What will it take to improve the characterisation of deep mineral deposits in order to assess "economic value" early in the discovery process?

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SUMMARY

In Australia, in particular, the consensus is that most, if not all, of the world-class non-ferrous mineral deposits that are either at or near the surface have been found. This means that we need to look deeper in the new greenfield search space characterised by thicker post-mineralisation cover. But in doing so the technical and financial risk increase considerably. One way of reducing the risk to be able to make an assessment of the "economic value" of any deep orebody much earlier in the discovery process. But what will it take to be able to achieve this? The answer lies in improving existing geophysical technology and applying it in novel ways, developing more effective 3D multi-modal inversions tightly calibrated to all available geological facts, and the application of machine learning approaches that permit robust assessment of uncertainty.

Key words: mineral deposits, economic value, geophysics, mining geophysics, borehole geophysics

INTRODUCTION

Across most non-ferrous commodities we are not finding enough high-quality resources to replace what we are mining. And this is despite the significant exploration expenditures over the years (Rio Tinto's latest discovery of copper-gold mineralisation in the Paterson Province not withstanding – it appears that the mineralisation is relatively shallow with 50-100 m cover, although not much information about the discovery is in the public domain). In Australia in particular, declining discovery rate is a function of the country's exploration maturity, meaning that most, if not all, of the world-class non-ferrous mineral deposits that are either at or near the surface have been found. This of course, has been affected by the disproportionate investment towards brownfield exploration where extensions to existing mineralisation have been discovered but not enough to replace aggregate reserves industry-wide.

When I refer to maturity, I am restricting it to those areas with little to minimal post-mineralisation cover. In Australia, this only represents some 30 percent of the continent. The corollary of this is therefore that there is an immense opportunity to expand the greenfield exploration search space to the remaining 70 percent of the Australian landmass. The implications are that we will need to look deeper to find the world-class deposit and that we will need to accept the increasingly technical and financial risk that it implies unless new technology and/or business models are developed to mitigate the risk. The need to look deeper of course also applies in brownfield areas as well – the advantage here, particularly near existing mines, is that the risks are lower and it is potentially more viable to develop lower grade deposits.

However, in my view to be successful in the new greenfield search space, it is not sufficient to improve the success rate in detecting deep orebodies. To make a major contribution to reducing technical and economic risk we need also need to be able to make some sort of assessment of "economic" value of the discovery as early as possible well before we embark on feasibility studies. Notwithstanding commodity prices, a deposit at depth can only be economically developed using current technology if it is large and high grade. To be sure in the future it may be possible to use in situ extraction which will open up much lower grade deposits to development, but this will be very site-specific. Although, such a technology can be readily adapted to deep block cave mining as well.

DISCUSSION

So, the question is, "*What will it take to improve characterisation of the deep deposits in order to asses "economic value" early in the discovery process?*". Given that post-mineralisation cover can reduce the effectiveness of traditional detection techniques, in my mind there only five things that collectively have the potential to assist us with this; geophysics, multi-modal joint inversion, the use of machine learning (or AI), a comprehensive database of geophysical properties, all backed up by an understanding of the geology. The former encompasses both surface/airborne, borehole to surface, and borehole to borehole geophysical techniques and of course wireline logging. If we can augment the above with smarter, quicker, cheaper drilling with real-time geochemistry using borehole analytical instruments even better.

I do concede, however, that application of novel geochemical technologies at the rig may well have something to say about the economic potential of the deposit by indicating where one is the mineralised system or its potential size for example. Furthermore, for us to make any headway in answering the question, conventional geophysics must be tightly intergraded with borehole information (both geological and geophysical). The question is what is the minimum number of holes required before we can make any such assessment with some degree of confidence?

Of course, this ignores the externalities, i.e. what investors may want to know before making appropriate investment decisions.

However, if we can make some decisions or at least be able to prioritise our targets based on some sort of "economic value early in the exploration process it would potentially be a great benefit because it will focus investment on those deposits that are most viable.

Firstly, let's define what we mean by some of the terms. What is deep? For the purpose of this discussion deep means below the economic open pit and underground limit. This is nicely illustrated in Figure 1 (AMIRA International, 2017)

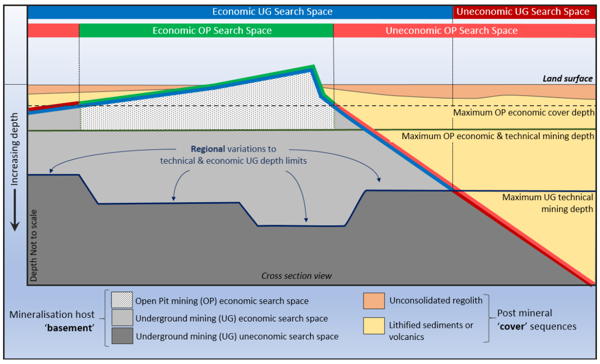

Figure 1. Economic search space for OP and UG mining.

The economic search spaces for open pit and underground mining varies from place to place – it also varies by the nature of the mineralisation itself. Obviously, understanding the economic portion of the undercover search space will enable geoscientists to focus their attention to those areas where future exploitation is realistically possible. It would be an important way of quarantining those areas that a simply too deep.

What is economic value? In answering this question, we can be guided by what is typically included in a pre-feasibility study. In addition to information relating to the geology and mine design, pre-feasibility studies look into factors that may impact or impede the development of the resource. Typically, pre-feasibility studies are undertaken after the delineation of a resource which means a lot of boreholes have already been drilled. A key objective of such studies is to assess the likely technical and economic viability of the resource. This would include the development of a geological model, resource model, reserve calculations and conversion, geotechnical assessment etc. Obviously defining the spatial variation of the important geologic variables and the structural context as early as possible is an important objective. However, the generally heterogeneous nature of the subsurface means that often we cannot sample sufficiently dense to be able to adequately characterise the spatial mineralisation in 3D and we, therefore, rely on geostatistical tools to alleviate this problem. Many geophysical techniques can help with this but some surface/airborne techniques are simply not applicable and even those that are applicable may not have the necessary measurement accuracy, resolution, sensitivity and precision to help in addressing the "economic value" question.

To truly assess the "economic value" of a resource one needs to thoroughly understand a whole set of variables about the resource – Table 1 lists some of these key variables as well some indication whether geophysics can help to map them.

Each geophysical technique responds to different (bulk) rock properties and has dissimilar:

- spatial resolution characteristics,
- depth of investigation (e.g. skin-depth in electrical geophysics),
- are affected in different ways by the characteristics of the overburden,
- require different field deployment strategies, and
- range from relatively cheap to expensive to deploy in the field.

Table 1. The geological parameters and how can geophysics can assist in defining them.

Geological variable	Which geophysical techniques can help?
3D spatial characteristics – i.e. geometry (mineable volume), and mineralised zones	In general, all surface/airborne geophysics can assist in defining the spatial dimensions of an orebody depending on the nature of the mineralisation. Both active and passive seismics (including tomography) can be applied including potential fields techniques, EM etc.
Structural setting – i.e. major & minor structures or fabric	All types of surface/airborne geophysics and their variants can assist in identifying the micro and macro structural setting of the orebody.
Nature of the mineralisation – lithology, alteration, weathering, chemistry, mineralogy, texture and deportment etc	It is very unlikely that surface/airborne geophysics will be able to assist with these parameters. If there is information from in situ sampling it is possible that borehole geophysics can potentially assist but only in mapping some of the macro characteristics that have appropriate geophysical proxies.
Grade of the mineralisation	Geophysics cannot generally assist; the exception is where proxies defined from in situ sampling with appropriate geophysical properties can be used in borehole geophysics.
Continuity of the mineralisation	Geophysics (surface/airborne and borehole) can generally assist in defining the continuity of mineralisation depending on the geophysical properties of the ore and host. Borehole EM, magnetics, gravity, radio and seismic tomography, GPR (surface and downhole) all have a potential role to play.
Geotechnical characteristics of the mineralisation and host rocks – e.g. intact rock strength, defect shear strength, rock mass strength, rock mass classification and the in situ stress state	Typically, only borehole geophysics can help to define the geotechnical parameters, and then only some of them, with any degree of confidence. For example, sonic velocity logging can yield a continuous in situ record of rock strength. However, using surface geophysics will require a degree of calibration with the results of in situ sampling and laboratory analysis.
Hydrogeology – e.g. location of aquifers relative to the orebody, hydrogeological units, hydraulic conductivities, flow regimes, phreatic surfaces, pore pressure distribution and water quality distribution	Geophysics, and particularly borehole geophysics, can potentially assist in defining some of the hydrogeological characteristics of the geological setting around the mineralisation. Borehole electrical, GPR (surface and downhole) have a role to play.
Nature of the and distribution of waste: gauge and deleterious minerals	Defining the characteristics of waste will require in situ sampling and laboratory analysis. This may reveal the presence of suitable proxies which may be mappable via borehole geophysics in the right circumstances.
Physical & metallurgical characteristics	Except in special circumstances and then only via borehole geophysics will it be possible to say something about the geometallurgical variables of a resource but they will need to be calibrated against in situ sampling and laboratory analysis.
Hazard detection	Radio and seismic tomography, and GPR (surface and downhole) and other techniques have a potential role to play in identifying potential hazards.

Notwithstanding the need for optimal field deployment, success with the geophysical techniques depends principally on a physical contrast between what we want to map and the host material. For example, in seismic surveys, the relevant parameter is acoustic impedance (a product of velocity and density), whilst in tomographic seismic surveys wave velocity changes is the principal parameter. As it has been shown, massive sulphides can generally "light up" seismically because of the acoustic impedance contrast but in a hard rock environment, the difference in seismic velocities between ore and host may be too subtle rendering seismic tomography potentially less useful, although it may be utilised to map in situ stress changes for example.

Of course, the other major difficulty with geophysics, particularly potential field techniques and to some extent dispersive field techniques as well, is the non-unique problem associated with inversion.

So how do we overcome the intrinsic deficiencies of geophysical techniques in order for us to be able to improve characterisation of the deep deposits in order to asses "economic value"?

Firstly, in my view there is a need to improve the measurement accuracy (to improve uncertainty), resolution (to enhance S/N), sensitivity (to able to measure small changes in properties), and precision (to ensure high reproducibility), of existing geophysical technologies as well as novel configurations – whether for surface, airborne or borehole applications. Although many existing technologies have reached the "flat" portion of the innovation S-curve, there may be novel technologies that need to be explored – for example utilising drones in ways that may enable new types of airborne data to be acquired more cost-effectively.

Secondly, we need to minimise the non-uniqueness problem by developing smarter 3D multi-modal joint-inversion algorithms. This means being able to utilise many different types of geophysical data from surface and borehole but tightly calibrated with the best geological information (what is known rather than what is the result of interpretation) including petrophysical data.

Finally, we could apply the new and emerging AI/machine learning technology to multiple data sets (geology, geophysics geochemistry etc). Certainly, the heterogeneous nature of many of the data sets poses challenges. However, in applying these algorithms, and there are many of them (from neural networks to logistic trees etc), we need to be cognisant that, generally speaking, they are not able to provide a robust assessment of the uncertainties associated with the resultant models. And despite the mathematical robustness of the algorithms, they focus on identifying correlations, not causation which means that they can identify patterns but cannot explain what gives rise to them. That is why data science without subject matter experts, i.e. geoscientist, is useless.

CONCLUSIONS

If we can improve geophysical technology, develop more effective 3D multi-modal inversions, and apply machine learning with appropriate enhancements to enable assessment of uncertainty we may have a real chance at improving our ability to characterise deep deposits in order to asses "economic value" early in the discovery process. In this way, we can make an informed decision early in the discovery process on what is technically and economically viable and thus significantly reduce risk.

REFERENCES

AMIRA International, 2017, Unlocking Australia's hidden potential - An industry Roadmap