Mines versus Mineralisation – Deposit Quality, Mineral Exploration Strategy and the Role of ‘Boundary Spanners’
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ABSTRACT
Resources added to the global metal inventory through exploration over the past 15 years have been generally of poor quality (declining grades, recoveries and lack of acceptable financial return). Similarly, companies opting for an acquisitions-based strategy have had to pick from a group of poorer quality resources left from previous exploration booms, and will struggle to deliver this metal to market economically. Increasing difficulty in obtaining sufficient social and community acceptance of mining projects and potentially an energy-constrained future may exacerbate this problem, redefining what is considered ‘ore’. There will need to be more focus on deposit quality, defined as sustainable margin in the future business environment.

Traditionally there has been a lack of translation of ‘mineralisation quality’ back to mineral project design and mineral exploration. This disconnect is due to two main factors: the first is technical – inherent deposit variability; and the second is organisational and socio-psychological – the mindset of explorers and project managers themselves.

There are four elements to value realisation for a mineral deposit: (1) social licence to operate; (2) geological factors (depth, geometry, water and geotechnical, and geometallurgy – influenced by texture, mineralogy, chemistry and grades); (3) financial engineering (capex, opex, future commodity prices, future energy prices), and (4) operating factors (production rate, recovery, energy consumption). These elements are strongly interdependent, and geology underpins and drives linkages between them. A quality deposit addresses all of these elements and thus can be developed in a time frame that allows acceptable returns to the owners of the invested capital.

Geological drivers of the above elements can be measured and mapped throughout a deposit. Moreover, when viewed in the context of mineral systems, a predictive understanding of the common causative processes of quality (despite deposit-scale variability) is emerging, and with it the ability to target quality of mineralisation, not just quantity of mineralisation.

The second factor is a ‘heuristic software problem’. Current lines of education (and consequently organisational and professional structures) are discipline-based, producing ‘silos’ that do not speak each other’s language and work with different ‘mental models’. People who effectively recognise systemic links between these silos are called ‘boundary spanners’, of which we propose two distinct types: outside-insiders and inside-outsiders. Outside-insiders are people who are within a community, but recognise advances in outside fields and effectively integrate them into the community. Inside-outsiders start outside of a community, and successfully bring new ideas into it. Common traits in boundary spanners are: they seek exposure to (and embrace) key ideas that are outside of the framework of their own specialisation; they have high mental processing ability (MPA) – the ability to connect systems that are currently not perceived to be connected; and they introduce ideas from outside a field into a new context in a way that re-frames the field.

The challenge is to identify and nurture potential boundary spanners that can build critical links, in particular between the (largely geoscientific) mineral exploration mindset and the (largely non-geoscientific) project development mindset. Critical linkages to be built are between mineral system science, targeting science, and whole of value chain modelling.

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IMPORTANCE OF RESOURCE QUALITY

Recent reviews of mineral exploration success and the mining project pipeline have shown a trend of decreasing effectiveness of exploration and declining quality of the mineral project pipeline (McKeith et al., 2010; Schodde, 2013, Figure 1). Figure 1 clearly illustrates that the current project pipeline is challenged, and will struggle to bring the metal required by society to market, leaving many of these resources as marginal projects, effectively ‘stranded’.

The problem of a marginal project pipeline is likely to be compounded in the future by at least two factors: increasing difficulty in obtaining sufficient social and community acceptance of mining projects, and a potentially energy and carbon constrained future. We are living in an increasingly environmentally aware society, which demands that our industry reduce its physical, energy and environmental footprint. These demands may progressively translate into legislation in many jurisdictions. Even more challenging will be the non-legislated social ‘licence to operate’ – a complex social exercise which takes long periods of trust building.

Mining is an energy intensive business. In Australia alone, the energy consumption of comminution is approximately equal to the consumption of the entire residential sector of the nation (Bye, 2011). In this light, we are likely moving into an energy (and probably carbon) constrained future of relatively high costs. Despite the current political environment in Australia, increasing pressure for the implementation of some form carbon emissions regulations, such as a carbon tax or trading scheme seems a plausible scenario for most developed nations. Therefore, the real cost of mining could continue to escalate.

These two factors of increasing social awareness and the plausibility of an energy and carbon constrained future would redefine what we consider to be ‘ore’ in the future; ie viable mineralisation from which useful products can be economically extracted. Many of the resources currently in the global inventory of mining companies will not fall into the ‘future ore’ category because rising costs of extraction, combined with technical and socio-political constraints, will render them unviable. In Figure 1, this will result in a contraction of the envelope of economic projects and expansion of the envelope of undeveloped projects, with many current projects in exploration, feasibility and development stages moving into the ‘stalled’ category.

Therefore, the challenge for the future is to focus on resource quality (Schodde and Hronsky, 2006). Although quality of mineralisation is clearly a multiparameter space, at the highest level it is defined by sustainable profit margin in the future operating environment. In practice, the industry has largely explored for size, hoping that quality will emerge. In the future operating environment, the degree of social licence to operate will both influence and be strongly influenced by geological, economic and environmental factors that are tightly coupled. For example, the degree of social licence will both influence and be strongly influenced by geological factors such as the impact upon the local water balance and the availability of water, mining, processing and waste stream engineering options.

The pathway to realisation of value from a mineral deposit discovery necessitates more than the location of potentially viable mineralisation in sufficient quantities. The four required elements are illustrated in Figure 2 and are:

1. **Social licence to operate** – arguably the term ‘licence’ is misleading here, because a licence is either obtained or not; whereas ‘social licence to operate’ is a progressive scale from complete socio-political enablement of a project that is seen as highly positive by stakeholders, all the way through to a project that is regarded as unviable and socio-politically toxic to significant stakeholders. In any case, a low degree of social licence to operate renders the realisation of sustainable value from a project impossible to most large mining companies, for whom delivering multistakeholder value is an important organisational objective.

2. **Geological factors** – the geometry, depth, geometallurgy (informed by texture, mineralogy, chemistry, grade) and other geotechnical properties of the deposit (including hydrogeological context) are essential to evaluation of financial viability. We discuss these factors further below. However, it is important to note that projects without economically viable pathways to solution of geotechnical, water, mining, processing and waste stream engineering options do not constitute an ‘orebody’ in any commercial sense.

3. **Financial engineering** – the availability and cost of capital and labour, infrastructure requirements, operating costs, and future evolution of both energy and commodity prices are pivotal to economic viability.

4. **Operational factors** – the ability of the owners to engineer mining, processing, infrastructure and operational solutions that enable sustainable, profitable operational viability. Key factors are decisions around mining and processing rates (and consequent infrastructure scale), metallurgical technologies and operating policies that enable sufficient recovery of saleable product, and the ability to do this within the constraint of attaining acceptable rates of energy consumption per unit of metal production.

Note that these elements are not independent, and in fact are tightly coupled. For example, the degree of social licence will both influence and be strongly influenced by geological factors such as the impact upon the local water balance and...
the propensity of the operation to generate environmentally unacceptable waste streams. Similarly, the cost of capital and operational cost (and complexity) are driven by geographical location and geological complexity. Nearly every factor mentioned is connected to others in a complex system, and ultimately the multiparametric geological character of the deposit (at all scales) drives these linkages.

A ‘quality deposit’ is therefore one which can address the elements described above, as shown schematically in Figure 2, in a manner that allows acceptable value delivery to the owners of capital, usually measured by Net Present Value (NPV) and rate of return, etc. Having defined what constitutes a quality deposit, it is therefore conceptually possible to spatially ‘map’ in the mineralisation the relevant geological parameters that enable or limit progression to value delivery and include them in deposit models. Note that there are always multiple alternative pathways to value delivery, and choosing among them is a complex combination of trade-offs, optimisation and seeking of robust solutions.

Today, many of the required parameters discussed above are not regularly recorded, especially at exploration stages. An example where progress is being made in this regard is the mapping of mineralogy in enough detail to start to build spatial models that can predict likely throughput in a subsequent metallurgical process. This is straightforward in deposits where texture and structure play small roles in determining throughput (for example, the hard plant feed is silicified and the soft feed has low quartz content). However, most deposits have throughput performance (and metallurgical recovery) that is strongly impacted by texture as well as mineralogy. Some textures facilitate rapid comminution (for example fissile laminated ores) while other textures with essentially identical mineralogy and geochemistry (eg massive or equigranular variants of the same material) may resist comminution. These latter types, despite having the same whole rock mineralogy and chemistry, may imply materially lower throughputs. Variants of texture can also depress metallurgical recovery. An example is to have exactly the same proportions of pyrite and chalcopyrite in a liberated sulfide grain which has a viable copper content. However, in one case the pyrite totally encloses the chalcopyrite and is separated as a non-economic grain and in the other the reverse is true and the copper is recovered.

The impact of geometallurgical thinking (and the required data sets as discussed above) goes further than impact on processing. It directly bears upon key social and environmental issues; for example, lower recoveries mean more waste, and not extracting sulfide content and allowing it to go through to waste streams increases the risk of acid rock drainage (ARD). In this case, the economics of improving recoveries aligns with environmental goals and we have a clear win-win.

The counter-argument against early geometallurgical work – that this is ‘… just more costly work to do at an early stage,
EXPLORING FOR QUALITY

Although knowledge of the required geological parameters can help with the design and optimisation of mining extraction and valuable mineral recovery, the parameterisation in this manner is most applicable at the scale of the deposit (or smaller). As such, it can be employed during resource definition or modelling and simulation of downstream mining and processing steps in the mining value chains. But can one explore for quality? How far upstream in the exploration process can the required geological parameters that drive ‘quality’ (ie realisation of value) be mapped and influence decision-making? Traditionally there has been lack of translation of ‘mineralisation quality’ back to mineral exploration strategy. This disconnect is due to two main factors: the first is technical – inherent deposit variability; and the second is organisational and socio-psychological – the mindset of explorers themselves. The combined result is that over the last decades, the focus of the majority of the industry has been on locating and then delineating mineralisation, not potential mines. We wish to explore how this could change over time.

There is much variation on the mine scale that is currently impossible to predict on the larger (district or regional) scale during the exploration process. Many parameters determining the quality of the mineral deposit – and thus likely success in navigating a pathway to ultimately acceptable value delivery – are dependent on a range of factors such as P-T-X (pressure–temperature–composition) conditions of the fluid/magma, the physical mechanism of fluid ingress, and the host rock, which in turn control the mineralogy and textures that form and the depositional mechanisms and deportment of the metal (eg McCuaig and Kerrich, 1998). Every deposit is unique in its own ways.

Given this complexity, there is no doubt that it is difficult to explore for deposit quality.

Quality can be measured by empirical business performance of deposit class types, for example, unconformity uranium deposits globally contain the highest average uranium grades by an order of magnitude, and therefore are priority targets (Kreuzer et al, 2010). Such deposit class performance does inform mineral exploration strategies (Penney et al, 2004; Kreuzer et al, 2010). Yet even within such deposit classes, deposit quality is quite variable. For example, many high quality examples of porphyry copper-gold deposits exist, and have long been a favoured target of mineral exploration companies, yet many of the stranded resources in Figure 1 are large porphyry deposits (www.minexconsulting.com).

This leads us to ask: what are common features of high quality mineral deposits that can be mapped, and used in predictive models for mineral exploration? With the ever-increasing availability of large multidisciplinary data sets on mineral deposits, should it now be possible to recognise the empirical patterns associated with high quality mineralisation in multiparameter space and model it throughout a deposit? This is an important first step to spatial prediction of further high quality mineralisation. The second step is to obtain a predictive understanding of the underlying causative processes that generate the empirical patterns and cause the formation of high quality ore.

One of the most important advances in understanding ore genesis in the past two decades has been the realisation that high quality mineral deposits generally form very quickly – geological lightning bolts on the order of 10^6 to 10^7 years in a larger and longer lasting maelstrom of deformation, magmatism, fluid flow and alteration lasting 10^5 to 10^6 years (McCuaig and Hronsly, 2013, in press). The broader fluid flow and alteration events may produce large metal anomalous, but do not form high quality mineral deposits (McCuaig and Hronsly, in press). Hronsly (2011) and McCuaig and Hronsly (in press) demonstrate that these brief periods of high quality ore formation likely reflect self-organised critical behaviour of the fluid system. This behaviour is promoted by the conjunction of two factors: energy supply (in the form of magmas, fluids, heat) continues to be added to the system, but a threshold barrier is established that prevents this energy from dissipating into a sink. In the case of ore deposits, the threshold barriers are usually a combination of local to regional physical and geodynamic barriers that combine to clamp permeability and cause the fluid system to self-organise. The system builds up extreme gradients of energy and fluid pressure, potentially with supersaturated metal concentrations, then releases them in short ‘avalanches’, with ore forming in the exit conduits above the threshold barrier.

The emerging understanding of self-organising critical system control on high quality mineralisation has important implications for understanding ore shoot formation on the deposit to camp scale. Firstly, the fluid flow during high quality ore formation is not controlled by actively deforming structures. The fluid pressure creates its own permeability pathways, taking the path of least resistance and exploiting any weakness in the rock mass. These pathways can be quite tortuous in nature, following combinations of structures and lithological contacts as the fluid moves rapidly down pressure gradient. In most hydrothermal ore systems, the fluid is advecting vertically through the crust, and will at some scale have vertical connectivity between seemingly isolated areas of high quality mineralisation within a deposit. Mapping these fluid exit conduits where they are not ore will be critical for targeting further high quality mineralisation. There has also been the recognition that multiple periods of mineralisation often occur in the same volume of rock separated by long periods of time, indicating that some architectures are more favourable, acting as ‘lightning rods’ for fluid flow and mineralisation. Therefore, it is critical to map the 3D architecture of the mineral deposit and surrounding district, detect the transient fluid exit conduits, then hunt the ore within them (McCuaig and Hronsly, in press).
Predicting the location of high quality mineralisation at a range of scales is now becoming possible through the application of a mineral system approach, whereby high quality ore formation is viewed as the rare conjunction of fertility (areas of the lithosphere or geological time periods that provide a preferred source of metal), whole lithosphere architecture (the pathways for mass and energy transfer through the lithosphere), transient geodynamic triggers that cause self-organised critical behaviour of fluid and magma flow, and preservation of the primary depositional zone (approximately the upper 10 km of earth’s crust) since the time of mineralisation (McCuaig and Hronsky, in press). This framework identifies high value questions for geoscientists to address to aid the search for high quality mineral deposits and districts at a range of scales:

- more effective ways to integrate geology and geophysics to image 3D architecture from deposit to craton scales
- how to map the fluid flow system associated with moments of high-grade ore formation
- distinct methods to identify that a district has experienced self-organisation of the fluid flow system
- at the largest scale, a better understanding of terrane fertility and methods to map it.

Figure 3 connects the realms of fundamental and applied geoscience in mineral exploration with the engineering, financial modelling and other largely non-geoscientific activities required to deliver value from mineral deposit discovery and exploitation. In the mineral exploration domain, the critical interface between the business of mineral exploration/discovery and the fundamental engine of geoscience is through understanding mineral systems, and translating them through to targeting systems. Targeting systems interface with the business and technology components of mineral exploration and deposit discovery. Yet within this process, mineral exploration activity is still largely focused on finding mineralisation per se, not high quality deposits and thus high value mines.

In the project development domain, the critical interface is the four elements of mineral deposit value realisation shown in Figure 2. Essential to the discovery of high quality/high value mineral deposits in the future is the alignment of these two domains, particularly at these critical interfaces. See text for discussion.
value chain modelling effort with fundamental geoscience and mineral deposit exploration science. Addressing this challenge will require that we determine taxonomic structures and generate models for fundamental rock properties at scales that impact value realisation in the mining and processing value chain. Since rocks are specified by their mineralogy, geochemistry, textures, petrophysical properties and structures, this work requires modelling of all of these properties. The fundamentals of modelling geochemistry and mineralogy are well understood (albeit there have recently been great steps in technology enabling application of this understanding). However, the quantitative modelling of fundamental textural properties at small scales is a very dynamic field. There has been significant work on this topic in petroleum geoscience (eg Avseth et al, 2010) and some interesting applications of mathematical morphology to the problem (eg Mauricio and Figueiredo, 2000), but the field is very immature in relation to geometallurgy.

Connections between texture modelling and mineral deposit characterisation, and ultimately exploration targeting thinking, is a prime example of ‘boundary spanning’ (Tushman, 1977 – see discussion in next section) constituting a fruitful area for future investigations. It would be unsurprising, for example, to find that advances in understanding and modelling textures (and perhaps spatial mapping of their variations) allow us to develop a richer comprehension of the mineral systems discussed previously. This may give interesting connections between macro-scale textural variations (which drive important aspects of deposit quality) with deposit-scale or even regional considerations. In this instance the requirement is to enable individuals with high-level conceptual knowledge of fundamental geoscience, mathematical morphology, mineral processing and mineral deposit targeting systems to construct a seamless interface at the critical linkages shown in Figure 3.

THE NEED FOR BOUNDARY SPANNERS

The problem of developing links between exploration thinking and targeting science (which is a geoscientific activity par excellence) to downstream economic utility necessitates a different cognitive approach. The concept of ‘boundary spanners’ is useful to describe individuals who are capable of forming such linkages. It was developed in the social sciences and is most frequently associated with the work of Michael Tushman in the field of organisational behaviour (Tushman, 1977). The idea has been considered in assessing the effectiveness of large scale organised research programs (Mangematin et al, 2014), with the boundary spanners acting as ‘scientific entrepreneurs’. As these authors (and others) point out, through training and experience scientists are ‘discipline grounded’. We argue below that this can become a limitation or an enabler depending on the contextualisation of the education process. Increasingly, in many areas of industry, providing answers to complex problems requires that professionals combine different disciplines, technological platforms or devices to produce solutions.

It is possible that formal education and organisational culture can combine to encourage boundary spanning as defined here. However the authors argue this will be a necessary but not sufficient step. There are likely to be specific cognitive traits for boundary spanners, for example, high MPA (mental processing ability) as defined by MacDonald et al (2006). The concept of MPA is imperfectly but positively correlated to intelligence: higher order MPA denotes complexity of thinking, specifically, the capacity to combine several systems into a single view, albeit with ambiguities. In fact the ability to tolerate ambiguity and paradox is a key component of this ability. The best management education aims to promote exactly this kind of synthetic and systems thinking. Synthetic thinking is difficult for intelligent people who operate perpetually in analytic mode (arguably this applies to many professionals who are taught to ‘pull problems apart’ rather than connect disparate problems). If a professional has deep expertise, the capacity to look laterally can be hobbled.

It is noteworthy that having broad expertise is often confused in the mining industry with being a ‘generalist’ and erroneously as an indication of an inability to specialise. There are implications in this for mining companies, universities and professional societies that need further contemplation and research: how do we train and enable ‘boundary spanners’?

The high order MPA described by McDonald and co-authors is a measure of an individual’s capacity to link and weave apparently separate systems together. The ultimate expression of this is Thomas Khun’s ‘paradigm shift’ (Khun, 1996). Though now much hackneyed and overused, the concept of paradigm shift originated in contemplating the work of scientists (with geological examples) and is still a startlingly original idea: in the face of general consensus about the nature and specifics of a given system, one or more observations are perceived that point to a re-framing of the system. These are almost classically seen by outsiders. It has been argued (Vann and Stewart, 2011) that, for geoscientists, Alfred Wegener is the archetype outsider bringing a radical idea to a scientific community. Wegener was a meteorologist who proposed and relentlessly promoted the idea of continental drift (Wegener, 1924) to an almost universally sceptical geological community. Such people rarely work out the implications of the new systemic view (they do not have the deep expertise to do so), but they perceive the connections against the grain of contemporary understanding, possibly because they do not have the limited view imposed by deep training in (and psycho-social commitment to) the current paradigm.

Outsiders as boundary spanners can thus be of two types, which we denote here as:

1. ‘Outside-insiders’ – who are inside a field, ie are part of an accepted community – insiders (say in this case geologists) bring in ideas from outside fields. Because they are inside the community they are trying to shift, they are ‘allowed’ to do this and ideas may be more acceptable.
2. ‘Inside-outsiders’ – people who start outside a field, and successfully manage to bring new ideas into it, which are accepted, and they themselves are ultimately accepted as an insider.

Like Alfred Wegener, Daniel Kahneman (eg Kahneman et al, 1982) is an archetype of the second category, the inside-outsider, starting out as a psychologist, but managing to be accepted as an economist – even getting a Nobel Prize in that discipline.

It was an outside-insider, Arthur Holmes, who proposed the mechanisms required for Wegener’s shocking ideas about continental drift and promoted (and put some initial geological details to) a deeply unpopular idea (Holmes, 1929). The identification of the inside-outside group raises the question of how do we bring them into our field? For example, we do not see very many economists (sensu stricto) at economic geology conferences or contributing to economic geology publications, partly because a degree in geology is a prerequisite either explicitly, or tacitly to join the community. What are the forums in our industry for inter-disciplinary cross-pollination; or do we need to develop these? It is also very difficult to criticise from the outside: geologists are
permitted to point to the flaws in geological and scientific thinking (even so, this is risky) but they bristle when an economist, ecologist or philosopher does so.

It is important to distinguish boundary spanning from more basic collaboration. The idea of boundary spanning involves a person with the right cognitive capacities (high MPA) looking across traditional discipline boundaries and seeing re-formulations of existing systemic thinking about a topic – or connecting different parts of a problem in a manner that is difficult for narrower specialists to do. This contrasts to more basic forms of collaboration: getting geochemists to speak to geophysicists, for example, is not boundary spanning, it is effectively running a geoscience function within an organisation. Systematically working collaboratively with other colleagues (especially those whose problems we are not fully familiar with) is the beginning of boundary spanning – literally going beyond your own personal paradigm. But the next stage requires one or more of the following additional steps:

1. be exposed to (and embrace) key ideas that are outside of the traditional training framework of our own specialisation
2. connect systems that are currently not perceived to be connected and/or
3. introduce ideas from outside a field into a new context in a way that re-formulates the problem (‘re-framing’, see also Kahneman et al, 1982).

We believe increased boundary spanning is required to identify and solve new problems in geosciences (and mining). However, there are significant barriers to the development and success of boundary spanners in the mining industry.

The first obvious problem is the compartmentalised nature of disciplines alluded to previously. The traditional main technical professions in the mining value chain are exploration geoscientists, production geoscientists, mining engineers, mineral processing engineers and mineral economists (or ‘techno-economic specialists’). The boundaries between some of these disciplines have overlaps (metallurgists and geologists share mineralogy; mine planning engineers and geologists share spatio-temporal thinking, etc). But the whole of the value chain has not historically been seen by any of these disciplines. The problems we now face to achieve step changes in the value delivery of our industry require seeing connections between the in situ properties of the mineral deposits and all subsequent modifying and transformational engineering and economic steps in the value chain (through to the product in the hands of the customer). This is clearly a complicated web of systems and a productive place for boundary spanning to identify new challenges and new solutions.

The barriers to boundary spanning can be conceived as a ‘heuristic software problem’ of the current structure and content of professional education (and consequently organisational and professional structures within universities, research institutions, mining firms and ultimately the industry as a whole), which remain fundamentally discipline-based. In practice, organisations, including mining companies, find it very difficult to create systemic linkage between disciplines not only because they do not speak each other’s language, but also arguably because they work with very different ‘mental models’ of the business. This is then exacerbated and reinforced by the ongoing separations of these functional silos. For example:

- geosciences is a different career path to mining engineering or mineral processing engineering
- these disciplines are often seated in different parts of offices (or even different geographical locations)
- problems defined as ‘cross-disciplinary’ may consequently remain unrecognised, or even if perceived, remain ill-defined and dormant due to these fragmentary organisational barriers.

The challenge: how to educate and develop professionals in a manner that enables the high MPA individuals to have sufficient vocabulary and conceptual perception to move across the boundaries. Being a boundary spanner effectively means being ‘multilingual’ across disciplines, and usually comes with significant breadth of experience. However, the most successful boundary spanners often have another common trait – they were educated (and took an interest) across disciplines at an early age, at least as early as undergraduate level. Therefore, one possible pathway for training in boundary spanning is by starting with the small (but also artificial) boundaries first; eg geophysics and geochemistry; mining engineering and mineral processing; then moving onto bigger boundaries ie geosciences and other natural sciences; geosciences and engineering, etc.

The traditional distinction between science and engineering is a particular barrier to progress in this regard. Science is conventionally defined as the endeavour of understanding the origins, nature, and behaviour of the universe and all it contains; engineering is about solving problems by using fundamental scientific knowledge as a lever. The truth is that most geoscientific work spans the boundary into problem solving and technology, but mining industry geologists are resolutely thought of (and think of themselves) as being outside the domain of engineering. This is an artefact of professional and educational cultures and an impediment to progress of the complicated work required to enable fundamental step-changes in the mining industry.

CONCLUSIONS

Mining projects are more and more challenged, with social and environmental issues increasingly important. Unlocking value in exploration and mine project development in the future will involve the targeting and subsequent development of projects that are viable in a world where environmental and social issues are critical factors. While technical professionals seek technically optimal project solutions that are socially and environmentally acceptable; we will increasingly need to seek socially and environmentally optimal projects that are technically and economically acceptable. This turns the traditional mind-set on its head.

We posit that a quality deposit needs to properly address the following four key elements:

1. social licence to operate
2. geological factors (depth, geometry, water and geotechnical, and geometallurgy (texture, mineralogy, chemistry, grade)
3. financial factors (capex, opex, future commodity prices, future energy prices)
4. operational factors (production rate, recovery, energy consumption).

Importantly, all of these elements are interconnected, thus cannot be considered in a linear manner and must be treated systemically. Geological factors do however underpin all these elements to greater or lesser degrees, thus they provide a tool for understanding (and potentially modelling) these interconnections. A ‘quality deposit’ thus requires that we...
Unlocking value from mineral deposit discoveries will require changes to both the way we consider a mining project, as well as a change in mindset of geoscientists and other professionals within the industry. Emerging multidisciplinary fields such as geometallurgy are beginning to tackle the challenge of translating these elements into measureable geological quality at the exploration stage; however, far more research of a much wider scope is still required (for example, can we translate specific social issues into measurable and mappable quantities?). This work will first require the development of an understanding of the empirical patterns that distinguish high-quality mineralisation from low-quality mineralisation, and then secondly will require a similar development in our ability to predict the occurrence of such mineralisation.

Exploring for high-quality mineralisation is likely to require a better understanding of the elements of mineral systems as a whole, rather than merely the parameters of deposit models. In turn this means that a minerals system approach to exploration is necessary, and it requires a better understanding of the following areas:

- **understanding 3D architecture by integrating geology and geophysics**
- **mapping effects of fluid flow**
- **identifying the signature of self-organisation of fluid flow**
- **understanding and mapping terrane fertility.**

Turning to the organisational challenges facing explorers and mine project developers in identifying high quality deposits, the requirement to connect various professional silos (geosciences, engineering, management, finance, environmental science, community engagement, etc) suggests that ‘boundary spanners’ will become increasingly important. Such people have the ability to bring together work from several fields to solve complex systems problems. Developing a sustainable and profitable mining operation from an initial discovery is a ‘type-example’ of a complex systems problem.

Companies and professional organisations should therefore focus on how to develop ‘boundary spanners’ within our currently siloed and profession-focused industry. Boundary spanners need to be developed from a young age, so the reliance on the current system of younger workers focusing in a silo with older professionals managing across silos may need questioning. Similarly, a change in opinion that generalists are merely failed specialists is required to encourage professionals into such roles which often require high, though different, cognitive abilities and skill sets.

Boundary spanners require the following cognitive abilities and experiences:

- high mental processing ability – the ability to connect apparently unrelated systems
- exposure to key ideas outside their field
- the ability to introduce key ideas from outside a field into a field allowing the reframing of a problem.

Two main types of boundary spanners are highlighted in this paper:

1. **outside-insiders** – who currently sit within a professional community and specialise on bringing outside ideas into the community, eg Arthur Holmes
2. **inside-outsiders** – who start outside a community and successfully bring ideas into the field and are thus accepted as part of the community, eg Alfred Wegener.

Connecting these two types of boundary spanner is important because the ‘outside-insiders’ can help bring potential ‘inside-outsiders’ into the community, for example, as Arthur Holmes (a geologist) did with Alfred Wegener (a meteorologist) and continental drift. The development of such boundary spanners is challenged by the current approach to education and professional development. In the case of geoscientists, we face the following challenges in becoming boundary spanners:

- geoscientists are separated into distinct exploration and mining streams
- geoscience is a different career path to engineering
- these disciplines are often in different organisational and geographical locations within a company
- the requirement for cross-disciplinary work is often missed – or unknowingly blocked – by organisations.

In the mining industry, the challenge now is to identify and nurture potential boundary spanners that can build critical links in particular between the (largely geoscientific) mineral exploration mindset and the (largely non-geoscientific) project development and sustainability mindset. The critical linkages to be built are between mineral system science, targeting science, and whole of value chain modelling.

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