Dynamic Links Between Geology and the Mining Process

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ABSTRACT

Geology is generally treated as a 'front end' step in mine development. After infill drilling, the majority of resource estimation, mine-planning, development, mineral processing strategies and operational procedures are planned and implemented with little geological input, particularly in open pit operations. However, significant benefits in overall costs, cash flow, and technical risk reduction can be realised when sound geology is utilised more rigorously throughout the mining process.

This under-utilisation of geology in the mining process has arisen due to a combination of factors:

1. A lack of interest in, or knowledge of the full mining process by geologists. Few geologists fully understand where their inputs make critical impacts on downstream users.
2. As a result of this, geologists generally do not focus their inputs towards areas of greatest value added, ie addressing issues critical for other members of the mining team.
3. Most importantly, few geologists effectively communicate their results to the downstream users of their geology models. The results are that the potential benefits of geology, and the appropriate status of geology in the mining industry, are not fully realised.

It is fundamental to realise exactly what geologists do. Geologists constrain geological processes and geometry. All geoscientific tools at the geologists' disposal are geared towards one of these goals. An emphasis on geological processes is present throughout the exploration process, whereas in the resource estimation and mine development process an emphasis on geometry is required.

The mining process is a web of disciplines that are attempting to optimise development of a resource to provide value to shareholders. Yet few people within these disciplines have a full appreciation of this web, and where sound geology inputs can add value through various feedback loops. Geology inputs do not end at the resource estimation stage, nor are they relegated to grade control implementation. If geologists have an appreciation of the mining process and close liaison with the other disciplines such as geostatistics, geotechnical engineering, hydrogeology, and mining engineering, they can significantly benefit project costs, timelines, and constrain technical risk by addressing their issues at the earliest possible stage. Furthermore, the mining process is not a single pass timeline, but an iterative process where the exploration, resource definition, mine planning and mining loop is continually repeated over the life of a project. Therefore, the potential inputs of geology are critical throughout the mining process.

Effective communication of the impacts of geology inputs on downstream users is often lacking on mining projects. The most effective way to communicate geological results is through where it impacts most – project risk. Focussing all geology inputs and communication in terms of potential material risk allows the geologist to be more effective in contributing value to the mining process, and allows the downstream users of geology inputs to better constrain the risks associated with their aspects of the mining project.

Through a program of geologists:

1. taking an interest in the entire mining process and identifying critical areas for geology inputs to downstream users (the geologists' clients);
2. focussing geology inputs to address the potentially material issues on mining projects; and
3. communicating their inputs to the 'clients' in terms of technical risk, geology will be much better integrated into the mining process.

As a result, the potential benefits of geology throughout the mining process will be realised, and the status of geologists within the mining process will be elevated to a more pivotal position.

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INTRODUCTION — UNDER-UTILISATION OF GEOLOGY IN THE MINING PROCESS

Geology is generally treated as a 'front-end' step in the mine development (Figure 1). After infill drilling, the majority of resource estimation, mine-planning, development, mineral processing strategies and operational procedures are planned and implemented with little geological input, particularly in open pit operations. Although geologists are employed throughout the mining operation, they are often fully occupied with grade control and production issues with little time allocated to assessing potential geology inputs to mining operations. This is particularly true with the recent trend towards reducing geological staff in the interests of reducing operational costs. However, significant benefits in overall costs, cash flow, and technical risk reduction can be realised when sound geology is utilised more rigorously throughout the mining process.

For example, rarely does a project finish infill drilling without requiring significant additional work to be done at the prefeasibility, feasibility or mining stages. While fully addressing all possible issues on projects is not a practically achievable goal, it is the authors' contention that such additional work, and resultant delays or fatal (material) flaws in project development, can largely be avoided. This can be achieved if geologists and management possess an acute awareness of the integration of geology in the mining process, and by directing data collection and synthesis at early project stages towards end-user requirements, eg resource estimation (domain definition issues; drill orientation, density and data quality issues impacting on resource classification), geotechnical (geometry and structure issues – early characterisation of structures and rock mass), metallurgical (recovery issues – early petrography of ore, assay for potential penalty elements), hydrogeological (water problems – installation of piezometers in exploration/infill drill holes), to name but a few.

This under-utilisation of geology in the mining process is rarely due to incompetence, but rather to mutual ignorance and lack of communication between various disciplines or stages in the mining process stream. Geologists often do not fully appreciate the requirements of their downstream users, and the downstream users do not fully appreciate what geologists can do for them.

Geologists who invest time and effort in understanding the potential downstream application to their inputs, and with the ability to communicate their potential contributions to mine planners and management will not only be more effective, but will assist in increasing the awareness, status and benefits of geology in the mining industry.

Similarly, resource estimation specialists, mining engineers, mine planners and metallurgists who seek to capitalise on the geologists' potential inputs will be better able to evaluate, mitigate and manage project risk in their respective technical fields.

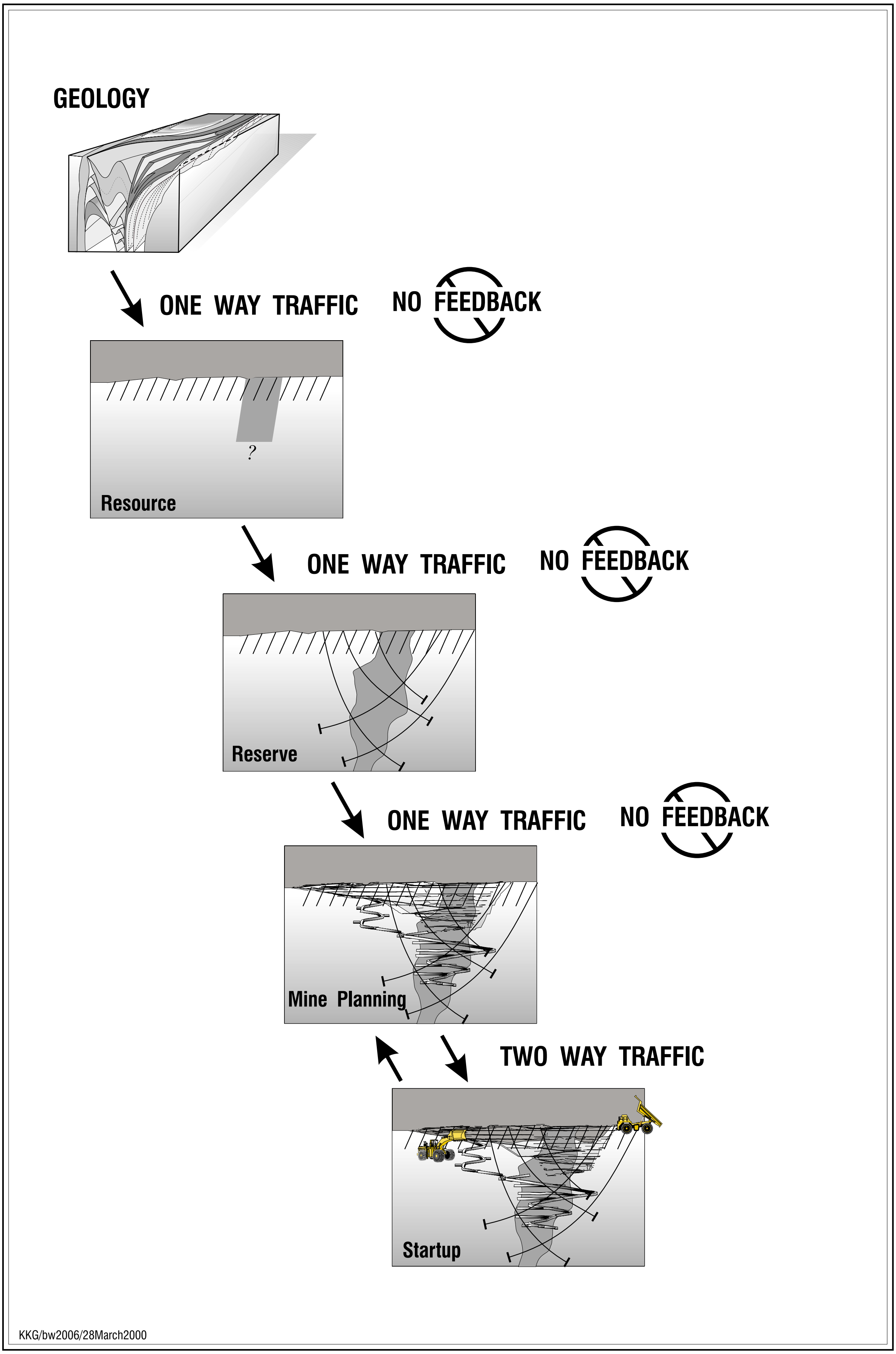

FIG 1 - Traditional view of the role of geology in the mining process.

THE GEOLOGIST'S TOOLKIT — WHERE IS IT THAT GEOLOGISTS ADD VALUE TO THE MINING PROCESS?

What is it that geologists can add to the mining process? What are the real issues that they address? Today's geologists have a plethora of geoscientific investigation techniques and datasets at their disposal (Figure 2). The challenge is to recognise what lines of investigation will add the most value, and thus where to direct data collection effort, interpretation effort, and dollars.

What geologists do – geometry vs genesis

In the opinion of the authors, geological investigations using the myriad tools listed in Figure 2 are all ultimately aimed at constraining either geological processes (eg genesis of ore) or geometry. For example, regional aeromagnetic data is used to determine the geometry of lithology and structure, or evidence that alteration processes have taken place (magnetite-producing versus magnetite-destructive), in order to make predictions as to the potential location of mineralisation (ore genesis). Structural analysis of orebodies is aimed at determining the geometry of ore, whereas kinematic analysis of oriented core is focussed on understanding structural processes that controlled the genesis of ore. Analytical geochemical studies on mineral deposits (SEM analyses of minerals, stable isotopes, fluid inclusions, radiogenic isotopes) are aimed at constraining geological processes that have operated in a region, and those which controlled the genesis of mineralisation. Gold assays are generally aimed at determining the presence or geometry of mineralisation during exploration phases, in addition to their use to quantify resources at a later stage.

Geological processes and genesis of orebodies

Geological processes that are investigated generally address controls on mineralisation, but may also involve other issues such as development of weathering profiles, or decay of mineralised waste at surface (acid mine drainage). In these studies, the geologists continually formulate hypotheses, as to the location of mineralisation for example, and determine what types of data they will require to test the hypothesis or better predict where mineralisation may occur. We emphasise the importance of focussing on process versus models in these investigations. Genetic models are essential in that they form a framework in which we can visualise and understand geological processes. However, models tend to take on a life of their own and tend to drive data collection in self-fulfilling directions (McCuaig and Hronsky, submitted). It is an appreciation of geological processes that advance our understanding, and result in the refinement of geological models or the generation of new geological models. The effective geologist must be a model-builder, not a model pusher. The search for evidence that mineralisation processes have occurred based on our understanding of ore genesis dominates in the exploration phase (Figure 3).

Determining orebody geometry

By the infill drilling stage, the empirical determination of lithology, structure and mineralisation distribution, albeit constrained by our understanding of processes, has begun to dominate the exploration psychology (Figure 3). During this exploration phase the geologists draws upon their 'toolkit' to constrain these geometrical issues, as they are the critical issues from this point through to the mine development stage. While genetic models and understanding of mineralisation processes

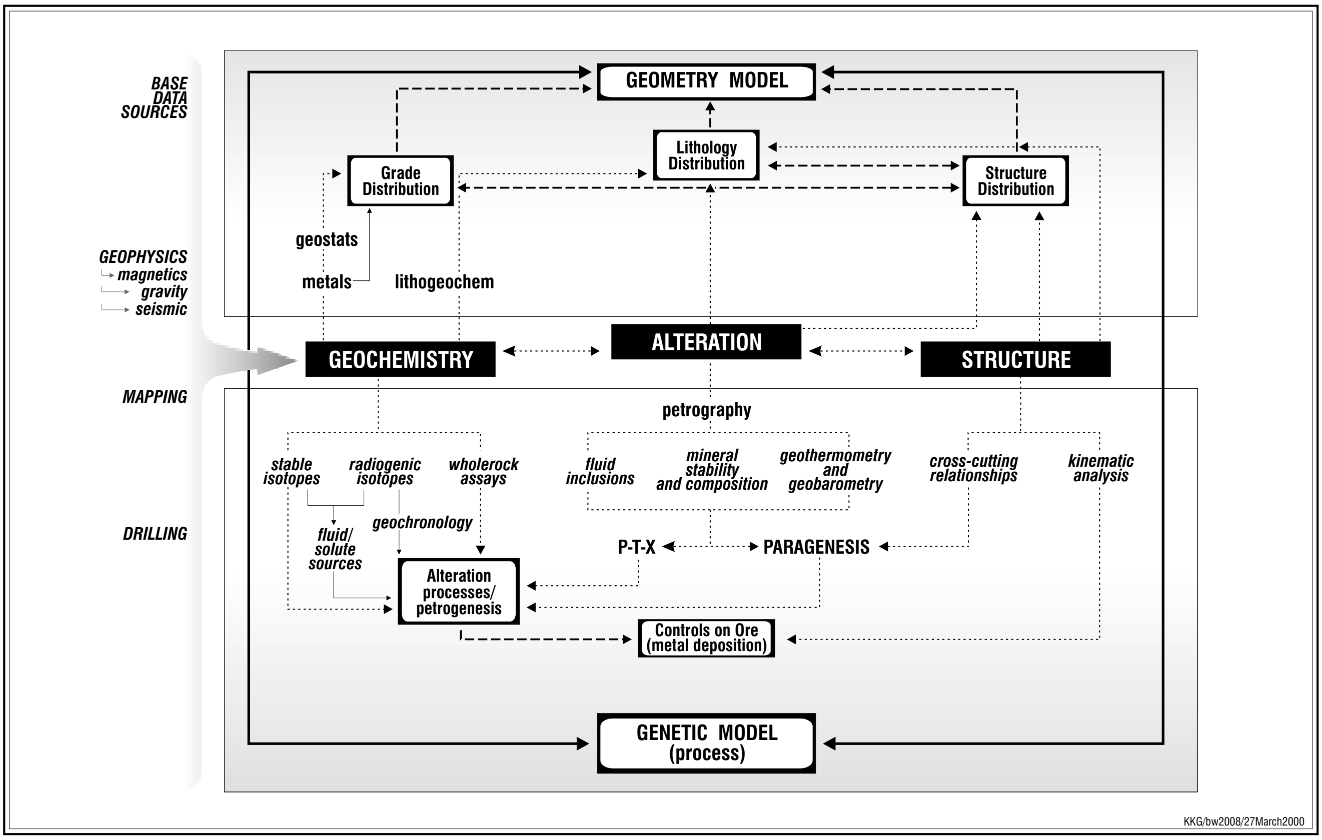

FIG 2 - Examples of the multiple geoscience subdisciplines and analytical techniques that modern geologists have at their disposal.

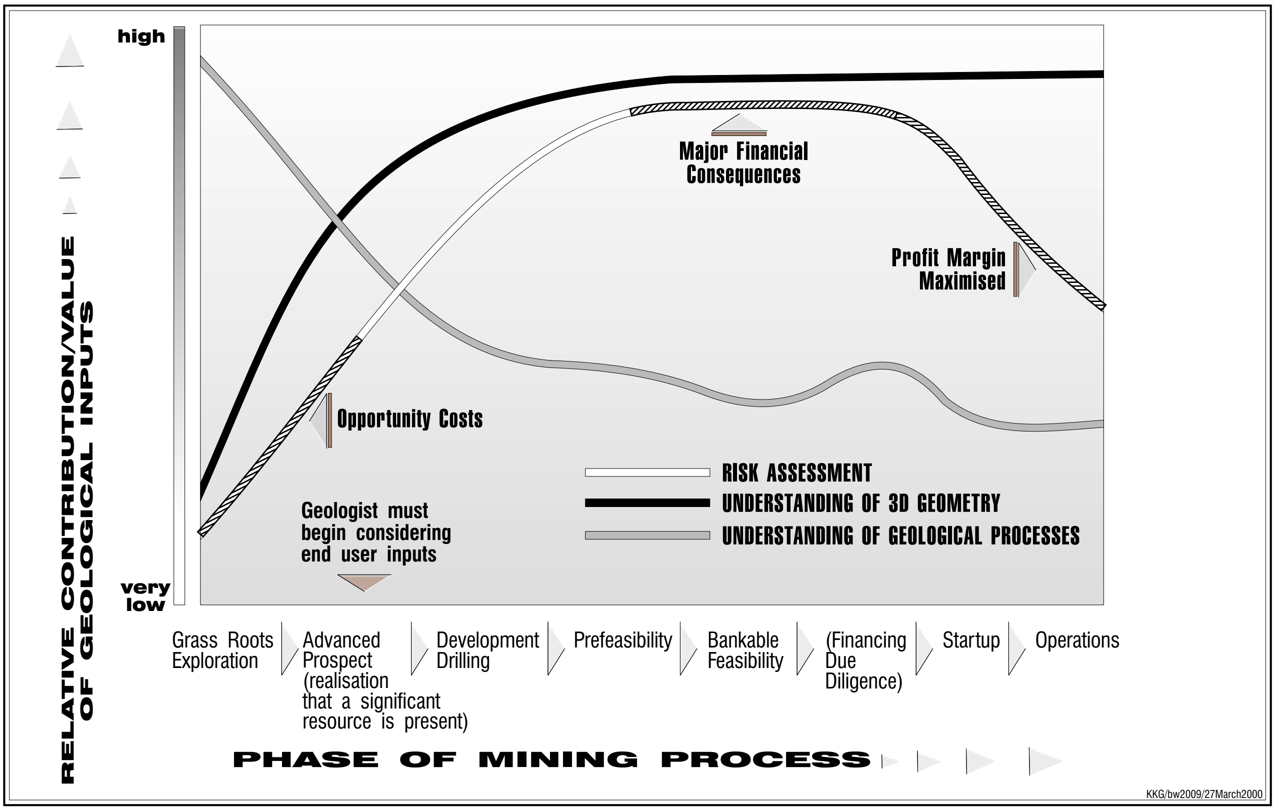

FIG 3 - Process, geometry and risk inputs through the exploration to operation phases of mine development.

are important to delineation of extensions to ore and near-mine to far-field exploration efforts, they are not as critical to resource estimation and optimisation. For example whether a deposit is intrusion-related or not is usually immaterial to its successful development … in fact, full genetic understanding of mineral deposits is rarely reached even after the resource has been fully exploited. Nevertheless, an understanding of processes is still important (eg understanding structural processes and kinematics as an aid to interpreting correct geometry of mineralisation).

Risk analysis and geology

A third issue that geologists' address is technical risk (Figure 3). Although often undertaken in an ad hoc manner, such assessment by geologists determines the risk (uncertainty x consequence) associated with both the empirical determinations of geometry and the understanding of genetic processes discussed previously.

In assessing geological processes, models, and geometric interpretations, an objective rather than subjective approach is the key. Believing that a geological interpretation of geometry is true will not make it so, and can lead to material errors in resource delineation and estimation. Such objective analysis is critical for effective risk evaluation of resources.

Geologists can significantly contribute to the risk assessment process through an understanding of the issues facing the downstream users of geology inputs. For example, inadequate understanding of the geometry of mineralisation is one of the critical contributors to resource risk, as it results in improper stationarity decisions for resource estimation. Many of such high risk issues in mining projects can be significantly ameliorated through the focussed application of sound geology, as we outline below.

So, having outlined the issues that geologists can potentially constrain, and the tools at their disposal, how exactly does the geologist fit into the mining process?

THE MINING PROCESS

Components of the mining process

The mining process comprises a number of subdisciplines and stages, which are summarised in Figure 4.

Figure 4 emphasises the role of the geologists in the mining process, and how their understanding of geometry and geological processes directly or indirectly impacts on the various mining subdisciplines. The fundamental contribution of geologists is to contribute a 3D geological model, utilising the tools at their disposal in the 'geologists' toolkit' (Figure 2, Figure 4). Examples of key issues facing downstream users that can have material effects on projects, and into which geologists can have significant inputs, are listed in Table 1.

The ore reserve estimation process as an example

Each aspect of the mining process has dynamic links with geology. To illustrate some of the dynamic links between geology and the mining process, we use the example of the resource estimation process as outlined in Figure 5. This reserve estimation process runs in parallel with the stages in the mining process outlined in Figures 3 and 4. Note that the inputs of various subdisciplines overlap, and have strong links in these areas. Geology is the one discipline that links strongly throughout the mining process.

Furthermore, Figure 5 emphasises that other subdisciplines of the mining process must be considered throughout the reserve estimation process. While examination of Figures 3 through 5 may suggest that this is obvious, it is remarkable in the authors' collective experience how often this cross-fertilisation between the various disciplines is not accomplished, with the tasks of geology interpretation, resource modelling, geotechnical engineering and mine planning and metallurgy being carried out

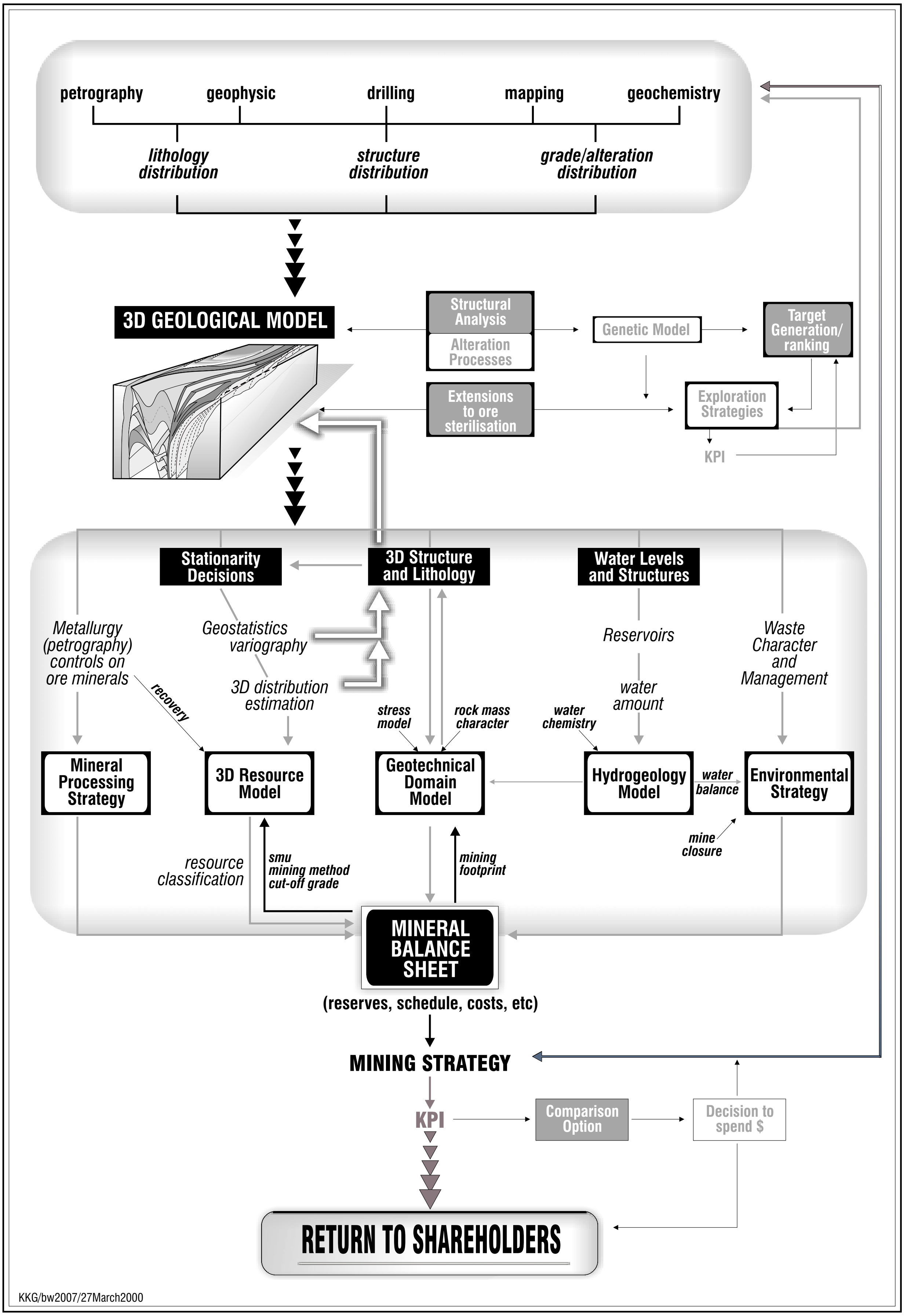

FIG 4 - Disciplines and stages in the mining process, emphasising major linkages.

TABLE 1

Techical subdiscliplines of the mining process amnd where geology impacts upon them. Items in bold type represent potentially material risks.

Sub-discipline/aspect	Key contribution	Examples of where geologists can make a difference
Geology/resource delineation	- 3D geological model for inputs into resource and mine planning - Understanding of mineralisation processes for inputs to near mine exploration/sterilisation.	Fully utilise geologist's toolkit to constrain both geometry and genesis of ore. Aim is to provide best geometric + genetic model possible
Geostatistics/resource estimation	3D grade distribution estimation block model	**Well constrained 3D geometry model to aid in stationarity decisions** (correct shapes, position and classification of boundaries) Close liaison throughout resource estimation, particularly in variography stages to clearly communicate geometric controls on ore Proofing of resultant block model to verify that it is geologically sensible Sound geology can severely impact on resource classification and reduce technical risk
Geotechnical engineering/rock mass characterisation, slope and support considerations	Geotechnical domain model	Knowledge of geotechnical domain logging Attention to nature, density and distribution of structures and lithology AWAY from mineralisation (eg pit walls) Identification of high-risk geotechnical domains Attention to geotechnical data collation during infill drilling can significantly reduce costs
Hydrogeology/water balance	Hydrogeological model	Attention to collation of water data during exploration. Installation of piezometers (relatively cheap) for water level information over as wide an area as possible from early exploration stages can save significant dollars at the feasibility stage by not having to redrill hydrogeology-specific holes Accurate delineation of potential aquifers/aquacludes (structural, lithological)
Metallurgy and process engineering/ore recoveries, processing technology and procedures	Recovery model and processing strategy	Petrography of mineralisation from early stages to help constrain mineralogical nature and controls on distribution of any refractory ore Assay for more than primary commodity (penalty elements, environmentally sensitive elements, Co, S for Cu deposits) - helps to get a handle on their spatial distribution before feasibility
Environmental	Environmental strategy	Early identification and distribution of potentially acid-forming material, acid neutralising material for design of waste management strategies Identification of any high concentrations of environmentally sensitive elements
Mine planning	Mineral balance sheet Life of mine plan	**Robust geometric model and genetic model to prioritise conversion of resources and reserves, identify potential extensions to ore, properly assess sterilisation of infrastructure sites** **Delineation of critical areas of risk in geometry interpretation that could affect scheduling/reserve conversion** Assistance in defining potential selectivity of mining Definition and subtleties of weathering profile Overall risk assessments
Operations	Effective execution and optimisation of mine plan	Design of adequate grade control procedures in conjunction with geostatisticians, particularly noting where geology can help constrain ore/waste blocks (eg highly visible alteration assemblages, prominent ore-controlling structures) **Continued improvement of geological model for multiple iterations and continued optimisation of resources and mine plans.**

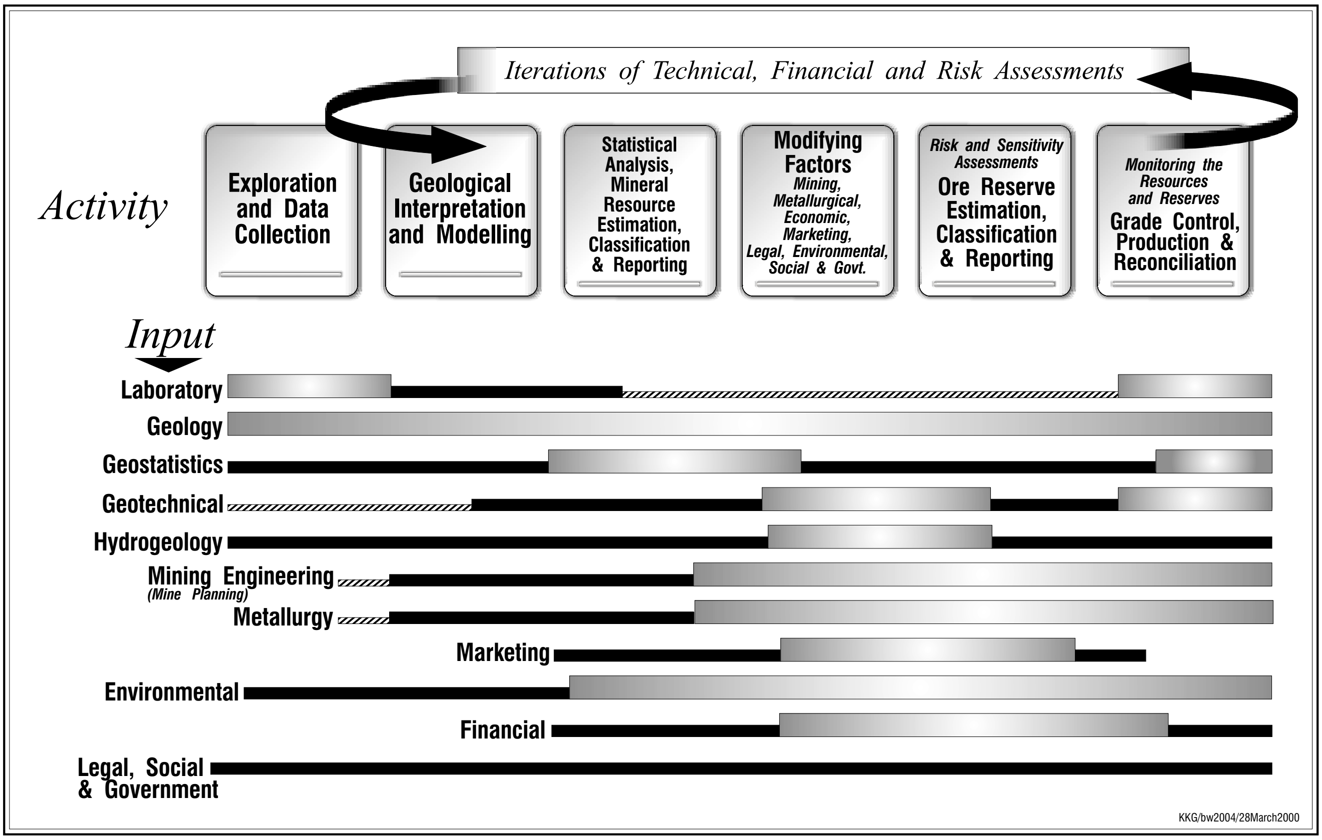

FIG 5 - The ore reserve estimation process.

in isolation from each other. Such insular approaches minimise the benefits of cross-fertilisation and significantly increases the technical risk and probability of fatal flaws in mineral projects.

It is also imperative to recognise that the mining process is iterative right through to the operational phase. As more information is gained during mining, geology models (geometric and genetic) are improved, resources recalculated and reclassified, and mine designs altered to optimise the project. Thus, since projects are not a single pass through Figures 3 - 5, there is even more opportunity for cross-fertilisation and geology inputs are critical throughout the life of mine.

RISK ASSESSMENT AND GEOLOGY

Given the keystone aspect of geology in the mining process outlined in the previous sections, it is natural that geologists should be instrumental in the evaluation of technical risk on projects, yet this is rarely the case. Geologists often tend to focus their investigations into areas that do not maximise value received versus expenditure of time and money. This arises because geologists by nature tend to be more interested in the genetic and theoretical side of mineral deposits (most geologists did not enter geology specifically to become mining geologists, or even to be involved in the mining industry), and because few geologists have a full appreciation of the concepts of how geology fits within the mining process as outlined above.

However, with an appreciation of where geology inputs impact on the mining process, a geologist can provide quality inputs to the above categories to evaluate, manage, and hopefully mitigate risk in all aspects of mining much more tightly. A geologist should focus inputs to those issues that could have a material impact on projects. In the current economic climate with low commodity prices, such input can make or break projects.

Effective risk management focuses on issues that could lead to material errors in mineral projects (high uncertainty and high financial consequence). Results of geological assessment of project risk must then be effectively communicated to other disciplines and management. Risk matrices are useful ways to accomplish this (Table 2). Presentation in this format clearly communicates where the risks lie and allows management to quickly comprehend the issues and decide where to commit resources to add value to projects. In the example presented in Table 2, it is clear that the geological inputs to the resource estimation are rated at moderate to high risk, and that more emphasis on constraining the structural controls on ore and the refractory nature of ore are required. Such tables rating the quality of geological inputs can be constructed for any or all aspects of the mining process.

GEOLOGISTS SHOULD LEAD THE WAY

The authors' contention in this paper has been that geology is presently under-utilised in the mining process. This situation has arisen through a combination of some or all of the following factors:

1. most geologists do not fully understand the mining process, and therefore where they can contribute more effectively to downstream users in mineral project development;
2. geologists do fully utilise the 'toolkit' at their disposal to address these issues;
3. geologists do not focus their inputs to prioritise issues with potential material effects on projects; and
4. geologists do not effectively communicate their results to the rest of the mining community.

TABLE 2

Example of a risk matrix for geological inputs into a resource estimation. Risks are classified as low = little risk to project, medium = moderate, but non-material risk to project and high = potentially material risk to project.

Aspect of data/interpretation	Contribution to overall project risk	Drill campaign 1	Drill campaign 2	Development	Comments
Survey data	low	low	low	low	Survey data is of high quality
Sampling procedures	medium	medium	low	low	Sampling procedures are adequate for resource estimation purposes. Development sampling is inadequate for estimation, but has not been used in estimation
Specific gravity data	low	low	low	n/a	Specific gravity data is of acceptable quality
Assay data	low	low	low	low	Assay data is of acceptable quality
Mapping/logging quality Lithology Structure[1] Alteration Weathering	 low medium low medium	low **high** medium medium	low medium low medium	low low low low	Structural logging is of poor quality due to poor orientation quality and logging techniques. Weathering has not been consistently logged.
Geology interpretation Lithology Structure[2] Controls on mineralisation/ alteration[3] Weathering surfaces	 low **high** **high** medium				Structure interpretation is poorly constrained, and controls on oreshoots are unconstrained. Weathering surfaces have not been adequately defined, but contributes only moderate risk as most of resource is in fresh rock.
Understanding of nature of refractory ore[4]	**high**	**high**	medium	low	Insufficient analysis of controls on refractory ore. Requires petrography on representative samples.
Stationarity decisions Position of domain boundaries[5] Nature of boundaries	 **medium-high** medium	**high**	medium	low	Geological domains for resource estimation purposes are only loosely defined due to uncertainty in structural interpretation.

1. Structural logging is inadequate due to poor core orientation. Drill campaign 1 also employed incorrect structural logging techniques.
2. The structural interpretation is poorly constrained, due to structural information quality, and misinterpretation of shallow mineralised links between steeper major shear zones. This is viewed as a high-risk issue that may have a material effect on the resource estimation.
3. The controls on mineralisation, oreshoots, and variation in mineralogy with host rock is poorly understood. Given the variably refractory nature of the ore, this could potentially have a material effect on reserve estimation.
4. The ore is variably refractory, with recoveries increasing with degree of weathering. However, the controls on refractory ore are poorly understood in the fresh rock (the bulk of the resource), and contributes high and potentially material risk to the project. However, it will not materially effect initial cash flows due to high Au recoveries in the weathered zone.
5. Due to the uncertainty in thestructural interpretation, the position of major boundaries for purposes of resource estimation may be in error, contributing high and potentially material error to the project.

The end result of this, and especially the latter point, is that the other mining disciplines do not fully appreciate where sound geology can assist them in their respective tasks.

The recent economic climate has resulted in a severe downturn in the geology profession. While the lack of appreciation of the potential applications of geology is widespread throughout the industry, the onus is on geologists to lead the way towards more fully integrating geology with the mining process by increasing the awareness, benefits and ultimately status of geology in mining.

The geologists' challenge is to utilise an appreciation and understanding of the complete mining process as outlined in Figure 2 through Figure 5 in a five-fold approach:

1. Become familiar with the geologist's toolkit. Fully understand what investigative techniques are at your disposal and what technical issues they can possibly constrain.
2. Take an avid interest in, and educate themselves in, these various aspects of the mining process.
3. Identify the major issues facing the downstream processes/users, and treat them as your 'clients'. Realise which will be potentially material in nature (prioritisation of high risk issues).
4. Focus geology data collection, interpretation and inputs to address these high-risk issues.
5. Communicate the results to 'clients' or project team members (downstream users) in a practical format (eg risk matrix).

In addition, it is necessary to adopt a mining process mindset and address these issues at the earliest possible stage of resource delineation. By being aware of and addressing issues such as those outlined in Table 1 early in the process, significant cost benefits, shortening of timelines to start-up, and technical risk reduction can be achieved. We emphasise that this can only be achieved through close liaison between all mining subdisciplines, each with a mutual appreciation of the other's abilities, limitations and required inputs.

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