Turning Geological Data into Reliable Mineral Resource Estimates[1]

By

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ABSTRACT

This paper deals with the building of geological interpretations from necessarily limited geological data and the use of such interpretations in the estimation of mineral resources. Since geological interpretations are a type of scientific model, the process of constructing such models in terms of the objectives and mechanics involved is briefly reviewed. Particular aspects of geological interpretations relevant to resource estimation are then described. The final robustness of resource estimates is highly sensitive to the domaining decisions made, which are in turn heavily dependent upon appropriate geological modelling. Difficulties in the journey from geological observations (data) to geological interpretations and then to estimation of mineral resources include: (1) potential biases in construction of models related either to data bias, knowledge gaps or to application of heuristics that yield error in interpretation; (2) inadequacies in the culture of developing the model, in particular deficient self- and/or external criticism applied to the model during and after construction; (3) failures or inefficiencies in the process of transferring geological interpretations into useful inputs for estimation of mineral resources – specifically the issue of appropriate domaining; and (4) the communication of geological understanding through a chain of professionals from those logging the holes to the end users of models (engineers and financiers). It is concluded that although geologists often claim to approach geological interpretation in the framework of 'multiple working hypotheses' the actual process of model construction rarely if ever follows that path. The dangers of 'locking into' models with unacceptable interpretative flaws at an early stage are highlighted. Such models may then acquire both technical and cultural momentum, making them hard or impossible to challenge. This makes it vital to foster a culture of open, professional criticism (in fact, to follow the falsification process of Popper) of geological models. Finally, management of the communication process is vital if high quality geological inputs are to be correctly utilised in order to lower the risk of material error in the mineral resource estimates.

Introduction

> *It's not the models we build in*
> *our geological interpretations*
> *that are the 'problem':*
>
> *it's the models we do <u>not</u> build.*

Geological Models

An important task of mining and resource geologists is to generate geological interpretations of mineral deposits to be used as inputs to the resource estimation process. In this paper the 'geological models' are restricted to those that have the principal purpose of being inputs to resource estimation, though such models may obviously have other uses, and alternative models may be specifically required for other purposes, e.g. characterisation of hydrogeological or geotechnical characteristics, or those describing paragenetic aspects of mineralisation.

Geological models for use in resource estimation require valid description of key geometric features of a deposit. Today, such models are usually summarised as three dimensional (3D) 'solid models' using computer software and have the express objective of providing envelopes within which statistical analysis and estimation of resources can proceed. Such models are scientific models in the sense that they represent or summarise hypotheses about the geometry, extent and character of the mineralisation. In discussing the development of this type of geological model, this paper commences with a brief discussion of what constitutes a scientific model.

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Scientific Models

A scientific model is a set of 'statements' that are postulated to describe the nature of a phenomenon being studied. The essence of the scientific method is to assemble such 'systems of statements' (models) and then compare them with observations of nature. The geometric models of geology that are used in resource estimation (and the assumptions underpinning them) thus constitute scientific models. Popper (1958) summarised the task of scientists as putting forward statements, or systems of statements, and testing them step by step.

Popper (1958) also provides a detailed definition and discussion of scientific method. The scientific method is rooted in the generation of hypotheses and testing of these against observed results. The value of scientific models lies in their use to generate predictions, and traditionally this implies the ability to predict the outcomes of experiments. The evolution and refinement of a scientific model proceeds by making predictions based on the model and comparing these with observations. A model may be refined or even abandoned if it fails to predict existing or new observations. The fundamental attribute of scientific models is that they are falsifiable and the essential mechanism for testing and refinement of models is to attempt such falsification. In other words, the objective is to 'criticise our models' by designing tests that maximise the likelihood of disproving our hypotheses.

In mining geology, the validity of the models constructed can be tested by the 'experiment' of obtaining additional drilling – or other observational data – from the deposit being evaluated. In terms of model improvement and refinement, such drilling will have maximum utility if a conscious strategy of designing holes to challenge or invalidate our model is adopted, or alternatively, if specific holes are sited to test areas of disagreement between two (or more) plausible models.

CONSTRUCTING GEOLOGICAL MODELS

Steps

In mining industry practice, a typical sequence of steps for the generation of a geological model for resource estimation purposes is as follows:

1. A database is assembled from observed and measured data including logging, assaying etc. The choice of features to log and elements to assay involves judgement and this may influence the flexibility and validity of subsequent modelling steps. At the early stages of interpretation, significant weight may be placed on geological analogues of the deposit under consideration for the simple reason that little is known of the deposit under consideration;
2. Based on the geological observations and geochemical information collected from drilling and other sources (if available), the geometry of key geological features is interpreted (lithological and weathering boundaries, faults, folds, alteration distribution, etc.). This interpretation usually occurs on sections and plans. In many cases, the only available hard data is obtained from drill holes;
3. The interpretation is transferred into a digital model, for example by wire-framing or surface modelling. The interpretation may thus be represented in space by surfaces representing various geologically significant features (again, judgement as to what is 'significant' needs to be made and this may influence subsequent steps);
4. This model then forms the basis of determination of estimation 'domains'. These domains are geometric volumes defined by individual features (e.g. such as a vein or a specific lithology); combinations of geological features (e.g. a lithology above a weathering surface) or a combination of signature geochemistry and geological features (e.g. elevated grades in the footwall of a specific fault); and
5. These domains are then statistically assessed to ensure that within them a reasonable degree of 'statistical homogeneity' (or 'stationarity') can be assumed. This important step is sometimes omitted in current industrial practice. In this step, consideration of combination of several domains or splitting of initially proposed domains on the basis of statistical and geostatistical characteristics can be allowed for. Note that geological characterisation is necessary, but is often not sufficient, to ensure that estimation domains are robust.

TURNING GEOLOGY INTERPRETATIONS INTO ESTIMATION DOMAINS

Failures or inefficiencies in the process of transferring geological interpretations into useful inputs for estimation of mineral resources represent significant risks on the final estimates (and thus on technical and financial decisions based on these estimates). Specifically, the issue of appropriate domaining is a 'first order' decision, affecting all subsequent steps in estimation. Since this domaining step is the practical use of the geological model in resource estimation, it warrants discussion here.

Estimation Domains and the Issue of Stationarity

In resource estimation it is usually necessary to define a partitioning of the data set into geologically and statistically acceptable 'domains'. In addition, a fundamental aspect of resource estimation is decision-making concerning 'domains of stationarity'. The term 'stationarity' is used in geostatistics to describe statistical homogeneity within a given volume. Refer to Journel and Huijbregts (1978) or Armstrong (1998) for a mathematical definition of stationarity.

> Domains of stationarity are generally closely related to geological, structural and/or weathering units. . The definition of domains for estimation may need to take into account some or all of the following factors:
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> 1. Distribution of lithology;
> 2. Distribution of weathering surfaces;
> 3. 'Structural architecture' of mineralisation (for example, at both at the gross 'mineralised envelope' scale, and at the scale of higher-grade shoots);
> 4. Sampling and analytical precision; and
> 5. Spatial distribution of grade *within* mineralised structures.

Because of 4 and 5, above, it is prudent to consider the variography[3] of grades when making stationarity domaining decisions. The variogram characterises spatial continuity. The short-scale behaviour of the variogram (nugget effect and short-ranges) is especially diagnostic of spatial behaviour of grades.

It is important to understand that stationarity is a property of the model, not of the phenomena we are considering. Furthermore, the correctness of the decision to assume stationarity in our model cannot be refuted or proven *a priori*. The decision of stationarity is thus an expert decision based on assumptions about the homogeneity of the zones over which estimation (e.g. kriging) is to take place.

Possible Problems

Assuming that the geological model adequately represents reality, the main problems that may occur when constructing estimation domains from geological models are:

1. The boundaries represented in the model do not define acceptably 'statistically homogeneous' zones. In this case, it may be necessary to further subdivide the domain. Increased domaining results in fewer samples per domain, thus eventually compromising inference of statistics (such as the variogram) within the resultant smaller domains. This is the age old geological problem of 'lumping' versus 'splitting': in resource estimation excessive splitting is self-defeating because we cannot reliably estimate the mean within domains with very few samples; and
2. There is no way to subdivide the deposit that avoids having significant trends in the data (also called 'drift'). In this case, the moving search neighbourhood used in estimation may be adequate to overcome the problem if the sense of stationarity is acceptable up to the dimensions of the search (see Vann et al, 2003 for discussion of searches strategies). Otherwise, more elaborate estimation methods may be necessary ('non-stationary geostatistics' – see Chiles and Delfiner, 1999).

Another serious issue is that the estimation step usually involves estimation of grades at the scale of (at least) selective mining units. Thus we estimate a 'block support' from sample data on much smaller support – usually several orders of magnitude smaller in volume and, in exploration stages, not uncommonly one millionth of the volume. Thus the interpretation should bear in mind this scale of estimation when boundaries are constructed. Elaborate geometry between drill holes may have a negative impact on the quality of tonnage estimates, especially in a local sense.

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[3] see Armstrong, 1998 for an introduction to variography

BIASES IN CONSTRUCTION OF MODELS

Difficulties in the journey from geological observations (data) to reliable geological interpretations and then to estimation of mineral resources include potential biases in construction of models related to data bias, knowledge gaps or to application of heuristics (this term is defined later in the paper) that yield error in interpretation. Reason (1990) gives a good overview of various types of error.

Data Bias

Data bias may have a number of sources, including:

1. Flawed sample collection strategies. For example, drill holes may be poorly oriented with the result that certain geometric features of the mineralisation are systematically over- or under-sampled;
2. Biases in the measurement of data: for example bias in core orientations due to design and use of the measuring device; or bias in the analytical results from sampling and assaying that may arise from sampling, sample preparation or analytical steps – see Pitard (2004) and François-Bongarçon (2004) for example;
3. Bias in observational data: we may choose to record or not record any number of types of observations and to record these in a range of ways. An example is that we may record sulphide species percentages (which may be of importance in interpretation for a particular deposit). However, the scale of measurement may encourage bias because of the way it is graduated, e.g. 'trace', 'minor', '<1%', '2-5%' etc. or the way geologists transform observation into numerical data may be biased (either collectively, or in different ways for different geologists).

The management of risk arising from these types of bias is in the domain of 'quality assurance', i.e. it is necessary to design the data collection steps in a way to prevent biases and 'quality control' i.e. it is necessary to repeat observations/measurements by the same method and against reference methods, in order to manage the quality of collected data and ensure that quality is not compromised. Deming (1986) gives an excellent general overview of the process and philosophy of quality management.

Knowledge Gaps

There are instances when the interpretation of mineralisation is significantly hindered by the absence of specific types of data or knowledge. For example, if the distribution of alteration in a gold deposit is complex and visually difficult to assess (for example due to weathering), then the absence of non-gold geochemical information can be a serious impediment to reasonable interpretation. Alternatively, if interpretation of the geology requires that we understand the distribution of sulphide or other mineral species, but the importance of these data were not recognised, and thus they have not been recorded, we have a literal gap in knowledge.

Heuristic Error

A 'heuristic' is informally defined as a guideline or rule of thumb that may be effective in dealing with a given situation. The word comes from the same Greek root (ευρισκω) as 'eureka', meaning 'to find'. The term 'heuristic' thus describes well the type of informal methods often adopted in geological interpretations where geologists attempt to 'solve problems' (of interpretation) in the absence of formal algorithms. Heuristics may be thought of as rules of thumb (conscious or sub-conscious), or rules that guide our thinking. In many cases they are not consciously expressed and operate without questioning or examination (see Solomon, 1992 for a discussion, in geological context). They are typically 'intuitive' and usually have only restricted applicability and limited likelihood of success. In some cases application of heuristics can severely bias our judgments.

However, a number of commonly used heuristic approaches to problem-solving have well-known potentials for error and specifically for the systematic introduction of bias. Tversky and Kahneman (1974) discuss a number of heuristics that may be relevant to the problem of geological interpretation (specifically, interpretation of geometry and of 'domains of stationarity' for resource estimation) and the ways in which bias can be generated by them.

Representativeness

Error arising from this heuristic involves making decisions about what class or category an object under consideration belongs to. One conclusion made by Tversky and Kahneman (1974) is that worthless evidence can introduce significant biases in judgement.

In the case of geological interpretations, an example of error arising from the representativeness heuristic is the use of grade data to guide structural or other geometric interpretation in the presence of very high 'nugget effect'. Nugget effect is a geostatistical term for the chaotic (or non-spatial) component of grade distribution (see Armstrong, 1998; or Journel, and Huijbregts, 1978). If 100% of the variability of grade can be described by the very short-scale variation, then two sample grades separated by a vector *h* are uncorrelated no matter how close they are. This situation is also called 'pure nugget effect', and is not unheard of, for example, in precious metals, diamond and uranium deposits, or for some deleterious variables in iron and coal deposits (e.g. phosphorous in iron or pyritic sulphur in coal). In addition to inherent geological variability, all sampling errors add to the apparent nugget effect (see François-Bongarçon, 2004).

For all practical purposes, in 'pure nugget' situation the data may as well be randomly drawn from the sample histogram: i.e. the data are 'spatially random'. 'Spatially random' does *not* mean that the data are blandly homogenous – there are often apparent patterns in statistically random data. In the presence of pure nugget effect, it is sometimes very difficult for geologists to ignore the grade data ('bad data is better than no data') when making interpretations. However, if the data are essentially uncorrelated from point to point, the grades in question represent 'worthless evidence' as discussed by Tversky and Kahneman (1974, pp.1125). It is strongly recommended that grade-driven geometric interpretations be treated as suspect unless supported by other geological information as well as appropriate geostatistical analysis.

Another example of the heuristic of representativeness in economic geology is the reliance on 'niche sampling' to draw strong conclusions about the relative metal endowment of several sets of veins in a deposit. Taking a small number of samples per vein set (a handful up to several dozen) and then making conclusions such as 'Set A is enriched at twice the level of Set B', for example, is highly likely to lead to interpretive error. If the data employed are chip samples of veins in a mine, the nature of the sampling (high sampling error) will add to the unreliability of the exercise. The higher the nugget effect, the riskier this sort of exercise is. For the conclusions to be scientifically defensible, we need to have some idea of the inherent noisiness of the data being used: if the nugget is very high, such exercises are likely to be misleading.

Availability

Tversky and Kahneman (1974) note that there are instances in which people judge the frequency of a class of events by the ease with which instances can be brought to mind. They give the following example: "Suppose one samples a word (of three letters or more) at random from an English text. Is it more likely that the word starts with *r* or that *r* is the third letter?" people approach this problem by trying to imagine words that begin with *r* (rose) and those that have *r* as the third letter (fare). However, it is cognitively easier to search for word starting with the letter *r* than to recall those with *r* as the third letter. They consequently – incorrectly – conclude that it is more likely that a word starts with *r* than has *r* as the third letter.

In geological interpretation, the geologists' ability to recall examples that match the observed data is heavily influenced by their experience base. It is unlikely that certain structural configurations will be postulated if the worker has not been exposed (at least through literature) to examples. This type of problem is not restricted to geology (or for that matter science) but is a general problem.

In cases where geologists have been exposed to many examples of a specific type, the tendency to see this type in a deposit under consideration is possibly increased. For example, geologists very familiar with a certain way of interpreting may be likely to seek (or 'force') similar interpretations in data from a new deposit. The author has seen an example where a group of geologists with strong skills and training in stratigraphy viewed a particular deposit as 'strataform' despite fairly easily observed evidence for structural controls.

Eliminating (or at least managing) biases resulting from the heuristic of availability requires that we have structured means of contemplating alternative models. External review of interpretations by experienced geologists (preferably geologists not intimate with the deposit or even deposit type) is advisable[4]. This is discussed further, below, in the section on 'cultural issues'.

Anchoring

The heuristic of anchoring describes the type of bias that can be generated when an initial estimate (or 'guestimate', or for that matter *guess*) is made and then adjusted to yield a final answer. The initial answer may bias the final result, in other words, we tend to adjust insufficiently as new information becomes available. The examples given by Tversky and Kahneman (1974) relate to numerical

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[4] Often breakthroughs in science come from apparent outsiders from the discipline in question.

estimates, but it is contended here that exactly this type of error can occur with geometric interpretations.

Returning to the example given above of the 'forced' stratiform interpretation: once the broad interpretation was constructed on widely spaced drilling, this 'template' guided subsequent interpretations despite increasing evidence that this schema was (at least) oversimplified. As for certain incarnations of the availability heuristic, while the origins are arguably psychological, the persistence of the problem may be seen as a cultural issue.

Salience

Solomon (1992) discusses a fourth type of heuristic which she terms 'salience' (salience is simply the degree to which something stands out or is otherwise easily seen). The salience heuristic is often associated with availability heuristics. Factors that make data salient are:

1. 'Concreteness', which is related to how 'real' the observation or data seem to be. This, in turn, is influenced by the amount of detail – even irrelevant detail – in which things are described. One of the dangers of highly aesthetic and intricate geological shapes inferred from few drill holes is that the more convoluted the models are, the more 'real' people viewing the models (especially non-geologists) may think they are ;
2. 'Proximity': we are more likely to find an observation salient if we have experienced that type of observation in an important context previously – especially recently; and
3. 'Emotional interest': for example, if a geologist has published many papers on a particular structural mechanism, it is possible that they find it more difficult to dispassionately entertain alterative plausible interpretations for the same data[5]. This belief perseverance phenomenon does not require publication, as such: the more we publicly defend (or promote) a particular model, the more difficult it is to radically challenge it.

Summary of Heuristic Biases

Tversky and Kahneman (1974) conclude that heuristic biases of the type discussed above are made by experienced, scientifically trained researchers *when they think intuitively*. Solomon (1992), who specifically studied the role of heuristic and cognitive bias in geologists, further concludes that biased reasoning is not delusional: when evidence against a model (or beliefs) becomes overwhelming, cognitive (and emotional) biases have little effect – the model will be abandoned. However, such heuristic biases are commonplace and require active management if we are not to make biased interpretations (and perhaps more importantly) *perpetuate* such biased interpretations.

Solomon (1992) notes, based on her study of the plate tectonic 'revolution', that the opposition of two schools of thought, both affected by the types of biases discussed above, was actually conducive to the radical interpretive change that occurred because they brought about a "division of cognitive labour" (Solomon, 1992, p.452) and thus increased the number of investigative efforts directed at the same data sets. This observation may have direct relevance for interpretation in a resource estimation context (where tens, hundreds or even thousands of millions of dollars of capital may be expended on the basis of estimates based on a particular geological model): perhaps a single team working on geological interpretations is not the optimal approach to getting a robust answer.

There is (quite rightly) a significant role for 'experienced intuition' in geological interpretation. However, simply being aware of the types of cognitive and heuristic biases introduced here gives us the opportunity to error-check for such biases, and this is discussed more fully in the section of this paper headed 'cultural issues'.

CULTURAL ISSUES

Inadequacies in the culture of developing the model, in particular deficient self- and/or external criticism applied to the model during and after construction represent significant risks to obtaining a robust geological model as an input to resource estimation. The cognitive and heuristic biases discussed previously do not occur in a cultural vacuum. In this sense culture may be the context of:

1. Groups of geologists working on a specific geological problem (and the dynamics within such groups);
2. The profession of geologists as a whole;

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[5] Miriam Solomon's paper (Solomon, 1992) gives an excellent case study drawing on the history of the scientific revolution that transformed the vast majority of geologists from 'immobilists' to adherents of plate tectonics. As part of this case study, she points out that the degree to which geologists resisted plate tectonic ideas was highly correlated to their publication rates: geologists with low publication rates were more likely to be early accepters of continental drift because "their beliefs were less entrenched (cognitively speaking) than those who had reasoned more and produced more [publications]" (Solomon, 1992, p. 449).

3. The broader scientific, professional and industrial culture within which geologists work; and
4. Society as a whole.

However, it is the first and second groups that probably have the greatest impact on the process of geological interpretation, and these are considered briefly, here.

Firstly, there is the problem of 'group think', whereby the geological team becomes convinced of the correctness of their interpretive approach and over time) ceases to properly explore alternatives and challenge their models. This leads to the problem of inadequate 'internal criticism', i.e. the critical process *within* the group of geologists working on a project becomes flawed, or in extreme cases, ceases to operate. Finally, there is the problem of inadequate 'external criticism', i.e. the group of geologists working on a project do not properly expose their ideas and models to independent scrutiny.

Some geologists may respond to the word 'criticism' used here as being 'negative'. However, the word cannot be shied away from: the whole point of developing robust, scientific models requires that these models are 'falsifiable', 'refutable' or 'testable' (Popper, 1958). The word 'review' does not convey the same sense that we are actively trying to refute the model, and such reviews are sometimes disparagingly referred to in the mining industry as 'box ticking exercises'.

The word 'criticism' is thus used here in this sense: to criticise a geological model is to actively and systematically look for possible flaws, omissions, biases or other problems. However, while this is necessary, it is not sufficient: it is also required that when alternatives are proposed, wherever possible, tests of the two (or more) competing plausible ideas be designed. This might involve drilling specifically sited holes to test the deposit in an area where the competing interpretations disagree, for example.

Group Think

Perhaps the most significant cultural problem is that a group mind set can be established and become difficult to change and this is strongly linked to the anchoring heuristic discussed previously. The cultural context is very significant, because most mineral exploration successes require that highly motivated and articulate geologists 'sell' their ideas to several levels of management above the operational team. The lower levels of management may have relatively current geological and scientific training, however the higher levels of management are unlikely to be in a position to challenge important technical details (see further in the comments on 'communication to non-geologists' below). This may allow homogeneity of ideas about the deposit to become entrenched, in the absence of appropriate internal and external criticism.

The dynamics of a team are strongly influenced by the structure of the team. If a strong, experienced and articulate leader is difficult to challenge (on matters of geology) then it is possible that the team composition alters over time to be more homogeneous, i.e. dissenters leave the team and the residual members (and new members who stay) tend to echo the same types of views. This problem can only be addressed by strong external review mechanisms.

Ideally, team leaders (and other team members) should invite criticism (internal criticism) of their models as an active part of the process of model development. It is particularly appropriate that the criticism of geological models be systematic and vigorous when they are used as primary inputs to resource estimates upon which enormous sums of capital are to be invested. Not to do so is professionally indefensible.

Internal Criticism

There are a number of possible ways of instituting internal criticism of geological models. One approach is to positively encourage geologists within a team to generate alternative interpretations and then assess the risks inherent in each of these. The spread of interpretations may tell us something about the coincidence of thinking (especially if data are sparse), or alternatively such coincidence may be informative about the limited degrees of freedom in the problem, i.e. they are few alternative geometrical solutions. Assessing which of these alternatives is the case would require recourse to external criticism.

Jackson et al. (2003, and re-presented at this meeting) gives a case study at a gold mine where three experienced geologists set out to independently interpret the geology of a widely drilled (but potentially economically significant) deposit. The resultant interpretations were treated as 'optimistic', 'median', and 'pessimistic' cases in a risk analysis that demonstrated that geometric interpretation ('geological risk') was a source of risk on contained metal equivalent to uncertainty on the grades ('geostatistical risk').

External Criticism

The role of external criticism is critical and with increasing scrutiny of decisions made in public companies, this type of active 'auditing' of geological models is surely set to become more prevalent. In order to reduce the risk of group think and/or poor internal criticism of models, appropriate, independent criticism of geological models is required. Such external criticism, if a part of the culture of an organisation, can become very powerful improvement tools for geological modelling. Furthermore, the cost can be easily justified in terms of risk management, and these advantages need to be communicated to the level of the board.

The key point about both internal and external criticism is that we should be in the business of ensuring that plausible alternatives to the models developed are properly considered, and used as tools to refine and thus improve our models. In extreme cases, these processes may lead to radical modification of interpretations, and this can only be a good thing. If our objective is 'getting the best model' (and thus the best financial decisions) then following the approach of attempting to falsify models must be a positive.

COMMUNICATION OF GEOLOGICAL MODELS TO NON-GEOLOGISTS

The communication of geological understanding through a chain of professionals from those logging the holes to the end users of models (engineers and financiers) is a significant source of risk.

Data Collectors to Data Interpreters

In many projects the geologists collecting data have no role in interpretation and vice versa (i.e. the geologists performing interpretation have no first hand data collection experience for that project). In fact, it is often the case that the most inexperienced geologists (in many cases new graduates working as contractors) are the main data collectors, for example, core loggers. This may be unavoidable, however, it is imperative in these circumstances that:

1. Logging geologists are aware of the bigger interpretive picture. The author recently met several geologists who had been logging drill core for up to a year on extensions of an actively mined deposit and had still yet to set foot in the mine itself. In these circumstances, the value of the logging geologists seeing the 'big picture' in the pit was self-evident;
2. The logging of inexperienced geologists is carefully mentored and managed/reviewed by more senior geologists as a routine quality control measure. Re-logging of selected holes by geologists other than the original logger should be routine, followed by discussions between the two geologists about the source and possible resolution of any discrepancies. This can be viewed simultaneously as professional development and quality control; and
3. Geologists performing the interpretations need to at least rapidly log key holes so that they can understand the context and meaning of information on sections.

Note that it can be an extreme risk to 'outsource' the interpretative steps (including the making of initial domaining decisions) to consultants who have no direct *geological* experience with the deposit. While such external advice may be useful and desirable to refine domains (for example by taking into account geostatistical factors) it is a poor approach to generating the initial geological models unless full collaborative ownership is taken by company geologists *and* external experts.

Interpreters to Estimators

It is also commonplace that the geologists performing the estimation are not those undertaking the interpretation and that a resource geologist or geostatistician generates the estimates based on a geological model as provided. In such cases a loop should be established between the builders of the model and the estimator in order that domains can be refined as discussed earlier in this paper.

It may, in addition, be the case that the estimation is 'outsourced' to consultants, in which case sufficient time needs to be allowed for the process of interaction between project geologists and resource estimators. Possibilities to misunderstand the inputs provided (or to simply make data transfer errors between software systems) abound. Significant time and effort is required to ensure that the model is correctly transferred, whether to 'in house' resource geologists or external consulting company. The statistics, variography and other geostatistical analyses should be communicated to the project geologists as the study progresses in order that results can be validated. Project timelines often do not allow for proper checking of inputs and outputs. One resource geologist captured the essence of the problem like this: "there is never enough time to do things properly, but always enough time to re-do them once we find out they're flawed!"

Geological / Estimation Team to End Users

Information transfer to the end users is often poorly managed. The value of spending significant time *during the process* communicating the important decisions with regard to geological interpretation and resource estimation cannot be overemphasised (see Stephenson and Vann, 1999, for more complete discussion). The complicated task of communicating the rationale for important classification decisions (JORC, 2004) is greatly aided by a structured approach to such communication. Ideally, mining engineers, metallurgists, environmental scientists and other end-users should be co-opted to evaluation teams from a very early stage.

Communication to Senior Management and Financiers

The communication of the key results from geological modelling and resource estimation exercises to senior (often non-geological) management is particularly sensitive. Since the important decisions on project feasibility are made at these levels, it is imperative that risk reduction steps taken are clearly communicated. Management today are used to asking 'what if' questions about the capabilities of processing plants and other engineering projects. It is analogous to ask questions about possible alternatives to interpretations of geology for resource estimates, but such questions may not be as frequently posed. Following and documenting a transparent process of criticism of geological models is proposed as an appropriate approach to managing and conveying the risk in such models to managers.

DISCUSSION

Geological models are conceived by a combination of inspiration, intuition and logic. The discussion presented in this paper is not in any sense original, but it does apply to the specific problem of interpretation of geology for resource estimation some ideas that are considered useful.

Specifically, the uses of the model are considered to be the primary driver of how the model should be constructed and assessed. Under this criterion, it is clear that the role of stationarity decision making in generation of domains from geological models is of primary importance. The models must perform acceptably in enough local detail given the envisaged approach to mining (certainly at feasibility stages). The types of errors that can materially change the interpreted geometry fall into several categories: those arising from data and knowledge inadequacies, those arising from decision-making biases (heuristics) and those arising from culture (both the culture of model criticism and the manner in which knowledge is conveyed in the chain from core logging through to management).

The key to development of robust models is that they be examined critically in the spirit of 'falsifiability'. While it may not be possible to generate and evaluate large numbers of alternative geological interpretations in the manner envisaged by Chamberlin's 'Multiple Working Hypotheses' (Chamberlin, 1897), it should be possible to envisage alternatives to key assumptions and test these by directed data acquisition (i.e. drill holes where the assumptions indicate divergent geometry).

Finally, the value of having not only external critical review, but also a robust internal critical review culture is emphasised. It is possible that the establishment of more than one interpretive team for major capital projects, if managed well, could be a significant risk-reduction mechanism. In becoming champions of particular ideas in the modelling process geologists run the risk of being their own worst enemies: it is hard to develop genuinely (and positively) critical environments for the generation of geological models. To quote T.C. Chamberlin:

> "The moment one has offered an original explanation for a phenomenon which seems satisfactory, that moment affection for his intellectual child springs into existence; and as the explanation grows into a definite theory, his parental affections cluster about his offspring and it grows more dear to him. While he persuades himself that he holds it still as tentative, it is none the less lovingly tentative and not impartially and intemperately tentative" (Chamberlin, 1897, pp. 358).

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