project's potential and future value are based.

Multiple sources of uncertainty are present in:

- When information is collected during a project and the time taken between collecting and testing samples during which the character of samples may change, primarily due to loss of moisture present in samples, or due to oxidation.
- How geological features are interpreted to exist between points of observation provided by geological mapping and drilling and informed by other sources of information, notably geophysical survey data;
- Estimates of grade, mineralogy, rock mass properties and other factors contributing to a mineral deposit's character;

- The consistency and availability of geological and related information used to support technical and commercial decisions; and,
- Bias, which is frequently an unintended consequence of a geoscientist's experience with comparable projects, The prediction and evaluation of mineral resources, the uncertainties of geological body and characteristics and geological process lead to errors in the prediction of geological anomalies and mineralisation, while the uncertainties of geological data and geological measurement inaccuracy and inaccurate expression of measurement results can also cause errors in geological forecast data and project value through life of mine.

Recognising potential sources and forms of uncertainty is essential to identify and implement measures to effectively manage it through measuring its significance or even eliminating it as a source of concern, which is a key role of data quality assurance. Ensuring the quality of data allows greater focus on uncertainty introduced during the development of interpretations.

Every mineral deposit should be considered unique to help ensure that it is evaluated on its merits. Importing practices applied to the evaluation of other deposits helps to ensure that the contribution and value of previous experience is maximised, but care must be taken not to adopt a recipe approach that may overlook significant features that combine to determine the deposit's potential and development options. Resource evaluation must also focus on geological features. Introducing consideration of mining parameters, such as the potential for selectivity during mining in developing sampling strategies, can be value destructive and lead to misleading, unduly conservative estimates of a project's value.

The oil and gas sector is arguably more attuned to the need to identify and manage exploration and resource evaluation risks than many minerals focussed groups, possibly reflecting the reliance on relatively few wells (drill holes) providing sampling information due to their cost. Most minerals drill holes, individually, represent a far less significant investment. The data that they provide is, however, no less significant in the evaluation and development of projects. Techniques adopted by the oil and gas sector can be applied directly and productively in mineral resource evaluation to improve technical effectiveness. Examples include use of high resolution seismic surveys to provide continuos geological information between points of observation, downhole geophysical logging, where compact instrumentation able to directly measure rock mass properties in relatively narrow drill holes used in mineral exploration and resource evaluation is being developed, measure while drilling instrumentation able to collect geotechnical and other data during drilling, and stochastic techniques for geostatistical dimension reduction, with applications in domaining data, and measuring uncertainty inherent in resource estimates.

In the subsequent sections we will outline a common progression for mineral resource projects and target potential areas for improvements to existing workflows. This will be done by identying similar workflows from other industries (e.g. oil and gas, statistics and data science) and applying their learnings to mineral resource evaluation. This should ensure that uncertainty present at all stages of a development project is better characterised, understood and communicated to stakeholders.

EXPLORATION AND RESOURCE EVALUATION STAGES

Mineral resource projects progress through a series of stages, each with its own stage-gates that comprise a set of requirements that the project must achieve to progress (Figure 1).

Each stage should be considered to represent a project pipeline, with a large number of projects at the entry to the pipeline but relative few proceeding to discovery, resource evaluation and feasibility studies. There are currently around 761 metals and materials companies listed on ythe ASX. During 2021, 2985 announcements were released by ASX participants in compliance with the exchange's continuous disclosure requirements. Only 305 of these, however, related to mineral resource and ore reserve estimates, or scoping, prefeasibility and feasibility studies. Of the 761 ASX listed exploration and mining companies, almost 500 have a market capitalisation less than A$5 million, while only 13 have a market capitalisation exceeding A4500 million (Figure 2). These figures provide an indication of how the project pipeline narrows from early stage exploration (dominated by small-cap companies) through to companies with considerable mineral resource asset portfolios. Small-cap companies include exploration companies that are valued according to perception of the quality of their exploration landholdings and their exploration strategy communicated to investors, which includes measures required to ensure a smooth transition from one stage of exploration to the next as positive results are obtained.

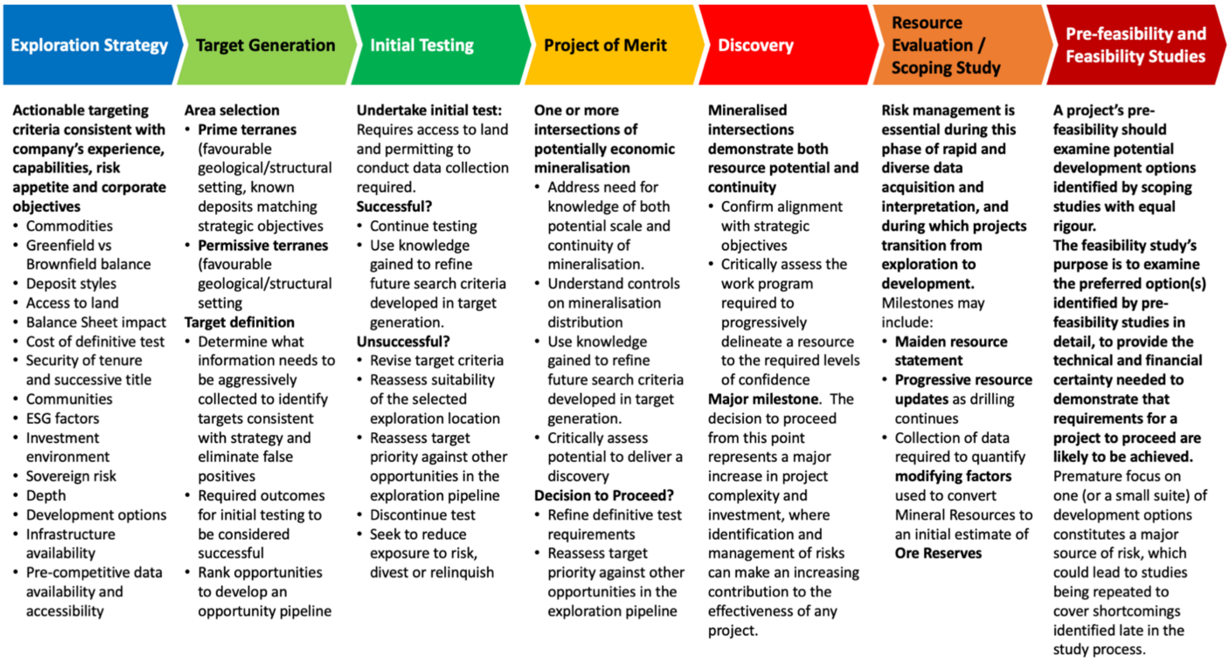

Figure 1. Stages in exploration and resource evaluation project development, including a description of the purpose of each phase and relevant milestones.

Figure 2. Market capitalisation of ASX-listed Exploration and Mining companies, November 2022.

EVOLUTION AND MANAGEMENT OF UNCERTAINTY DURING EXPLORATION AND RESOURCE EVALUATION

Each stage is associated with sources of uncertainty and risk that need to be carefully considered and managed. Where this is not possible, appropriate contingencies are identified and put in place to mitigate or characterise their potential impact.

Sources of uncertainty may be categorised as:

3. **Internal**: largely technical in nature and frequently able to be managed and even quantified through quality assurance measures and parallel collection of confirmatory data as well as the utilization of available exploratory data analysis techniques ; and,
4. **External**: frequently associated with critical issues affecting the security of tenure, access to land and permitting of specific work, particularly when land disturbance or disruption of existing land use may result.

The most acute impact of external uncertainty is delays in project execution, which are critical for all companies as they result in costs being incurred that potentially reduce funds available for actual exploration work. The magnitude of these delays and costs is frequently difficult to determine, especially in jurisdictions where timelines are not specified in relevant regulations and legislation.

Exploration Strategy

Establishing and annunciating a clear, executable exploration strategy is critically important to effectively managing risk. Consideration of stakeholder needs is essential, especially divisions within a company that are ultimately responsible for developing and operating projects delivered by exploration teams. Exploration discoveries have been shown to be the lowest cost means of adding resources to a company's asset portfolio, but the value of discoveries is impaired if the divisions within the company responsible for developing resources are not prepared to accept them. This is frequently the result of misalignment of strategic vision and objectives. There are many different issues that need to be considered in implementing an effective strategy, which need to be consistent with a company's appetite for risk and its current position, growth objectives and ability to pursue resource portfolio growth objectives, some of which are listed in Figure 1.

Uncertainty is addressed at this level by companies ensuring that they have, can access, or develop the technical experience and resources needed to pursue the commodities and styles of mineralisation identified as desired growth opportunities, and to operate in selected geographies. Existing producers can manage risk through electing to explore in both brownfield and greenfield settings.

An exploration strategy needs high-level endorsement to be effective. This should come from a company's board, given the strategy's role in setting out the growth opportunities to be pursued by the company.

Target Generation

Target generation represents the initial step in implementing an exploration strategy by setting out actions required to identify targets for testing. The exploration search space concept (Hronsky, 2009) provides a systematic approach by which targets may be identified and prioritized. The concept promotes the need to identify what information needs to be collected by explorers to identify targets consistent with their exploration strategy and effectively exclude false positives. Knowing the data that needs to be collected allows measures to be designed and implemented to ensure its accuracy and reliability, which could include:

- ensuring that pre-existing land disturbance is adequately documented (especially important in areas that have been subjected to previous exploration and mining);
- sample and drill hole locations are accurately recorded by licenced professionals;
- procedures are in place for systematic, structured recording of geological observations to ensure consistency of observations, and distinguish observations from interpretations;
- appropriate geochemical standards are available to ensure the accuracy of both analytical and physical properties data as part of a broader suite of quality assurance measures; and,
- ensuring projects will be adequately resourced to collect the increasingly broad spectrum of information required to enable work to progress to more detailed resource evaluation and studies in response to positive initial results.

Exploration is, appropriately, recognised as a high risk activity, with only a relatively small proportion of projects progressing beyond initial testing. Success, however, is frequently the catalyst for rapid allocation of additional resources to accelerate project execution which is not a setting that is conducive to pausing activity to review existing procedures and implementing improved practices. The search space definition needs to extend to the need to collect data describing all features of a deposit that could influence its development and extraction, including geometallurgical characteristics, rock mass properties and groundwater conditions.

Initial Testing

Initial testing should seek to identify the specific target (mineralisation style and lithostructural setting) described in the search space established for the project to ensure that a definitive test can be conducted. Failure to intersect the desired target requires development of new search parameters that are consistent with results to date and recognise what additional data is needed to achieve a different outcome. The choice of whether to proceed with further testing is made clearer by whether development of an updated target that remains consistent with the overarching exploration strategy is feasible.

Initial testing marks the point at which **observations** begin to inform **understanding** and **interpretations** of mineralisation. Observations are **essential facts** that fundamentally contribute to knowledge of the character of mineralisation. All observations need to be considered in the development of geological **interpretations** which must continue to evolve as knowledge of a deposit becomes progressively more detailed and better informed during exploration and resource evaluation.

Another essential aspect is the consistency of observations, especially when they are being collected by teams with different backgrounds and experiences, and what will be considered significant by individual team members will be unconsciously influenced by their previous experience. Several studies (e.g. Ward (1986), Ferm & Weisenfluh (1981)) recognised the importance of systematic recording of salient characteristics, including lithology, texture and grainsize, colour, sedimentary structures, and alteration to develop diagnostic, unambiguous descriptions of rocks intersected in drill core. Ward (1986) also recognised the importance of a structured logging form in promoting consistent recording of salient features. When asked to describe core specimens in freehand form, geologists recorded only the features they considered important. When presented with a form that provided a structure for the descriptions, the same geologists recorded features overlooked in their freehand descriptions, producing results that were far more consistent and comparable. This work was then used to form a scheme of coded lithologcal descriptions amenable to management using database tools.

This approach, developed in coal-bearing sequences, is equally applicable to both minerals and oil and gas exploration and development and represents a considerable refinement of coded logging systems that aim to simply record data in searchable, coded form without consideration of the consistency of descriptions.

Any association between mineralisation and lithology, structure and alteration should be evident at this point. Structural and lithological controls on mineralisation development will, largely, be expected from the styles of mineralisation being targetted strategically. Where present, this needs to be honoured in sampling protocols implemented for the project which must prevent mixing of fundamentally different materials in samples if an accurate interpretation of mineralisation distribution is to be developed, and unmineralised materials are to be appropriately characterised for geotechnical and environmental purposes. Appropriate sampling also has an important role in recognition of comparable materials used to group, or domain, data for resource estimation purposes. When clear lithological or structural controls on mineralisation distribution are evident in drill core, sampling must honour this to prevent mixing of unrelated materials. This may require the use of cored rather than non-cored drilling to ensure that accurate, undiluted grade information is obtained for projects. Uncontrolled mixing of materials through the use of regular downhole sampling intervals invariably produces an uncertain amount of mixing of materials in samples spanning mineralisation boundaries, which can have a marked impact on estimated resource grades and project value when resource estimates are converted to ore reserves through over allowance for ore loss and dilution.

Systems and procedures needed to ensure the fundamental data quality need to be in place at this point in the project's development (e.g. use of standards, duplicates, repeats and blanks to monitor sample preparation and analytical data quality). Processes for estimating or measuring bulk density also need to be considered (e.g. direct measurement of bulk density using quantitative, downhole geophysical logging coupled with laboratory measurements of specific gravity adjusted for pore volume and moisture content).

When combining this constant stream of incoming information with the variability of data quality, observation scale and data source (e.g. core data, geophysical surveys, log data and geological maps), the magnitude of this challenge quickly becomes inherent. Successfully handling this stream of information therefore makes supporting tools for automated data storing, data quality processing and data visualization impeccable for todays geoscientists to better understand and communicate the meaning of data.

Project of Merit and Discovery

A project reaches "Project of Merit" when one or more intersections of potentially economic mineralisation consistent with strategy are obtained. The term recognises that there is evidence that mineralisation with the characteristics needed to make a discovery is present.

A "Project of Merit" differs from a "Discovery" in that continuity needed to establish a resource has yet to be demonstrated. Declaration of a "Discovery" should constitute a milestone marking demonstration of confidence in the presence of mineralisation with demonstrable economic potential and continuity that suggests reasonable prospects for demonstrating the presence of a viably recoverable mineral resource. The required assessment of continuity introduces a new source of uncertainty in correlation of points of observation provided by drilling to provide estimates of mineralisation volume which are an essential component of both an exploration target and, ultimately, resource estimate for the project. Assessment of continuity tends to be secondary to the assessment of potential deposit scale, despite the former being essential to predicting the density of drilling required to establish required confidence in mineral resource estimates and development of a meaningful plan for collecting the required observations. Mineralisation continuity is usually assessed using semi-variograms where the nugget effect, sill and range are all critical parameters, but widely spaced drilling designed to assess the potential scale of a deposit may not provide accurate estimates.

Structural data provided by drilling has potential to play a major role in reducing uncertainty of correlations between drill holes. The angle of intersection between geological features and the core axis provides a range of potential dip angles that can be considered in connecting data between drill holes. Oriented core or geophysical orientation measurements provided by dipmeter, microresistivity or televiewer logs provide direct, quantitative measurements of bedding and discontinuity azimuth and dip that may be used directly in geological model development (Figure 3).

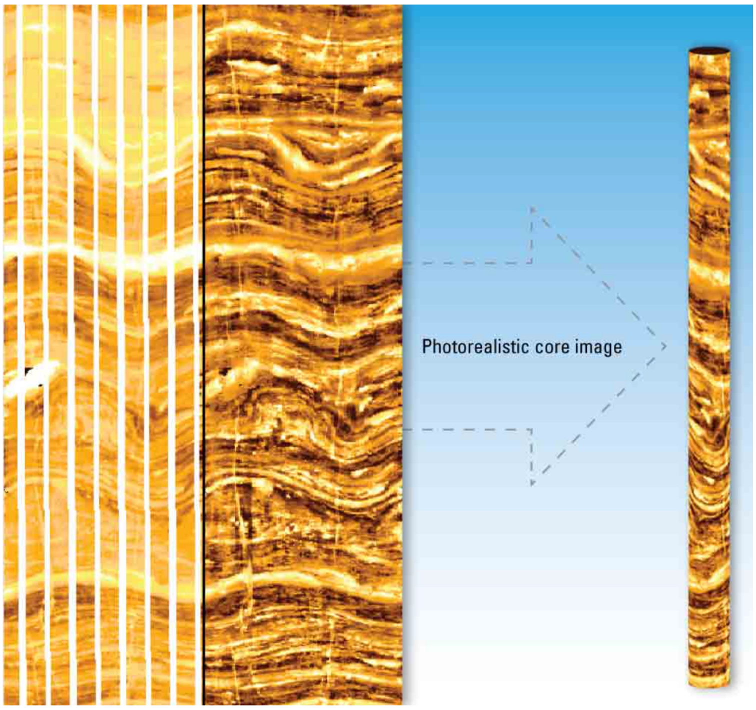

Figure 3. An example of the use of microresistivity logs to provide a photorealistic core image and derive quantitative structural and physical properties information from both cored and non-cored drill holes (Schlumberger, 2022)

High resolution reflection seismic data is being increasingly used to provide detailed mapping of the continuity of interfaces between rocks with contrasting physical properties to better understand mineralisation distribution (Manzi, Cooper, Malehmir, Durrheim, & Nkosi, 2015) (Figure 4).

Both techniques are applications of techniques widely used in oil and gas applications that have been adapted for minerals industry applications. Exploration and mining software providers are quickly introducing tools that enable geologists to readily use this information in mineral deposit modelling.

These techniques are most applicable to deposits where close lithological and structural control of mineralisation is evident. A different approach is necessary in deposits where the controls on mineralisation distribution are less evident to objectively group samples with comparable characteristics to provide geostatistically stationary conditions for grade estimation. The most widely used approach, currently, requires univariate and bivariate, exploratory statistical assessment of grade distributions and correlations between grades of different metals of interest to identify and begin to spatially differentiate samples with distinct characteristics.

The use of dimension reduction techniques is currently the subject of significant research where techniques including Principal Component Analysis (PCA), t-distributed stochastic neighbour embedding (t-SNE) and Uniform Manifold Approximation and Projection (UMAP) have been identified as means of objectively identifying subsets of data with comparable characteristics (Steffens, 2022) The results of these procedures, coupled with the application of clustering techniques to produce a manageable number of categories, have potential to form the basis of robust domains when examined in a spatial context (Figure 5).

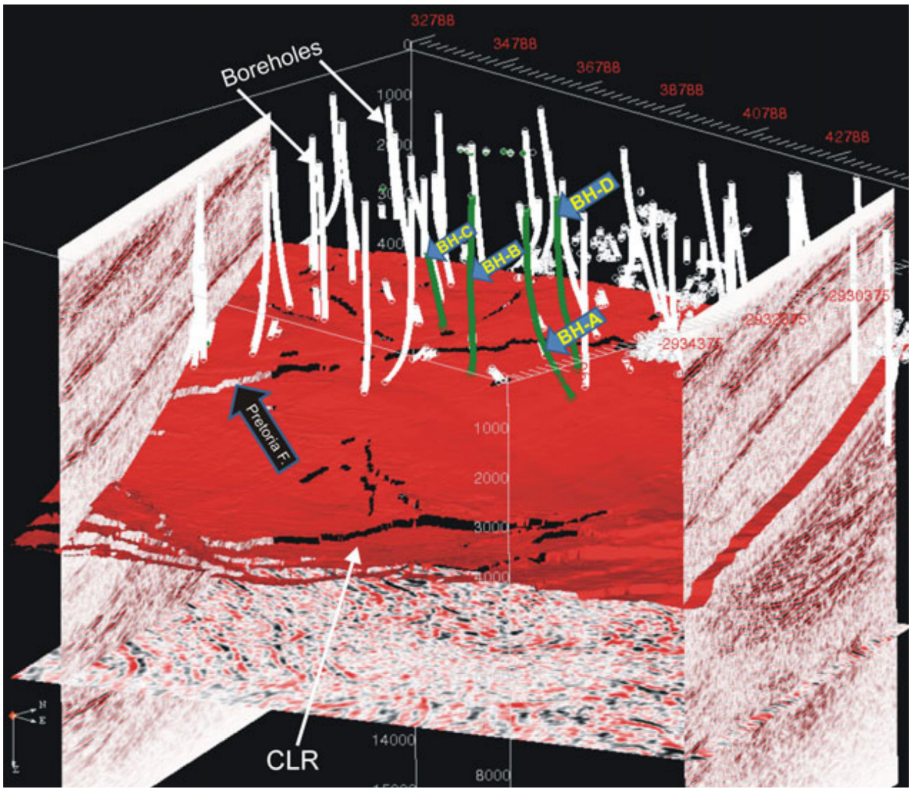

Figure 4. 3D visualization of the 3D seismic data integrated with boreholes. The Carbon Leader Reef (CLR) forms a prominent seismic reflector between basic to ultrabasic Klipriviersberg lavas and clastic sediments of the Central Rand Group, readily recognised in drill core, Witwatersrand Goldfield, South Africa (Manzi, Cooper, Malehmir, Durrheim, & Nkosi, 2015)

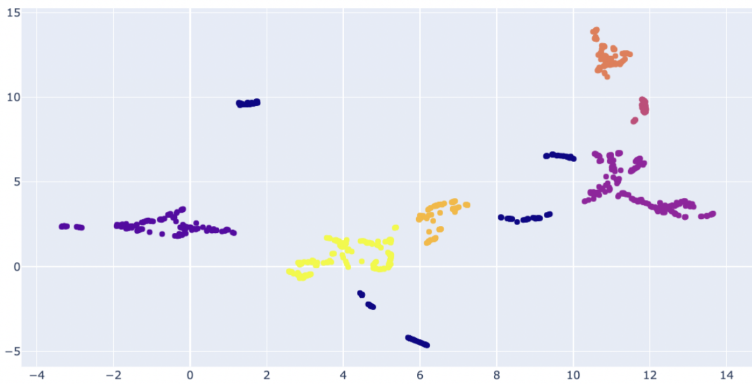

Figure 5. An example of UMAP dimension reduction of geochemical borehole data that are subsequently grouped together (color-coded) with the help of HDBSCAN clustering. The x-y axes are numerical representations of the reduced dimensions, not sample locations. Data need to be viewed in spatial context to assess the geological potential of the data subsets derived using this form of approach, but considerable potential exists for robust grouping of samples with comparable characteristics (B. Steffens pers.com.)

Resource Evaluation

The Resource Evaluation phase of mineral resource project development contributes, literally, to an explosion of the quantity and breadth of data being collected to provide a basis for pre-feasibility and feasibility studies, and ultimately development of a project if all necessary technical, economic, environmental, and social requirements are realised. This phase of activity may include the release of public statements of Exploration Results, Mineral Resources and Ore Reserves prepared in compliance with industry standard reporting codes (including JORC (2012)), where Competent

Persons are required to express the extent of uncertainty inherent in Exploration Targets through use of ranges of values, and Mineral Resources and Ore Reserves, and classifications using specified categories.

The criteria used to classify Mineral Resources and Ore Reserves are at the discretion of the Competent Persons responsible for the statement, but they are frequently based on relatively subjective criteria, including the underlying quality, relative spacing and configuration of observations compared with the interpreted continuity of mineralisation. It is also crucial for stakeholders and other geologists to be able to understand how a block model used for Mineral Resource and Ore Reserve classification was developed. This helps in assesing the credibility of the developed block model and the assesment of its geological realism. A transparent display of data utilized should be available to make the development process of the block model relateable to stakeholders and allow for cross validation between the data used and the developed block model.

Mineral Resource and Ore Reserve estimates are also frequently based on a single geological model and mineral resource assessment, despite most reporting codes requiring examination of potential alternatives.

Assessing Alternative Interpretations

There has been considerable progress in the development of machine learning-based systems for rapid geological model development, e.g. Cracknell, (2014), Tao Bai (2020), Maptek's DomainMCF service (Maptek, 2022) Some workers in this field have developed and are continuing to refine stochastic approaches to geological model development that produce both a "central case" geological model and a range of alternative, equally probable alternative realisations based on the available data (e.g. GemPy, 2022) where differences between model realisations may be identified and used to plan additional drilling specifically to reduce uncertainty. Similar approaches for grade estimation have been the subject of extensive research, with stochastic prediction of reservoir characteristics now a widely available technique in reservoir characterisation software used extensively in the oil and gas sector. Kriging variance has been proposed as a means of measuring uncertainty inherent in grade estimates due to it measuring the degree of smoothing applied to estimates, which increases with distance from data on which the estimate is based. Simulation variance is favoured as a measure of uncertainty inherent in estimates due to the manner in which simulation corrects for smoothing associated with kriging (Deutsch, 2003) but requires management and analysis of a large quantity of information to obtain results. Rapid developments in cloud computing are creating an environment in which management and interpretation of large, complex datasets, such as those required for effective, stochastic estimates of geology and grades, are becoming increasingly accessible by users with internet access without the need for capacity to run and analyse models on their local computers. Advances in this technology should be expected to make practical applications of these techniques for uncertainty quantification accessible with continued research and development.

In the interim, independent peer review forms an important means of accessing alternate interpretations and inconsistencies evident in any form of data used in resource evaluation. Objective presentation of data is essential, as is initiating reviews regularly throughout the course of projects, acting to implement review recommendations and maintaining an audit trail of actions undertaken to improve confidence in information on which major decisions regarding the development and future potential of projects are based.

OPPORTUNITIES FOR IMPROVEMENT

Measures designed to monitor and maintain the quality of data and information to address uncertainty in exploration and mining projects may follow documented procedures but may not be recorded in a consolidated form that ensures ready access to recommendations and required actions that should form part of a project's audit trail.

Transitioning from spreadsheets and file notes to a structured, curated and accessible set of records have benefits for any project. This, coupled with leveraging cloud computing capabilities to enhance the generation and interpretation of stochastic models contributing to improved domaining of data during resource estimate preparation and presentation of multiple, equally probable geological models and accompanying grade estimates, will undoubtedly deliver tangible improvements in the assessment and presentation of uncertainty inherent in all aspects of mineral resource development projects. This involves the use of both established and emerging techniques and technologies. There are numerous examples already of where both the oil and gas and minerals sectors have benefitted from cross-pollination of ideas and adaptation of established, well understood techniques. Demonstration of demand for improvements has potential to be a catalyst in continued refinement of existing and continued innovation in this important field.

There is a significant difference between recognising the presence and extent of uncertainty inherent in exploration and mining projects and actually acting in response to it:

- to implement practices, including collection of additional, supporting data, to help quantify the impacts of undertainty; and,
- adhering to strategy by reviewing project progress and potential according to pre-established metrics forming stage gates that must be achieved before a project progresses to the next stage of exploration, or attracts further

resources at the expense of projects at an earlier point in the project pipeline, which can only advance if resources are available to allocate to them.

These create an opportunity cost associated with failure to act which detracts from exploration success.

REFRENCES

Cracknell , M. J. (2014). *Machine learning for geological mapping: algorithms and applications PhD Thesis.* Hobart: ARC Centre of Excellence in Ore Deposits (CODES) School of Physical Sciences (Earth Sciences), University of Tasmania.

Deutsch, C. V. (2003). *Geostatistics, in, Encyclopedia of Physical Science and Technology (Third Edition), Meyers R.A. (ed.) pp 697-707. https://doi.org/10.1016/B0-12-227410-5/00869-3.* Academic Press.

Ferm, J. C., & Weisenfluh, G. A. (1981). *Cored rocks of the southern Appalachian coalfields.* Lexington: Kentucky Geological Survey.

GemPy. (2022, November 11). *GemPy Open-source 3D geological modeling*. Retrieved from GemPy.org: https://www.gempy.org/

Hronsky, J. (2009). The Exploration Search Space Concept: Key to a Successful Exploration Strategy. *C.E.T. Quarterly Newsletter No. 8*, pp. 14-15.

JORC. (2012). *Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (The JORC Code).* Melbourne: Joint Ore Reserves Committee of The Australasian Institute of Mining and Metallurgy, Australian Institute of Geoscientists and Minerals Council of Australia (JORC).

Manzi, M. S., Cooper, G. R., Malehmir, A., Durrheim, R. J., & Nkosi, Z. (2015). Integrated interpretation of 3D seismic data to enhance the detection of the gold-bearing reef: Mponeng Gold mine, Witwatersrand Basin (South Africa). *Geophysical Prospecting 63(4): DOI: 10.1111/1365-2478.12273*, 881-902.

Maptek. (2022, November 11). *Maptek DomainMCF - machine learning assisted domain modelling*. Retrieved from maptek.com: https://www.maptek.com/products/domainmcf/

Schlumberger. (2022, November 11). *Quanta Geo photorealistic resewrvoir geology service*. Retrieved from slb.com: https://www.slb.com/reservoir-characterization/surface-and-downhole-logging/wireline-openhole-logging/quanta-geo-microresistivity-imager

Steffens, B. (2022). *Integrating geological uncertainty and dynamic data into modelling procedures for fractured reservoirs.* Edinburgh: PhD Thesis, Institute of GeoEnergy Engineering School of Energy, Geoscience, Infrastructure and Society, Heriot-Watt University.

Tao Bai, P. (2020). Hybrid geological modeling: Combining machine learning and multiple-point statistics. *Computers and Geosciences: 142 https://doi.org/10.1016/j.cageo.2020.104519.*

Ward, C. R. (1986). *A guide to cored rocks in the Sydney Basin.* Sydney: Earth Resources Foundation, The University of Sydney.